低ベータＭＨＤリコネクションにおける圧縮流体効果

銭谷 誠司 [1]; 三好 隆博 [2]
[1] 国立天文台; [2] 広大・理・物理

Low-beta MHD reconnection as a showcase of compressible fluid dynamics

Seiji Zenitani[1]; Takahiro Miyoshi[2]
[1] NAOJ; [2] Phys. Sci., Hiroshima Univ.

In the solar corona, in the magnetosphere, and in other astrophysical settings, magnetic reconnection often occurs in a low-beta plasma. Unfortunately, less is known about low-beta reconnection, partially due to lack of attention and partially due to numerical difficulties. Recent MHD simulations revealed several new features of low-beta reconnection; For example, Zenitani et al.(2010,2011) [1,2] discovered a normal shock which is perpendicular to the Petschek shock and a repeated shock-reflection in front of a magnetic island.

In this contribution, we extend earlier works with improved MHD codes and organize the results from the perspective of compressible fluid dynamics. In fluid dynamics, once a flow speed becomes comparable with the local sound speed, various compressible effects take place. This is the case for low-beta reconnection, because an Alfvenic reconnection jet becomes supersonic. Many phenomena can be understood as compressible fluid effects: the normal shock is equivalent to a recompression shock on a transonic airfoil, the shock-reflection corresponds to shock-diamonds in an over-expanded supersonic flow, the adiabatic acceleration similarly takes place as the Laval nozzle, and so on. They appear regardless of Sweet-Parker, plasmoid-mediated, or Petschek reconnections.

We further discover another shock-diamonds in extreme cases. A critical condition for these hidden shocks is derived. All these issues can be applied to more extreme cases of relativistic reconnection, in which the sound speed is “relatively” slow. We will also address the relevance to the physics of extragalactic jets.

References:

[1] Zenitani, Hesse, & Klimas, ApJ, 716, L214 (2010).
[2] Zenitani and Miyoshi, Phys. Plasmas, 18, 022105 (2011).

太陽コロナ、地球磁気圏、あるいは高エネルギー天体環境では、磁気圧の方がプラズマ圧力よりも強い低ベータプラズマ中で、磁気リコネクションが起きることがある。あまり関心が払われなかったことや、数値的な難しさもあって、このような低ベータ環境でのリコネクションの振る舞いは実はよく知られていない。しかし最近、現代的なＭＨＤシミュレーション研究が進んで、低ベータ環境のリコネクションの新しい側面が見えてきた。例えば、Zenitani et al.(2010,2011) [1,2] は、Petschek の遅進衝撃波と直行する縦衝撃波や、磁気島先端で斜め衝撃波が繰り返し交差する現象を報告している。

本発表では、高精度のコードを使ってこれらの研究を拡張し、圧縮性流体力学の立場から結果を整理する。流体力学では、典型的な流れ速度が音速と同程度になると、さまざまな圧縮流体効果が現れる。これはまさにアルヴェン速度が音速を超える低ベータプラズマでのリコネクションにも当てはまる。例えば、縦衝撃波は、遷音速パラメーター領域で飛行機の翼面に現れる再圧縮衝撃波であり、斜め衝撃波の交差は過膨張超音速流の中に出来るショック・ダイアモンドであり、ラバルノズルと同様の断熱加速も起きている。これらは、Sweet-Parker、プラズモイド型、Petschek といったリコネクションの形態に関わらない一般的なものである。

我々はさらに、同じリコネクション系内に潜んでいる不足膨張タイプのショック・ダイアモンドを紹介し、その臨界出現条件を議論する。これら一連の議論は、音速に上限がある相対論ＭＨＤリコネクションにも適用可能である。時間があれば、銀河系外ジェットの物理との共通点も議論したい。

References:

[1] Zenitani, Hesse, & Klimas, ApJ, 716, L214 (2010).
[2] Zenitani and Miyoshi, Phys. Plasmas, 18, 022105 (2011).

流れ場のあるプラズマシートでの電磁流体不安定と乱流

星野 真弘 [1]; 東森 一晃 [1]
[1] 東大・理

Streaming MHD instability and turbulence in a plasma sheet

Masahiro Hoshino[1]; Katsuaki Higashimori[1]
[1] University of Tokyo

It is known that magnetic reconnection plays an important role in plasma universe such as the earth's plasma sheet, solar corona, and accretion disks. So far many researchers have investigated the tearing mode as the elementary process of reconnection in the Harris-type plasma sheet at rest. In some plasma sheets, however, the bulk plasma flows are often observed before the onset of the instability, yet our understanding of the stability of the plasma sheet with the bulk flow is poor. We investigated the linear stability of the plasma sheet with a localized bulk plasma flow, whose speed is less than the lobe Alfven speed. We found that (1) the linear growth rate of the tearing mode can be enhanced under the subsonic bulk flow, (2) while the growth rate is suppressed for the supersonic flow. (3) However, as increasing the bulk flow speed, the resistive tearing mode metamorphoses into the sausage mode without the magnetic energy dissipation, and the sausage mode with the symmetric density perturbation to the neutral sheet can grow. (4) Further increasing the bulk flow speed, the sausage mode can be transformed into the kink mode with the asymmetric perturbation. In this presentation, we discuss the characteristics of these streaming instabilities and its application to the generation of turbulence in the plasma sheet.

磁気リコネクションは、地球磁気圏プラズマシートを始め、太陽コロナ、降着円盤など宇宙では重要な役割を果たすことが知られており、リコネクションの素過程としての Tearing モードは、ハリス型のプラズマシートに対して数多くの研究がなされてきている。しかしプラズマシートにおいては、しばしば反平行磁場に平行なプラズマの流れ場が存在することがあるが、流れ場中での不安定性はあまり研究されていない。流れ場が、ローブのアルフベン速度程度以下で、電流層と同程度に空間的局在化するときのプラズマシートの不安定性について線形解析を行った。その結果、(1) 流れ場が亜音速のときは、従来から知られている Tearing モードの線形成長率が増大するが、(2) 超音速になると成長が抑制される性質があること、(3) さらに流れ場の速度を上げていくと、抵抗性 MHD 不安定の Tearing モードは電気抵抗と無関係な理想 MHD 不安定の Sausage モードへと性質を変えて成長することができる。(4) また更に流れ場の速度があがると、密度の揺らぎが磁気中性面に対して対称の Sausage モードは、反対称の構造をもつ Kink モードへと変化することがわかった。本講演では、これらの不安定モードの性質に加えて、磁気圏プラズマシートでの乱流励起にも重要であることも議論する。

降着円盤におけるトロイダル磁場に沿った不安定性

平林 孝太 [1]; 星野 真弘 [2]
[1] 東大・地惑; [2] 東大・理

Instability along Toroidal Magnetic Field in Accretion Disks

Kota Hirabayashi[1]; Masahiro Hoshino[2]
[1] Earth and Planetary Sci., Univ. of Tokyo; [2] University of Tokyo

We discuss a new type of instability expected to take place in an accretion disk, which contains a differentially rotating plasma threaded by a weak magnetic field. In particular, the stability of a disk with a localized, toroidal magnetic field varying in the radial direction, which can be expected in an accretion disk during the nonlinear evolution of the magneto-rotational instabilities (MRI), is investigated by using linear eigenvalue analysis and nonlinear magneto-hydro-dynamic (MHD) simulations.

