

Full PIC simulations on plasma electromagnetic disturbance in the vicinity of spacecraft

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Space exploration has been rapidly increasing, and a strong demand arises regarding comprehensive understanding of spacecraft-plasma (SP) interactions [1]. This is clearly required to ensure survivability and proper operations of space-based systems, and also for correct interpretation of measurements and other information collected in situ by scientific spacecraft.

In space environments, spacecraft are electrically charged due to plasma contact to spacecraft surface and its floating potential is basically determined by the current balance at spacecraft surface. The current consists of incident background plasma, emission of photoelectrons/secondary electrons from spacecraft surface as well as active emission of plasma beam in electric propulsion system such as ion engine. Due to the spacecraft charging, plasma environment near spacecraft is influenced. Non-uniform plasma distributions such as sheath and wake structures are formed near spacecraft surface and in the downstream region with respect to the solar wind, respectively. Field components near spacecraft can be also disturbed by the plasma response to spacecraft. Understanding of the SP interactions is important from a view point of spacecraft observation of plasma environment as well as its data analysis. To discriminate plasma phenomena artificially disturbed by spacecraft from observational data, quantitative understanding of SP interactions is necessary. In designing science instruments such as electric field sensor, plasma disturbance near spacecraft has to be minimized as much as possible to obtain reliable and valuable data. To obtain self-consistent solution of these plasma disturbances near spacecraft, we perform plasma simulations including spacecraft body in a simulation domain.

For solving SP problems, we have developed the EMSES plasma particle simulation code [2]. EMSES is based on the standard electromagnetic PIC method, and also has the capability to include the conducting bodies of a spacecraft, based on the capacitance matrix method. In addition, a number of crucial physics such as the photoelectron emission and the secondary emission are modeled numerically in the latest version of EMSES. The code has been applied so far to some specific spacecraft, e.g., Geotail, Cluster, BepiColombo/MMO, and Solar Probe Plus.

In this talk, first we will briefly explain the numerical treatment of spacecraft in EMSES. Then we will show a few examples of EMSES applications to scientific spacecraft. One of such applications is an enhanced wake formed behind the Cluster satellite in tenuous streaming plasma [3]. In the simulation we have included the conducting surfaces of very thin (in an order of mm) wire booms by using the fictitious surface technique. We found that even the extremely thin wire booms can contribute substantially to the formation of an electrostatic wake because of highly positive spacecraft charging in the tenuous plasma environment. We will also show a recent research topic on the SP interactions in the near-Sun environment. Large photoelectron emission current caused by an intense solar flux forms a negative potential barrier on the spacecraft surface, leading to negative charging of the spacecraft. Electromagnetic environments around these specific spacecraft will be presented in the talk.

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Keywords: Spacecraft plasma environment, Spacecraft-plasma interactions, Electromagnetic Particle simulation, Spacecraft charging, electromagnetic disturbance

General relativistic simulations of magnetized binary neutron star merger on K

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Binary neutron stars are a binary which is composed of two neutron stars and nine binaries have been observed so far. They gradually lose the orbital energy and angular momentum due to gravitation wave emission and merge in the end. Within the observed binaries, six of them will merger within the Hubble time. Gravitational waves emitted during the merger would be detectable with the ground-based gravitational wave detectors such as KAGRA, advanced LIGO, and advanced VIRGO at a frequency of about ten times per year. If we could observe the gravitational waves, they would tell us the validity of General Relativity in a strong gravitational field and the equation of state of neutron star matter which is poorly known to date as well.

This situation facilitates a theoretical study of binary neutron star mergers. During the merger, the density is as high as 10^{15} g/cc and the temperature rises as high as 10^{10} degrees. Therefore, any analytical approaches break down and we need a numerical modeling. Our group is approaching this problem in the framework of Numerical Relativity. It is a research field whose aim is figuring out phenomena in a strong gravitational field by solving the Einstein equation as well as the hydrodynamical equation and neutron radiation transfer.

