プラズマ波動交番電界中の衛星電位変動現象の数値モデリング

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Numerical Modeling of Spacecraft Potential Modulations due to Time-varying Plasma Wave Fields

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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 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 current modulations due to wave electric field. Although its dependencies on wave frequency and magnetic field strength have been examined experimentally [e.g., Wang et al., 2014], there are a number of remaining issues such as effects of wave polarization or spacecraft geometry. Also, 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 talk, we will discuss such unresolved issues based on particle-in-cell simulations. The typical spatial scale of plasma wave lengths is much greater than that of the spacecraft size. Hence, we apply a spatially-uniform and time-varying electric field to the whole computational domain as an external force term in the simulations. We have confirmed that this model can reproduce the photoelectron-mediated spacecraft potential fluctuations in the presence of a circular-polarized wave electric field. We examine the case of multiple spacecraft bodies corresponding to the spacecraft chassis and the probes, which will elucidate detailed mechanism of detecting spacecraft potential modulations in in-situ observations.

本研究では、プラズマ波動の交番電界中における衛星電位変動現象をプラズマ粒子シミュレーション手法により再現する。バンアレンプローブによる最近の観測ではコーラス波動の検出と同時刻に衛星電位の変動が確認されており、波動電界による光電子放出電流の変動が原因と予想されている。これまでに本現象の波動周波数や背景磁場強度に対する依存性がチャンバー実験により調査されているが、同時に波動の偏波や衛星形状による影響など理解が十分でない点も指摘されている。また衛星電位の計測は、衛星筐体とプローブ間の電位差を測ることにより行われるため、本現象を正しく理解するためには、衛星筐体とプローブ電位それぞれの波動電界に対する応答（の違い）を考慮する必要がある。

本発表では、これらの問題に関して、プラズマ粒子シミュレーションを用いた数値研究経過を報告する。ここで対象とする VLF 波動の典型的な波長スケールは衛星サイズより十分に大きい。したがって波動電界は空間的に一様な交番電界であるとして、シミュレーション空間中に印加した。この計算モデルにより、右回り円偏波を持つ波動電界に対して、光電子電流の変調とそれに起因する衛星電位変動を再現することに成功した。現在、衛星筐体とプローブなど複数の物体を考慮した解析を進めており、これにより観測結果を説明するより詳細な物理過程が明らかになると期待される。

グローバルシミュレーションにおけるコヒーレントな磁気圏渦ダイナミックス

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Coherent Vortex Dynamics in Magnetospheric Flow

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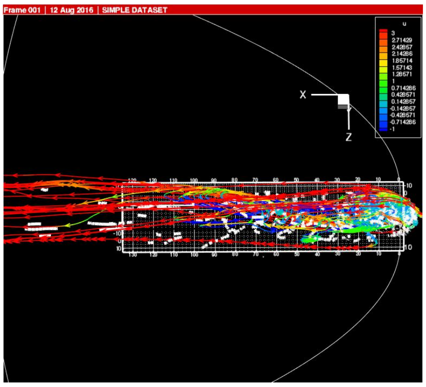
In the northward IMF configuration, the energy transfer between the magnetosphere and solar-wind has been discussed based on Kelvin-Helmholtz (K-H) instability and its vortices.Unfortunately, no single precise definition of a vortex is currently universally accepted, despite the fact that many space plasma researchers claim that many observations have detected vortices (as Kelvin-Helmholtz vortices at/around the magnetopause).In the present report, we identify the 3D magnetic vortex structures by using various vortex identification criteria as follows: 1,The first criterion is Q-criterion that defines vortices as regions in which the vorticity energy prevails other energies; 2, the second criterion is the lambda_2-criterion that is related to the minus of the Hessian matrix of the pressure related term;3, the third criterion requires the existence of vortex-core-lines that is the Galilean invariance. We visualize (please see Figure) and identify vortex structures using these identification method and the coherent vortex dynamics can be summarized as follows: (1) The K-H vortices that are transverse to the flow grows in the shear layer generated between the solar-wind and magnetopause, and are quickly shed-off from the magnetopause shear layer after the Dawn-Dusk (DD) line; (2) The vortices move freely until reaching the stable configuration forming two vortex rows (i. e., Karman vortex street) inside/outside the velocity shear region across the magnetopause, which is a part of the large wake flow field of the magnetosphere; (3) They are developed into vortices that have spiral or helix structure; (4) The optimally aligned transverse vortex structures (Karman vortex street) inside the velocity shear region mentioned above gradually form the so-called longitudinal or transverse vortices [Kida, 2006]; (5) Both transverse and longitudinal vortex-cores form this ""grid"" structure, although the grid structure is highly unstable, and both the vortex-cores are broken into pieces by the instabilities (vortex-break-down and the flow become turbulent-like [Kida, 2006; Kida and Miura, 1998]); and (6) Finally, those scraped vortex-cores mainly in stream-wise move tailward, survive over long time-range, and form a large or global scale tail spiral motion (see Figure). This persisting stream-wise tail spiral motions will significantly contribute to the transfer of solar-wind energy into the magnetosphere [Kida, 2006].



Ion and electron accelerations during magnetic reconnection

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The acceleration of nonthermal particle in collisionless plasma has been a long standing puzzle. Magnetic reconnection is known to be one of important acceleration processes, yet the acceleration efficiency of ions an electrons in reconnection is not clearly understood. For example, the satellite observations in the Earth's magnetotail reported many efficient electron acceleration events during the plasma sheet crossing in reconnection, but the ion acceleration events associated with nonthermal ions are few. Furthermore, recent particle-in-cell (PIC) simulation results performed by several researchers also suggested the efficient acceleration for electrons but less acceleration for ions during reconnection. In this study, we investigate how and where the ions and electrons are acceleration during reconnection by using two- and three-dimensional PIC simulations. Specifically, we focus on the effect of the so-called driven reconnection with an external Poynting flux injection into the plasma sheet. We also pay a special attention to the coupling between reconnection and the lower hybrid drift instability (LHDI). Based on our simulation results, we discuss that (1) the electron acceleration can be enhanced by the coupling to LHDI in reconnection, and (2) the reconnection can generate quite a few nonthermal ions and electrons under the driven reconnection.

無衝突磁気リコネクションにおける電子軌道の全ラグランジュ解析

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Full Lagrange analysis of electron orbits in collisionless magnetic reconnection

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In order to study inner workings of magnetic reconnection, NASA recently launched the Magnetospheric MultiScale (MMS) spacecraft. It is expected to observe electron velocity distribution functions (VDFs) at high resolution in magnetotail reconnection sites in 2017. To understand the physics of magnetic reconnection, it is important to clarify the relation between electron orbits and VDFs.

In this work, we study electron orbits and associated VDFs in magnetic reconnection by using a two-dimensional particle-in-cell (PIC) simulation. We manage to obtain electron orbits as many as possible in our simulation. By extensively analyzing the dataset, we discover several new electron orbits. In this contribution, we will discuss basic properties of these new orbits, by modifying a theory of nongyrotropic particle orbits (Buchner & Zelenyi 1989 JGR). Surprisingly, a majority of electrons follow new orbits. This raises a serious question to our present understanding of physics of collisionless magnetic reconnection.