The MRI is believed to be a strong source of MHD turbulence and the resultant angular momentum transport in the accretion disk, which is required for the gas to accrete onto the central object. Once the MRI grows, the disk is chiefly governed by the toroidal and radial magnetic field newly generated by the dynamo action of MRI. Such a situation allows Alfven waves to propagate along toroidal direction.

In this talk, we study the linear stability of the Alfven wave in the shearing periodic box, and show that the toroidally propagating Alfven wave can become unstable provided its wavelength is larger than the gradient scale of the magnetic field. We investigate our results of the linear eigenvalue analysis by changing the structure of the localized magnetic field, and discuss some properties of the instability with examining the eigenvectors and eigenvalues. While a differentially rotating plasma with an uniform toroidal filed is completely stable, it is revealed that weak non-uniform magnetic field can lead to instability and the resultant turbulence. We also find that this type of instability can be totally suppressed in a rigid body rotation, but the instability can be recovered in a non-rotating plasma. In addition to the linear analysis, the corresponding nonlinear behavior will also be discussed by using numerical simulations. This instability plays an important role in the plasma transport since it probably couples with the magnetic reconnection occurring in the equatorial plane and then contributes to the saturation mechanism of the MRI.

ケルビン―ヘルムホルツ不安定性の非線形発展に対するイオンジャイロ運動の効果

上野 悟志 [1]; 梅田 隆行 [2]; 中村 琢磨 [3]; 町田 忍 [4]
[1] 名大 STE 研; [2] 名大 STE 研; [3] 宇宙研; [4] 名大・STE 研

The effect of the ion gyro motion to nonlinear processes of the Kelvin-Helmholtz instability

Satoshi Ueno[1]; Takayuki Umeda[2]; Takuma Nakamura[3]; Shinobu Machida[4]
[1] STEL, Nagoya Univ; [2] STEL, Nagoya Univ.; [3] ISAS,JAXA; [4] STEL, Nagoya Univ.

Nonlinear evolution of the Kelvin-Helmholtz instability (KHI) 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 same, there exists a strong ion cyclotron damping. In this case, spatial inhomogeneity inside the primary KH vortex is smoothed and the secondary Rayleigh-Taylor instability is suppressed. The ion gyro motion also suppresses the formation of secondary vortices in the spatial scale smaller than the ion gyro radius, when the rotation direction of the vortex and the direction of ion gyro motion are same. As a result, the secondary instabilities take place at different locations in the primary KH vortex, where the rotation direction of the secondary vortex and the direction of ion gyro motion are opposite. These results indicate that secondary instabilities occurring in the nonlinear stage of the primary KHI at the Earth's magnetospheric boundaries might show dawn-dusk asymmetries.

Hybrid Simulation of Magnetic Reconnection on the Equatorial Plane of the Differentially Rotating Disk

Keisuke Shirakawa[1]; Takanobu Amano[1]; Masahiro Hoshino[1]
[1] University of Tokyo

Differentially rotating disks threaded by weak magnetic field is subject to a plasma instability called Magneto Rotational Instability (MRI) [Velikhov 1959, Chandrasekhar 1961, Balbus and Hawley 1991]. This instability is considered to generate turbulence in the disk and may contribute to an effective transport of angular momentum of the plasma. Magnetic Reconnection, at the same time, can be an important process to determine the saturation level of MRI induced turbulence through annihilation of magnetic field enhanced by MRI.

In collisionless accretion disks, which are often found around blackholes, several non-MHD process such as evolution/relaxation of the pressure anisotropy and Hall effect would modify the evolution of MRI and magnetic reconnection which would exist in the MRI induced turbulence. In the past study we have carried out a Hybrid simulation of magnetic reconnection in a meridional plane of differentially rotating disk and found that the coupling of the Hall term and differential rotation leads to asymmetric evolution of the magnetic reconnection.

In this study, by adopting a shearing periodic boundary condition, we have carried out a two dimensional Hybrid simulation of magnetic reconnection in the equatorial plane of a differentially rotating disk. Like in the simulation in the meridional plane, we also found asymmetric evolution of the reconnection. This can be interpreted as a coupling of the Coriolis/Tidal force effect and the out flow of the magnetic reconnection. In the presentation we would like to discuss an implication of the results to the modification of MRI induced turbulence.

ヘリコン波動の伝搬とプラズマ生成過程

諫山 翔伍 [1]; 羽田 亨 [1]; 篠原 俊二郎 [2]; 谷川 隆夫 [3]
[1] 九大総理工; [2] 東京農工大・工; [3] 東海大・総科研

Helicon wave propagation and the physical process of helicon plasma production

Shogo Isayama[1]; Tohru Hada[1]; Shunjiro Shinohara[2]; Takao Tanikawa[3]
[1] ESST, Kyushu Univ; [2] Inst. Eng, TUAT; [3] RIST, Tokai Univ.

Helicon plasma is a high-density and low-temperature plasma generated by the helicon wave i.e., electromagnetic whistler wave bounded typically in the cylindrical geometry. Helicon plasma is expected to be applications for various fields including next generation electric thrusters. On the other hand, there still remain unsolved physical issues regarding how the plasma is generated using the helicon wave.For further optimization of plasma production, it is important to clarify the mechanism of helicon plasma production.

Helicon plasma production involves such physical processes as wave propagation, mode conversion, and collisionless as well as collisional wave damping that leads to ionization/recombination of neutral particles. In particular, Shamrai proposed the linear mode conversion process that can contribute to high efficient RF power deposition. According to his scenario, the long wavelength helicon wave is linearly mode converted to the TG wave, which then dissipates rapidly due to its large wave number. On the other hand, the efficiency of the mode conversion depends strongly on the magnitudes of dissipation parameters. When the dissipation is dominant, the TG wave is no longer excited and the input helicon wave directly dissipates.

We will discuss the dependence of mode conversion efficiency on the parameter of electron-neutral collisions and the structure of plasma heating by fluid simulations. And we will discuss the processes of plasma heating and plasma production by using self-consistent model which includes processes of inelastic collisions between electrons and neutrals, and ionization/recombination of neutrals.

