3-6 Space Weather Research with Computer Simulations

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Computer simulations in space weather researches are reviewed. We introduce two different points of view and methods of the computer simulation, which are characteristic of the space weather simulations: One is the view from global macro-structure and the other is the one from fundamental micro-structure.

Keywords
Space weather, Plasmas, Computer simulation

1 Necessity of simulation

In recent years the behavior of space plasma near the earth has come to be referred to as "space weather," in consideration of its effect on human life. Generally phenomena produced by the space plasma are complicated, and provide rich sources of nonlinear phenomena for study. For example, both magnetic storms and substorms are so diverse in generated processes, regions, characteristic length scales, characteristic time scales, and coupling processes that the causal relationship between each process remain poorly understood in many ways. In particular, macroscopic phenomena (with characteristic lengths comparable to the radius of the earth or larger) and microscopic phenomena (with characteristic lengths of a few meters) are known to interact in cases where it is difficult to separate cause from effect clearly. To understand such phenomena, computer simulation has proven extremely effective and has been used to produce results both in Japan and overseas. If the coupling between macroscopic phenomena and microscopic phenomena can be clarified, it will contribute greatly to quantitative evaluation of space weather phenomena, forming the first step toward the realization of numerical forecasts.

Although the term "simulation" is used with various meanings, here the author would like to define it as solving combined derivative equations describing physical phenomena numerically using computers after differentiating the equations. In the case of space weather phenomena, simulation involves solving a system of equations that describes the plasma. In many cases, the simulation may involve tracking the temporal development of the plasma.

Thanks to recent improvements in computer calculation speeds, larger-scale simulations have been performed. In the study of space weather phenomena, since it is impossible in practice to deploy observation apparatuses everywhere in space, simulation has played a significant role. This paper gives a general view of the research aimed at understanding space weather phenomena through techniques of computer simulation. More specifically, this paper introduces two positions specific to the simulation of space weather: simulations that place weight on global (macroscopic-scale) processes and simulations that place weight on fundamental (microscopic-scale) processes.

2 Techniques of simulation

Depending on the system of equations to be solved, the method of simulation may vary.

In the same way that many introductory textbooks on plasma physics adopt a three-part structure addressing the motion of charged particles, magnetohydrodynamics, and plasma kinetics, plasma simulations are broadly grouped into three methods corresponding to these segments. For the motion of charged particles, simulation is designed to track the trajectories of charged particles by solving an equation for the motion of charged particles within a given electromagnetic field. Although this simulation may assume one of several forms (depending on which adiabatic invariant is preserved and whether the equation is solved in real space or in phase space), it can be applied only to plasma for which the temporal development of the electromagnetic field is known beforehand. In this respect, this type of simulation is only marginally suitable for research into space weather phenomena, and its use is thus restricted.

Magnetohydrodynamics simulation is designed to solve a system of fundamental equations of magnetohydrodynamics, and particle simulation is based on a system of fundamental equations of plasma kinetics. Both simulations share a common point in that the Maxwell equations (describing the electromagnetic field) and the equation of motion (describing the motion of plasma) are coupled and solved.

2.1 Magnetohydrodynamics simulation

In magnetohydrodynamics, the plasma is approximated as a fluid, and the Navier-Stokes equation (in which the electromagnetic force is included) is used. Normally, since the phenomena under study display slow temporal variation, an approximation is used in which the displacement current term is ignored in the Maxwell equations. These equations are coupled and solved.

Magnetohydrodynamics simulation is performed according to the same technique as would apply to simulation of a neutral fluid with the inclusion of an electromagnetic field. Therefore, the simulation method for neutral fluids has been applied to magnetohydrodynamics simulation as is. In space weather research, although a combination of finite difference and the two-step Lax-Wendroff method has often been used[1], TANAKA has achieved highly accurate calculations through the application of the TVD method to magnetohydrodynamics simulation for systems with a potential magnetic field[2].

2.2 Particle simulation

Particle simulation is performed by solving kinetic equations for the particles that constitute the plasma[1]. Usually, a method referred to as "particle-in-cell" is used, and it is known that with this method the kinetic effect can be investigated in a simulation with a much smaller number of particles than in the actual plasma[3]. This is because in these cases we are studying phenomenon on a scale larger than the Debye length; hence it is sufficient to calculate only the motion of a particle, referred to as a super-particle, that is large enough to study on a scale greater than the Debye length. Even with this method, a huge number of particles must be treated; particle simulation thus requires much more computer memory and calculation time than in magnetohydrodynamics simulation.