磁気リコネクションの内部物理を探るために、2015 年に NASA は Magnetospheric MultiScale (MMS) 衛星を打ち上げた。MMS は 2017 年以降に、磁気圏尾部のリコネクション領域で電子の速度分布関数（VDF）を詳しく観測することが期待されている。観測データを読み解き磁気リコネクションの物理を理解するために、電子軌道と速度分布関数の関係を明らかにしておくことは重要である。

本研究では、磁気リコネクションの２次元粒子シミュレーションデータを解析して、リコネクション系における電子軌道を徹底的にサーベイした。まず、粒子データを 8 ステップ毎に書き出して 2000 万個の電子軌道を生成した。そして、このデータセットを解析した結果、静電場に跳ね返されて中央平面を横切らない軌道など、これまで知られていなかった新しいタイプの電子軌道を多数発見した。また、これらの軌道の性質は、曲がった磁場の中の軌道運動論（Buchner & Zenelyi 1989 JGR）を拡張して議論できることがわかってきた（Zenitani & Nagai 2016, submitted）。驚くべきことに、これらの新しい軌道を通る電子は数密度の大半を占めている。これは旧来の軌道を想定した多くの理論に再考を促す結果である。

無衝突プラズマの不可逆性

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Irreversibility of Collisionless Plasmas

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It is often said that physical processes in collisionless plasmas are reversible. This is because the collision term, which is believed to cause reversibility, is absent in the Vlasov equation. It is true that the collision term is the source of irresponsibility, but it does not necessarily mean it is the only source of reversibility, Moreover, the collision term in the Boltzmann equation is *an ad hoc* term introduced to express the relaxation process in collisional gases; microscopic equation of each particles is reversible.

What is discussed in this presentation is the reversibility resulting from microscopic equations,; collsionless plasmas is an good example. When we define an irreversible process as 'a process whose time reversal evolution does not spontaneously happen almost for sure', then irreversible processes may take place in a system with large number of degree of freedom even without dissipations. For example, suppose an instability leads a perfect fluid to turbulent flow starting from an equilibrium state. The time reverse process of this turbulence never happen *almost surely*, in mathematical meaning (means zero probability measure). In this sense, the process is as irreversible as processes in collisional gases.

There had been long controversy on the origin of reversibility from the very beginning of statistical physics. In the presentation, controversy such as Loschmidt's reversibility paradox or Poincare's recurrence theorem will be discussed along with the modern perspective of typicality. Also, the problem of statistical equilibrium for collisionless system will be examined.

講演者は，2016 年春の地球惑星連合大会でランダウ減衰の不可逆性について論じた。多くの教科書では、ブラソフ方程式に衝突項がないため、無衝突プラズマで起こる現象は可逆であると解説している。しかし、衝突項によって不可逆性が生じるという事実は、衝突項がなければ可逆であるということを必ずしも意味しない。また、衝突項というのは気体の緩和過程を表現するために ad hoc に入れられた現象論的な項と考えられ、このため、もともとの微視的な運動方程式は可逆であるのに、巨視的には不可逆性があらわれてくる。

流体的線形波動などのごく限られた場合をのぞいて，可逆な方程式で記述される巨視的な現象の多くが不可逆であり、無衝突プラズマもその一例である，というのが本講演の論点である。「可逆」という言葉を字義通り、つまり「時間逆転をした過程が実際に起こりうる」という意味に解釈すると、衝突のあるなしに関わらず，多自由度系の現象は不可逆性をしめす。たとえば，散逸のない理想流体で、動的平衡状態から不安定性で乱流がおこる場合，乱流が飽和した状態を長時間放置しておくと初期状態にもどるような現象は，ほぼ確実（数学的に確率測度ゼロという意味で）に起こらないからである。

不可逆性の起源については，統計力学の黎明期から現在に至るまでいろいろな議論がなされている。講演ではロシュミットの逆行性批判やポアンカレの再帰定理などの歴史的な話題から，近年盛んになってきた典型性の議論までをふまえて，無衝突プラズマの不可逆性について論じる。また，その不可逆性が行き着く先である，無衝突系の平衡状態についても考える。

我が銀河系中心部ブラックホール・バイナリ―を対象としたデカメータ電波パルス電波源方位の観測における電離層効果の再検討

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Source Direction of Decameter Radio Wave of the Galaxy Center BH Binaries Decided by Eliminating Ionosphere Effects

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1. Introduction

Through the current studies on the detection of Ker Black holes located at the center

part of our Galaxy, being based on the observations of decameter radio wave pulses, the investigation of the accurate source direction had been deferred from the last works. In this study, the method of determination of the direction of the pulse sources is newly developed, considering the symmetry of the ray paths, for pair station of the interferometer system ,through the ionosphere. Though the deviation of the arrival direction of radio wave pulses are large apart from the original directions at individual station of the interferometer system, we can completely neglect the ionosphere effects in the case of taking average for a long period . Data analyses to confirm this developed method have been made using newly observed data in June, 2016

2. Confirmation of the symmetry of the ray paths

The exact ray traces of the paths of the arriving radio wave pulses from our Galaxy

center,which are made being based on the ionosphere electron density profiles detected from the ionogram applying the lamination method, show large excursion of the arrival direction from direct arrival directions for the case of non-ionosphere effects ; the deviation angles indicate the range from 5 to 15 degree. Exact investigations of the ray trace results, however has revealed that there are high level of symmetry between the configuration made by pair observation points and incident points of radio waves from the Galaxy center. It is , then, concluded that we are able to neglect the ionosphere effect when the accuracy of a few arc minute is acceptable.

3. Observation System

The observations to determine the source direction of the decameter radio wave

pulses have been carried out using the long baseline decameter radio wave interferometer of Tohoku university which consists of three observation stations located at Yoneyama, Kawatabi and Zao in Miyagi Prefecture, Japan; the longest baseline is 84km and shortest baseline is 44km. The signals observed at 21.860MHz with band width of 1kHz are sent from each station through the telemetry system directly to the central station at Sendai where the detected signals are converted into digital signals by AD converters with conversion rate of 3000 data per second being divided into 3 channels with the 100Hz band width for each.

4. Observations and Data Analyses

From observation data in June , 2016, we have selected two data sets that consist of

8 observation nights with 5 hour continuous observations for each; the first set has been selected from data observed from June 5, to morning of June 17,and the second set has been selected from data observed from night of June 17 to June 30.

FFT analyses have been made for each data series of 5 hour duration by taking

correlation with template interferometer fringes which correspond to the source direction with selected deviation angles centered at the Sgr A that is located at RA 17h45m40s, Dec-29deg 00min28sec.

5. Results and Discussions

FFT results are indicated for averaging 8 data elements of each set, by calculating

the average values in terms of the ratio to the standard deviation. In both sets of analyzed data, calculated FFT levels which represent 5 systems of black hole binary have indicated clear level dependence that reveal the location of source positions in a region centered at the Sgr A within allowance range of 30 arc minute without disturbance effect of ionosphere. Because the accuracy of detection by FFT is limited in their frequency resolution ability, we can expect much higher accuracy to decide the source position in the stage of box car analyses to determine pulse form and accurate pulse periods.

１．序 わが銀河系中心部より到来するデカメータ電波パルスの解析を通じてカー・ブラックホールがバイナリ―を形成していることを結論してきた。研究は最終段階に入りその確かさの検証を行っている。検証の課題の一つには解析の基本ステップである FFT 解析に対し、銀河系中心部の出現とブラックホールバイナリー群の存在の根拠とする FFT 結果の出現との対応を明確にすることがある。今回、この課題に関わり、2014 年来、東北大学・長距離基線デカメータ電波干渉計を用いた電離層効果を考慮したデカメータ電波パルスの到来方位の解析について再検討をこころみた。これまでの研究では電離層効果を十分に考慮して、+-40 分角の精度で Sgr A を中心に存在するカー・ブラックホール・バイナリ―群の存在を結論づけてきた。しかし、これまでの電離層効果の取り扱いは簡単な２層構造の電離層モデルに依存していて、正確さにおいて議論の余地を残していた。この議論を踏まえ、今回さらに 2016 年 6 月の１か月間を中心に新たな

