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. To evaluate the spacecraft-plasma interactions quantitatively, we have been developing a proto model of "Geospace Environment Simulator" which consists of full-particle plasma simulation code and global MHD simulation code. By treating both electrons and ions as particles, we started to investigate influence of the heavy ion emission on the space plasma. For charge neutralization, thermal electrons are also emitted from the beam source. Preliminary results on the ion beam dynamics and the electron response have been obtained. Prior to the simulations we improved the efficiency of parallelization of the domain decomposition model of the 3D EM-PIC simulation code developed for the Earth Simulator. We successfully achieved 99.75% of the efficiency of parallelization. In addition, by global simulations with the 3D MHD model, we investigated the space plasma environment in which the ADEOS-II (Midori-II) received unrecoverable damage at the end of October 2003. We examined formation of the hot plasma region around the geosynchronous orbit just after the arrival of the shock in the solar wind.

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

1. Introduction

The geospace is a space surrounding the Earth, where electromagnetic dynamics of space plasmas plays dominant roles. The geospace environment is influenced by the solar activity through the interaction between the solar wind and the magnetosphere. In the geospace environment many spacecraft such as commercial satellites and space station are now in operation in the geostationary orbit (GEO) as well as in the low-earth orbit (LEO). In the near future, large-scale structure with high power/ voltage such as Space Solar Power System (SSPS) will be constructed and utilized. Since spacecraft surface is basically made of conductor and dielectric materials, it is influenced by dynamic variation of the ambient space plasma and suffered from charging and discharge. In addition, for the purpose of propulsion and potential control, some spacecraft actively emit plasma beam. In order to mitigate the influence of the space plasma as well as the plasma beam emission on the spacecraft, we need to understand the interaction process occurring between the spacecraft and the plasma environment prior to the actual space activities. Conventionally, vacuum chamber experiments have been conducted to test the spacecraft-plasma interactions. However, because of the limited size of chamber the results obtained in the experiments are easily affected by the chamber wall which is electrically grounded. Meanwhile, owing to the recent remarkable progress of computer technology, numerical simulation has become one of the powerful and important research methods in various fields. In the solar-terrestrial physics, space plasma simulation is recognized as the powerful and useful method for quantitative analysis of various plasma phenomena. In the current research project, we apply the conventional space plasma simulations to understand the spacecraft-plasma environment with Geospace Environment Simulator (GES).

GES is a numerical chamber for the research of spacecraft-environment interactions and the obtained results can contribute 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. To analyze the background plasma environment, we basically apply three-dimensional global MHD simulations. Interactions between the spacecraft and the plasma environment can be solved with particle model simulations.

In the present report, we show some preliminary results for the case of heavy ion beam and thermal electron emission for the charge neutralization obtained with 3D EM Particle-In-Cell (PIC) simulations. 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.

2. 3D EM-PIC simulation on heavy ion beam and thermal electron emission from ion engine

For the orbit-transfer of huge amount of materials for the SSPS construction from LEO to GEO, large-scale electric propulsion engine such as advanced ion engine has been studied as one of possible propulsion systems. In the previous study using 2D hybrid code, where ions are treated as particles and electrons as a fluid, we examined 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 to perform 3D EM-PIC simulation for this model in which both ions and electrons are treated as particles. Schematic illustration of the simulation model is displayed in Figure 1. We hired a domain decomposition model created by multiple nodes such as 8 cubic nodes maximum. In the center node, we assume an ion engine and emit ion beam and thermal electrons from a localized source region with the same amount of charge at each time step. Background plasma is uniformly placed and they are also solved as particles. Prior to the simulations we improved the efficiency of parallelization of the domain decomposition model of 3D EM-PIC simulation code. The efficiency of 99.75% has been achieved successfully.

Figure 2 shows snapshots of spatial distribution of ion beam and electrons at different times. Red and blue dots indicate ion beam and electrons, respectively. Considering the definition of ion flux $F_i = N_i V_{i0}$ and the net electron thermal flux $Fe = 0.25 N_e V_{the}$, where N_i, N_e, V_{i0}, and V_{the} denote ion and electron density, ion beam velocity and electron thermal velocity, respectively, $V_{the} = 4V_{i0}$ and $N_e = N_i$ have to be satisfied for the ion beam neutralization from the theoretical point of view. In the current simulations, however, we hired V_{the} which is smaller than V_{i0}. Therefore it is rather difficult for the emitted thermal electrons to neutralize the ion beam with the beam parameter adopted in the current model. Even this condition is satisfied, simple neutralization process cannot be applicable in the case with the external magnetic field B_0 along the z direction perpendicular to the beam direction. The emitted electrons have the Larmor radius of approximately 10 m and it is much smaller than that of the beam ion which has more than 10 km . The emitted electrons tend to be trapped by B_0 while ions can keep propagating along the x direction as shown in Figure 1. Then charge separation occurs between beam ions and electrons and intense electric field due to this charge separation can be induced. This electric field can affect the distribution of electrons continuously emitted along with ion beam. Although not dis-

