R008-01 会場: B 時間: 11月3日 9:40-9:55

3次元乱流磁気リコネクションによる高効率の非熱的粒子加速

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High-efficiency nonthermal particle acceleration by 3d turbulent magnetic reconnection

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Nonthermal particles whose energy much larger than the thermal plasma are ubiquitously observed in astroplasma environments, and the energy density of the nonthermal particles is known to be often larger than that of the thermal plasma. Among many variety of acceleration processes of these nonthermal particle, the accelerations by shock wave and magnetic reconnection are believed to play the most important role for the origin of the observed nonthermal particles. Roughly speaking, two elementary plasma acceleration processes are occurring: one is the stochastic acceleration under the resonant interaction of a charged particle with turbulent waves, and the other is the direct acceleration where a charged particle can gain its huge energy only by a single interaction with a localized, large-amplitude electric field. However, the acceleration mechanisms in details are still controversial.

In this presentation, we focus on the turbulent reconnection in many magnetic islands, which is thought to be responsible for determination of the maximum attainable energy of accelerated particle in the system. We have already demonstrated by using 2d PIC simulation that the particle acceleration efficiency of the classical 2nd order Fermi acceleration with many magnetic clouds becomes to be 1st order of the ratio of Alfven speed and the speed of light, if we take into account of many magnetic islands instead of those magnetic clouds (Hoshino, PRL, 2012). However, the behavior of three-dimensional reconnection remains elusive. Based on our result of 3d PIC simulation, we discuss that the acceleration process of multiple magnetic islands seen in 2d PIC simulation can work in more realistic 3d magnetic islands as well.

宇宙プラズマ中では、熱エネルギーを凌駕する非熱的高エネルギー粒子が普遍的に観測され、非熱的粒子のエネルギー密度が、熱的プラズマのエネルギー密度を上回ることが知られている。非熱的粒子の起源には多種多様のプラズマ加速機構が考えられるが、その中でも高効率の加速過程として衝撃波加速と磁気リコネクション加速が注目されている。そしてそのミクロなプラズマ過程に着目すると、乱流場と荷電粒子が繰返し共鳴する統計的加速に加えて、局在化した大振幅の電場と一回の共鳴で大きなエネルギーを得る直接加速が効くこともあり、加速の物理は必ずしも統一的な理解にいたっていないのが現状である。

本発表は、加速粒子の最高エネルギーを決定するのに重要であると考えられる、多数の磁気島中での乱流磁気リコネクションに着目する。我々は既に２次元 PIC シミュレーションを用いて、磁気雲との相互作用による古典的な２次オーダのフェルミ加速について、磁気雲の代わりに磁気リコネクションを考えることで、アルフベン速度と光速の１次オーダで加速される高効率の加速が起きることを示した（Hoshino, PRL, 2012）。しかし磁気島が三次元構造を持つ場合には今後の課題となっていた。今回は３次元 PIC シミュレーションの結果を下に、現実的な３次元構造を持つ磁気島においても、２次元で得られた加速と同様な機構が働くことを議論する。

R008-02 **会場: B** **時間: 11 月 3 日 9:55-10:10**

非対称磁気リコネクションにおける拡散領域の構造変化

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Time variation of diffusion region in the asymmetric magnetic reconnection

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Magnetic reconnection is widely accepted as an important elementary process of mass, momentum and energy transport in the geomagnetosphere and the solar atmosphere. Especially, the asymmetric reconnection is more general than the symmetric one, such as Anemone type solar flares and flux transfer events at the dayside magnetopause. However, it is also a phenomenon that has many unsolved problems. We aim at clarifying the nature of the asymmetric magnetic reconnection using MHD simulation.

In the previous work by Cassak & Shay in 2007, a structure of the Sweet-Parker type diffusion region for an asymmetric reconnection was studied. As a result, it was shown that the reconnection point (X-point) and the stagnation point (S-point) separate and the X-point shifts toward the higher beta side from the S-point in the steady state. In this study, the relation between X-point and S-point for the spontaneous reconnection is studied by the numerical simulations using the current driven anomalous resistivity model.

磁気リコネクションは地球磁気圏や太陽における質量・運動量・エネルギー移送に関する重要な素過程の一つとして受け入れられている。 特に非対称な磁気リコネクションは対称なものよりも一般的であり、太陽コロナ／彩層におけるアネモネ型フレアや、地球前面で起こる FTE の解明に重要である。 しかし、未解決な問題の多い現象でもある。我々は、 MHD 計算を行うことで非対称磁気リコネクションを理解することを目指している。

Cassak & Shay(2007) の先行研究では、非対称磁気リコネクションに対する Sweet-Parker タイプの拡散領域の構造が調べられている。その結果、定常状態では Reconnection point (X-point) と Stagnation point (S-point) が分離し、X-point が S-point よりも高ベータ側に位置することが示されている。本研究では電流駆動型の異常抵抗モデルを用いて数値計算を行い、自発的磁気リコネクションにおける X-point と S-point の分離を確認し、それぞれの運動について調べた。

磁気リコネクションに起因する 3 次元アウトフロージェット

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3D outflow jets originated from magnetic reconnection

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The 3D dynamics of magnetic reconnection is one of the key issues in space and astrophysical plasmas. The observations in the Earth's magnetosphere, solar flares, and laboratory experiments have suggested that the reconnection processes are fully three-dimensional, accompanied by intense wave activities at the x-line and localized flow burst downstream of the x-line. In particular, the present study has focused on the 3D structure of the outflow jets generated by collisionless magnetic reconnection. The outflow structure of reconnection is considered to be three-dimensional from the observations, but the mechanism leading to the 3D reconnection jets has been poorly understood, mainly because of the limitation of computer resources.

