Fast magnetic reconnection onset for different equilibrium configurations: from analytical results to 3D simulations

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We investigate the onset of fast magnetic reconnection starting from equilibrium configurations relevant for astrophysical as well as for laboratory plasmas, that differ from the simple Harris current sheet configuration. In particular we present an analytical as well as a numerical study of the linear instability for equilibrium magnetic fields which go to zero at the boundary of the domain and of a double current sheet system, the latter previously studied as a proxy for the m=1 kink mode in cylindrical plasma. We show how the "ideal" tearing trigger condition is changed by assuming such different equilibrium profiles. Finally we present results for incompressible 3D MHD simulations of a double current sheet, in triperiodic geometry. We examine and contrast the destabilization and transition to turbulence describing the evolution of the magnetic energy and dissipation, and possible application to heliospheric phenomena, in particular CME evolution and relaxation.

Keywords: plasma physics, space plasma, magnetic reconnection

High-order leapfrog scheme of the Vlasov-Ampère system for the electrostatic plasma

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The simulation result of Vlasov code has high signal-to-noise ratio, in comparison to PIC (particle-in-cell) code. In the past, due to the scarcity of computing power, most researchers use PIC code as a tool toward novel explorations and investigations. With the rapidly enhancement in computing power of supercomputers, the high resource-demanding Vlasov simulation of potency has become wildly adoptable and efficiently achievable. In this study, we adopt grid-base Eulerian solver, instead of the customary semi-Lagrangian method, to solve Vlasov-Ampère equations for electrostatic plasma. We use three-step high-order leapfrog scheme for the solutions of energy-conserving Vlasov-Ampère equations. We use fifth-order central finite difference method to calculate the first derivative in Vlasov equation along the real space. We use cubic spline method to calculate the first derivative and integration along velocity space in the Vlasov equation and Ampère law without magnetic field, respectively. We use forth-order leapfrog method for time stepping. Subsequently, we examine the correctness of grid-base Eulerian solver in solving Vlasov-Ampère equations for electrostatic plasma by linear Landau damping test.

Keywords: Vlasov simulation, electrostatic plasma

Evaluation of Numerical Properties of Constrained-Transport-Type Schemes for Hybrid Simulations

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Numerical simulations of space and astrophysical plasmas need an accurate method for solving Maxwell's equations. The divergence-free property of the magnetic field is the fundamental constraint in the system that must be satisfied in a numerical solution because otherwise, the simulation will become unstable. The Constrained-Transport (CT) scheme, which exactly preserves the discrete divergence-free property, has been quite successful in numerical Magnetohydrodynamics (MHD). In recent years, the CT scheme for Maxwell's equations has been ingeniously combined with an HLL-type (Harten-Lax-Van Leer) Riemann solver for the hydrodynamics part in a consistent fashion. The scheme known as the HLL-UCT shows excellent performance in numerical MHD as well as two-fluid plasma simulations.

It is straightforward to apply the same technique to kinetic Particle-in-Cell (PIC) type simulation method. However, the numerical properties of the scheme as applied to kinetic simulations are not known very well. In fact, artifacts arising from numerical noise inherent in the PIC method (which is absent in a grid-based fluid code) should carefully be analyzed.

In this study, we apply the HLL-UCT scheme to a quasi-neutral plasma hybrid code in which ions are treated as kinetic macroparticles whereas electrons are assumed to be a fluid. We found that naive application of HLL-UCT to a hybrid code may lead to artificial heating and/or cooling of ions, presumably because of excessive dissipation in the HLL-UCT scheme. We thus quantify the numerical artifact by extensive numerical experiments with varying mesh size, the number of particles per cell, plasma beta, etc. We found that the numerical heating/cooling may be explained by absorption (or dissipation) of spontaneous emission of waves arising from a discrete particle effect. Practical workarounds to minimize the numerical artifact for long time simulations will be discussed.

Keywords: Maxwell's equations, numerical simulation, plasmas

Designing high-order finite difference scheme for magnetohydrodynamics: shock capturing and divergence-free conditions.

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Space and astrophysical plasmas are rich in dynamic phenomena such as convection, eruption, shock, accretion, and so on. Their macroscopic dynamics is well described by magnetohydrodynamics (MHD). Since the system of MHD equations are highly nonlinear, a numerical simulation is an indispensable tool to reveal its complicated physics.

The plasma is frequently associated with supersonic flows such as the coronal mass ejection, supernova, and jet, which yield various shocks and discontinuities. Furthermore, these flows are almost inviscid, thus will become turbulent. Reliable MHD simulations need to resolve these phenomena simultaneously, which is a contradictory issue for computational fluid dynamics and thus is challenging. Moreover, the MHD simulation should carefully handle errors of the divergence for magnetic field, which is not necessarily free in numerical simulations.

