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MHD–PIC connection model in a magnetosphere–ionosphere coupling system

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Abstract. A new simulation model is developed, in which the interaction between the macroscopic and microscopic plasma processes is able to be taken into account self-consistently. Magnetohydrodynamic (MHD) simulation and particle-in-cell (PIC) simulation are directly connected and performed simultaneously. This MHD–PIC connection model is first applied to the study of the quiet auroral arc formation process. It is an example of our challenge to create the *holistic* simulation framework, that is, the heterogeneous schemes that can be unified by the state-of-the-art numerical technique. In this paper, we will explain the algorithm of our new model and show the results which have been calculated on the Earth Simulator.

1. Introduction

Although many kinds of simulation models have been developed to understand the complex plasma systems, the physical process and the spatial-temporal scales included in the simulation must be restricted by the fundamental assumption of each model. In addition, the multiple scale coupling may play a crucial role in some plasma phenomena. Magnetosphere–ionosphere coupling is a typical example. The large-scale magnetohydrodynamic (MHD) instability of the Alfvén wave resonance instability may be modified with the kinetic plasma process of the electron acceleration in the double layer (DL) structure. The ionization process by the accelerated electron increases the ionosphere plasma density. Therefore, the ionospheric condition as the Alfvén wave resonator should be modified by the kinetic effect. Another example of the multi-scale plasma phenomena is magnetic reconnection, in which the large-scale field structure is controlled by the kinetic process in the diffusion region. The anomalous resistivity must be generated by the micro-instability in particle dynamics.

In the conventional way, the micro-processes such as the ionization process and the anomalous resistivity have to be included in the macro-process simulation as an empirical rule. The empirical parameters are independently calculated in micro-simulations and should be tabulated. In this case, the macroscopic variables are included in the microscopic simulation as the initial/boundary conditions. It may work if the characteristic timescale of the micro-process is quite a lot shorter than the timestep size of the macro-simulation. However, if the temporal scale of the micro-process is of the same order as or longer than the timestep size of the macro-simulation, the empirical parameter is not enough to take the multiple

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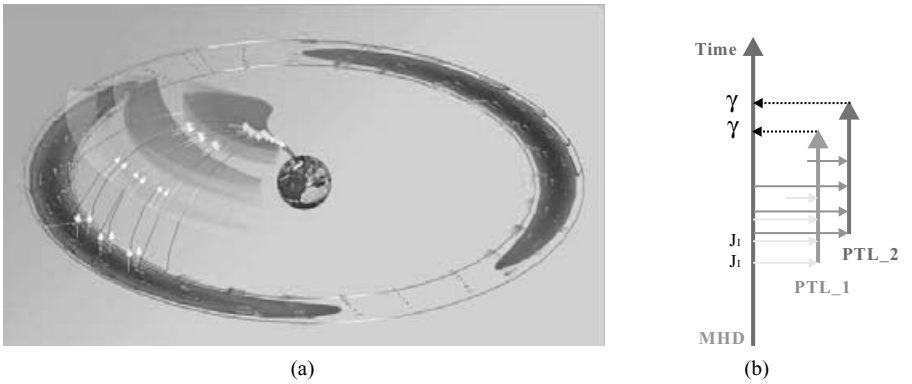


Figure 1. Schematic illustration of (a) the simulation spatial configuration and (b) the time sequence in the connection model.

scale processes into account. This is because the hysteresis of the micro-process affects the dynamics. In order to capture the hysteretic information, we have to make time-dependent tables, but this is not realistic because of their huge size. Moreover, when the temporal scale of these micro- and macro-processes is overlapped, the modulation of spatial scale should be considered because a MHD wave could propagate into/from other area. One of the ways to avoid this difficulty is the self-consistent scale-coupling model, where both the micro- and macro-simulations are simultaneously performed. In this paper, we explain the algorithm of the first simultaneous simulation model and show the results of the application to the magnetosphere–ionosphere coupling problem to understand the quiet auroral arc formation process.

2. Simulation model and algorithm

The equations and the boundary conditions used in the MHD simulation are essentially the same as those given by Watanabe and Sato (1988) except for the coordinate system. We have applied the *modified dipole coordinate* reported by Kageyama et al. (2006). This coordinate can redress the disproportionate distribution of grid points by equalizing the steepened metric distribution along the magnetic field line in the conventional dipole coordinate. We assume that the density changes as a function of the magnetic field strength, so that the Alfvén speed is constant in space. The simulation box is the three-dimensional annulus region bounded by two flux surfaces of the dipole field rooted at the different latitudes (70° and 72°) on the ionosphere, as shown in Fig. 1(a) left. The latitudinal boundaries aligned with the magnetic field lines extending from the ionosphere to the equatorial plane, on which the symmetric condition is applied and the cross-equatorial flow is inhibited. On the equatorial plane, however, the twin-vortex plasma flow is supposed to be driven by the Solar wind, and thus the positive and negative twin-vortex potential pattern is imposed in the dawn and dusk side, respectively. This potential pattern causes field aligned current running into/out of the ionosphere in the dawn/dusk side through the Alfvén resonance instability (Sato 1978). The ionosphere can be represented by a slab model, i.e. the ionospheric dynamics are described by height-integrated equations. One of these equations is

$$\frac{\partial N}{\partial t} + \nabla \cdot \left(N \frac{\mathbf{E} \times \mathbf{B}}{B^2} \right) = J_{\parallel}/e - \alpha\left(N^2 - N_0^2\right) + \gamma(J_{\parallel}) \tag{2.1}$$

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where N and N_0 are the height-integrated plasma density and its initial value, and **E** and **B** are the ionospheric electric and magnetic field. J_I is the field aligned current calculated in the MHD model at the ionosphere height. α is the recombination factor and γ is the function of the ionization process caused by the accelerated electron in the DL structure. It is our main subject to determine the ionization function γ not by the empirical procedure but by the self-consistent MHD–PIC connection model.