Further, there is an intermediate method lying between these two methods, referred to as "hybrid simulation," which includes both fluid and particle calculations[4]. Using hybrid simulation in space weather research, ions constituting the plasma are treated as particles and electrons are treated as a fluid. The method has its merits in that a quasi-neutral condition can be imposed through the stipulation that the density of electrons and that of ions are equal at any grid, respectively. Furthermore, since electrons are treated as a fluid, this method has the advantage that small-scale temporal or spatial variations (such as plasma oscillation of electrons and the Debye length) do not need to be taken into account. Therefore, a time step and a grid can be large relative to particle simulation. On the other hand, this method cannot handle the electron effect or other phenomena on scales equivalent to the ion Larmor radius or smaller.

2.3 Proper use

Proper use of these various simulation methods is dependent mainly on the time scale and spatial scale of the plasma to be handled. Magnetohydrodynamics simulation is used for phenomena on a spatial scale larger than that of the ion Larmor radius and on a time scale longer than the ion cyclotron period. On the other hand, particle simulation is applicable to phenomena on any scale but requires a huge amount of computation. Therefore, it is often the case that phenomena on a macroscopic scale are treated using magnetohydrodynamics simulation while particle simulation is applied to phenomena on a microscopic scale. In the case where particular emphasis is placed on phenomena on a scale comparable to the ion Larmor radius, the hybrid code is used.

Recently in the field of particle simulation, a calculation method has been developed that, using implicit time integration, allows the user to disregard phenomena on small temporal or spatial scales, such as the plasma oscillation of electrons and the Debye length[5].

3 Global processes and fundamental processes

Simulation is performed in such a way that essential quantities that characterize the system in question are selected from the actual system; a combination of these quantities are then represented on a computer. If the quantities thus selected are larger in number and are more essential than those of other simulations, the simulation is judged to more closely describe reality. That is, depending on the manner of selecting the quantities in question, a variety of systems of simulation can be established. Concretely, the selection of quantities includes a consideration of the size of the system (for example, whether the simulation is for a small region or for a system that includes the entire earth), whether the simulation takes some forces and chemical reactions into account, and so on. The simulation of space weather research is divided broadly into global simulation and fundamental process simulation, based on the system size.

Global simulation handles large systems that include the earth or the sun and is characterized by its handling of the subject system as a complex system of regions of different characteristic temporal and spatial scales (solar wind, the magnetosphere, and the ionosphere). Since this type of simulation deals with large systems, the magnetohydrodynamics simulation method is adopted. The critical element of this research lies in the interaction between regions and the topology of accompanying magnetic field lines. Global simulations in recent years have advanced our understanding of the reconnection between the interplanetary magnetic field and the earth's magnetosphere and of the structure and origin of the magnetospheric convection[6].

In fundamental process simulation, the main objective is to gain an understanding of the physics of fundamental processes produced in space by performing particle simulation for a small region. Specifically, research activities are being conducted relating to the reconnection of magnetic field lines, collisionless shock waves, and so on. Particle simulation has previously proven very useful in the examination of the diffusion of space plasma and of particle acceleration through research into the reconnection of magnetic field lines, collisionless shock waves, and other phenomena. Research continues in this area, as the results of particle simulation can be compared with data from in-situ satellite observation, fed back to basic physics and applied to astrophysics[5].

4 Bu approach and Ej approach

There are two approaches to the interpretation of space weather phenomena : the Bu approach and the Ej approach. The Bu approach is based on the magnetic field (B) and velocity (u), whereas the Ej approach is based on the electric field (E) and current (j).

Generally, global simulation takes the Bu approach and fundamental process simulation adopts the Ej approach.

In magnetohydrodynamics, a system can be described with eight independent variables, including density and pressure. Depending on the elements selected for the remaining six parameters (i.e., two parameters in a vector notation) besides density and pressure, either of the above-mentioned two approaches may be applied. Both approaches are equivalent, but provide different ways of observing the phenomenon in question. In ideal magnetohydrodynamics, in which electric conductivity can be considered infinite, the Bu approach should be taken[7]. At first glance, the Ej approach is appealing in its simplicity, as it is based on the principles of the electric circuit. However, when the plasma is regarded as a simple electrical circuit, it becomes easy to overlook the fact that fluid motion and pressure variation play important roles[8]. In addition, E and j can be found by vector calculation and differential calculation, as follows:

$$E = -u \times B$$

$$j = (1/\mu) \text{ rot } B,$$

where μ is permeability. However, the reverse process requires integration operation; therefore, the Bu approach is, theoretically, the natural approach to ideal magnetohydrodynamics.