Many works have been devoted to develop exact or approximate Riemann solvers (upwind schemes) for (M)HD to accurately capture shocks and discontinuities. Nowadays, such shock capturing schemes are adopted as a standard method for MHD simulations (Kritsuk et al. 2011). On the other hand, various high-order interpolation techniques are proposed to improve the resolution of small scale structure (e.g., turbulence), and they can be incorporated into shock capturing schemes.

Shock capturing schemes are based on the finite volume method, which automatically satisfies the conservation laws but has a difficulty in achieving high order of accuracy in multi-dimension. The finite difference method is rather convenient for designing multidimensional high-order scheme. Conservative finite difference schemes have been proposed by approximating fluxes to high order, and succeeded in high resolution MHD simulations (Jiang et al. 1999; Mignone et al. 2010).

We consider another type of the conservative finite difference scheme for MHD, which interpolates physical variables to high order and utilize a variety of Riemann solvers to capture shocks. We also take special care of the divergence-free condition for magnetic field. Combination of the upwind scheme and the constrained transport (UCT) method, which satisfies divergence-free condition within machine accuracy without violating upwind property (via Riemann solvers), is thought to be a powerful strategy especially for low beta plasmas. We test various type of the UCT method. In this paper, we will present details of our code design and its performance, especially focusing on the comparison among different interpolation techniques, Riemann solvers, and UCT methods.

Keywords: MHD simulation, Numerical method

Study of anisotropic electrons distributed around the wake of an ionospheric sounding rocket by a 1D Vlasov-Poisson simulation

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Ionospheric sounding rockets travel in plasma at supersonic velocity with rarefied regions called 'plasma wakes'. In a rocket wake, plasma waves with frequencies near the upper hybrid resonance (UHR) frequency, plasma frequency, and Z-mode cutoff frequency in the wake are observed as reported by Yamamoto [PhD. thesis, Tohoku University, 2001]. From the results of the S-520-26 rocket experiment, Endo et al. [JGR, 2015] suggested that the waves observed in the wake were electrostatic waves such as electrostatic electron cyclotron harmonic (ESCH) waves and UHR mode waves because plasma waves with long wavelengths cannot be generated in a narrow region like the rocket wake. The intensities of these waves, as well as of whistler mode waves observed in the same experiment, had spin-phase dependence, which is different depending on kinds of plasma waves. These results indicate that there was inhomogeneous spatial distribution of hot electrons with some anisotropic velocity distribution functions around the rocket wake.

In order to investigate inhomogeneity of hot electrons around the rocket wake, we are now developing a Vlasov-Poisson code. In the simulation with this code, we can calculate wake filling process of ambient ions and electrons in one-dimensional space along the X-axis, which is parallel to the ambient magnetic field. The grid spacings of the space and of the velocity spaces of electrons and ions are $\Delta X = \lambda_D$ (λ_D: Debye length), $\Delta V_e = 0.1V_{the}$ (V_{the}: thermal velocity of electrons), and $\Delta V_i = 0.0025V_{the}$, respectively. The range of the space is $-600\lambda_D X 600\lambda_D$, and a void is set at $-25\lambda_D X 25\lambda_D$ at the initial time. The ranges of the velocity spaces of electrons and ions are $-10V_{the} V_e 10V_{the}$, and $-15V_{thi} V_i 15V_{thi}$ (V_{thi}: thermal velocity of ions), respectively. The time step Δt is $\Delta t=0.1\,\omega_p^{-1}$ (ω_p: plasma frequency). Accordingly, the CFL (Courant-Friedrichs-Lewy) condition, which should be satisfied to carry out numerical simulations stably, is $E/E_0 1$ ($E_0 = \lambda_D \omega_p^2 m_e / e$), where E is the electric field, m_e is the electron mass, and e is the elementary charge. The rational CIP method [Xiao et al., CPC, 1996] is applied to solve the Vlasov equations, and Fourier transform [Birdsall and Langton, Taylor & Francis Group, 2008] is used to obtain electric fields through the Poisson’s equation. If we assume that the plasma is also flown in the y direction, the plasma distribution along the X-axis as a function of time can be understood as that as a function of distance in the y direction.

In our current code, electric oscillations whose amplitudes increase with time are observed outside the wake near the wake boundaries, which makes the CFL condition be unsatisfied at $t=469\Delta t$ (corresponding to 3.4 mm downstream). However, the calculation has to be proceeded until at least $t\tilde{}60000\Delta t$ because we are going to check the velocity distribution functions in the region including the tail of the wake (about 0.4 m downstream) to discuss plasma waves observed in the S-520-26 rocket experiment. Therefore, the electric oscillations must be damped such as by selectively and artificially attenuating the electric fields or by making the density gradients at the wake boundaries be shallower. Even in the calculation before $t=469\Delta t$ with our current code, we can see several hot electrons such as multi-stream electrons on the wake axis, and a single beam component outside the wake. The multi-stream electrons are considered to be composed of electrons periodically coming into the wake from the outside, and the single electron beam may be owing to the reflection of electrons by the polarized electric field at the wake boundaries.