The particle-in-cell (PIC) simulation is performed by a one-dimensional electrostatic full-particle code in initial ion rest frame. The dynamics of both electrons and ions are simulated. The spatial coordinate is aligned to the magnetic field. In our model, the upward field-aligned current excites the ion-acoustic waves by the downward electron beam. The excited ion-acoustic waves nonlinearly develop into a DL structure, in which electrons are accelerated. The electron beam velocity V_e is calculated from J_I as $V_\mathrm{e} = J_\mathrm{I}/(eN_\mathrm{I})$. N_I is a plasma density at the upper ionosphere where the DL is formed. The drifting electrons of V_e are continuously injected from one boundary of the magnetosphere side corresponding to the temporal variation of J_I. Therefore, through the electron injection speed V_e, the macro-simulations are connected to the micro-simulation. The accelerated electrons can ionize neutral gas when they are precipitated into the ionosphere, and then the ionospheric plasma density is increased in time. The time sequence of γ is calculated from the results of micro-simulations, that feed back to the MHD instability. Several PIC simulations are carried out simultaneously, when J_I at some point on the ionospheric boundary exceeds a criterion of the field aligned current (J_Ith) for the ion-acoustic instability to create the DL structure. As a result of that, the connection between the MHD and kinetic effects in the auroral arc formation process can be handled more accurately than the conventional method based on an empirical scaling between the electric current and the ionization rate.

The program is parallelized using the Message-Passing Interface (MPI). By splitting the global communicator of MPI, MHD or PIC code runs in individual communicators. In each communicator, MHD or PIC code is also parallelized using MPI. In our MHD–PIC connection model, the main time sequence is in the scale of MHD (see Fig. 1(b)). A PIC simulation starts when the electric current density at a grid point on the ionospheric boundary in MHD code exceeds a criterion ($J_\mathrm{Ith} < J_\mathrm{I}$) and stops when the current density decreases ($J_\mathrm{I} < J_\mathrm{Ith}$). The current information of J_I in MHD code is continuously sent to PIC code and the boundary condition of PIC code is changed in time. The information of γ obtained in PIC code is sent to MHD code. These information of J_I and γ are iteratively exchanged with time integration of the macro-simulation. One of the key areas is a timestep synchronization. Generally, the characteristic time scale of PIC code is smaller than that of MHD code. In the present work, we have balanced the load in both codes by only changing the amount of resources for calculation in each code. This is realized by the highly parallelized PIC code. The number of resources of PIC code is three times larger than that of MHD code. In addition, since the grid width at the ionosphere is quite a lot shorter than that in the other region, the timestep size (Δt_MHD) of MHD code determined by CFL condition is so smaller than the characteristic Alfvén transit time (τ_A), that is, $\Delta t_\mathrm{MHD} \sim 10^{-4}$–$10^{-5}\tau_\mathrm{A}$. This is only about a hundred times of the inverse of the plasma frequency (ω_pe) in the present PIC model, that is $\Delta t_\mathrm{MHD} \sim 100/\omega_\mathrm{pe}$.

Figure 2 shows the results from our connection model. Plotted are the distribution of the ionospheric density variation. Figure 2(a) (Fig. 2(b)) shows the case with (without) the γ function in the above equation. The ionospheric density is enhanced with striated structure in the longitudinal direction. In addition, in Fig. 2(a), the

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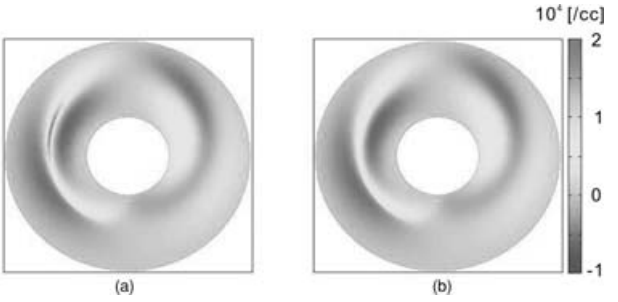


Figure 2. Simulation results. The plasma density distribution of the ionosphere (a) by the MHD–PIC connection model and (b) by the MHD-only model without the PIC mode.

density is locally enhanced by the ionization function γ. Therefore, the ionosphere condition as the Alfvén resonator is modified.

3. Discussion

We have developed a *holistic* simulation algorithm and have performed the micro- and macro-scale simulations simultaneously which are connected with each other. Information is frequently exchanged between the two different models, so that the multi-scale interaction is able to be taken into account self-consistently. We have composed the connection program using only normal MPI. The task schedule and information exchange methods are well managed to reduce the communication time and to improve the load balance. In the present work, one of the most challenging points has been to create the time-synchronization algorithm. Since the characteristic timescale of micro-simulation is generally much shorter than that of macro-simulation, the macro-simulation should wait until the calculation of the micro-simulation is computed. In this case, however, the overall calculation time becomes very long because of the waiting. To avoid this waiting in the present work, we have developed a highly parallelized code for micro-simulation and have used a number of MPI tasks for micro-simulation. It is still as open question what is the more generic method to integrate the time with time synchronization.

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