ヘリコンプラズマとは、アルゴンなどの中性ガス中に電磁波（ヘリコン波）を励起して生成するプラズマである（広い意味においてヘリコン波は、有限円柱境界をもつ「ホイッスラー波」として定義できる）。ヘリコンプラズマは室内で効率よく低温・高密度なプラズマを生成できるため、次世代の電気推進機など、幅広い分野での応用が期待されている。その一方でヘリコンプラズマの生成過程には未だ未解明の部分が多く残されている。生成機構を解明する事により、プラズマ生成の最適化が期待され、ヘリコンプラズマのさらなる応用領域の拡大につながると考えられる。

ヘリコンプラズマ生成のメカニズムには、ヘリコン波動の伝搬、プラズマ密度の非一様性によるヘリコン波から TG (Trivelpiece-Gould) 波へのモード変換、衝突・無衝突によるプラズマの加熱、中性粒子の電離・再結合を考慮した分散関係の時間発展が挙げられる。特にアンテナからの高効率なパワー吸収機構として Shamrai の提唱したモード変換機構がある。Shamrai のシナリオによれば、アンテナより励起されたヘリコン波は非一様密度プラズマ中で TG 波へモード変換し、モード変換によって励起された TG 波はその大きな波数のため大きく減衰する。一方で、モード変換効率すなわち TG 波の励起はプラズマ中の散逸の大きさに強く依存する。特に散逸が大きい場合には TG 波は励起されず、ヘリコン波の直接減衰によるパワー吸収が主となる。

本発表では、流体シミュレーションによりモード変換効率の散逸パラメータ（電子ー中性粒子間衝突）への依存性、プラズマ加熱機構の変化を議論する。さらに、電子ー中性粒子間の非弾性衝突, 中性粒子の電離・再結合過程をセルフコンシステントに取り入れたモデルによりプラズマ加熱、生成過程を議論する。

高マッハ数衝撃波における磁気リコネクション誘発と電子加速

松本 洋介 [1]; 天野 孝伸 [2]; 加藤 恒彦 [3]; 星野 真弘 [2]
[1] 千葉大理; [2] 東大・理; [3] 広大・理

Electron acceleration during turbulent reconnection in a high MA shock

Yosuke Matsumoto[1]; Takanobu Amano[2]; Tsunehiko Kato[3]; Masahiro Hoshino[2]
[1] Chiba University; [2] University of Tokyo; [3] Hiroshima Univ.

Acceleration of charged particles is a fundamental topic in astrophysical, space and laboratory plasmas. Very high energy particles are commonly found in the astrophysical and planetary shocks, and in the energy releases of solar flares and terrestrial substorms. Evidence for relativistic particle production during such phenomena has attracted much attention concerning collisionless shock waves and magnetic reconnection, respectively, as ultimate plasma energization mechanisms. While the energy conversion proceeds macroscopically, and therefore the energy mostly flows to ions, plasma kinetic instabilities excited in a localized region have been considered to be the main electron heating and acceleration mechanisms.

We present that efficient electron energization can occur in a much larger area during turbulent magnetic reconnection from the intrinsic nature of a strong collisionless shock wave. Supercomputer simulations have revealed a multiscale shock structure comprising current sheets created via an ion-scale Weibel instability and resultant energy dissipation through magnetic reconnection. A part of the upstream electrons undergoes first-order Fermi acceleration by colliding with reconnection jets and magnetic islands, giving rise to a nonthermal relativistic population downstream. The unprecedented dynamics reported here has shed new light on magnetic reconnection as an agent of energy dissipation and particle acceleration in strong shock waves.

無衝突衝撃波の実験的研究に向けたプラズマ計測法の検討

松清 修一 [1]
[1] 九大・総理工

Examination of plasma diagnostics for experimental study on collisionless shocks

Shuichi Matsukiyo[1]
[1] ESST Kyushu Univ.

http://www.esst.kyushu-u.ac.jp/˜space/

Collisionless shocks are ubiquitus in a variety of space and astrophysical phenomena. Recently, high power laser facilities have successfully reproduced collisionless shocks. A laser experiment is now expected to be a new research tool for collisionless shock physics. In collaboration with the Institute of Laser Engineering at Osaka University we plan to investigate multi-scale phenomena in a collisionless shock reproduced by Gekko XII laser. A single foil target in a gas is ablated by the laser irradiation. The ablated plasma expands in a surrounding plasma of the gas origin, which leads to the formation of a shock. In the experiment local plasma quantities in the shock transition region are measured by using collective Thomson scattering measurement. The collective Thomson scattering is the interaction between a sufficiently low frequency incident electromagnetic wave and collective oscillations of a plasma. The interaction produces scattered waves which include information of collective plasma phenomena. The Thomson scattering measurement has been widely used so far to measure experimental as well as space plasma. However, the scattering theory has not been well established in the case that the plasma is highly non-equilibrium as in a shock transition region. In this study we discuss the scattering processes in highly non-equilibrium plasmas typical in a shock transition region and suggest that the so-called electron features of the Thomson scattering, which are usually weak signals in an equilibrium plasma, may be a good measure of a microinstability in a shock transition region.

近接・衝突する二つの斜め衝撃波の数値実験

中野谷 賢 [1]; 松清 修一 [2]; 羽田 亨 [3]
[1] 九大総理工; [2] 九大・総理工; [3] 九大総理工

Numerical Experiment of Two Colliding Oblique Shocks

Masaru Nakanotani[1]; Shuichi Matsukiyo[2]; Tohru Hada[3]
[1] ESST, Kyushu Univ.; [2] ESST Kyushu Univ.; [3] ESST, Kyushu Univ

Mechanisms of the particle acceleration at a collisionless shock have been intensively studied analytically, numerically, and observationally. Most of the previous studies assume that energetic particles interact with a single shock. However, shock waves are ubiquitous in space, and two shocks frequently come close to or even collide with each other. For instance, it is observed that a CME (coronal mass ejection) driven shock collides with the earth's bow shock [H. Hietala et al., 2011], or interplanetary shocks pass through the heliospheric termination shock [J. Y. Lu et al., 1999]. Colliding shocks are observed alspoin high power laser experiments [T.Morita et al., 2013]. The energy of self-emission from a plasma is increased during the shock-shock interactions. However, detailed structures of such colliding shocks and the accompanied particle heating/acceleration processes are still not clear.

Here, we perform one dimensional full Particle-in-Cell (PIC) simulations to examine colliding two oblique shocks. In particular, the following three points are discussed in detail.

1. Energetic electrons are observed upstream of the two shocks before their collision. These energetic electrons are efficiently accelerated through multiple reflections at the two shocks (Fermi acceleration). Moreover, a part of the accelerated electrons are further energized by interacting with increasing magnetic field during the collision, or as they continue to be trapped at the shock surface after the collision.