The observations of the pulsars have revealed that the neutron stars are magnetized with about 10^{12} Gauss in general. Moreover, some of them could have 10^{14} Gauss. However, it is still unknown what the role of magnetic field during binary neutron star mergers is. There are several hydrodynamical instabilities which amplify the magnetic field and a short wavelength mode is essential in all cases. Therefore, it is mandatory to perform a high-resolution simulation. In the previous studies of this subject, it is hard to say that enough resolution is assigned to resolve these instabilities. Our group is performing a numerical simulation with the highest resolution on the supercomputer K and figuring out the role of the magnetic field during the merger of binary neutron stars. We summarize the result as follows.

When the two stars come into contact, the shear layer between the stellar surface becomes unstable against the Kelvin-Helmholts instability. The vortices are produce by this instability and the shorter the wavelength is, the larger the growth rate of the instability is. If there exists magnetic field lines, they are curled by these vortices and are expected to be amplified exponentially. By performing the convergence study against the numerical resolution, we have found the maximum magnetic field is amplified by the factor of about thirty at least at the merger.

After the merger, a hypermassive (HMNS) neutron star is transiently formed, which is supported by a rapid and strong differential rotation in addition to the thermal pressure. Although this star is unstable against the magnetorotational instability (MRI), it is difficult to resolve the MRI because the wavelength of the unstable mode is quite short due to the high density and high angular velocity of the HMNS neutron star. In our simulation, we have resolved this unstable mode and we have shown that the HMNS neutron star has the magnetic field as large as 10^{16} - 10^{17} Gauss as a result.

In the HMNS neutron star, the angular momentum transport due to the non-axisymmetric structure as well as due to the MRI works. In addition, the star loses a significant amount of the angular momentum due to the gravitational wave emission. Then, the star collapses to a black hole which is surrounded by the accretion disk. Inside the accretion disk, the magnetohydrodynamical turbulence transports the angular momentum and its surface is unstable against the Kelvin-Helmholts instability. Vortices produced by these two mechanisms transport the energy outwardly and the disk wind activates as a result. In this talk we will introduce the simulation result in details.

Electromagnetic Vlasov simulations of magnetized plasma with a finite-volume multi-moment advection scheme

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The Vlasov simulation, which directly discretizes the Vlasov equation on grid points in phase space, has been proposed as an alternative method to the common Particle-In-Cell simulation, to improve the accuracy of kinetic plasma simulations. Although the electrostatic Vlasov simulations have been successfully carried out thus far, the electromagnetic Vlasov simulation of magnetized plasma is still limited, owing to numerical difficulty in solving the distribution function in velocity space.

To overcome the difficulty, we develop a new numerical scheme, specifically designed to solve the Vlasov equation in magnetized plasma. The scheme advances multiple piecewise moments of a physical profile based on their governing equations, to preserve the profile with high accuracy. The scheme allows us to perform a long-time calculation of the distribution function of magnetized plasma with small numerical diffusion.

In this talk, we first present the scheme and its performance. Then, we report the application of the scheme to two-dimensional (2D3V) electromagnetic Vlasov simulations. Long-time simulations of the linear wave propagation in magnetized plasma are conducted with quite small numerical errors. We also conduct the simulation of collisionless magnetic reconnection. The simulation resolves macroscopic structure without numerical noise, and is in good agreement with previous studies. Furthermore, the simulation resolves microscopic structure of the non-Maxwellian plasma velocity distribution around the reconnection site, e.g., acceleration by the reconnection electric field at the X-point, high energy beams around the boundary layer, and heating by the magnetic compression at the downstream. Since the simulations have been successfully carried out with the grid size much larger than the Debye length, the Vlasov simulation is a powerful technique to treat global-scale kinetic plasma phenomena.

Keywords: Advection equation, Vlasov simulations, Magnetic reconnection

Generalization of Plasma Hybrid Simulation Model

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The hybrid simulation model has been widely used as one of the self-consistent simulation methods in investigating nonlinear space plasma phenomena, which treats ions as kinetic macro-particles whereas electrons are assumed to be an inertialess fluid. It can correctly simulate from magnetohydrodynamic to the ion inertia length scale. However, the assumption of the inertialess electron makes it sometimes numerically difficult to handle high-frequency whistler waves. We have recently shown that the problem may be resolved by appropriately including finite electron inertia effect, which also makes it possible to handle vacuum regions in a hybrid code. In this report, we discuss extension of the model which may be able to incorporate electron kinetic effect. Ignoring the displacement current and assuming charge neutrality, we adopt the Vlasov-Ampere system of equations. An equation to determine the electric field is derived from the basic equation without any approximations. We demonstrate that by using the equation, the electron cyclotron resonance can be properly included.