We have challenged the 3D reconnection problem by means of the particle-in-cell (PIC) simulations with adaptive mesh refinement. Large-scale 3D PIC simulations have revealed that the thin current layer formed around the x-line is unstable to two types of the shear-driven modes in the anti-parallel configuration. One is a current sheet shear mode which has an intermediate scale between the ions and the electrons. This mode is generated due to the velocity shears in the inflow direction, so that the current sheet is perturbed in the inflow direction. The other is an electron shear mode driven by the electron velocity shear in the outflow direction. Since the shear scale in the outflow direction is much larger than that in the inflow direction, the wavelength of the electron shear mode is larger than that of the current sheet shear mode. The electron shear mode fluctuates the current sheet in the outflow direction. As a result, the flux ropes arising from the secondary tearing mode have a typical scale in the current density direction, corresponding to the wavelength of the electron shear mode. Because the flux ropes move downstream much slower than the ambient plasma, the reconnection jets tend to be blocked by the flux ropes and generate 3D flow channels between the flux ropes. Therefore, it is found that the reconnection outflow jets have a typical scale corresponding to the electron shear mode arising in the thin current layer. The interesting point is that the scale is roughly consistent with that of fast plasma flows termed the bursty bulk flows (BBFs) observed frequently in the Earth's magnetotail. It is surprising that the BBFs have an MHD scale (much larger than the ion inertia length), but they are originated from the electron instability where the electron inertia plays an important role.

In the presentation, we show the recent results of a large-scale 3D PIC simulation of magnetic reconnection and explain how the 3D reconnection jets are generated from turbulence arising at the reconnection x-line.

Kinetic Ohm's law in relativistic magnetic reconnection

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Magnetic reconnection draws recent attention in relativistic astrophysics, in particular after the discovery of Crab gamma-ray flares. Owning to this, kinetic modeling of relativistic reconnection has now become an active topic of research. From the physics viewpoint, relativistic reconnection is an ideal material to test the traditional theories.

In nonrelativistic kinetic reconnection, it is widely accepted that the reconnection electric field at the X-line is balanced by the divergence of the pressure tensor in the electron Ohm's law. This term, the local diffusion of the electron momentum, is sometimes referred to as the thermal inertial effects. This pressure-tensor paradigm was recently questioned by a numerical work on asymmetric reconnection, which reported that the bulk inertial term is a major player at the X-line.

In this contribution, we examine a relativistic Ohm's law in kinetic magnetic reconnection. With some help from radiation physics, we decompose the relativistic stress-energy tensor to derive the kinetic Ohm's law. Then we evaluate the the composition of the Ohm's law in particle-in-cell (PIC) simulation. It was found that a new inertial term plays a role at the X-line in the relativistic regime. We discuss our physical interpretation, by using these results.

ランダムな密度揺動を含む太陽風プラズマにおける円偏波アルヴェン波の変調不安定性

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Modulational instability of circularly polarized Alfven waves in solar wind plasmas with random density fluctuations

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Radial evolution of low-frequency Alfven waves in solar wind plasmas has not been fully understood yet. Since nonlinear Alfven waves are nonlinearly coupled with longitudinal fluctuations, the characteristics of density fluctuations can affect the damping of the Alfven waves. In this presentation, we report the result of our theoretical analysis, in which Ruderman's model (Ruderman, POP, 2002) is extended to include the non-zero beta ratio.. The roles of novel dispersion terms are discussed.

太陽風プラズマ中の磁気流体波（アルヴェン波）が太陽から遠ざかるにつれて発展していく過程は、まだよく分かっていない。有限振幅を持つ太陽風アルヴェン波はイオン音波などの揺動の縦波成分と非線形的に結合するので、縦波成分の性質はアルヴェン波の減衰に影響を与える。本研究では、Ruderman(POP, 200) により提唱された密度揺動場におけるアルヴェン波の発展を記述するモデルを有限ベータを含む形に拡張し、議論した結果について報告する。密度揺動の性質に応じて現れる新しい分散項がアルヴェン波の変調不安定性に与える影響を議論する。

プラズマ圏ヒスの微細構造の理論解析

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Theoretical analysis on coherent elements of plasmaspheric hiss

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Recent observations of plasmaspheric hiss emissions by the Van Allen Probes show that broadband hiss emissions in the plasmasphere comprise short-time coherent elements with rising and falling tone frequencies. Based on nonlinear wave growth theory of whistler-mode chorus emissions, we have examined the applicability of the nonlinear theory to the coherent hiss emissions. We have generalized the derivation of the optimum wave amplitude for triggering rising tone chorus emissions to the cases of both rising and falling tone hiss elements. The amplitude profiles of the hiss emissions are well approximated by the optimum wave amplitudes for triggering rising or falling tones. Through the formation of electron holes for rising tones and electron hills for falling tones, the coherent waves evolve to attain the optimum amplitudes. An electromagnetic particle simulation confirms the nonlinear wave growth mechanism as the initial phase of the hiss generation process. We find very good agreement between the theoretical optimum amplitudes and the observed amplitudes as a function of instantaneous frequency. We calculate nonlinear growth rates at the equator and find that nonlinear growth rates for rising-tone emissions are much larger than the linear growth rates. The time scales of observed hiss emissions also agree with those predicted by the nonlinear theory. Based on the theory, we can infer properties of energetic electrons generating hiss emissions in the equatorial region of the plasmasphere.

Quasilinear theory of the expanding box model for proton cyclotron and parallel firehose instabilities

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It is generally believed that the temperature anisotropy-driven kinetic instabilities play an important role in regulating the measured proton temperature anisotropy in the expanding solar wind. Linear and quasi-linear theories as well as numerical simulations in uniform plasmas are often employed in order to understand the properties of locally excited instabilities. However, since the solar wind itself expands in inhomogeneous interplanetary plasma, the effect of the expansion on the kinetic instabilities should be taken into account. In this study, we present quasilinear theory of the expanding box model to investigate how the solar wind expansion affects proton cyclotron and parallel firehose instabilities in the expanding solar wind.