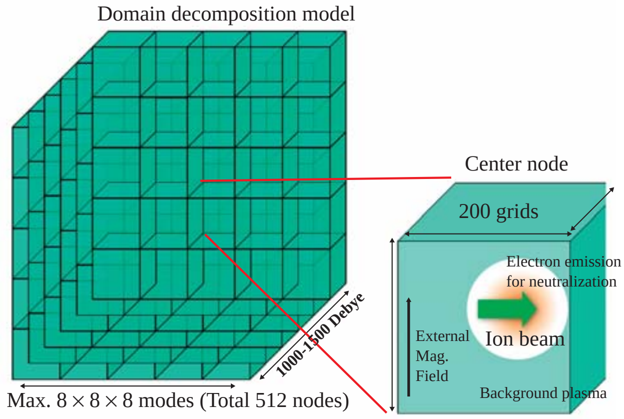

Fig. 1 Schematic illustration of Domain decomposition model for heavy ion emission.

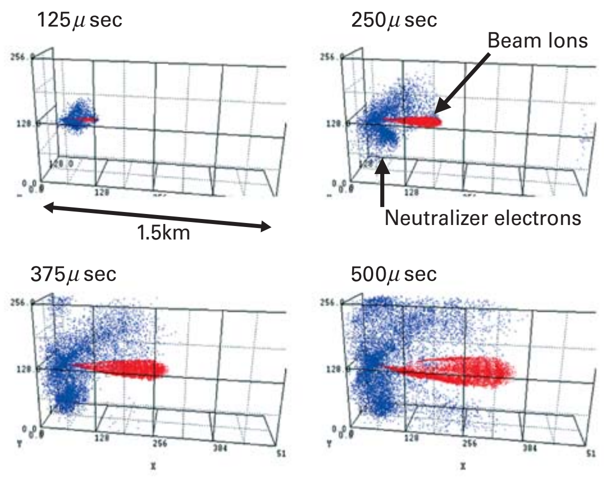

Fig. 2 Temporal evolution of ion beam (red) and electrons from the neutralizer (blue).

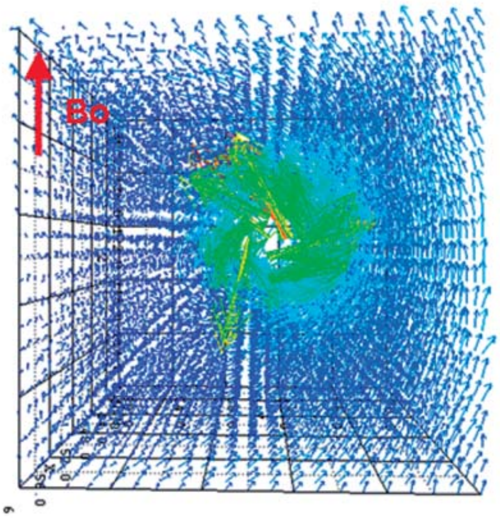

Fig. 3 Distortion of the magnetic field by intense ion beam current.

played, the background plasma, particularly electrons, are also affected by the ion beam dynamics and associated enhanced electric field in the vicinity of the beam source region, which should be analyzed in detail.

Figure 3 shows a snapshot of magnetic field defined at each grid point. Because of ion beam which is not fully neutralized with the background and neutralizer electrons, ion current becomes dominant at the beam region and induces intense magnetic field which rotates around the ion beam. This induced magnetic field can modify the dynamics of electrons and it becomes difficult for the background electrons to approach to the ion beam for the neutralization. The process of this electron response to the ion beam should be analyzed in detail, which is left as a future work.

In order to understand the influence of the plasma environment on the spacecraft surface, we need to introduce non-plasma interface representing spacecraft surface in the simulation domain. To obtain the simulation results which are reliable enough to be applicable to the actual design of ion engine or spacecraft, the spacecraft geometry treated in the simulation should be modeled as accurate as possible. The property of the surface material should be also considered in the simulation model, which is closely associated with photoelectron and secondary electrons from the spacecraft surface. In order to realize complex geometry of spacecraft in simulations, we started to develop EM PIC simulation code using unstructured grids last year. We already succeeded in generating unstructured grid system for several simple cases. We have been working on the implementation of a subroutine for solving the Poisson's equation to obtain the potential values at each grid point for the unstructured-grid model.

3. Space environment causing ADEOS-II damage

The three-dimensional MHD model, which treats the plasma as a single fluid described by MHD and Maxwell's equations, is a powerful tool to provide environments during an extreme solar condition in which unexpected problems in spacecraft devices tend to occur. Since last year, we have been working on the analysis of the specific space environment in which the solar battery panels onboard ADEOS-II (Midori-II) suffered a degradation of power supply at 16:13-16:17 UT on October 24 2003. Before the damage, a shock in the solar wind was estimated to have arrived at the nose point of the Earth's magnetosphere around 15:29 UT.