2. Before the two shocks collide, large amplitude waves are excited by electrons flowing into the upstream via the electron fire hose instability [X. Li et al., 2000]. The waves scatter the electrons in such a way that the average pitch angle increase. Those electrons can be easily reflected when they encounter the shock, leading to even more enhanced abundance of the energetic electrons upstream. This implies that the self-generated waves give a positive feedback to electron acceleration in converging two shocks.

3. After the two shocks collide, we find that downstream plasma density and pressure are lower than the values estimated from MHD theory. The reason is that energetic electrons upstream affect the shock structures. Fluid quantities of the shocks obtained from the PIC simulation are compared with MHD theory to discuss the effect of the back-reaction of accelerated electrons to the collision of the shocks.

プラズマ中に発生する無衝突衝撃波（以下、衝撃波）は高エネルギー粒子を効率よく生成すると考えられている。その加速機構を明らかにするために多くの研究がなされてきたが、従来の議論はどれも単一の衝撃波を仮定しており、複数の衝撃波による加速はほとんど考えられてこなかった。実際、宇宙には衝撃波が普遍的に存在しており、衝撃波同士が接近・衝突することは頻繁に起こる。例えば、コロナ質量放出により生じた衝撃波と地球磁気圏衝撃波の衝突 [H. Hietala et al., 2011]、惑星間空間衝撃波が太陽圏終端衝撃波を横切ることが報告されている [J. Y. Lu et al., 1999]。また、室内レーザー実験においても衝撃波同士の衝突が観測されており、衝突の際に放射エネルギー (熱制動放射) が強まることが報告されている [T. Morita et al., 2013]。これらの衝撃波-衝撃波相互作用は宇宙高エネルギー現象を正しく理解するうえで重要となると考えられるが、相互作用による衝撃波構造の変化や粒子の加速・加熱などの物理過程は未解明である。

本研究では、1 次元 Full-Particle-in-Cell シミュレーションを用いて二つの衝撃波の近接・衝突過程を調べる。特に、斜め衝撃波同士の衝突において次の 3 点の結果に注目する。

1. シミュレーションでは、接近しつつある 2 つの斜め衝撃波上流域で高エネルギー電子の存在が確認された。これらは、二つの衝撃波による反射を繰り返して効率的に加速（フェルミ加速）されており、被加速粒子の一部は、衝撃波衝突時に増幅される磁場や衝突後の衝撃波によってさらに加速されることが分かった。

2. 衝突前において、上流に染み出した電子によって大振幅波動が励起されることが分かった。この波動は電子 fire hose instability[X. Li et al., 2000] によって励起されたものと考えられる。また、この波動は被加速電子のピッチ角を変化させ、衝撃波による反射 (衝撃波ドリフト加速 [L. Ball et al., 2001]) の効率を高めることが分かった。これは波動が加速に対して正のフィードバックを与えることを示唆している。そして波動の影響も含めた二つの衝撃波による加速機構を議論する。

3. 衝撃波衝突後の下流域でのプラズマの密度や圧力が磁気流体力学 (MHD) により求められる値よりも低いことが分かった。その原因としては上流に流出した高エネルギー電子が衝撃波構造に影響を与えたためであると考えられる。磁気流体力学で求められる衝突後の衝撃波の物理量（磁場の大きさ、衝撃波の速度 etc.）と PIC シミュレーションの結果との比較を行い、運動論的効果の影響を議論する。

R008-10 **会場: C** **時間: 11 月 1 日 16:30-16:45**

宇宙線変成衝撃波の加速効率に対する磁場増幅の効果

斎藤 達彦 [1]; 星野 真弘 [2]; 天野 孝伸 [2]
[1] 東大・理; [2] 東大・理

Effects of magnetic field amplification on the particle acceleration efficiency at cosmic ray modified shocks

Tatsuhiko Saito[1]; Masahiro Hoshino[2]; Takanobu Amano[2]
[1] EPS, Univ. of Tokyo; [2] University of Tokyo

Shock waves with the feedback effects of accelerated particles (cosmic rays: CRs) are called cosmic ray modified shocks (CRMSs) [Drury & Voelk 1981]. In CRMSs, the shock structures change globally, the energy spectrum of CRs becomes concave. Such features typical of CRMSs were reported by recent observations of supernova remnants (SNRs) [Vink et al. 2006]. Therefore, it is important to consider the feedback effect of CRs.

On the other hands, recent observations of SNRs imply that the magnetic fields are amplified up to mG [Vink & Laming 2003; Uchiyama et al. 2007]. In such situations, the pressure of the amplified magnetic field may also play a role for modification of the shock structure, and hence the acceleration efficiency of CRs.

In our research, we assume that the background plasma is described as a fluid whereas the distribution function of CRs is governed by the diffusion convection equation. Reville, Kirk & Duffy (2006) found the steady-state solution of CRMSs for this system by using an iterative approach. However, they did not consider of the effect of magnetic field amplification. In this study, we extend the system by introducing the generations of magnetic field and its dissipation that leads to non-adiabatic heating of the background plasma in the precursor region. The non-adiabatic heating of the background plasma leads to the decrease in Mach number in the precursor, resulting in a weaker subshock. Therefore, the CR acceleration efficiency in a modified shock may be substantially reduced. We will quantify the acceleration efficiency of the modified shock in such an extended system, and discuss the stability of the steady-state solutions by using non-linear time-dependent simulations.

衝撃波に対して被加速粒子 (宇宙線) の反作用効果が効いた衝撃波は宇宙線変成衝撃波と呼ばれている [Drury & Voelk 1981]。宇宙線変成衝撃波では、衝撃波の構造が大きく変化し、それに伴い被加速粒子のエネルギースペクトルも低エネルギー側で急峻で、高エネルギー側でなだらかな凹型の形状を示す。実際の超新星残骸衝撃波などでは、こうした特徴的な構造が見つかっており [Vink et al. 2006]、宇宙線加速を論ずる際にはこの効果を考慮することは非常に重要である。

一方、衛星観測から、超新星残骸衝撃波では mG 程度の非常に大振幅な磁場が生成されていることが示唆されている [Vink & Laming 2003; Uchiyama et al. 2007]。このような状況では宇宙線の反作用効果に加えて、励起された波の圧力も十分に衝撃波を変成し、宇宙線の加速効率に寄与を与え得ると考えられる。

本研究では、背景プラズマを流体、宇宙線を分布関数として宇宙線変成衝撃波を記述する。同様の枠組みにおいて時間定常解が Reville, Kirk & Duffy (2006) によって得られているが、この先行研究では衝撃波での磁場増幅の効果を無視している。そこで、我々は新たに磁場の生成と、減衰による背景プラズマの非断熱加熱の効果を取り入れて系を拡張した。この拡張された系では、背景プラズマの加熱によって subshock 上流でのマッハ数が低下し、subshock が弱まる。従って、宇宙線が加速効率が低下することが予想される。今回の発表では、この宇宙線の生成効率を見積もり、さらに、非線形な時間発展を追うことで、この系が安定して存在できるかどうかも議論する。

EMICトリガード放射と相互作用する相対論的電子のシミュレーション

久保田 結子 [1]; 大村 善治 [2]
[1] 京大・工・電気; [2] 京大・生存圏

Simulation of relativistic electrons interacted with EMIC triggered emissions

Yuko Kubota[1]; Yoshiharu Omura[2]
[1] RISH, Electric engineering, Kyoto Univ.; [2] RISH, Kyoto Univ.