Nonlinear Processes in Space Plasmas

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Many, if not all, physical processes in nature exhibit nonlinear behavior. Space plasma is no exception. In this talk some examples of nonlinear processes in space plasma will be discussed. The underlying theme in all the examples is the kinetic plasma turbulence theory. The first example is the problem of non-Maxwellian plasma velocity distribution function widely detected in space environment. A theory based on kinetic plasma turbulence formalism explains the origin of non-Maxwellian electron distribution function in terms of a concept where it is viewed as a dynamical steady-state between the electrons and plasma turbulence. Such a steady-state may be termed the turbulent quasi-equilibrium, and it may be described heuristically as the non-additive thermo-statistical state. A second example is taken from the Earth's auroral ionosphere where the precipitating energetic electrons excite upper-hybrid waves, which in turn, nonlinearly merge to produce the harmonic extraordinary mode. Such a process has recently been observed. A process that is similar but is a reverse counterpart takes place in the ionospheric modification experiment. In the ionospheric heating experiment, a powerful ordinary (O) mode pump wave is launched to the auroral ionosphere from the ground. When the O mode coverts to the upper-hybrid mode, them the high-intensity upper-hybrid mode subsequently undergoes decay interaction with electron Bernstein and lower-hybrid waves. The nonlinear interaction involving the upper-hybrid, Bernstein, and the lower-hybrid mode is considered important for the ionospheric heating, and thus represents the third example. These are but a few examples that lend themselves to nonlinear kinetic plasma turbulence theory. The kinetic plasma turbulence theory is at an incomplete stage when compared with the more mature linear theory, and many scientists are unaware of its usefulness. It is the purpose of the present talk to disseminate the notion that nonlinear kinetic theory is important for studying natural plasma processes.

ヘリコンプラズマ放電の自己無撞着モデル

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Self-consistent discharge growing model of helicon plasma

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Helicon plasma is a high-density and low-temperature plasma generated by the electromagnetic (Helicon) wave excited in the plasma. It is thought to be useful for various applications including electric thrusters. Physics of helicon plasma production involves such fundamental processes as the wave propagation (dispersion relation), collisional and non-collisional wave damping, plasma heating, ionization/recombination of neutral particles, and modification of the dispersion relation by newly ionized plasma. There remain a number of unsolved physical issues such as, how the Helicon and the TG modes influence the plasma density, electron temperature and their spatial profiles. While the Helicon mode is absorbed in the bulk plasma, the TG mode is mostly absorbed near the edge of the plasma. The local power deposition in the helicon plasma is mostly balanced by collisional loss. This local power balance can give rise to the inhomogeneous electron temperature profile that leads to time evolution of density profile and dispersion relation. In our study, we construct a self-consistent model of the discharge evolution that includes the wave excitation, electron heat transfer, and diffusion of charged particles.

ランダウ積分路を使わないランダウ減衰の導出

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Derivation of Landau damping without Landau contours

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Landau damping is one of the most important ingradients in plasma physics, and it is usually derived by deforming the integration contour in v (= velocity) complex plane to avoid poles of wave dispersion. This procedure is purely mathematical one coming from inverse Laplace transform, and the deformation of the contour has no

physical meaning. However, confusion is often found even in textbooks and some physical meaning is provided for the contour deformation. Interestingly the volume of "Physical Kinetics" in the Landau textbook series, which was written after the Landau's death, has fallen into this pitfall.

To clarify this point, a derivation of Landau damping without Landau contours has been developed here. The knowledge of analytical continuation or integration contour deformation, which may be hard to understand for who are not familiar to the theory of complex analysis, is not required. Though one need to know complex numbers enough to understand Laplace transform, an simple elementary integration formula can perform velocity integration to obtain Landau damping.

ランダウ減衰は，どのプラズマ物理の教科書にも載っている重要な無衝突プラズマの基本過程である。ランダウによるオリジナルの導出では，速度を複素数に解析接続し，その複素平面上で積分路を変形する，いわゆる「ランダウ積分路」を使うことによって実軸上の極をさけるという手法をもちいている。これはラプラス逆変換がω平面（周波数平面）上の Im(ω) が十分大きい積分路にそってなされることに対応しており，必要な積分を評価する上での純粋な数学的操作である。したがって積分路の変形自体に物理的意味はない。しかし，この事情はあまりよく理解されてはおらず，ランダウ積分路に物理的な意味をもたせようとする解説が教科書などにも散見される。たとえば本家のランダウ物理学教程の「物理的運動学」（ランダウの死後に書かれた）の中には「時間 t = -∞から無限にゆっくりと加わる電場を考察しよう」などとあきらかに矛盾する記述が見つかる。ここでの計算であつかうのは閉じた系の時間発展であり，外から電場が印加されているわけではないからである。

本研究では教育的な目的で，このような混乱を明らかにするために，ランダウ積分路をつかわずに，初等的な積分公式 ∫ 1/x dx = log x を使ってランダウ減衰を導出する。この計算には，ラプラス変換の知識は必要であるが，解析接続や積分路の変更などの難解な複素解析の知識は必要ない。また，この計算法は，分布関数を有理関数で近似するという手法を用いているが，それにより，マックスウェル分布以外の任意の分布でも分散関係を計算できるという利点もある。

相対論的衝撃波における航跡場加速

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Wakefield Acceleration in Relativistic Shock Waves

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Many particle acceleration mechanisms have been proposed to explain the origin of high energy cosmic rays. Among many important acceleration processes in astrophysical plasmas, however, a wakefield acceleration has not been understood yet. After the discovery of the theoretical concept of plasma wakefield acceleration by Tajima and Dowson (1979), the particle acceleration by an ultra-intense laser pulse has been widely investigated in laboratory plasmas. When an intense laser pulse of the transverse electromagnetic wave propagates through plasma, a longitudinal plasma wave can be excited by the ponderomotive force, which expels electrons from the region of high laser intensity. The phase velocity of the excited plasma wave, which is equal to the laser pulse group velocity, is close to the speed of light in vacuum. The electric field associated with this fast plasma wave is then able to accelerate particles efficiently.

In astrophysical plasmas, Chen et al. (2002) discussed the possibility by the wakefield acceleration of Alfven waves and suggested that the ultra-high energy cosmic rays may be generated by the wakefield acceleration. Lyubarsky (2006) argued the large-amplitude precursor electromagnetic waves generated in relativistic shock waves, and suggested the electrostatic field generated by the large-amplitude electromagnetic waves accelerates particles. Hoshino (2008) extended the previous studies and demonstrated the efficient particle acceleration by the incoherent wakefields induced by the large-amplitude precursor electromagnetic waves in the upstream region of a relativistic shock wave by using one-dimensional Particle-In-Cell (PIC) simulation.