Taking magnetosphere-ionosphere coupling as an example, the Ej approach considers that a convection electric field of the magnetosphere is projected on the ionosphere through equipotential magnetic field lines, whereas the Bu approach considers that the Maxwell stress accompanying convection motion acts on the ionosphere. The Bu approach makes it easier to take field-aligned current and pressure variation into consideration.

However, the Bu approach is workable only in cases of ideal magnetohydrodynamics, in which electric conductivity is infinite, and where the "motion of the magnetic field line" can be defined[9]. In particle simulations that include the kinetic effect, the Ej approach can be used as a basis of calculation. When the kinetic effect is included, the distribution of plasma particles is not necessarily a Boltzmann distribution, and it is often the case that defining the velocity u makes no sense. This is because the current j creates the magnetic field B and what performs work is not the magnetic field B but the electric field E.

5 Calculation examples

As there are many references dealing with simulation results, here we will present part of the researches of the Communications Research Laboratory. In terms of global simulation, reference[8] provides a detailed account.

In particle simulation, electron dynamics in a collisionless shock wave were examined [10]. Fig.1 shows a phase-space distribution of electrons and ions in the plane of a shock surface and the electromagnetic field. In the uppermost figure, a vortex of electrons in the phase space can be seen. This vortex of electrons is the result of nonlinear development of strong two-stream instability that occurred between ions that were reflected by the shock surface and incoming electrons, and represents one of the actual states of a shock diffusion mechanism. Although the shock surface is considered to have a thickness of almost zero in magnetohydrodynamics, the figure indicates that microscopic structural dynamics are present in this thin layer. Furthermore, although a value of diffusion must be assumed in magnetohydrodynamics, particle simulation allows the diffusion to be determined from the results of the simulation.

The interaction between the solar wind and a planet was examined in hybrid simulation[11], to determine the ways in which a microscopic process affects a macroscopic process. A reaction referred to as "charge exchange" was selected as the microscopic process, and the asymmetry of the shock wave in the direction of the electric field was selected as the macroscopic process. Under the magnetohydrodynamics approach, such asymmetry in the electric field direction does not appear. However, from observations of Venus, it has been determined that such asymmetry is present in small proportions[12]. Results of the simulation proved successfully that such asymmetry may be produced by charge exchange (Fig.2).

6 Future Objectives

When considering simulations from the viewpoint of space weather, numerical forecasts should be the goal, as with terrestrial weather forecasts. To achieve this, both global processes and fundamental processes must be included within a single model. This is because if either the subject of global simulation (the topology of magnetic field lines and coupling of regions) or the subject of fundamental process simulation (diffusion and particle acceleration) is assumed and entered into the simulation as a parameter, space weather phenomena will not be reproduced consistently by the simulation in question. This indicates that in this context the combination of macroscopic phenomena and microscopic phenomena is essential.

However, for the moment, it is not realistic to include both global processes and fundamental processes in a single model because of the complexity such a model would present and the vast amount of computation required. As a realistic alternative, a method is under study whereby each of the various regions involved (the sun, the solar wind, the magnetosphere, the plasmasphere, the radiation belt, etc.) is calculated using a separate model and the results are combined using a given method. Presently this approach does not seem to work well. One of our main goals in the future is to determine how different regions are coupled and how phenomena of different scales are coupled; in this way we will be able to unify global processes and fundamental processes.

It is also important to link simulation results with observation. Through comparison with observation data, the simulation results can be verified. Moreover, simulations in which conditions can be set freely represent indispensable tools in the understanding of the essential elements of observation results. Furthermore, such comparison enables prediction of phenomena that have not yet been observed and can suggest future subjects of observation. If accurate simulations become feasible, it will be possible to supplement insufficiencies in observation, and, in some cases, to replace observation.