We perform test particle simulations of relativistic electrons interacting with electromagnetic ion cyclotron (EMIC) triggered emissions. EMIC triggered emissions are characterized by large wave amplitudes, rising-tone frequencies, and coherent left-handed circularly polarized waves. EMIC triggered emissions are generated by energetic protons injected into the inner magnetosphere. We study trajectories of relativistic electrons drifting eastwards interacting with longitudinally distributed EMIC triggered emissions. Relativistic radiation belt electrons interact with EMIC triggered emissions, some are trapped by wave potentials and efficiently guided down to lower pitch angles. Repeated interactions occur due to the mirror motion, and result in the scattering of particles into the loss cone. We use two EMIC wave models for the test particle simulations. One assumes that the wave amplitude is constant and the other assumes a time dependent wave amplitude that characterizes sub-packets. For both models, approximately 25% of the total injected number of particles in the energy range 0.5-6.0 MeV are precipitated of a time scale 2 minutes. We determine the timing, distribution in pitch angle, and longitudinal location of the relativistic electron precipitation with respect to different particle energies.

プラズマ圏ヒスの微細構造と非線形成長理論

大村 善治 [1]; 中村 紗都子 [2]; Summers Danny[3]; Kletzing Craig A.[4]
[1] 京大・生存圏; [2] 京大・理・地球惑星; [3] Memorial Univ. Newfoundland; [4] Department of Physics and Astronomy, UoI

Nonlinear wave growth theory for discrete hiss emissions in the plasmasphere

Yoshiharu Omura[1]; Satoko Nakamura[2]; Danny Summers[3]; Craig A. Kletzing[4]
[1] RISH, Kyoto Univ.; [2] Dept. of Geophys., Kyoto Univ.; [3] Memorial Univ. Newfoundland; [4] Department of Physics and Astronomy, UoI

Recent observations of plasmaspheric hiss emissions by the Van Allen Probes show that broadband hiss emissions in the plasmasphere comprise short-time discrete elements with rising and falling tone frequencies. Based on nonlinear wave growth theory of whistler-mode chorus emissions, we examined the applicability of the nonlinear theory to the discrete hiss emissions. We have generalized the derivation of optimum wave amplitudes for triggering rising tone chorus emissions for both falling and rising 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 formation of electron holes for rising tones and electron hills for falling tones, the coherent waves grow up to the optimum amplitudes. We find an excellent agreement between the optimum amplitudes and the observed amplitudes as a function of instantaneous frequency. The frequency sweep rates and time scales of the hiss emissions also agree 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.

古典場の方程式の正準形式について

中村 匡 [1]
[1] 福井県大

On Multidimensional Hamiltonian

Tadas Nakamura[1]
[1] FPU

http://mira.bio.fpu.ac.jp

Conventional Hamiltonian for multidimentional classical fields (Electromagnetic fields, Klein-Goldon field, etc.) sigles out one coordinate (usually temproal coordinate) to define canonical conjugate variables. Consequently the equations obtained fail to be manifestly covariant. Moreover, one need to introduce some constraints when applied to vector fields, such as electromagnetic fields. For instance, the four dimensional vector potential has four components in electromagnetic theory, whereas the electric field, which is canonical conjugate to the vector potential, has only three components; one needs to eliminate one degree of freedom somehow.

Recently Nakamura (2002) and Kaminaga (2012) proposed a new approach in which all coordinates are treated equally to define the canonical conjugates. The present study is s to extend these two approaches to more general form. Several coordinates are picked up to defined the conjugats, and the canonical equations are constructed with them. The resulting form becomes a mixture of Hamilton and Lagrange formulations.

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Y. Kaminaga, EJTP 2012, http://www.ejtp.com/articles/ejtpv9i26p199.pdf

Maxwell 方程式や Klein-Goldon 方程式などのような，多次元空間での偏微分方程式の正準形式は，従来，ひとつの座標（普通は時間座標）に対する微分に対応して正準共役量を定義していた。このアプローチをとると，そのひとつの座標だけ他の座標と違うあつかいをすることになり，たとえばミンコフスキー空間内での方程式の場合だと，形式上，いわゆる相対論的共変性を失うことになる。また，たとえば Maxwell 方程式のようなベクトル場の方程式の場合，ベクトルポテンシャルが４成分なのに対し，共役量の電場が３成分しかなく，なんらかの拘束条件を導入しなければ閉じた方程式系が得られないという欠点もあった。

近年，これに対し，すべての座標に関する微分によって正準共役量を定義するというアプローチが開発され，電磁場や重力場の方程式について拘束条件を必要としない正準形式が導かれている（中村 2002, Kaminaga, 2012)。本研究ではこの両者を両極端とする一般的なあつかいについて考える。ここでは，多次元の座標のうち任意のいくつかをとりだして正準共役量を定義し，それによって正準方程式をみちびく。得られた方程式はハミルトン形式とラグランジュ形式が混合したものになる。

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デカメータ電波パルスの観測に基づく我が銀河系中心部ブラックホール・バイナリーの電離層効果を考慮した位置決定

大家 寛 [1]
[1] 東北大・理・地物

Determination of the Direction of Black Hole Binary at the Center Part of Our Galaxy Considering the Ionosphere Effects

Hiroshi Oya[1]
[1] Geophysics, Tohoku Univ.

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 has been deferred to the later works. In this study, the directions of the pulse sources are analyzed using data newly observed in 2014 considering the deviation effects on the propagating direction of radio waves through the ionosphere.

2.Observation System

The observation 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 consist of three observation stations located at Yoneyama, Zao, and Kawatabi in Miyagi prefecture , Japan; the longest basline is 83 km and shortest baseline is 44 km.The signals observed at 22.186 MHz with band width of 1 kHz are sent from each station through the telemetry sysytem directly to the central station at Sendai where the detected signals have been converted into digital signals by AD converters with conversion rate of 6000 data per a second being devided into 6 channels with 100Hz band width each.