In this study, we argue and demonstrate the wakefield acceleration in relativistic shock waves by using the PIC simulation. The wave coherency of the precursor wave, which is required for the ponderomotive force, is essential to the wakefield acceleration. However, the previous one-dimensional simulations could not solve this subject. In this presentation, we will pay a special attention to the wave coherency in two-dimensional simulation and report my results.

宇宙線に含まれる高エネルギー粒子の生成メカニズムとして、多くの粒子加速機構が考えられてきたが、いくつかの有力な加速メカニズムの中でも航跡場加速の研究はあまり進んでいない。航跡場加速自体は実験室プラズマではよく知られた加速機構であり、Tajima and Dawson (1979) によってその基本原理が考えだされた。プラズマ中に超高強度の横波の電磁波であるレーザーパルスを入射すると、レーザーパルスのポンデロモーティブ力で粒子が跳ね飛ばされて疎密が生まれ、縦波のプラズマ波が励起される。レーザーパルスに追随するようにプラズマ波が励起されるので、このプラズマ波の位相速度はほぼ光速であり、そのポテンシャルに補足された粒子は効率よく加速される。これがレーザーを用いた航跡場加速である。

宇宙プラズマでは、 Chen et al. (2002) によって、アルフベン波による航跡場加速は超高エネルギー宇宙線を生成し得ることが指摘された。また、Lyubarsky (2006) は、相対論的衝撃波では大振幅電磁波が励起され、この電磁波によって衝撃波上流では電子が加速されることを示した。Lyubarsky の研究を受けて、Hoshino (2008) が、衝撃波上流に伝播する大振幅電磁波が航跡場を励起し、衝撃波上流で非コヒーレントな航跡場加速が生じることを 1 次元 Particle-In-Cell (PIC) シミュレーションによって示した。

本研究では、相対論的衝撃波における航跡場加速を、PIC シミューレーションコードを使用してシミュレーションする。航跡場加速の問題点は電磁波のコヒーレンスにあるが、従来の 1 次元シミュレーションではそれはわからなかった。今回の発表では、２次元における電磁波のコヒーレンスも視野に入れて、１次元における先行研究と比較検討する。

高マッハ数衝撃波の三次元構造と電子加速

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Three-dimensional structures of a high-Mach-number shock and associated electron accelerations

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Astrophysical shock waves have been a candidate for the origin of cosmic-rays. In particular, X-ray emissions from supernova remnant shocks have provided great opportunities to examine how high-energy electrons are produced at collision-less shocks. Numerical simulations have revealed that electrons can be efficiently heated and accelerated via resonant interactions with plasma kinetic waves, such as the electron shock surfing acceleration mechanism in which electron-scale Buneman instability played key roles. Recently, Matsumoto et al. [2015] proposed a new acceleration mechanism by turbulent reconnection in the shock transition region through excitation of the ion-beam Weibel instability.

In order to deal with the two different acceleration mechanisms in a self-consistent system, we examined 3D PIC simulation of a quasi-perpendicular, high-Mach-number shock. With the help of the high computational capability of the K computer, we successfully followed a long time evolution in which the two different acceleration mechanisms coexist in the 3D shock structure. The Buneman instability was strongly excited ahead of the shock front in the same manner as have been found in 2D simulations. In the transition region, the ion-beam Weibel instability generated strong magnetic field turbulence in 3D space. The turbulence was much stronger than those found in 2D simulations. Plasma blobs found in the turbulent region indicated magnetic reconnection took place in 3D magnetic field structures. As a result, electron energy spectrum in the downstream region exhibited a high energy tail following a power-law distribution. In this talk, we present how such relativistic electrons are produced during traveling in the 3D shock structure.

無衝突衝撃波の高強度レーザー実験：ミクロ構造の計測に向けて

松清 修一 [1]
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High power laser experiment on collisionless shock: Potential of Thomson scattering measurement

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A collisionless shock often plays some crucial roles in high energy phenomena in space, since it is a sort of an efficient energy converter. At a shock, upstream flow energy is converted into various different types of energies. While a part of it is dissipated as downstream thermal energy, some parts are used to produce high energy non-thermal particles, large amplitude waves, etc. However, detailed mechanisms of the energy conversion have not been well understood.

We have performed the laboratory experiment on collisionless shocks by using high power laser in collaboration with the Institute of Laser Engineering at Osaka university for the past few years. In the experiment expanding target plasma sweeps and compresses a surrounding gas plasma resulting in a discontinuous structure in its density. The density jump at the forward edge of the structure appears to satisfy the theoretical jump condition of a stationary plane shock. In the experiment planed to be performed in this year the local structure of a shock transition region will be measured by using collective Thomson scattering measurement. The potential ability as well as issues of this method to measure the local non-equilibrium plasma is discussed.

コンパクト差分法とLAD法を用いたMHDスキームによる磁気回転不安定性の計算機実験

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Nonlinear evolution of MRI by an MHD simulation with the compact difference and the LAD method

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The magneto-rotational instability (MRI) (Balbus & Hawley, 1991) is one of the most important phenomena in accretion disks and causes turbulence driving the mass accretion in the disks. Recent studies suggested that MRI is saturated by the parasitic instability (Goodman & Xu, 1994; Pessah, 2010), which is related to the Kelvin-Helmholtz instability and magnetic reconnection. These phenomena generate not only turbulence but also discontinuities simultaneously. Therefore, for the study of the time variation of turbulence caused by MRI, we should use an MHD code of high accuracy, low dissipation, and robustness at discontinuities.

In the present study, we have developed an MHD simulation code using an 8th-order compact difference scheme (Lele, 1992), local artificial diffusivity (LAD) method (Kawai, 2013), and shearing box boundary condition (Hawley et al., 1995). Our developed code can solve the wide wave number range without numerical dissipation and thus our code can resolve the structure of MRI more accurately. We carry out a simulation of the evolution of MRI using the developed code in the local shearing box with the number of grid points (256, 256, 128) and the initial net B_z magnetic field. In the simulation result of MRI, we find the anisotropy of the energy cascade process and waves excited through the parasitic instability. We find that wave number spectra of generated waves are consistent to results of the previous analytical study. Our newly developed code enables us to solve the MRI driven turbulence accurately, which is important in solving not only a wide range of the evolution of the disk but also the fine structure of the saturation and nonlinear evolution of MRI.

