S12-6

Global Vlasov Simulation of a Weakly-Magnetized Small Body
弱磁化小天体のグローバルブラソフシミュレーション

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The interaction between the solar wind and solar-system bodies, such as planets, satellites and asteroids, is one of the fundamental global-scale phenomena in space plasma physics. In the present study, electromagnetic environment around a small dielectric body with a weak intrinsic magnetic field is studied by means of a five-dimensional full electromagnetic Vlasov simulation with two configuration spaces and three velocity spaces, which is a challenging task in space plasma physics as well as high performance computing. The direct comparison between the low- and high-resolution runs would show importance of fully kinetic global simulations.

1. Background

The electromagnetic environment around a solar-system body is formed by the interaction between the solar wind and the magnetosphere of the body. The structure and dynamics of the electromagnetic environment are quite different depending on the strength of the intrinsic magnetic field and the condition of the surface of bodies. The intrinsic magnetic field generally acts as an obstacle to the solar wind. When the intrinsic magnetic field is weak, ionized gases from the upper atmosphere of a body act as a conducting obstacle. When a body has neither intrinsic magnetic field nor atmosphere, on the other hand, the solar-wind plasma directly impacts the body. The Earth's satellite Moon is one of examples for a dielectric or insulating body without intrinsic magnetic field and atmosphere.

The interaction between the solar wind and an unmagnetized body is one of fundamental “global-scale” issues in space plasma physics. This process is conventionally studied by means of MHD simulations where all the plasma particles are treated by the single-fluid approximation. On the other hand, one of major purposes of the present study is to extend the conventional single-fluid simulation to a first-principle kinetic simulation [1-3], which is a challenging task in space plasma physics as well as high performance computing.

2. Method

We use a parallel full electromagnetic Vlasov code [4], which solves the full set of the Maxwell equations (1) and the Vlasov equation (2),

$$\left.\begin{aligned}\nabla\times\mathrm{B}&=\mu_0\mathrm{J}+\frac{1}{c^2}\frac{\partial\mathrm{E}}{\partial\mathrm{t}}\\ \nabla\times\mathrm{E}&=-\frac{\partial\mathrm{B}}{\partial\mathrm{t}}\end{aligned}\right\},\quad\left.\begin{aligned}\nabla\cdot\mathbf{B}&=0\\ \nabla\cdot\mathbf{E}&=\frac{\rho}{\epsilon_0}\end{aligned}\right\}\tag{1}$$

$$\frac{\partial f_s}{\partial t}+\mathbf{v}\cdot\frac{\partial f_s}{\partial\mathbf{r}}+\frac{q_s}{m_s}(\mathbf{E}+\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_s}{\partial\mathbf{v}}=0\tag{2}$$

where $\mathbf{E},\mathbf{B},\mathbf{J},\rho,\mu_0,\epsilon_0$ and c represent electric field, magnetic field, current density, charge density, magnetic permeability, dielectric constant and light speed, respectively. The Vlasov equation (2) describes the development of the distribution functions by the electromagnetic (Lorentz) force, with the collision term in the right-hand side set to zero. The distribution function $f(t,\mathbf{r},\mathbf{v})$ is defined as a function of time t, position $\mathbf{r}$ and velocity $\mathbf{v}$ with the subscript s being the species of singly charged particles (e.g., $s=i$ and e for ions and electrons, respectively). The quantities q_s and m_s are the charge and the mass of the particle species s. By integrating the Vlasov equation (2) over the velocity $\mathbf{v}$ and getting the sum for all the particle species s, the continuity equation for charge is obtained, which describes the necessary condition for the electric current density,

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\mathbf{J}=0\tag{3}$$

These equations are regarded as the “first principles” of the collisionless plasma.

Our Vlasov code solves two spatial dimensions (x,y) and three velocity dimensions (v_x,v_y,v_z). The numerical schemes are based on a conservative semi-Lagrangian scheme with several recent improvements [5-8] and hybrid parallelization with MPI and OpenMP [9]. The details on the numerical schemes are found in the literature [4].

The detailed simulation parameters and setting are described in the literature [3]. Even with the fastest supercomputer in the world in 2014, it is impossible to use the realistic physical parameters of the Moon in the first-principle full kinetic simulation. Hence, the radius of the body is "reduced" to be $R_L \sim 2.72$ km, which corresponds to a typical size of an asteroid.

In the present study, we compare two simulation runs. One is the low-resolution run [3] and the other is the high-resolution run performed on the K computer. In the low-resolution run, the spatial grid size is set to be $\Delta x = \Delta y = 10\lambda_{Di}$ and total of $N_x \times N_y = 160 \times 240$ grid points are used for the two spatial dimensions. In the high-resolution run, the spatial grid size is set to be $\Delta x = \Delta y = \lambda_{Di}$ and a total of $N_x \times N_y = 1920 \times 2560$ grid points are used for the two spatial dimensions. A total of $N_{vx} \times N_{vy} \times N_{vz} = 60 \times 60 \times 60$ grid points for the three velocity dimensions in both runs.

3. Result and Summary

Figure 1 shows the temporal development of the ion density together with the configuration of magnetic field lines as a result of the interaction between the solar wind and a small dielectric body with a weak intrinsic magnetic field. The location of the inner boundary is indicated by the magenta circle at the center of the simulation box.

At $\omega_{ci}t = 0$, the simulation box is filled with the solar-wind plasma propagating from the left to the right. The magnetic field lines are open on the nightside while they are closed on the dayside. As the time elapses, a very-low-density region is formed on the nightside by absorption of the solar-wind plasma on the surface of the body, which is known as the wake tail. The configuration of magnetic field lines is also modified to follow the shape of the wake tail. On the dayside, on the other hand, a high-density region is formed which indicates the formation of a bow-shock-like structure by the compression of the solar-wind plasma by the intrinsic magnetic field of the body. The profile of ion density shows asymmetry with respect to the x axis. The system reaches almost the quasi-steady state at $\omega_{ci}t = 6$.

One can easily find from the square blocks around the body that the result in the top panels is obtained by the low-resolution run. It may be surprising, even for those who are familiar with plasma physics, that the difference between the two runs is very small although there is minor difference in the magnetic and plasma environments on the dayside. However, the present result seems to be consistent with the conventional understanding of plasma physics that the structure and dynamics of global magnetic fields, which are generally described by the MHD equations, are not affected by electron-scale microphysics.

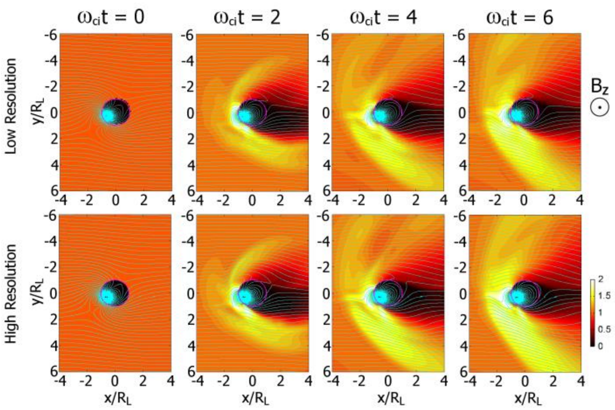

Fig.1. Development of the ion density together with the configuration of magnetic field lines as a result of the interaction between the solar wind and a small dielectric body with a weak intrinsic magnetic field.

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