3. Observations and Data Analyses

Observations in 2014 have been made from early February to 10th of April. As the first trial, 6 observation days, 24, 25, and 26 March and 7, 8, and 9 April are selected for analyses. The pulse form has been detected by applying period correlated accumulation method (so called box car method) together with analyses of the correlation between the observed interferometer fringe and template fringe to detect a selected source direction. To form the template fringe, the ionosphere effects on propagation of radio waves at 22.816MHz have been considered by applying 2-layer-ionosphere model where foF2 values observed at Kokubunji station are applied. a fine direction adjustment to compensate the systematic bias of the detected source direction due to the characteristics of the selected ionosphere model, has been made by sweeping the direction of the template fringe.

4. Results and Discussion

The predicted deviation angle in the elevation of the center part of our Galaxy caused by the propagation of the decameter waves at, 22.186 MHz , through the ionosphere shows smooth variation versus the elevation of the sources with a maximum around 4 degree and minimum of 0.5 degree. Fine adjustment procedure has provided an average compensation angle of -2 arc minutes with standard deviation of 22,3 arc minutes for pulses from Gaa which indicates the pulse period ranging from 127.96 sec to 130.310 sec and average compensation angle of -14 arc minutes with standard deviation of 38.8 arc minutes for the pulses from Gab which indicates the pulse period ranging from 110.92 sec to 116.55 sec . the results of average separation angle of 15.6 arc minutes between Gaa and Gab is about half of the standard deviation to decide the position of Gaa and Gab. Considering all of these statistic parameters, we can conclude that the binary Gaa and Gab are located at the center part of our Galaxy within allowance angle 40 arc minutes.

5. Conclusion

Considering the feature of the observed pulse periods from Gaa and Gab which reveal the variation of periods with anti symmetric phase between Gaa and Gab due to the Doppler effects caused by orbital motion with orbit period of 2050 sec, and also considering the speed ratio to the light velocity that are deduced from the rate of period variation, we conclude that these two pulse sources are black hole binary located center part of our Galaxy. The sources, Gaa and Gab correspond to the Ker black holes with mass approximately proportional to the pulse periods; Gaa and Gab , respectively have 1.03-1.38 million solar mass and 0.92-1.21 million solar mass.

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ーを形成していることを結論してきた。その到来方向が銀河中心部にあるとの詳細な実証はあと送りとなっていたが、本研究では東北大学・長距離基線デカメータ電波干渉計による新たな観測に基づき、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をおこなった。＋ー 40 分角の精度で SgrA を中心に考えられるカー・ブラックホールのバイナリーの存在が結論される。

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。22.816MHz にて帯域 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。各信号は帯域幅 100Hz の狭帯域 6 チャンネルに分割され、各々サンプリング率 6kHz 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 4 月 10 日にわたる期間にて実施された。

３．データ解析

データ解析は第一段階として、銀河系中心部が、観測地方時午前１時半より観測可能となる 3 月 24,25, 及び 26 日、さらに、４月 7, 8, 及び 9 日の６観測日について行っている。解析に際しては、電離層を 2 層モデルで近似し銀河中心の方位 (RA ,Dec) を補正しつつ干渉計フリンジとの相関を求めた。電離層パラメターは各観測日ごとに対応し、国分寺観測点における foF2、15 分値を基礎に３次補間関数により１分値として使用した。2 層モデルによる予想方位と実観測方位の系統差を補正する手段として、電波源方位の微調正検出を行っている。これには干渉計フリンジとの相関を求める方位基準フリンジを発生する際、検出方位を掃引しつつ結果として得られるパルスの波形の整形度とパルスレベルが最大となるよう、探査する方式である。

４．結果と検討

観測周波数 22.186MHz においては、電離層による銀河中心部の方位角の固有の赤経、赤緯からの偏向は、仰角の低い時刻にはかなり顕著で、４度近くのずれを示し、南中時にも 0.5 度程度の差のあることがモデル電離層から示された。さらに、モデルと実際との間に起こる差に対する補正値はパルス周期 127.96sec-130.310sec と観測される Gaa に対し赤経、赤緯がともに平均-2arc min, 分散に相当する絶対ずれ角度の平均は 22.3 arc　 min が示された。また、パルス周期 110.92-116..secc と観測される Gab に対し赤経、赤緯がともに平均-14arc min, で、分散に相当する絶対ずれ角度が 38.8 arc　 min となった。こうした観測精度の条件のもと、Gaa と Gab の方位角ずれの平均値は 15.6 arc min で,Gaa, Gab の方位決定における分散値の 1/2 に近いことを考慮すると、今回観測される２つのパルス源は赤経 17h45m40s, 赤緯-29o00　’28 ”に対し約 40arc min 以内で同じ方位に位置することが認められる。

5. 結論

２つの電波源からのパルスはその源が周期 2050sec で公転し Doppler 効果による周期変動は互いに 180 度の位相ずれを示す。バイナリーの公転軌道パラメターとパルス周期がカーブラックホールのスピン周期と仮定すると、Gaa が 103˜138 万太陽質量、Gab が 92˜121 万太陽質量となり。その位置は 40arc min 以内の精度で SgrA を中心に考えうる。

垂直衝撃波における再形成と微視的不安定性

梅田 隆行 [1]; 木谷 佳隆 [1]; 松清 修一 [2]
[1] 名大 STE 研; [2] 九大・総理工

Reformation and microinstabilities at perpendicular collisionless shocks

Takayuki Umeda[1]; Yoshitaka Kidani[1]; Shuichi Matsukiyo[2]
[1] STEL, Nagoya Univ.; [2] ESST Kyushu Univ.

Large-scale two-dimensional (2D) full particle-in-cell (PIC) simulations are carried out for studying the relationship between the dynamics of a perpendicular shock and microinstabilities generated at the shock foot. The structure and dynamics of collisionless shocks are generally determined by Alfven Mach number and plasma beta, while microinstabilities at the shock foot are controlled by the ratio of the upstream bulk velocity to the electron thermal velocity and the ratio of the plasma-to-cyclotron frequency. With a fixed Alfven Mach number and plasma beta, the ratio of the upstream bulk velocity to the electron thermal velocity is given as a function of the ion-to-electron mass ratio. The present 2D full PIC simulations with a relatively low Alfven Mach number (MA ∼ 6) show that the modified two-stream instability is dominant with higher ion-to-electron mass ratios. It is also confirmed that waves propagating downstream are more enhanced at the shock foot near the shock ramp as the mass ratio becomes higher. The result suggests that these waves play a role in the modification of the dynamics of collisionless shocks through the interaction with shock front ripples.

Parametric instabilities of whistler waves revisited

Yasuhiro Nariyuki[1]; Shinji Saito[2]; Takayuki Umeda[3]
[1] Faculty of Human Development, Univ. Toyama; [2] Nagoya Univ.; [3] STEL, Nagoya Univ.