観測を行い、電離層効果はより近く実測に基づく電離層に対する Ray Trace 法を導入するアプローチを行った、しかし、電波干渉計観測の場合電離層効果は、数 arc min 以内での方位決定を目的とするかぎり、考慮の必要がないという、電離層効果を厳密に取り扱う方法と裏腹に意外な結論に達した。

２．観測システムと観測実施期間 今回観測に用いられた東北大学長距離基線デカメータ電波干渉計は Yoneyama、 Zao、および Kawatabi の 3 局よりなり、最長 83km、最短 44km の 3 基線が設定される。21.860MHz にて全帯域 1kH で観測された受信信号は仙台局にテレメータ伝送される。伝送された各信号は帯域幅 100Hz の狭帯域 3 チャンネルに分割され、各々サンプリングレート３ kHz でＡＤ変換された後、干渉データとして処理される。観測期間は銀河中心部が出現する以前の 1 月下旬から銀河中心部観測の条件が整う３月中旬を経て銀河中心部の衝の期間を含む 7 月中旬に至る期間にて実施された。

３．電離層効果の再検討 データ解析の方針は第一段階の試みとして、観測期間中の、WDC-電離層データセンターより提供された国分寺でのアイオノグラムよりラミネーション法で求めた電離層データに対して銀河系中心部より到来する 21.860MHz の到来方位を決定し、これを基準とする干渉計フリンジをテンプレートとして観測された電波源方位の決定を試みた。結果は夜間電離層の F1 層底の高さに大きく依存し、算出された電波到来方向は、電波源直線方位から 5 度から 15 度も偏移する。従って夜間電離層の F1 層底の高さの不確定さから、この方法が成立しないことが判明した。しかし Ray Trace 結果を吟味すると基線長 100km 程度の干渉計では干渉計の対局への Ray Path は全く対称で、方位決定精度が数 arc min までの要求であれば電離層効果は削除できることが判明した。

４．データ解析 データ解析は、2016 年 6 月 5 日から６月 30 日の期間の観測データに対し、それぞれ５時間の連続観測よりなる 8 夜分の観測期間からなる 2 セットのデータ、すなわち、6 月 5 日から 6 月 17 日午前３時に至る全半のデータセット、および 6 月 21 時より 6 月 30 日に至る後半のデータセットを対象として行った。ＦＦＴ解析は、最長周期 8160sec 最短周期 40sec にわたり、その解析結果の平均を求めた。その結果、２セットのデータに対する結果は、ともに、パルス電波源が赤経 17h45m40s, 赤緯-29 度 28 秒に対し約 30arc min 以内で同じ方位に位置することが認められた。

４．結果と検討　観測周波数 21.860MHz において、電離層による影響をラミネーション法で得られた実際に近い電離層に対する Ray Trace によって検討した。電離層の影響は大きく、銀河中心部の方位角の固有の位置からの偏向は、特に仰角の低い時刻には、8 度から 15 度近くのずれを示し、南中時にも 5 度程度の差がある。こうした電離層効果を追跡しての方位決定は電離層の実際値の決定の不確定さから、不可能であると結論された。しかし Ray　Trace の結果は干渉計の場合、電離層効果は対局間で対称であることが確認され、電離層効果除去して電波源位置が解析されることが示された。　問題としている５組のブラックホールを起源とするパルス電波の方位探査を加味した FFT 結果は、赤経 17h45m40s, 赤緯-29 度 28 秒にある SgrA を中心に 30arc min に存在すると結論される。FFT 解析結果をもとに、今後 Box Car 法によりパルス波形を厳密に求める解析ではその方位情報は数 arc min 以内で確定されると予想される。

高次精度 MHD シミュレーションコード CANS+の開発と応用

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High-resolution Magnetohydrodynamic Simulation Code CANS+: Assessments and Applications

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We developed a new MHD simulation code with the aim of providing accurate numerical solutions to astrophysical phenomena where discontinuities, shock waves and turbulence are inherently important. The code implements the HLLD approximate Riemann solver, the fifth-order, monotonicity preserving interpolation scheme, and the hyperbolic divergence cleaning method for the magnetic field. This choice of schemes greatly improved numerical accuracy and stability, and therefore saved computational costs in multi-dimensional problems.

In one-dimensional benchmark tests, including linear Alfven wave propagation and shock tube problems, adopting the spatially fifth-order scheme gave superior results as compared with the second-order scheme even additional computational costs arising from the higher order reconstruction were considered. In two-dimensional tests of the K-H turbulence, the Orszag-Tang vortex problem, and the magnetic reconnection, it was shown that CANS+ code enables to solve discontinuities including shock waves and turbulence at the same time with high accuracy and stability. The test problem of the Parker instability also showed a high capability of solving very low-beta (~10^{-3}) plasma in which the numerical divergence errors of the magnetic field maintained within reasonably low levels.

As an application of CANS+ code, we present global simulations of the accretion disk around a black hole. With a given initial set up and grid resolutions, CANS+ code could follow a long-term evolution of the accretion disk in which the MRI and resulting mass accretion into the black hole sustained for 50 rotational periods. The long-term evolution characterized by compressible MHD turbulence clearly benefited from adoption of the fifth-order scheme, while they quickly decayed in the results from the second-order scheme owing to the strong numerical damping effects of the TVD property.

HLLI-UCT 法：HLLI 近似 Riemann 解法と風上型 CT 法による誘導方程式の高解像度化

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HLLI-UCT: improving resolution of induction equation by HLLI approximate Riemann solver and upwind CT method

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The induction equation is one of the basic equations in the magnetohydrodynamics (MHD). Since this equation has the form of curl rather than divergence of its flux, not like in other conservation equations, the divergence of the magnetic field must be preserved, and it should be zero due to nonexistence of a magnetic monopole. Any numerical scheme which breaks this constraint leads to spurious force along the local magnetic field and returns a physically incorrect solution.

A constrained transport (CT) algorithm is a feasible prescription to construct a divergence-free scheme by the use of staggered arrangement for the magnetic and the electric fields, which guarantees that the divergence error is kept within machine precision. As a CT method simply requires the electric field evaluated at cell edges, there has been several variants of the CT method depending on interpolation schemes for the electric field. An HLL-upwind CT (UCT) method is one of the most important schemes, which enables one to construct a higher-order scheme by combination of an arbitrary interpolation method and an HLL approximate Riemann solver. As long as the scheme involves simple HLL averaging, however, one inevitably suffers from the dissipative nature of the HLL Riemann solver, especially for high-beta plasmas. Recently, moreover, it has become clear that the resolution of the HLL-UCT method cannot be improved simply by replacing the HLL scheme with other HLL-type, non-linear, and high-resolution Riemann solvers such as HLLC, HLLR and HLLD. The problem arises from the fact that these non-linear Riemann solvers cannot be separated into an averaging term and a dissipation term in contrast to the HLL scheme. This fact leads the effect of the numerical dissipation to enter into the interpolated electric field twice, which is the so-called dissipation doubling.

In this work, we made use of the idea that the dissipation doubling can be avoided by employing the recently proposed HLLI approximate Riemann solver, where substructure of a Riemann fan is linearly reconstructed consistently with the eigensystem. By combining the HLLI method and the upwind CT technique, we developed an HLLI-UCT scheme. The use of our scheme successfully overcomes the dissipative property of the original HLL-UCT scheme. Moreover, because the HLLI scheme does not rely on specific non-linear jump conditions, which are approximated in a heuristic manner in the case of a non-linear HLL-type Riemann solver, it is also possible to apply the HLLI-UCT to other non-ideal MHD systems if the eigensystem can be obtained; of course it can be obtained for any hyperbolic system. Examples include the kinetic MHD system with pressure anisotropy, which may play an important role in collisionless plasmas. Even in such a system for which a non-linear Riemann solver is not developed, one can apply the HLL-UCT method straightforwardly. In our presentation, we will discuss the impact and some technical details of the new HLLI-UCT scheme.