Multidimensional divergence-constrained relativistic two-fluid simulation code

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Relativistic plasmas are known to exist around compact astrophysical objects such as neutron stars and/or black holes. Ideal relativistic magnetohydrodynamics (RMHD) approximation has commonly been used to investigate the dynamics of high-energy plasmas. There has been growing interest in incorporating resistive effect into the model to take into account dissipation of magnetic field energy, which often dominates the total energy of the system. In contrast to the classical counterpart, however, resistive RMHD is not so commonly adopted because implementation of Ohm's law is much more involved.

On the other hand, the relativistic two-fluid model has rarely been considered as a macroscopic model, mainly because it contains small-scale physics that appears to be unimportant in large-scale phenomena. We here explore the possibility of the relativistic two-fluid model being used as an alternative model to RMHD, in particular, with the effect of resistivity. Since the resistive effect in the two-fluid can easily be taken into account as a friction term between the fluids, we think that it may offer a numerically more convenient model. We have developed a second-order three-dimensional simulation code for the two-fluid equations. The code employs the HLL (Harten-Lax-van Leer) approximate Riemann solver and the UCT (Upwind Constrained Transport) scheme originally proposed for MHD. By carefully designing discretization of the electromagnetic field, we show that the divergence constraints for both the magnetic and electric fields are simultaneously satisfied up to machine precision. Finite difference approach for extension to higher orders will also be discussed.

木星磁気圏におけるコーラス放射発生過程に関する電子ハイブリッド・MHD 連成計算

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Study of whistler-mode chorus in the Jovian magnetosphere by electron hybrid and MHD simulations

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Whistler-mode chorus emissions are electromagnetic plasma waves commonly observed in planetary magnetospheres. Chorus emissions are a group of coherent wave elements showing a variety of frequency shifts in time; typically rising tones, occasionally falling tones, and sometimes observed as hiss-like broadband emissions. While the generation process of chorus has been reproduced by numerical experiments [e.g., Katoh and Omura, GRL 2007a] and has been explained by the nonlinear wave growth theory [Omura et al., JGR 2008, 2009], numerical experiments have revealed that nonlinear wave-particle interactions between chorus and energetic electrons play essential roles not only in generating chorus but in energizing relativistic electrons. Since the nonlinear trapping of resonant electrons by chorus results in very efficient acceleration of trapped particles, chorus should play significant roles in the energization process of radiation belt electrons in planetary magnetospheres. On the other hand, previous studies revealed similarities and differences of the spectral characteristics of chorus in planetary magnetospheres, which has not been understood yet.

In the present study, by carrying out cross-reference simulations by electron hybrid and MHD codes, we investigate physical processes which differentiate the spectral characteristics of chorus emissions in planetary magnetospheres. Our previous simulations have revealed that the spectral characteristics of chorus vary depending on both the inhomogeneity of the background magnetic field and the velocity distribution function of energetic electrons in the equatorial region of the magnetosphere. We use the MHD code for the investigation of the range of variation of the spatial scale of the Jovian magnetosphere in the region from 5 to 20 Rj, where Rj is the radius of Jupiter, corresponding to the region where intense chorus emissions are identified by the Galileo spacecraft observations [Katoh et al., JGR 2011]. By referring the results of the MHD simulations, we conduct a series of electron hybrid simulations for the condition required for the chorus generation and resultant spectral characteristics of chorus in the Jovian magnetosphere. Our simulation results should provide important clues in understanding similarities and differences of chorus emissions in planetary magnetosphere and also the energization process of relativistic electrons.

ホイッスラーモード・コーラス放射は惑星磁気圏に共通して観測されるプラズマ波動であり、周波数が時間的に変化するコヒーレントな波動である。コーラス放射は惑星磁気圏の磁気赤道領域を発生源として、keV 帯の高エネルギー電子との非線形波動粒子相互作用によって生成されることが明らかとなっている [e.g., Katoh and Omura, GRL 2007a]。さらに、コーラス放射の発生過程では、相対論的な高エネルギー電子を作り出す非断熱加速過程も同時に生じることが、近年の計算機シミュレーションにより明らかとなった [Katoh and Omura, GRL 2007b;Katoh et al., Ann. Geophys. 2008]。近年では、磁気嵐回復相における地球放射線帯外帯電子の加速過程においてコーラス放射が重要な役割を果たすとされ、また、木星放射線帯の形成過程においてもコーラス放射の重要性が指摘されている [e.g., Horne et al., Nature Physics, 2008; Katoh et al., JGR 2011]。コーラス放射の発生機構に関する理論は近年著しい進展を見せている [Omura et al., JGR 2008, 2009]。

一方で、スペクトル特性と相対論的電子加速過程との関連や、探査機による観測結果に見られる惑星磁気圏ごとのスペクトルの違いについては、未解明の問題が多く残されている。例えば、木星は太陽系最大の磁気圏と放射線帯を有しているが、コーラス放射の波動強度は地球磁気圏のコーラス放射よりも一桁以上小さいことが明らかとなっている。どのような環境で相対論的電子が高効率に作り出されるかを理解する上で、コーラス放射の波動特性がどのように決定されるのかを理解する事は重要である。

本研究は惑星磁気圏でのコーラス放射の波動特性を理解する事を目的として、惑星磁気圏の構造を解く MHD コードと、磁力線上を運動する高エネルギー電子とプラズマ波動との相互作用を解く電子ハイブリッドコードとを用いた連成計算機実験を実施する。コーラス放射の波動特性は、磁力線に沿った背景磁場の空間勾配と、波動の励起エネルギー源である keV 電子の速度分布関数とによって大きく変化する事が電子ハイブリッドコードを用いた計算機実験により明らかとなっている。この知見に基づいて、木星磁気圏において Galileo 探査機によりコーラス放射の発生が同定されている 5-20 木星半径の領域を対象として、MHD シミュレーションにより背景磁場の空間勾配の変動範囲を同定し、さらに同定された背景磁場構造を初期条件として電子ハイブリッドコードを用いたシミュレーションにより、コーラス放射の発生条件とその波動特性を明らかにする。

Gyro-averaging method for simulation of whistler-mode wave-particle interactions at oblique angles