Although we have not yet addressed the

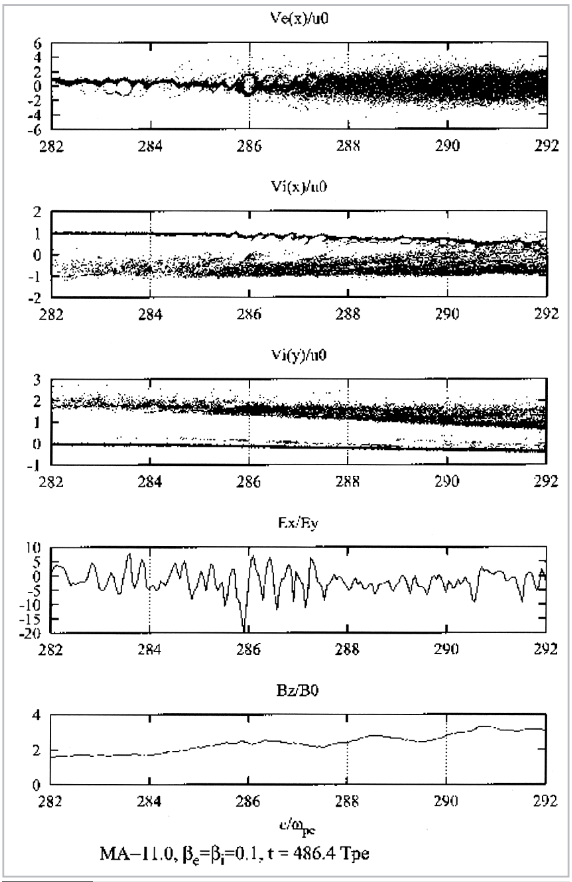

Fig.1 *Results of particle simulation on collisionless shock wave*

The figures show the internal structure of a collisionless shock surface. From top to bottom, the x-component of electron velocity, x-component of ion velocity, y-component of ion velocity, x-component of the electric field, and the z-component of the magnetic field are shown. Each is normalized with a suitable value. The horizontal axis represents x-coordinates.

issue, the technical aspects of numerical calculations are also important. For example, since a determination as to the shape and size of the generated grid affects simulation accuracy and computation, a careful examination of these elements is required. The shape and size of the grid must be set appropriately, to represent the physical phenomenon under study most accurately.

Improvements in calculation speed achieved in recent years are greatly due to parallel processing, in which a large number of computer processors are used simultaneously. Parallel processing technology has advanced not only in supercomputers but also in personal computers, while an approach referred to as grid computing has also begun to attract attention. In simulation research it is always necessary to keep pace with the evolution of computer technology.

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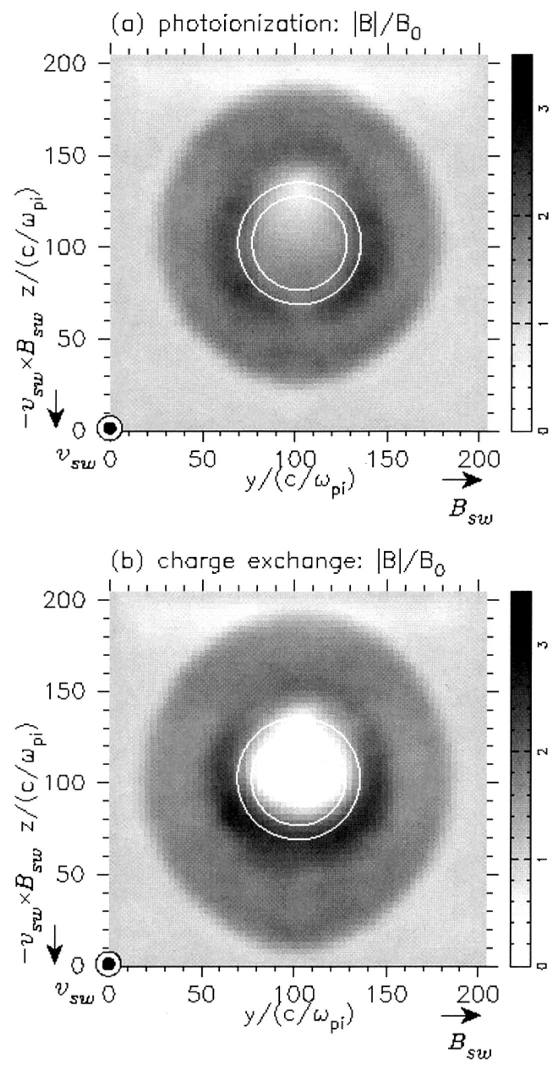

Fig.2 *Results of hybrid simulation of the interaction between the solar wind and Venus*

This figure shows the magnitude of the magnetic field in a cross section normal to the direction of the sun (as viewed from the center of the planet). The inner circle represents the planet and the outer circle represents the region in which chemical reactions occur. It was found that (a) the inclusion of a photo-ionization reaction causes the expansion of the reverse side of the electric field (upper part of the diagram), and (b) inclusion of a charge-exchange reaction causes expansion of the side facing the electric field (lower part of the diagram). From reference[11]. Copyright [2001] American Geophysical Union. Modified by permission of American Geophysical Union.

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