ヘリコンプラズマ放電の数値シミュレーション

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Numerical simulation of helicon plasma discharge

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Helicon plasma is a high-density and low-temperature plasma generated by the electromagnetic (helicon) wave excited in the plasma. The helicon plasma is expected to be useful for various applications. On the other hand, there still remain a number of unsolved important physical issues on the helicon plasma. One of them is the abrupt transition of the plasma density (the helicon jump) from the low -density (~10^{17} /m^3) to the high - density (~10^{19} /m^3) regime as the input power is gradually increased.

Some theoretical models (K. P. Shamrai, 1997, F. F. Chen, 2007) predict that the transition of discharge modes is closely related to the stability of the steady state, in which the power absorbed and lost by the electrons is balanced. However, the physical mechanism behind the mode transition needs to be further investigated, since in previous models, such seemingly important effects are neglected as the plasma transport, spatial inhomogeneity of the plasma density and the electron temperature. In the present research, we study the mode transition process of the helicon discharge by constructing a fluid discharge model which includes the wave excitation, electron heating, the power balance between the absorbed energy and the energy loss, and the effects of plasma transport.

相対論的衝撃波における大振幅電磁波

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Large-amplitude electromagnetic precursor waves in relativistic shocks

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The origin of cosmic rays has been mystery for a long time in astrophysics. Diffusive shock acceleration in supernova remnants is considered a plausible model for the origin of galactic cosmic ray. On the other hand, the acceleration mechanism of high energy cosmic rays is still far from fully understood. Recently Chen et al. (PRL, 2002) proposed the particle acceleration by the large-amplitude Alfven waves in relativistic shocks as a model of the generation of ultra-high energy cosmic rays, based on the wakefield acceleration mechanism (Tajima and Dowson, PRL, 1979). Since then much attention has been given to the wakefield acceleration mechanism in astrophysical field. Lyubarsky (ApJ, 2006) suggested that large-amplitude electromagnetic precursor waves, which are excited in the shock front by synchrotron maser instability (Hoshino and Arons, PoP, 1991), induce the electrostatic field and argued that it may be responsible for the particle acceleration. Hoshino (ApJ, 2008) extended the previous studies and demonstrated the efficient particle acceleration by the incoherent wakefields induced by the ponderomotive force of the precursor waves in the upstream region of the shock wave by means of one-dimensional Particle-In-Cell (PIC) simulation.

In two-dimensional systems, however, several problems about the wakefield acceleration may arise because of the nature of the precursor wave. One is the problem of wave coherence of the precursor wave. The wave coherence is essential for the ponderomotive force, which induces the wakefield acceleration. The precursor waves may overlap with each other, and the wave coherency may be broken. Another problem is the generation of precursor wave under a competition between synchrotron maser instability and Weibel instability. The growth rate of the synchrotron instability might get smaller than that in one-dimensional systems due to the Weibel instability, and the amplitude of the precursor wave might be insufficient to cause the wakefield acceleration. Since the previous studies in one-dimensional systems could not solve these problems, we investigated in this study the nature of the precursor waves in relativistic shocks by using the two-dimensional PIC simulation and argue the possibility of the wakefield acceleration in two-dimensional systems. Our simulations were performed with high spatial resolution in order to capture the precursor waves because growth rates of the synchrotron maser instability at high harmonics are significantly large. We observed that large-amplitude, semi-coherent precursor waves were excited in two-dimensional, relativistic shocks and found that the amplitude of the precursor waves was large enough to induce the wakefield acceleration, even if Weibel instability occurs. In this presentation, we compare two-dimensional simulations to one-dimensional simulations, and discuss the possibility of wakefield acceleration in multi-dimensional, relativistic shocks.

ホイッスラーモード・コーラス放射による低ピッチ角電子の非線形ピッチ角散乱

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Nonlinear pitch angle scattering of small pitch angle electrons by whistler mode chorus emissions

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Chorus emissions are coherent whistler mode waves with frequency sweeping observed in the inner magnetosphere. Previous ground-based and satellite observation have indicated that there is strong relation between chorus emissions and pulsating auroral precipitation. Conventionally, it has been considered that electrons in the energy range from a few keV to tens of keV satisfy the cyclotron resonance condition and are scattered toward the loss cone by whistler mode waves. Larger amplitude waves can more effectively scatter the pitch angle of energetic electrons toward loss cone and contribute to the enhancement of the auroral precipitation. However, the simulation result of Li et al. (2015) indicates that small pitch angle particles tend to be scattered away from the loss cone by whistler mode wave. While the nonlinear motion of resonant particles encountering a coherent wave has been studied more than 40 years (cf. Omura et al., 1991), in the derivation of the equations, previous studies assumed small wave amplitude compared to the ambient magnetic field B_0 (Dysthe, 1971) and large pitch angle of energetic electrons (Nunn, 1974).

In this study, we derive the equations without both of the assumptions, and theoretically evaluate the additional term related to the Lorentz force caused by the wave magnetic field and the parallel component of the velocity of a resonant particle. Furthermore, we carry out a test particle simulation and reproduce that the additional term plays a role of the pitch angle scattering away from the loss cone. In the simulation results of parallel propagating coherent waves with constant frequency, diffusion-like scattering of resonant electrons is observed in the case of waves with weak amplitude (0.1 % of B_0). On the contrary, all of resonant electrons are scattered in the pitch angle away from the loss cone in the case of waves with larger amplitude (more than 0.5 % of B_0). We also carry out simulations for the case of waves with frequency sweeping and find that particles near the loss cone are more effectively scattered away from the loss cone by the wave with large amplitude (more than 0.7 % of B_0). Additionally, we calculate the motion of the large number of electrons and evaluate the variation of pitch angle distribution. As a result, the wave intensity and the number of particles in the loss cone are not necessarily proportional. These results suggest that the relation between chorus wave intensity and the flux of auroral electron precipitation is not straightforward and should be investigated by considering the nonlinear effects.

電子ハイブリッド・MHD連成計算に基づく惑星磁気圏コーラス放射の発生条件

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Electron-hybrid and MHD cross-reference simulations of whistler-mode chorus in planetary magnetospheres

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We carry out a series of electron hybrid and MHD "cross-reference" simulations for the study of the generation process of whistler-mode chorus emissions in planetary magnetospheres. Chorus emissions are electromagnetic plasma waves commonly observed in planetary magnetospheres and 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. We use the MHD code for the investigation of the range of variation of the spatial scale of the Jovian magnetosphere at the region of 15 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]. We use the results of MHD simulations as the initial condition of electron hybrid simulations and reproduce the generation process of whistler-mode waves in the Jovian magnetosphere. By a series of electron hybrid simulations for different properties of energetic electrons at the equator, we clarify the condition for the chorus generation in the Jovian magnetosphere. Our results can be applied to the condition of chorus generation in other planetary magnetospheres.

本研究は、ホイッスラーモード・コーラス放射の発生過程を再現する電子ハイブリッドシミュレーションを、惑星磁気圏の空間構造の時間・空間変化を解き進める MHD シミュレーションの結果を初期条件に用いて実施する連成計算により、惑星磁気圏でのコーラス放射の発生条件と波動特性を究明する。

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]。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ており [Katoh and Omura, GRL 2007b;Katoh et al., Ann. Geophys. 2008]、惑星放射線帯の形成過程における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]。

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。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 [e.g., Katoh et al., JGR 2011]。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。

本研究では、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領域のうち、木星半径の 15 倍・Ganymede 衛星付近を対象として、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た。さらに同定し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を実施して、ホイッスラーモード波動の励起過程を再現した。keV 帯の高エネルギー電子の初期速度分布として与える温度異方性と数密度を変化させることで、発生するホイッスラーモード波動の強度と波動特性との関連を定量的に示し、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。

2次元における大振幅ホイッスラー波の減衰

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Rapid decay of nonlinear whistler waves in two dimensions

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Decay of a nonlinear, short-wavelength, and monochromatic electromagnetic whistler wave in low-beta plasma is investigated by utilizing a two-dimensional (2D) fully relativistic electromagnetic particle-in-cell code. It has been shown that the nonlinear (large-amplitude) parent whistler wave decays through the parametric instability in a one-dimensional (1D) system. The present study shows that there is another channel for decay of the parent whistler wave in 2D which is much faster than in 1D. Detailed analysis of the decay process will be reported.