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Whistler-mode chorus waves propagating with oblique normal angles have been observed by many satellite missions in the Earth' inner magnetosphere. In this study, we have analyzed the propagation condition of an obliquely propagating coherent wave, and have developed a wave model with the whistler-mode dispersion relation. Solving the equations of motion of relativistic electrons interacting with the wave, we perform test particle simulations of energetic electrons along the Earth's inner magnetosphere field line to reveal the interactions between oblique whistler-mode waves and energetic electrons. By confirming that the Poynting vector of oblique whistler-mode wave is nearly parallel to the background magnetic field, we apply gyro-averaging method, which just treat particle motion as its guiding center motion to simplify the complicated cyclotron motion and reduce the simulation system from 2 dimension to 1 dimension. This method was successfully examined in a recent study [1]. We can achieve higher numerical efficiency through this gyro-averaging method than the method which we directly solved the 2 dimensional equations of motion. In the simulation, the energetic electrons undergo multiple cyclotron resonances. The simulation result shows the validity of gyro-averaging method, how the waves trap and accelerate the energetic electrons, and how the waves develop after the interactions.

Reference:

[1] Nunn and Omura (2015), A computational and theoretical investigation of nonlinear wave-particle interactions in oblique whistlers, J. Geophys. Res. Space Physics, 120, doi:10.1002/2014JA020898.

Decaying Whistler Turbulence at Ion Scales: Particle-In-Cell simulation

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Solar wind observations show that a magnetic fluctuation spectrum has two spectral break points around 1Hz and a few tens of Hz in a spacecraft frame at 1AU. The spectrum becomes steeper at the break points in frequency. The Taylor hypothesis in the solar wind implies that these scales correspond to ion and electron inertial (or Larmor) scales. The hypothesis suggests that ion and electron kinetic properties have an important role to make the steeper spectra of the magnetic spectrum in the solar wind. Dissipation and/or dispersion properties of kinetic turbulence should be investigated in more details including kinetic properties of ions and electrons.

Two-dimensional electromagnetic particle-in-cell simulation in magnetized, homogeneous, collisionless electron-ion plasma has been done to demonstrate the forward cascade of decaying whistler turbulence at ion scales. Fluctuations with right-handed polarization at scales larger than ion inertial length are applied as an initial condition of the simulation, which satisfy a dispersion relation of whistler waves in cold-magnetized plasma. The particle-in-cell simulation, which includes full kinetic properties of electrons and ions in collisionless plasma, demonstrates turbulent cascade and dissipation of fluctuation energy self-consistently.

Discussion will focus on properties of decaying whistler turbulence at ion scales, such as the power-law index, wavenumber anisotropy, and plasma heating. Comparison of properties of whistler turbulence at ion scales with electron scales will also be discussed.

Electron acceleration by lower-hybrid waves near the geomagnetic equator: One-dimensional test particle simulation study

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THEMIS satellite mission observed equatorial emissions with a multi-banded frequency structure in the Earth's inner magnetosphere (Wang et al, 2015). The observed waves are in a range between proton gyrofrequency to lower-hybrid frequency, propagating nearly perpendicular to the background magnetic field, and almost linearly polarized. These features of observed waves are consistent with the properties of lower-hybrid waves. These lower-hybrid emissions are related to whistler-mode waves, which are well known for their capability to accelerate radiation belt electrons. In this presentation, we focus on modeling the electron accelerations by the lower-hybrid waves. Specifically, the test particle simulation method is adopted. In this simulation, we construct the lower-hybrid waves based on a cold plasma dispersion relation using parameters consistent with the THEMIS observation on 7 May 2008. The relation between the extent of electron accelerations and the wave angle, the angle between the wave vector and the background magnetic field, will be investigated and reported.

外部回転磁場による電子電流生成のテスト粒子計算：次世代無電極推進機関への応用

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Test particle simulation of electron current generation by RMF: next generation electric thrusters

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For long-term space missions such as exploration of outer planets, electric thrusters are considered to be useful because of their high specific impulse (fuel efficiency). On the other hand, lifetime of many of the conventional electric thrusters is limited by electrode wastage. In view of these circumstances, we have been engaged in research and development of the next generation electric thrusters in which electrodes do not contact with the plasma directly.

Presently we are dealing with the concept utilizing the Rotating Magnetic Field (RMF), which has been developed primarily for an application to the plasma confinement in the field-reversed configuration. In the RMF, the transverse magnetic field drives the azimuthal electron current, which in turn pushes the plasma via the Lorentz force in a presence of radial component of the background magnetic field.

One of the central issues of the RMF is the generation of azimuthal electron current. While many of the past studies focused on penetration of the RMF into the plasma from fluid (MHD) point of view, in this presentation we show results of test particle simulations in which we discuss how electrons react to the RMF, leading to the azimuthal current. Some interesting nonlinear physical processes appear such as the phase synchronization and the resonance broadening. Application to the thrusters will be presented as well.

惑星探査等の長期間ミッションにおいて、化学推進機関と比べ比推力（燃費に相当）が高い電気推進機関が注目されている。一方、イオンエンジンなどの既存の電気推進機関の多くは内部に加速のための電極を持ち、これが加速した荷電粒子と直接接触することで電極摩耗を生じるため、推進機関の寿命が制限される。

現状を踏まえ、電極を内部に有さない無電極の次世代型電気推進機関として、我々は回転磁場（RMF）型の加速機構について検討を行っている。この方式では、円柱プラズマに対してその軸と垂直方向に回転外部磁場を印加することで、プラズマ内部に周方向の定常電子電流を誘起する。これは核融合分野で知られた回転磁場による磁場逆転配位のプラズマ閉じ込め（FRC）の方法と同様のものである。さらに、背景磁場の径方向の磁場成分と励起された電子電流とのローレンツ力により、軸方向の定常推進力を得る。

RMF 型のプラズマ加速機構を理解するためには、外部回転磁場による電子電流の発生について考える必要がある。従来、流体的な立場から外部回転磁場のプラズマ浸透と電子電流生起の研究が多く行われてきた。本研究では純粋に科学的な観点からの考察も念頭に、テスト粒子計算を用いて回転磁場による電子電流の生起を検討した結果を発表する。回転磁場強度、回転磁場周波数、電子のサイクロトロン周波数の関係により、電子運動の共鳴、位相の引き込み等の興味深い非線形現象が起こる。さらに、発散磁場を加えた場合の推進力の評価も行う。

プラズマディタッチメントの数値モデル

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Numerical modeling of plasma detachment

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Electric thrusters, characterized with high specific impulse, are considered to be useful for long-term space missions such as those to outer planets. On the other hand, the performance of many of the conventional electric thrusters (e.g., ion engines) is limited by electrode wastage due to the direct contact of the electrodes with plasma. We have been involved in the research and development of ”””’electrodeless”””” (no direct contact of electrodes with plasma) thrusters.