Keywords: plasma, numerical simulation

Optimization of Magnetohydrodynamic Simulation Code for Planetary Magnetosphere to Xeon Phi

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For investigating the global structures of plasma, such as the planetary magnetospheres, the Magnetohydrodynamic (MHD) equations are often used, in which full kinetics of plasma are neglected by taking the moments of the Vlasov equations. The MHD equations are highly nonlinear and are very complex to solve by hand calculations. Thus computer simulations play essential roles in studies of global magnetosphere.

The numerical MHD code for the magnetosphere has been optimized for vector-type supercomputers for a long time because the MHD code is a kind of fluid code and most of supercomputers with vector processors have high performance to solve the fluid codes in 1990's. These codes often have achieved a very high computational efficiency (the ratio of the effective performance to the theoretical performance). However, almost 100% of the "Top 500" supercomputer systems in the world adopt the massively parallel scalar type processors and more than 85% of systems consist of the x86 processor architecture in these days. The other scalar type computers are POWER and SPARC architectures. Recently the new coprocessor Xeon Phi which has many cores (~60 cores) of X86 architecture is introduced to the supercomputer system and achieved good performance of the Linpack benchmark.

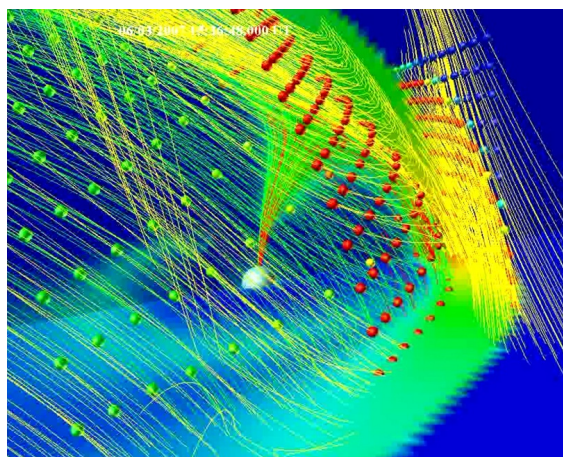
In this study I evaluate the performance of MHD code for the planetary magnetosphere on the single Xeon Phi coprocessor. For the performance evaluation, I use the three-dimensional domain decomposition method and a cache-hit type of three-dimensional domain decomposition method with the flat MPI and hybrid MPI. As the results, I found that normal three-dimensional decomposition of the MHD model with the hybrid MPI is suitable for Xeon Phi coprocessor and achieved computing performance efficiency of ~7%. Furthermore, I add the optimization to the MHD code based on the Xeon Phi architecture and obtained the computing performance efficiency of almost 10% which is the double performance of FX10 single node.

A Study of Fluid Element Tracing in Global MHD Simulations via Parallel Data Processing on the NICT Science Cloud

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The NICT Science Cloud is a cloud system designed for scientific researches, and expected as a new infrastructure for big data sciences. Not only parallelization of CPU as in super-computers, but I/O and network throughput parallelization are crucial for the big data science. A high-performance visualization system is constructed on the NICT Science Cloud using Gfarm/Pwrake middleware. We examined performance of this parallel visualization environment for a set of computer simulation with 1000 files (2.3TB in all). After setting higher priority to access to local file on local disk, we finally achieved 124 times higher visualization using 192 core cpu.



Development of magnetic field tracking module for analyzing a decaying sunspot

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In order to analyze the structures of magnetic fields using the data from Solar Optical Telescope (SOT) on board the Hinode satellite, we have developed the automatic tracking module, which detects the magnetic region and tracks the time variation of each region.

The module, based on three thresholds, intensity, size, and distance, has main three functions: (1) detect the magnetic fields based on the intensity threshold, (2) remove the micro region by the size threshold, (3) based on move distance by time variation, detect the same regions and track them.

We made simple sample data for test and checked on the accuracy of our tracking module.

We applied the module to sunspot and analyzed the time variation of decaying sunspot which is one of the sources of magnetic element in the solar surface.