Whistler Turbulence at Ion and Electron Scales: Particle-In-Cell Simulations

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At magnetohydrodynamic (MHD) scale, power-law spectrum of magnetic fluctuations in the solar wind is similar to the Kolmogorov spectrum for a hydrodynamic spectrum with an index -5/3. The MHD turbulence cascades the fluctuation energy into shorter scales, and supplies fluctuation energy into kinetic turbulence where the MHD approximation is no longer valid. The kinetic turbulence is expected to consist of some kinds of fluctuations, which are kinetic Alfven waves, whistler waves, and nonlinear structures. Important issues of the kinetic turbulence are, how the MHD turbulence is converted into the kinetic turbulence, what fluctuations have a key role in the kinetic turbulence, and how they are dissipated and scatter plasma particles.

In this study we focus on cascade of whistler turbulence from ion scales to electron scales. We demonstrate nonlinear development and the dissipation of the whistler turbulence by using two-dimensional fully kinetic particle-in-cell simulations. We found a power-law spectrum of magnetic fluctuation with a power-law index -2.5 at ion scales, which is predicted by a scaling law discussed in Narita and Gary (Ann.Geo 2010). At electron scales, the spectrum clearly shows a steeper spectrum than ion scales, which is evidence that whistler turbulence at electron scales is dissipated through wave-particle interactions. We will discuss nature of whistler turbulence at ion scales and dissipation process at electron scales.

[1] Y. Narita and S. P. Gary (2010), Inertial-range spectrum of whistler turbulence, Ann. Geophys., 28, 597-601.

宇宙線のフラクショナル拡散輸送モデル

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Fractional convection diffusion model for the cosmic ray transport

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Transport of cosmic rays (energetic particles) in a turbulence field remains to be an important issue, both from astrophysical and nonlinear science points of view. In particular, it is known that the transport in a plasma with large amplitude MHD turbulence can exhibit properties of non-gaussian statistics. A natural formalism to model such anomalous transport processes is the fractional diffusion equation, in which the time and/or spatial derivative contain fractional differentiation operators. In this presentation, first we briefly introduce the idea of the fractional differentiation/integration operators, and explain how to evaluate them numerically. Then, as an important application of this model, we discuss the diffusive shock acceleration process by solving numerically the fractional convection diffusion equation. The results will be compared with those obtained by test particle simulations using sub- and super- diffusive particles. Possible applications of the present model to other high-energy astrophysical phenomena will be discussed as well.

乱流場中の宇宙線（高エネルギー荷電粒子）輸送は、天体物理学や数理科学の観点から重要な問題であり続けている。特に、乱流が大振幅の磁気流体乱流の場合、非ガウス的な統計性質を持った輸送があらわれる。このような異常輸送を表現する自然な数理モデルとして、時間微分または空間微分項にフラクショナル（分数）微分を含んだフラクショナル拡散方程式がある。講演ではまず、フラクショナル微分および積分について簡単に紹介し、その数値評価の方法を説明する。次に、重要な応用として、フラクショナル衝撃波拡散方程式の数値解を求め、準拡散および超拡散を行う粒子によるテスト粒子計算の結果と比較議論する。本モデルが適用可能な他の高エネルギー天体現象についても言及する。

原始惑星系円盤におけるダスト沈殿層でのストリーミング不安定性によるダスト濃集過程

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Dust Enrichment process by streaming instability in the dust layer of a protoplanetary disk

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The formation process of planetesimals is one of the most important unresolved problems in our understanding of the origin of the solar system. Understanding the process is crucial for our universal understanding of planetary system formation as well. Protoplanetary disks, where the planetary system formation process is taking place, are made up of gas and dust and the dust-to-gas mass ratio is around ~0.01 overall. This led previous research on the planetesimal formation to consider only the effects of gas on the dust motion but to neglect the back-reaction from dust to gas dynamics. Recent studies, however, has proposed the scenario that the streaming instability, excited by the velocity gap between gas and dust in the presence of gas pressure radial gradient, may create concentrated dust patches that may become seeds for the self-gravitational instability which forms planetesimals. In particular, the streaming instability is enhanced strongly when the local dust density is comparable or higher than that of the gas. This leads to the recognition that it is necessary to consider precisely the interaction between gas and dust in the dust layer where dust density is enhanced due to vertical precipitation onto the disk plane.

In this study, to take the interaction between gas and dust into account, we perform hybrid simulations, where gas and dust are treated as fluid and particles, respectively, and the dust-to-gas mass ratio is set to be ~1 in the dust layer. A focus is given to investigating the relationship between the stopping time of dust particles and dust enrichment resulting from the streaming instability.

惑星形成の初期段階に存在していたとされる微惑星の形成過程は未解明な部分が多く，それを解決することは普遍的な形で惑星系形成過程を理解していく上で非常に重要である．微惑星形成の現場である原始惑星系円盤はガスとダストで構成されており，ダスト・ガス質量比は〜0.01 程度であることが知られている．そのため，微惑星形成を調べた先行研究では，質量において卓越するガスの運動に対するダストからの影響（back-reaction）は無視されてきた。しかし近年の研究によって，動径方向のガス圧力勾配に伴いガスとダストとの間に速度差が生じる場合，ストリーミング不安定性と呼ばれる機構によってダストを濃集させ，重力不安定を引き起こすシナリオが提唱されている．特に，この不安定性はダスト質量密度が局所的にガス質量密度と同等か支配的な状況においてより強く働くことが分かっている (Johansen & Youdin 2007)．以上の理由から，ダスト沈殿層のようなダストが集積した状況を考える際，ガスとダストの相互作用を正確に解くことが必要である．

本研究では，ダスト・ガス質量密度比〜1 のダスト層を考え，ストリーミング不安定性によるダスト濃集過程を様々なダストサイズ（すなわち、ガス抵抗によりガスとの速度差が緩和する Stopping time）を仮定して数値実験で調査する．本研究は、ガスとダスト間の相互作用を導入するために，ガスは流体，ダストは粒子として扱う、プラズマ物理におけるハイブリッドシミュレーションの手法を応用した計算コードを活用して行った．

Secondary instabilities in the collisionless Rayleigh-Taylor instability: Full kinetic simulation

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The Rayleigh-Taylor instability (RTI) is a well-known hydrodynamic instability in neutral fluid as well as in magnetized plasma, which grows at an interface between two fluids when a light fluid supports a heavy fluid against an external force such as gravity. In previous studies, various numerical simulations for the RTI have been performed by using the MHD code, the Hall MHD code, the Finite-Larmor-Radius MHD code and the hybrid particle-in-cell code. In this study, the nonlinear evolution of the RTI at a density shear layer transverse to magnetic field in collisionless plasma is investigated by means of a fully kinetic Vlasov simulation with two spatial and two velocity dimensions. The primary RTI in the MHD regime develops symmetrically in a coordinate axis parallel to gravity as seen in the previous MHD simulations. Small-scale secondary instabilities are generated due to secondary density/velocity shear layers formed at the nonlinear stage of the primary RTI. The secondary instabilities take place asymmetrically in the coordinate axis parallel to gravity. It is suggested that these secondary instabilities correspond to the electron Kelvin-Helmholtz instability generated by the electron velocity shear, whose evolution depends on the sign of the inner product between the magnetic field and the vorticity of the velocity shear layer.