One of the central issues of the electric thrusters is the plasma detachment. If the plasma remains guided by the magnetic field provided by the thruster, it does not escape into free space and no thrust will be obtained.

In this presentation, we propose a new numerical model to simulate the plasma detachment. By using this model, we show under what conditions the plasma can be separated from the thruster. We mention also the issue of the plasma detachment is equivalent to the physics of solar wind acceleration.

宇宙開発の技術目標の一つに宇宙探査機・宇宙船等に使用される推進機関の高比推力化がある。現在使用されているイオンエンジン等、既存の電気推進機関の多くはプラズマの放出時に電極がプラズマに接触する有電極型のため、電極摩耗による寿命の制限が大きな問題となっている。そこで、我々はプラズマ生成、プラズマ加速、プラズマ分離の 3 段階ともに電極とプラズマが接触しない、完全無電極型の新しい電気推進機関の開発研究を行ってきた。

電気推進の大きな課題の一つに、プラズマディタッチメント（プラズマ分離）がある。プラズマは基本的に磁場に沿って運動する。推進機関起源の背景磁場を考えると、これはループ状になっているため、もしもプラズマが完全に磁場に捕捉されていれば、放出されたプラズマは必ず推進機関に戻ってきてしまう。この場合、推進力は得られない。

我々は、粒子的な運動をするプラズマと背景電磁場とを交互に解く、ディタッチメントの新しい数値モデルを作った。これを用い、どのような状況でプラズマがディタッチされて宇宙空間に放出されるか、検証を行った結果を報告する。プラズマディタッチメントの問題は太陽風加速と同等であることについても言及する。

非平衡プラズマによる協同トムソン散乱の理論的研究

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Theoretical study of collective Thomson scattering in a non-equilibrium plasma

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Recently, a variety of high energy astrophysical phenomena have been successfully reproduced in laboratory experiments using high power laser. We take part in the experiment of collisionless shocks in collaboration with a group at the Institute of Laser Engineering at Osaka University. The transition region of the collisionless shock is usually in a highly non-equilibrium state. In order to understand the mechanism of energy dissipation at the collisionless shocks, we need to clarify the relaxation processes occurring there. To diagnose such a local plasma, the Thomson scattering (TS) measurement has been widely used. Here the TS is defined as an elastic scattering of a low frequency incident electromagnetic wave due to its interaction with free electrons in a plasma. Although the TS measurement has been used for a long time to measure the plasma not only in experimental devices but also in space (ionosphere), detailed theory of the TS in a non-equilibrium plasma is not well established.

In this study, we investigate how a non-equilibrium plasma near the shock transition region is observed by the TS measurement. First, we assume that a plasma just upstream of a shock consists of background electrons, ions, and beam electrons. The beam instability generated in such an unstable local plasma is reproduced by using one-dimensional full particle-in-cell (PIC) simulation. The linear growth rate as well as the trapping frequency at non-linear stage of the instability are confirmed to be consistent with theoretical predictions. The obtained spectrum of the electron density fluctuations are utilized to investigate the virtual TS. A wave equation of the scattered waves when a probe light is incident into this non-equilibrium plasma is numerically solved to examine the spectrum of the electron density fluctuations.

近年、様々な高エネルギー天体現象を、高強度レーザー実験を用いて再現できるようになってきた。我々は、大阪大学レーザーエネルギー学研究センターとの共同研究により、無衝突衝撃波の実験的研究に参画している。無衝突衝撃波の遷移層はしばしば非平衡状態にあり、そこで起こる緩和過程の理解は、衝撃波のエネルギー散逸機構の解明に不可欠である。現在、遷移層の局所的なプラズマを計測する方法としてトムソン散乱計測が広く用いられている。トムソン散乱とは自由電子による光の弾性散乱であり、さまざまな実験室プラズマや電離層プラズマの計測に応用されているが、非平衡プラズマによるトムソン散乱理論は十分に確立されていない。

本研究では、共同実験で見られる衝撃波遷移層の非平衡プラズマが、トムソン散乱計測によってどのように計測されるかを調べる。まず、衝撃波直上流のプラズマとして、背景電子、イオン、ビーム電子から成る典型的な非平衡プラズマを仮定し、一次元 PIC シミュレーションを用いて局所的なプラズマ密度揺動を再現した。ビーム不安定性の線形成長率やその非線形発展における電子の捕捉周波数が理論値と矛盾しないことを確認した。得られた密度揺動スペクトルをもとに、別途散乱光の波動方程式を解いて、そのスペクトル特性を議論する。

高精度 MHD 計算を用いた高速磁気リコネクションの研究

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Study of fast magnetic reconnection by using newly high resolution MHD scheme

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Magnetic reconnection is an important process to drive explosive release of magnetic energy by reconnecting anti-parallel magnetic lines in space plasma, such as particle acceleration in solar flares and large-scale convection in the Earth's magnetosphere. Magnetohydrodynamics (MHD) simulation where plasmas are treated as fluid is one of the useful methods to learn macroscopic effects of magnetic reconnection. However, kinetic effects of plasma particles around an X-line are significant to drive fast reconnection, since the MHD approximation is broken in the vicinity of the X-line. Consequently, reconnection rate which means energy release efficiency is low ,the so called slow reconnection. Previous researches have shown that particle simulations including kinetic effects achieve fast reconnection, while MHD simulations do not[e.g., J. Birn et al., 2001].