Nonlinear wave-wave interactions such as parametric instabilities play an essential role in plasma turbulence. The existence of the spectrum anisotropy in solar wind turbulence near 1AU suggests that the damping of quasi-parallel propagating right-handed polarized magnetohydrodynamic (MHD) waves (whistler waves) may occurs in the interplanetary space. Although the parametric instabilities of whistler waves have been studied over for more than forty years, recent studies do not pay much attention to these. This may be because it is believed that the linear collisionless damping dominates the damping of these waves. However, the recent numerical simulation suggests that the parametric instabilities take place, even if the frequency of the parent wave is very close to the electron cyclotron frequency (Umeda, Saito, Nariyuki, submitted to ApJ). In the present study, we revisit the linear analysis of the parametric instabilities of parallel propagating whistler waves. We apply the Hall-MHD system including finite electron mass and collisionless damping to our analysis. The importance of the parametric instabilities to the ion and electron heating (the energy dissipation scale of the whistler waves) is discussed by comparison with the past theoretical analysis.

HLL Riemann Solver with Divergence-free Constraint for Two-Fluid Simulations

Takanobu Amano[1]
[1] University of Tokyo

There has been growing interest in incorporating small scale physics in Magnetohydrodynamic (MHD) simulations, because rapidly increasing computational resources may enable one to use sufficiently small grid size even in macroscopic simulation models, such as global MHD simulation of a planetary magnetosphere. For instance, attempts have been made to include Hall physics in global magnetospheric simulations. The Hall term introduces dispersion in the eigenmode of the system, making numerical treatment much more difficult due to the appearance of high-frequency whistler waves. Since the phase speed of whistler waves increases without bound in the Hall-MHD, fully or partially implicit treatments are sometimes employed for numerical stability.

In this report, we extend the conventional Hall-MHD to two-fluid equations with charge neutrality constraint, that takes into account finite electron inertia effect. Because of the assumption of charge neutrality, the number of eigenmodes in this system is the same as the ideal MHD, whereas dispersive characteristics appear due to ion and electron inertia effects. In contrast to the Hall-MHD, there is a limit in the maximum phase speed introduced by finite electron inertia, a property desirable for numerical simulations.

The system may be written in a conservative form that resembles the MHD, with modification in the generalized Ohm's law. Therefore, the mass, momentum, and energy conservation laws may exactly be satisfied by using a proper conservative scheme. We have implemented the single state HLL Riemann solver for this system, that is combined with Upstream Constrained Transport (UCT) scheme of Londrillo & Del Zanna (2004). The UCT scheme employing the staggered definition of magnetic field is specifically designed for the divergence-free constraint and can be combined with any Riemann solvers. The present scheme thus guarantees the divergence-free condition for the magnetic field. Several numerical examples have shown that the code is able to capture discontinuities as well as dispersive signature arising from finite electron and ion inertia. The code, now being extended to incorporate kinetic effects, may become a useful next generation simulation model with a lot of applications in space physics and astrophysics.

地上磁力計データを用いたFLR周波数自動検出と、磁気圏プラズマ質量密度の緯度経度構造の統計解析

北川 雄一郎 [1]; 河野 英昭 [2]; Mann Ian R.[3]; Milling David[4]; 林 幹治 [5]; 北村 健太郎 [6]; 吉川 顕正 [7]; MAGDAS/CPMN グループ 吉川 顕正 [8]
[1] 九大・理・地惑; [2] 九大・理・地球惑星; [3] The University of Alberta; [4] アルバータ大; [5] なし; [6] 徳山高専; [7] なし; [8] -

Automated FLR detection and statistical analysis of the latitude and longitude structure of the plasma mass density

Yuichiro Kitagawa[1]; Hideaki Kawano[2]; Ian R. Mann[3]; David Milling[4]; Kanji Hayashi[5]; Kentarou Kitamura[6]; Akimasa Yoshikawa[7]; Akimasa Yoshikawa MAGDAS/CPMN Group[8]
[1] Earth and planetary, Kyushu Univ; [2] Earth and Planetary Sci., Kyushu Univ.; [3] The University of Alberta; [4] Alberta Univ.; [5] none; [6] Tokuyama CT.; [7] ICSWSE/Kyushu-u; [8] -

Applying the power-ratio and cross-phase methods to the magnetic field data from two stations closely located along the same meridian, we can identify the Field Line Resonance (FLR) and obtain the FLR frequency. In addition, from the obtained FLR frequency we can estimate the plasma mass density along the magnetic field line running through the midpoint between the two stations.

In this work, by using several stations belonging to three ground-based magnetometer networks (MAGDAS, CARISMA and STEP Polar Network) and located along a meridian in Canada, we perform the power-ratio and cross-phase analyses, identify the FLR frequency and study the latitude and longitude structure of the plasma mass density. Because it is time-consuming to visually identify the FLR frequency in a large amount of data, we have developed an automated computer program for FLR detection, referring to and adding a few new features to the method of Chi et al. [2013].

緯度方向に近接した磁場観測点 2 点 (2 点間の距離は 100 km オーダー) のデータに位相差法, 振幅比法 (以下二点法と総称) と呼ばれる解析を行うと、磁力線共鳴 (Field Line Resonance, FLR) を同定でき、その周波数から 2 観測点の中点を通る磁力線沿いの磁気圏プラズマ質量密度を推定できる。

カナダの CARISMA 磁力計ネットワーク中には、多くの磁力計が並んだ子午線帯が 2 つあり、Alberta line (地理経度 250 度近辺) 、Churchill line (地理経度 265 度近辺) と呼ばれている。その 2 lines に沿っては、二点法を順次適用する事で密度の L 分布を推定できる。一方、その 2 lines の中間の子午線には、高緯度側には東京大学 STEP Polar Network 磁力計が以前より存在したが、低緯度側には磁力計が無く、近年、MAGDAS の WAD 観測点と CARISMA の WEYB 観測点が設置された。この 2 点は、MAGDAS と CARISMA の共同研究として、二点法が可能な間隔で設置された。STEP-WAD-WEYB 観測から、Alberta line と Churchill line の中間の子午線に沿っての密度 L 分布が求められ、より詳細な経度方向の密度構造を研究できると期待される。これが本研究の最終的目的である。

本発表ではそれに向け、WAD 観測点と WEYB 観測点を中心とし、STEP Polar Network も用いて、二点法によって FLR 周波数を求め、プラズマ質量密度を計算し、その統計解析からその緯度経度構造について調べる。

大量データ中の FLR 同定は目で行ったのでは時間がかかるため、Chi et al. [2013] をもとにして FLR 周波数の自動検出プログラムを作成した。このプログラムの FLR の選定条件には Chi et al. [2013] とは異なるものもある。それら検出の条件やプラズマ質量密度の統計解析の結果は発表で示す。

ダスト間静電相互作用の N 体シミュレーション

伊東 保崇 [1]; 天野 孝伸 [1]; 星野 真弘 [1]
[1] 東大・理

N-body investigation of electrostatic interactions between dust grains

Hotaka Itou[1]; Takanobu Amano[1]; Masahiro Hoshino[1]
[1] University of Tokyo

A dusty plasma is usually known as a plasma consisting of three components, electrons, ions, and charged dust grains and exists in space universally. Immersed in the plasma, dust grains are thought to acquire large amount of charges due to various charging processes. Such charged grains are electromagnetically coupled with the ambient plasma, giving rise to characteristic phenomena in dusty plasmas. We may be able to find dusty plasmas in several astrophysical environments, e.g., interstellar molecular clouds, protoplanetary disks, planetary rings, earth's magnetosphere, and tails of comets. In addition, in laboratories, the crystallization of dust grains, known as the Coulomb crystallization, has been fascinating many researchers. For astrophysical applications as well as industrial applications, the dusty plasma has been studied.