太陽風磁気流体乱流の非等方な多次元波数スペクトル：現象論

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Multi-dimensional wave-number spectra of solar wind MHD turbulence with the finite cross-helicity: A phenomenology

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Although the magnetohydrodynamic (MHD) turbulence in the solar wind has been extensively discussed for several decades from the observational and theoretical points of view, the consensus of the community on the statistical law has not been achieved yet. One of the significant alienated points between observational and theoretical studies is the existence of the finite cross helicity in the solar wind, which is not consistent with the well-known standard phenomenology of the MHD turbulence (Goldreich+Sridhar, ApJ, 1995; Boldyrev, PRL, 2006). While some authors proposed the several models including the finite cross helicity (e.g., Chandran, ApJ, 2008; Podesta, POP, 2011), those models are also not consistent. On the other hand, Narita (AnGeo, 2015) recently proposed the multi-dimensional wave-number model, which agrees with the past phenomenology (Goldreich+Sridhar, ApJ, 1995) through the integration. The important advantage of the multi-dimensional model is that it expresses each wave number mode of the anti-sunward/sunward propagating waves clearly, which should be parameterized in the one-dimensional perpendicular wave number spectrum using the cross-helicity. In this presentation, we demonstrate that the phenomenology including the finite cross-helicity can be obtained as a natural extension of Narita's model. We also discuss the influence of the cut-off scale of the wave-number spectra, which can make the pseudo-breaking point in the one-dimensional spectrum.

太陽風中の磁気流体 (MHD) 乱流は数十年に渡り観測・理論両面から研究が進められているが、その統計則に関しては分野におけるコンセンサスを得るまでには至っていない。観測研究と理論研究が最も大きく乖離している点は、現在知られている標準的な MHD 乱流の現象論 (Goldreich+Sridhar, ApJ, 1995; Boldyrev, PRL, 2006) が実際に太陽風中で観測されている有限なクロスヘリシティーを取り込めていない点にある。既に有限なクロスヘリシティーを含む現象論がいくつか提案されてはいるが (e.g., Chandran, ApJ, 2008; Podesta, POP, 2011)、モデル間の差異が大きく、統一した見解を得るまでには至っていない。一方で、近年になり成田 (AnGeo, 2015) によって過去の現象論 (Goldreich+Sridhar, ApJ,1995) を包括した多次元波数スペクトルモデルが提案された。多次元波数スペクトルモデルの大きな利点は、有限なクロスヘリシティーを生成する波動の伝搬方向の非対称性を明示的に取り扱えることである。本講演では、このような多次元モデルの特性を活かすことで有限なクロスヘリシティーを含む現象論が、成田のモデル (AnGeo, 2015) の自然な拡張として得られることを示す。また、一次元の波数スペクトル上に擬似的な折れ曲がりを作り得る波数スペクトルの特徴スケール (積分区間) についても議論を行う。

Simulation study of the asymmetric magnetic reconnection in the shear flow

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Asymmetric magnetic reconnection is studied using MHD simulations on the basis of the spontaneous fast reconnection model. Assymetric magnetic reconnection with shear flow and shear field commonly occurs at planetary magnetopause. It is believed that these shear field and shear flow prevent reconnection process. In this study, particularly, the effect of the shear flow is studied in detail.

Ion dynamics and Hall field structure in large-scale steady magnetic reconnection

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We investigate the ion dynamics and the Hall electric and magnetic field structure in the large-scale steady fast magnetic reconnection of antiparallel fields using hybrid simulations. The Hall field is induced by the currents due to the ion-electron dynamics in the diffusion region. The Hall field structure expands within the ion reconnection jet whose width increases monotonically with increasing distance downstream away from the diffusion region. The leading edge of the Hall field propagates farther away in the pre-existing plasma sheet boundary layer. We discuss a cause-effect relationship between the ion dynamics and the Hall field structure in the large-scale steady fast magnetic reconnection.

Triggering of explosive reconnection in a thick current sheet by temperature anisotropy boosted tearing mode

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It has been widely believed that collisionless magnetic reconnection is triggered when the current sheet thickness thins and becomes comparable to the ion larmor/inertia scale. Here we challenge this argument by performing two-dimensional kinetic simulations of magnetic reconnection triggering. In the simulations, the current sheet subject to reconnection is filled with plasmas having temperature anisotropy and its thickness (L) is larger than the ion scale. Previous studies showed that the growth rate of the tearing mode is enhanced by the anisotropy and the current sheet with L=1, in which the ordinary tearing mode is not effective in triggering vigorous reconnection, is destabilized by the temperature anisotropy boosted tearing mode. What we newly show here is that the temperature anisotropy boosted mode seeds explosive magnetic reconnection even when the initial current sheet thickness is made more than an order of magnitude thicker. The highlight results are: (1) the mass ratio is not an issue in this study allowing us to explore the unprecedented large-L case mentioned above, and (2) the maximum reconnection rate has no dependence on the initial sheet thickness and peaks at 0.2 (in the widely used normalized unit). We also discuss the physical process through which the non-linear tearing instability evolves into explosive magnetic reconnection.

外部回転磁場によるプラズマ加速領域生成のテスト粒子計算

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Test particle simulation on generation of plasma acceleration region by external rotating magnetic field

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For long-term space missions such as exploration of outer planets, electric thrusters are considered 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 directly with the plasma. Among a few types of the proposed next generation thrusters, we are dealing with the concept utilizing the Rotating Magnetic Field (RMF), which has been first developed 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.

In the present test particle simulation study, we provide the magnetic field by superposition of the RMF and the background divergent magnetic field created by a series of ring currents. The electric field is given in accordance with the time evolving RMF. The angular frequency of the RMF is chosen so that only the electrons but not the ions can follow the rotation, so that the resultant electric current produces the Lorentz force perpendicular to the magnetic field. Due to the inhomogeneity of the background field and the finite width of the region where the RMF is applied, the Lorentz force is expected only in a spatially limited area. By performing the test particle simulations with varying such parameters as the RMF strength, RMF angular frequency, and the background magnetic field configurations, we will discuss how the acceleration region can be most efficiently produced.

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。この現状を踏まえ、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きた。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。

本研究では、数値計算内で回転磁場をかけ、環電流を複数並べた時の発散磁場を加え、RMF 型加速機構を再現する。電場は RMF に対応するものを与える。電子のみが回転に追従できるように RMF 回転周波数を選ぶ。電子の運動により電子電流が生まれ、これがローレンツ力を発生させる。背景磁場の非一様性と回転磁場領域が限られた領域のみにあることにより、ローレンツ力が発生する領域も限定的になるはずである。回転磁場の周波数、強度、発散磁場の強度をパラメータとし、効率よくローレンツ力を得るためのパラメータの考察を行う。

磁気回転不安定性の乱流駆動プロセスの高次精度 MHD シミュレーション

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MHD simulation of transition process from MRI to turbulence by using a high-order MHD simulation scheme

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In accretion disks, magneto-rotational instability (MRI; Balbus & Hawley, 1991) makes the disk gas in the magnetic turbulent state and drives efficient mass accretion into a central star. MRI drives turbulence through the evolution of the parasitic instability (PI; Goodman & Xu, 1994), which is related to both Kelvin-Helmholtz (K-H) instability and magnetic reconnection. The wave number vector of PI is strongly affected by both magnetic diffusivity and fluid viscosity (Pessah, 2010). This fact makes MHD simulation of MRI difficult, because we need to employ the numerical diffusivity for treating discontinuities in compressible MHD simulation schemes. Therefore, it is necessary to use an MHD scheme that has both high-order accuracy so as to resolve MRI driven turbulence and small numerical diffusivity enough to treat discontinuities.