We have use the magnetograph data which was observed by Hinode/SOT from 29 Dec 2009 to 2 Jan 2010. We also discuss the north-south/east-west asymmetry of the decaying process in the active region.

Keywords: sunspot, development of module, auto detection, auto tracking

Application of feature recognition technique in the investigation of magneto-convection on the solar surface

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We show the recent feature recognition technique and its benefits in the investigation of magneto-convection on the solar surface using observational and numerical approaches.

The magneto-convection on the solar surface is important not only as a trigger of many surface energetic events, e.g. solar flare, jet, and X-ray bright point, but also as an actual example of the most detailedly observed and numerically simulated magneto-convection on the stellar surface owing to its closeness to the earth. However, the elements of magneto-convection (<1,000km), the basic convective cells and magnetic patches formed by convective motion, are much smaller than solar global scale (~70,000km). It means that we need large field of view to catch up enough number of structures simultaneously with high spatial resolution to capture such small scale structures. Thanks to the improvement of engineering technique for satellite observation and computers for numerical calculation, we are now able to catch such a large scale structure at the same time. However, the new difficulty, how to investigate statistical characters of convective cells and magnetic structures in such huge data sets, has just shown up in the analysis.

Because of this situation, feature recognition and tracking technique is now focussed on. In this presentation, we want to introduce the auto-recognition and tracking code of magnetic patches and convective cells on the solar surface. Further it is shown that the statistical characters obtained through the analysis of observational data and numerical calculation data based on the auto-recognition and tracking code. We want to note that the feature tracking technique drastically improve statistics of the analysis drastically. We also want to discuss about the applicants of feature tracking technique with the scientists in the other fields though this collaborative session.

Keywords: the Sun, magneto-convection, feature recognition

On stability properties of the numerical Cherenkov instability in relativistic plasma flows

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We examined stability properties of the numerical Cherenkov instability in relativistic plasma flows. Particle-in-cell simulation code package, pCANS, was used for the numerical analysis. With the implicit FDTD method for Maxwell equations, we found that the instability was greatly inhibited with the CFL number of 1.0. Numerical tests with various CFL numbers ranging from 0.5 to 1.0 showed that the growth rate remarkably decreased at CFL = 1.0 following a gradual decrease from the value at CFL=0.5. The implicitness factor ($\alpha=0.5$ for Crank-Nicolson method) was also found to control the width of the dip. The present result contrasts with the recently reported results (Vay et al., 2011, Godfrey & Vay, 2013) in which the magical CFL number were 0.5 and 0.7 respectively for their different explicit field solvers. We present the result with the detailed dispersion relation of the implicit field solver and its application to relativistic collisionless shock simulations.

Keywords: particle-in-cell simulation, relativistic plasma, numerical Cherenkov radiation, shocks

Electron hybrid code simulations with OhHelp load balancer

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A spatially one-dimensional electron hybrid code has been developed for the study of the generation process of whistler-mode chorus emissions and relativistic electron acceleration in the Earth's inner magnetosphere [1-3]. In the electron hybrid code, we treat cold electrons as a fluid and energetic electrons as particles by the Particle-in-Cell (PIC) method. Since we assume an inhomogeneous background magnetic field in the simulation system so as to treat the bounce motion of energetic electrons along a magnetic field line, the distribution of energetic electrons in the system is non-uniform and energetic electrons move around the magnetic equator assumed at the center of the simulation system. While the electron hybrid code has been parallelized through the particle decomposition method, we need to improve the scalability of the electron hybrid code so as to use a large simulation system and billions of particles for simulations under initial conditions corresponding to the real magnetosphere.

In the present study, we have developed a spatially one-dimensional electron hybrid code domain-decomposed by OhHelp [4]. The OhHelp is a library which enables us to conduct PIC simulations by achieving both dynamic load balancing and scalability. The efficiency and scalability of OhHelp have been confirmed by a 3D full PIC simulations [5]. We show the efficiency and scalability of the developed code tested on the system A (Cray XE6) of Academic Center for Computing and Media Studies, Kyoto University. We compare the performance of the developed code and those of the code with the particle decomposition.

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Keywords: dynamic load balancer, PIC simulation