In this study,we attempt to simulate the fast magnetic reconnection by using a newly high order MHD scheme proposed by S. Kawai[2013]. The results show reconnection rate is higher than previous results by MHD simulations. In addition, as the resolution is higher, the reconnection rate is expected to be higher, since current sheet becomes thinner. As a result, simulations with high resolution allow secondary magnetic islands and generate multiple X-lines. We confirm, however, local reconnection rate at the most major X-lines, and the rate is equivalent to that from previous particle simulations. Consequently, these results show that the newly scheme enables us to perform fast magnetic reconnection. Furthermore, we check this argument is consistent at other various condition and verify this scheme is useful to study magnetic reconnection in the MHD-scale phenomenon.

磁気リコネクションとは反平行な磁力線が繋ぎ変わることで磁場のエネルギーを爆発的に解放する現象である。この現象は太陽フレアでの粒子加速や地球磁気圏内の大規模な対流などを駆動する重要な物理過程である。磁気リコネクション研究の有用な手法には計算機シミュレーションがあるが、その中でも本研究では電磁流体力学 (MHD) シミュレーションを用いた．MHD はプラズマを流体として扱うため，個々の粒子の集団的な振る舞いを記述できる．すなわち MHD はマクロスケールの物理現象の再現に適した手法だと言える．しかし，磁気リコネクションは大規模な物理現象を駆動する過程である一方で，磁力線がつなぎ変わる現場である拡散領域では MHD 近似が破れ，プラズマ粒子の運動論的効果が重要になる．従って運動論的効果を含まない MHD では，磁気リコネクションのエネルギー解放効率を示すリコネクションレートが小さくなる（遅いリコネクションと呼ばれる）．過去の研究において，運動論的効果を含む粒子コードなどの計算では高いリコネクションレートが達成できるのに対し，MHD コードによるリコネクションレートは低くなり，MHD では速いリコネクションが再現できないことが示された [e.g., J. Birn et al., 2001].

本研究では S. Kawai[2013] により提案された、新たな高精度 MHD スキームを用いて高速磁気リコネクションの再現を試みた．その結果，過去の MHD 計算のリコネクションレートよりも高い値が得られた．また，より高解像度で計算を行った場合，より薄い電流層が再現できるため，より爆発的なリコネクションが起こることが予想される．結果，高解像度計算ほど磁気島が複数発生し，複数の X-line ができることが分かった．その中の最もメジャーな X-line に注目して，ローカルなリコネクションレートを求めると，各解像度で粒子計算と同等の値に収束することが分かった．これは低解像度でも一定の高速磁気リコネクションが再現できることを示唆している．さらに，他の様々な条件下で同様の結果が得られるかどうかを確認し，今回用いたコードが今後大規模なスケールのリコネクションの研究に適用可能であるかを検証する．

リコネクション率に伴って変化するX-line近傍の電場構造に関する研究

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Variation of X-line electric field structure associated with variation of reconnection rate

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We have inspected how the electric field structure around an X-line varies according to reconnection rate. Reconnection rate is controlled not by electron physics in the vicinity of the X-line but by the macroscopic circumstances surrounding the X-line. In a very simple simulation of collisionless magnetic reconnection, where reconnection is initiated in a thin current sheet with anti-parallel magnetic field bounded by a periodic boundary, reconnection rate explosively increases, hits a peak, slowly declines, and then reconnection terminates. We show that spatial structure of out-of-plane electric field (reconnection electric field) and temporal variation of the current-sheet-normal component of magnetic field according to the phase of reconnection. Reconnection electric field at the outer edge of the electron diffusion region (EDR) reflects the MHD condition at an electron frame. The time evolution of the normal magnetic field at the edge of the inner EDR is closely related to the temporal behavior of reconnection rate. Comparing between the developing phase and the decaying phase of reconnection, we find that reconnection rate is affected by the reconnection electric field at the edge of the outer EDR though the gradient of the reconnection electric field at the edge of the inner EDR. This perspective is also applicable to complex cases including X-line's retreating and plasmoid ejection.

レイリー・テイラー不安定性のブラソフシミュレーション

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Vlasov simulation of the Rayleigh-Taylor instability

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The Rayleigh-Taylor instability (RTI) develops at an interface between two fluids with different densities when an external force is applied from a heavy fluid to a light fluid. The RTI is seen as a secondary instability of the Kelvin-Helmholtz instability taking place at the magnetopause. The spatial scale of the secondary RTI is on the ion inertial scale or ion gyro scale where non-MHD effects are important. In the previous studies of ideal MHD simulations, the RTI develops symmetrically in the horizontal axis. On the other hand, previous hall-MHD and Finite-Larmor-Radius (FLR)-MHD simulations have shown that the RTI develops asymmetrically in the horizontal axis. In this study, basic processes of non-MHD scale RTI are of interest. We perform four-dimensional Vlasov simulations of the RTI with two spatial dimensions and two velocity dimensions. We vary the ratio of the ion inertial length and/or the ion gyro radius to the spatial scale of the density gradient layer, and discuss the effect of the non-MHD effects on the linear growth and nonlinear development of the RTI.

Ion kinetic effects to nonlinear processes of the Kelvin-Helmholtz instability

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The nonlinear evolution of the Kelvin–Helmholtz (KH) instability at a transverse velocity shear layer in an inhomogeneous space plasma is investigated by means of a four-dimensional (two spatial and two velocity dimensions) electromagnetic Vlasov simulation. When the rotation direction of the primary KH vortex and the direction of ion gyro motion are the same (i.e. the inner product between the vorticity of the primary velocity shear and the magnetic field vector is negative) there exists a strong ion cyclotron damping. In this case, spatial inhomogeneity inside the primary KH vortex is smoothed and the secondary Rayleigh–Taylor/KH instabilities are suppressed. It is also found that another secondary instability on the electron inertial scale is simultaneously generated at secondary shear layers for both cases, but at different locations. The small-scale secondary instability takes place only when the inner product between the vorticity of the secondary shear layer and the magnetic field vector is positive, suggesting the damping of small-scale processes by ion gyro motion. These results indicate that secondary instabilities occurring in the nonlinear stage of the primary KHI show different evolutions depending on the sign of the inner product between the magnetic field and the vorticity of the velocity shear layer. The difference of the nonlinear evolution depending on the ion-to-electron mass ratio will also be discussed.