We have originally developed an MHD code by employing the scheme proposed by Kawai (2013). This scheme focuses on resolving turbulence accurately by using a high-order compact difference scheme (Lele, 1992), and meanwhile, the scheme treats discontinuities by using the localized artificial diffusivity method (Kawai, 2013). Our code also employs the pipeline algorithm (Matsuura & Kato, 2007) for MPI parallelization without diminishing the accuracy of the compact difference scheme.

We carry out a 3-dimensional ideal MHD simulation with a net vertical magnetic field in the local shearing box disk model. We use 256x256x128 grids. Simulation results show that the spatially averaged turbulent stress induced by MRI linearly grows until around 2.8 orbital periods, and decreases after the saturation. We confirm the strong enhancement of the K-H mode PI at a timing just before the saturation, identified by the enhancement of its anisotropic wavenumber spectra in the 2-dimensional wavenumber space. The wave number of the maximum growth of PI reproduced in the simulation result is larger than the linear analysis. This discrepancy is explained by the simulation result that a shear flow created by MRI locally becomes thinner and faster due to interactions between antiparallel vortices induced by K-H mode PI, and this structure induces small scale waves which break the shear flow itself. We report the results of the simulation, and discuss how the saturation amplitude of MRI is determined.

宇宙プラズマ中の波動モード変換過程の粒子シミュレーション

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PIC Simulations of Wave-mode Conversion in Space Plasmas

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Bernstein modes are electrostatic waves in plasmas propagating perpendicularly to an external magnetic field [1]. They have characteristic frequencies close to the electron cyclotron frequency/upper hybrid frequency and its harmonics. The Bernstein waves can couple with electromagnetic waves (like whistler mode chorus) on density irregularities. It means that the electromagnetic wave can scatter on such an irregularity to the electrostatic mode [2,3]. It was proposed that similar mechanism might exist for direct scattering of electrostatic mode to electromagnetic mode [4]. In this contribution we study scattering of the electron Bernstein wave modes to electromagnetic L-O mode using 2D-3V electromagnetic PIC code which allows us to analyze both the longitudinal electrostatic waves and transversal electromagnetic waves. Our results are compared with observational results described in [4] since authors suggest this mechanism as a source of wideband nonthermal radiation.

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Nonlinear dynamics of electrons interacting with oblique whistler-mode chorus in the magnetosphere

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We perform test particle simulations for relativistic electrons interacting with a whistler-mode chorus packet propagating at oblique angles. By confirming that the energy transport of oblique lower-band chorus is nearly along the ambient magnetic field, we apply the gyro-averaging method in calculating equations of motion of electrons. We trace evolution of a delta function of relativistic electrons in a phase space of kinetic energy and equatorial pitch angle, and obtain numerical Green's functions of the chorus wave particle interactions. Examining the Green's functions in a wide range of kinetic energies, we find that Landau resonance can accelerate MeV electrons efficiently, and that higher n-th resonances such as n = -1 and n = 2 also contribute to acceleration of electrons at high equatorial pitch angles (~70 degree) and high energies (~2 MeV). We investigate the rate of energy gain of the cyclotron resonance acceleration and the Landau resonance acceleration, and find that the perpendicular component of wave electric field dominates both accelerations for MeV electrons. Furthermore, the proximity between the parallel components of Vp and Vg of oblique whistler-mode waves and the nonlinear trapping condition make the interaction time of Landau resonance much longer than that of n = 1 cyclotron resonance, resulting in efficient acceleration of MeV electrons.

BEN 低周波成分に関する３次元電磁粒子シミュレーション

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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 a statistical analysis of the low-frequency component of the BEN, was investigated it prone magnetic field strength, ion density and ion temperature of the relationship, however, could not be confirmed. So the results of the analysis on the assumption PSBL region. The low frequency component of BEN is two kinds of conditions, which the magnetic field strength and ion density are both high or both low Then, based on these statistical analyses, we are going to perform a series to reproduce PSBL region of three-dimensional electromagnetic particle simulations with different parameters, and clarify the generation process of the low frequency component of BEN.

これまでに，BEN の低周波成分が，その高周波成分である ESW と同様にビーム不安定性の非線形発展の結果励起されるという仮定に基づき，ビーム不安定性からの低周波波動励起に関する 2 次元粒子シミュレーションを行った．その結果，磁場に垂直方向のイオン温度と低周波波動との関係は見られたが，ビーム不安定性と BEN の低周波成分との明確な関係は確認できなかった．そこで Geotail 衛星に搭載されている電界検出器（EFD）によって観測された BEN の低周波成分について統計解析を行い，BEN の発生しやすい磁場強度とイオン密度・イオン温度の関係を調査した．しかし，観測頻度による解析では明確な関係を確認できなかった．そこで BEN の低周波成分が多く観測されている PSBL 領域を想定して解析を行った．結果，BEN 低周波成分は磁場強度とイオン密度が共に高い，もしくは共に低いという 2 種類の条件で BEN の低周波成分が発生しやすいことがわかった。この結果に基づいて，PSBL 領域の環境を再現した 3 次元電磁粒子シミュレーションを行い，BEN の低周波成分の生成メカニズムを明らかにしていく

非平衡実験室プラズマの協同トムソン散乱計測のための数値実験

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Numerical simulation of virtual Thomson scattering measurement of non-equilibrium laboratory plasmas

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Recently, a variety of high energy phenomena in space have been successfully reproduced in laboratories by using high power laser facilities. We have performed the laboratory experiment on collisionless shocks by using Gekko XII high power laser in collaboration with the Institute of Laser Engineering (ILE) at Osaka University. To measure the local plasma quantities in the shock transition region, collective Thomson scattering (CTS) measurement is utilized. The CTS is the elastic scattering of low frequency and long wavelength incident electromagnetic waves by collective oscillations of plasma electrons. The spectrum of the scattered waves enables us to infer the local plasma quantities such as the streaming speed of the plasma, electron density, electron and ion temperature, the valence of ions, etc, as functions of local position along the path of the incident probe laser light. If the plasma is nearly in thermal equilibrium, scattered wave spectrum typically has two double-peaks called electron and ion features. The electron (ion) feature is produced when an incident wave is scattered by Langmuir (ion acoustic) waves. On the other hand, the CTS theory in a non-equilibrium plasma has not been established. In the foreshock region a back-streaming plasma is often observed as a beam by which beam instability is easily generated. Although the electron feature is usually too weak to be detected in an equilibrium plasma, it maypossibly be enhanced by the beam instability in the foreshock. Here, we try to diagnose the non-equilibrium plasma in the shock transition region from the characteristics of electron feature.

In this study the CTS in a non-equilibrium plasma is numerically simulated to directly compare with experimental results. First, PIC simulation is performed to reproduce a beam instability occurring in the vicinity of a shock wave. The obtained data of electron density fluctuations is incorporated into the wave equation of the scattered waves of the CTS. The wave equation is solved with an arbitrary time resolution which can be much finerthan that typically used in PIC simulations. Here, we discuss modification of the electron feature of the CTS spectrum due to the effect of ion beam instability expected to occur in the foreshock region. An eminent modification is the amplified asymmetric electron feature, when the beam velocity normalized to electron thermal velocity is 5 and 10. As the beam velocity becomes sufficiently large, the amplified electron feature has a wide spectrum due to nonlinear effect of the beam instability. Details of parameter survey in terms of the beam velocity, relative beam density, temperature, and so on, will be reported. If possible, the comparison with the results of Gekko XII experiment planned in October will also be reported.