In this presentation, we will describe the configuration and schemes of our simulation first, and then will show the calculation results. We will especially discuss the spatial distribution of anisotropic electrons and their generation process.

Keywords: wake, sounding rocket, Vlasov-Poisson simulation, velocity distribution function, ionosphere

Particle Simulations on Near-Spacecraft Plasma Perturbations in Polar Ionospheric Environment

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This paper reports the international collaborative project on spacecraft-plasma interactions in the Polar Ionospheric environment, which is initiated by Kobe University and University of Oslo. It is widely known that plasma density irregularities with various spatial scales are generated frequently in the Ionospheric environment. A series of ICI rockets have been launched from Norway for studying such ionospheric phenomena. One of the outstanding issues regarding the rocket experiments is near-spacecraft plasma perturbations, possibly influencing the in-situ observations. We applied the 3-dimensional plasma particle simulations to the problem, in order to have better understanding of such processes.

Our preliminary results confirmed 1. rocket surface potential depending on an angle between the geomagnetic field and the rocket axis and 2. asymmetric wake structure due to strong magnetization of plasma electrons. We analyzed their associated electron dynamics around the rocket and found that electron motion creates a circular current center at the body, which may be attributed to the ExB drift as well as the diamagnetic effect. We have also started a numerical study on frequency spectra of potential fluctuations and their relevance to plasma wave modes near a spacecraft/rocket.

Keywords: Polar Ionospheric plasma, sounding rocket, spacecraft charging, wake, PIC simulation

Numerical Modeling of Plasma Wave Electric Field Effects on Spacecraft Charging

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Based on the particle-in-cell (PIC) method, we numerically model the modulation of a spacecraft potential in the presence of time-varying electric fields of plasma waves. Recent observations by Van Allen Probes showed apparent spacecraft potential fluctuations associated with chorus wave detection [e.g., Malaspina et al., 2014], and a major physical factor of the effect was speculated as photoelectron-escape current modulations due to wave electric field. Although its dependencies on wave frequency and magnetic field strength have been examined experimentally [Wang et al., 2014a; 2014b], there are a number of remaining issues such as effects of wave polarization or configuration of spacecraft chassis and probes. In particular, in-space spacecraft potential measurements are conducted by seeing a potential difference between spacecraft chassis and electrostatic probes, and thus it is necessary to consider the difference of their responses to external wave electric fields.

In this paper, we perform plasma particle simulations to address such unresolved issues. Our original PIC simulation code EMSES has a capability of reproducing plasma wave excitation/propagation as well as spacecraft charging in a self-consistent manner. Meanwhile, such analysis with realistic physical parameters requires too large computational resources, because the typical spatial scale of plasma wave lengths is much greater than that of the near-spacecraft environment. Thus, we propose another modeling of the phenomena by applying a spatially-uniform and time-varying electric field to the whole simulation domain as an external force term. We have confirmed that this model can reproduce the photoelectron-driven spacecraft potential fluctuations in case of a circular-polarized wave electric field. We have also constructed a theoretical model to explain the simulated potential fluctuations in consideration of a photoelectron escaping current though an RF sheath around the spacecraft [Boehm et al., 1994].

Keywords: plasma wave, spacecraft charging, wave electric field, chorus waves, photoelectron emission, particle-in-cell simulation

3D Electromagnetic Particle Simulations about the Low Frequency Component of BEN

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According to PIC simulations, ESW (Electrostatic Solitary Waves) are generated from electron beam instabilities. ESW correspond the upper frequency component of BEN (Broadband Electrostatic Noise) which is frequently observed in space plasma. The generation mechanism of the low frequency component of BEN, however, is still unexplained. We went statistical analyses of the low-frequency component of the BEN observed by EFD onboard Geotail spacecraft, and investigated the relation between magnetic field strength, ion density and ion temperature. According to the spctrum analysee of the low frequency component of BEN, there are two different types of spectrum. We performed the 3-dimensional electromagnetic particle simulations about these two types of the low frequency component of BEN, and found low frequency waves are excited in both cases.We are going to further simulations with sufficient scale in time and space, and make clear the generation mechanism of the low frequency componet of BEN.

Keywords: Broadband Electrostatic Noise, 3-dimensional Electromagnetic Particle Simulations, Geotail Spacecraft