The 3D MHD model has been applied to investigate this problem. We used solar wind data obtained by the ACE spacecraft for the initial and boundary conditions of the model. The x component of interplanetary magnetic field (IMF) was ignored in this model. The important signatures found in the simulation are shown by polar plots of plasma velocity in Figure 4 and configuration of expanded magnetosphere in Figure 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. Although not displayed, we simultaneously found the plasma sheet twist caused by a variation in the y component of IMF from negative to positive value. Due to the sudden decrease of IMF during the variation of IMF By, dayside

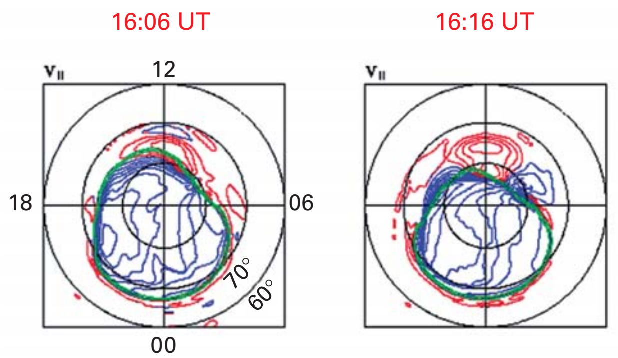

Fig. 4 Polar plots of velocity (parallel velocity in red) at 16:06 UT and 16:16 UT.

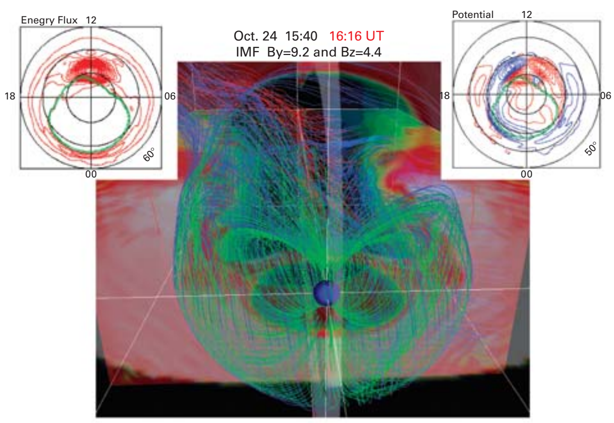

Fig. 5 Magnetospheric configuration and polar plots for the sudden decrease of IMF at 16:16UT.

reconnection decays, the magnetosphere expands and the open/closed boundary indicated by green line in Figure 4 shifts toward the high latitude around 70-80 degrees, which is shown around the dayside region in the right panel of Figure 4. Then the region of the field-aligned plasma entry with parallel velocity indicated in red contour is also shifted at the high latitude region. This plasma entry could be closely related to the drastic change of the space environment at the ADEOS-II orbit.

In order to examine the cause of the unexpected failure of spacecraft, it is very important to know the background plasma environment of the spacecraft orbit. The current global plasma simulations can play an important role in understanding the dynamic evolution of the background plasma environment.

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宇宙開発・利用に不可欠な飛翔体環境の定量理解とその宇宙技術開発へのフィードバックを目指し、実際的な宇宙仮想実験を行う数値チェンバーとして「宇宙環境シミュレータ」を構築することが本プロジェクトの目的である。本年度は、まず、新規に開発を行った領域分割型3次元電磁粒子シミュレーションコードを用いて、イオン推進エンジンからの排出重イオンによる地球磁気圏への影響に関するシミュレーションを開始し、低軌道から静止軌道上への大規模宇宙構造物（例えば宇宙太陽発電システムSSPS）輸送において利用される大規模イオン推進エンジンからのイオン放出に対する宇宙空間の環境応答の定量解析に着手した。計算機実験に先立ち、3次元電磁粒子コードの並列化効率を99.8978%まで向上させた。初期結果からは、イオンビーム放出初期において電荷中和のため放出された電子が地球磁場の影響を受けるためイオンビームを中和しきれず、イオンビーム電流による大きな電磁界擾乱が発生することが確認できた。また、様々な形状をもつ宇宙飛翔体をできるだけ正確にモデル化するために非構造格子を採用したコード開発を開始した。既存の格子生成ツールを用いて衛星形状を含めたシミュレーション領域全体の非構造格子化を行うことができるようになった。 一方、太陽活動度変動に起因する宇宙環境変動が飛翔体に及ぼす影響を定量的に調べるためにはその背景となる宇宙環境のモデリングを定量的に行う必要がある。2003年10月末に起きた環境観測技術衛星「みどり2号」の故障原因を探るべく、太陽風観測衛星「ACE」で実際に観測された太陽風データを入力値として地球を取り囲む宇宙環境の3次元MHDグローバルシミュレーションを前年度に引き続き行った。その結果、故障に先立ち、太陽風変動により地球磁気圏前面における衝撃面の形成、これによる磁気圏圧縮、磁気圏尾部からみどり2号軌道付近への高エネルギープラズマ流入に関して惑星間空間磁場の時間変動と関連付けて確認することができた。

キーワード：ジオスペース，宇宙プラズマ，粒子コード，MHDコード，宇宙飛翔体環境