近年、高強度レーザーを用いて宇宙の高エネルギー現象を実験室に再現できるようになってきた。我々は、激光 12 号レーザー（大阪大学）を用いた無衝突衝撃波実験を行っている。実験では、衝撃波遷移層の局所構造を計測するのに、協同トムソン散乱計測を用いる。協同トムソン散乱は、自由電子による比較的低周波（<<mec2/h）かつ長波長（>デバイ長）の光の弾性散乱であり、散乱光の特徴から、プラズマの流速、電子密度、電子およびイオン温度、イオン価数などの諸量を、プローブ光経路に沿った位置の関数として見積もることができる。平衡プラズマにおける散乱光スペクトルはよく研究されており、イオン音波により散乱されたイオン項と、ラングミュア波により散乱された電子項の二つのダブルピーク構造を持つ。実験では通常、電子項は強度が弱く検出が困難なため、しばしばイオン項のみ計測する。一方、非平衡プラズマにおける協同トムソン散乱はこれまであまり研究されておらず、その理論的整備が遅れている。無衝突衝撃波近傍の非平衡プラズマでは、しばしばビーム不安定性が起こるため、これによって励起されたラングミュア波が、増幅された電子項として観測される可能性がある。ここでは、この電子項の特性から、遷移層の非平衡プラズマの状態を診断することを目指す。

本研究では、実験結果との直接比較を念頭に、非平衡プラズマ中の協同トムソン散乱を数値実験により再現する。まず、衝撃波近傍で起こるビーム不安定性をＰＩＣ計算で再現する。これで得られる電子密度揺動の時空間データを、協同トムソン散乱の散乱光の波動方程式に移植して別途これを解く。この際、散乱光の周波数帯はＰＩＣの時間分解能を超えるので、電子密度揺動のデータを適宜補間する。これにより、実パラメータの下で多次元協同トムソン散乱を再現する数値実験システムを開発した。ここでは、衝撃波前面のフォアショック領域を念頭に、イオンビーム不安定性が電子項に与える影響を議論した。ビーム速度を電子熱速度の 5 倍、10 倍としたケースでは、不安定性の影響が非対称な電子項として現れることを確認した。ビーム速度が十分大きくなると、増幅された電子項が非線形性によって広帯域になることが分かった。ビームの速度や相対密度、温度などをさまざまに変えたパラメータ調査の詳細を報告する。また、可能であれば 10 月に予定されている激光 12 号実験の結果との比較も行う。

高強度レーザー実験で生成される静電衝撃波の構造

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Structure of electrostatic shocks produced in high power laser experiments

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We have performed high power laser experiment on collisionless shocks by using Gekko XII laser at Osaka University. In the experiment an electrostatic shock is produced by irradiating a target Aluminium foil with the Gekko XII hyper laser in a chamber filled with 5 Torr Nitrogen gas. When the target foil is ablated, strong radiation is emitted and fully ionizes the surrounding Nitrogen gas. In such a situation a relatively hot and dense target plasma sweeps a relatively cool and tenuous gas plasma. As a result, an electrostatic shock wave is formed in the gas plasma.

While the shock formation scenario based on the above fluid-like viewpoint has been accepted, the detailed process with a kinetic point of view has not been understood. In this study the interaction between a target and a gas plasmas is reproduced by using a full particle-in-cell simulation. Initially, two different plasmas are contact, where the gas plasma is at rest and the target plasma has a finite bulk velocity in the direction pressing the gas plasma. Although the two plasmas are initially separated, strong electrostatic instability leads to mixing of the two plasmas. In the region initially filled with the gas plasma a sharp density jump is formed and propagates away from the target with a supersonic velocity, i.e., a shock wave is formed. The electron and ion foreshocks are produced in front of the shock. The foreshocks are turbulent due to the beam instabilities generated locally. Detailed electron and ion distribution functions are also discussed.

プラズマディタッチメントの計算機シミュレーション

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Numerical simulation of plasma detachment

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Recent space exploration projects are highly developed both in terms of scientific objectives and technologies involved. Accordingly, electric thrusters with long time duration and high performance are considered indispensable, in particular for long-term space missions such as those to outer planets. 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. In order to overcome this difficulty, we are involved in research and development of electrodeless thrusters, in which there is no direct contact between the plasma and the electrodes.

One of the central issues of the electric thrusters is the plasma detachment, the process where the accelerated plasma travels far away and "detached" from the magnetic field originating from the thruster. If the plasma remains guided by the magnetic field, it does not escape into free space and no thrust will be obtained as a result.

In order to identify the conditions where the detachment takes place and also to understand the physics of the plasma detachment in detail, we are performing computer simulations of the plasma detachment using PIC (Particle-In-Cell) code. First we produce the diverging magnetic field by a pair of d.c. currents, a continuous stream of both electrons and ions are provided at a central region of the simulation domain, imitating the acceleration region of the thruster. Plasma flows from the region with intense magnetic field to the region with weak magnetic field, which is similar to the transition of the solar wind from sub-sonic to super-sonic to the Alfven speed. The plasma with enough initial motional energy density can drag the magnetic field and eventually escape from it as the ions become un-magnetized. We show under what conditions the plasma can be detached from the thruster, and also discuss details of the particle orbits and a curious wavy structures observed in electron trajectories.

近年の宇宙探査は高度化・長期化し、宇宙探査機・宇宙船等に使用される推進機関には更なる長寿命化が求められている。従来のイオンエンジン等の有電極型推進法は、プラズマの放出時に電極がプラズマに接触するため、電極摩耗による寿命の制限が問題となっている。これを解決するために、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推進法が有望視されている。

ここでは、プラズマ分離（プラズマディタッチメント）について考える。磁化されたプラズマは磁場に沿って運動する。推進機関起源の背景磁場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推進機関に戻ってきてしまい、推進力は得られない。

我々は、PIC (Particle-In-Cell) 法によりプラズマディタッチメントの計算機シミュレーションを行っている。まず直流電流のペアにより発散磁場を作り、この中心部分からプラズマ流を発生させる。プラズマ流は強磁場領域から遠方の弱磁場領域に拡がって行くが、これはアルフヴェンマッハ数が 1 よりも小さい「亜音速」の領域から 1 よりも大きい「超音速」の領域への移動であり、太陽風の加速過程と物理的に同等である。十分な初期運動エネルギー密度を与えられたプラズマは、磁場をともなって拡がり、ディタッチされる。そうでない場合、プラズマは磁場に捕捉されつづけ、ディタッチされない。ディタッチされる場合とされない場合のパラメータ領域の検証、プラズマ軌道の解析、またプラズマ流にみられる波動構造などについて報告する。

Vlasov シミュレーションにおける保存型無振動スキームのパラメータ特性

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Parameter characteristics of a conservative and non-oscillatory scheme in Vlasov simulations

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Vlasov simulations are noiseless methods for directly simulating the development of the distribution functions in phase space. There are a number of methods for interpolating numerical fluxes at the time update of the distribution functions. Among them, a conservative and non-oscillatory scheme called Positive Interpolation for Conservations (PIC) is a particularly powerful tool. A limiter function is introduced in this scheme, which preserves the mass conservation, non-oscillatory and positivity of the distribution functions. However, the limiter function has a number of parameters that needs to be carefully chosen. In this research, we perform Vlasov simulations using simple models and discuss the relationship between conservation laws such as the entropy conservation and the chosen set of parameters.

Vlasov シミュレーションは位相空間における分布関数を直接取り扱うノイズレスな手法である。分布関数の時間更新に必要な数値フラックスを補間する方法は様々であるが、その中でも有力なスキームとして、保存型無振動スキームが挙げられる。このスキームにはリミッターが導入されているため、分布関数における質量保存、無振動性および正値性が保持される。しかしながら、このリミッターにはいくつかのパラメータを設定しなければならず、これらパラメータセットのチューニングが重要となる。本研究では、簡単なモデルの Vlasov シミュレーションを行い、エントロピー保存等とパラメータの関係について議論する。