As mentioned above, dust grains acquire charges in plasmas. It is thought that dust grains are negatively charged when the collision between dust grains and plasma particles is the dominant charging process. This is because the electron flux into grains is usually larger than the ion flux. Therefore, it is easily expected that the repulsive shielded Coulomb forces act among negatively charged grains. However, forces acting on the grains may be much more perplexing because they are largely influenced by the ambient plasma. In reality, many types of forces have been suggested (e.g., Shukla and Eliasson, (2009)). The interaction among dust grains is quite significant because it may dominate aggregations and crystallizations in dusty plasmas.

We have investigated the electrostatic interaction between two dust grains by N-body first-principles simulation. The first-principles approach, where we solve equations of motion of all particles allows us to simulate the behavior of the dusty plasma with any assumptions. The main purpose of our investigation is to test the possibility of the attractive interaction due to overlapping Debye spheres proposed by Resendes et al., (1998). Our simulations have demonstrated that the interaction between two dust grains is repulsive and there may be no electrostatic attractive interaction. In this presentation, by comparing the simulation results and the orbital motion limited (OML) theory we discuss the validity of the OML model. In addition, simulation results and the electric field around a single isolated grain are compared to quantitatively investigate the applicability of the superposition principle.

ダストプラズマとは、通常電子やイオンに加え帯電したダスト粒子からなるプラズマとして知られており、宇宙に普遍的に存在している。プラズマ中でダスト粒子はさまざまな帯電過程によって大きな電荷を得ると考えられていて、そのようなダスト粒子は背景のプラズマと電磁気的に結びつき、ダストプラズマの特徴的な現象を起こす。ダストプラズマは宇宙のさまざまな環境、例えば分子雲、原始惑星系円盤、惑星環、地球磁気圏、流星の尾などで発見することができるだろう。加えて、実験室でも Coulomb 結晶と呼ばれるダスト粒子の結晶化が多くの研究者を魅了し、天文学的応用のためのみならず産業的な応用のためにも盛んに研究されている。

先に述べたように、ダスト粒子はプラズマ中で帯電する。通常ダスト粒子は、プラズマ粒子との衝突が支配的な帯電過程であるときは負に帯電すると考えられており、これはダストに流入する電子がイオンより多いためである。したがって、負に帯電したダスト間には遮蔽された Coulomb 斥力が働くと思われるが、背景のプラズマの影響を強く受けるのでダストに働く力はもっと複雑であろう。実際にダスト間引力を含む様々な力が提案されている（例えば Shukla and Eliasson, (2009)）。ダスト間相互作用はダストプラズマの集積や結晶化で大きな役割を果たす可能性があるため、非常に重要である。

我々は Ewald 法を用いた第一原理的な N 体計算によって、二つのダスト間の相互作用を調査した。すべての粒子の運動方程式を解く第一原理的なアプローチによって我々は仮定なしにダストプラズマの振る舞いを見ることができる。我々の主な目的は Resendes et al. (1998) によって提案された Debye 球の重なりによる引力を検証することであったが、我々のシミュレーションによるとダスト間の静電相互作用が斥力的であり、静電的な引力が存在しないがことを示した。今回は我々のシミュレーション結果を orbital motion limited（OML）理論を用いた結果と比べ、その妥当性を議論する。さらに、ひとつのダスト粒子周りの電場と比較することによって重ね合わせの効果を定量的に調べる。

GEOTAIL 衛星によって観測されたBENの低周波成分に関する3次元電磁粒子シミュレーション

永安 翔 [1]; 三宅 壮聡 [2]; 大村 善治 [3]; 小嶋 浩嗣 [3]
[1] 富山県立大; [2] 富山県大; [3] 京大・生存圏

3D Electromagnetic Particle Simulations about the Low Frequency Component of BEN observed by GEOTAIL Spacecraft.

Sho Nagayasu[1]; Taketoshi Miyake[2]; Yoshiharu Omura[3]; Hirotsugu Kojima[3]
[1] Toyama Pref. Univ.; [2] Toyama Pref. Univ.; [3] RISH, Kyoto Univ.

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.

To clarify whether such low frequency waves are generated, we made statistical analysis on generation conditions of low frequency component of BEN observed by Electric Field Detector (EFD) onboard Geotail spacecraft. We detected low frequency component of BEN automatically from EFD data, and made an occurrence frequency distribution of these waves. Low frequency component of BEN are observed in PS and PSBL region in the magnetosphere. We studied several plasma parameters at the time when low frequency component of BEN were observed, and found that these waves were observed in the conditions with low ion density and strong B field in these regions. Then, based on these statistical analysis, we are going to perform a series of three-dimensional electromagnetic particle simulations with different parameters on PC-Cluster built in our laboratory, which has 4 nodes and 64 Gbytes memory per node, and clarify the generation process of the low frequency component of BEN, in time as well as in space.

地球磁気圏のプラズマシート境界層を始めとする様々な宇宙プラズマ領域中で広帯域静電ノイズ（BEN）が観測されている．BEN の波形は GEOTAIL 衛星の観測結果によって，静電孤立波（ESW）の孤立したパルス状の波形によって構成されていることが確認できた．しかし，BEN の高周波成分は ESW として解明されているが，その低周波成分の波動モード，励起メカニズムに関しては未解明である．

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に関する 2 次元粒子シミュレーションを行った．観測結果によると BEN の低周波成分は外部磁場に垂直方向に振動している．そこで，ビーム不安定性の長時間発展の結果現れる磁場に垂直方向の低周波波動に着目し，そのパラメータ依存性について検討した．様々なパラメータでシミュレーションを実行，比較することで BEN の低周波波動が励起される条件を検証した結果，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．BEN の低周波成分の励起メカニズムが電磁波に起因している可能性もあるため，静電粒子コードでのシミュレーションは不十分であると考えられる．そこで新たに 3 次元電磁粒子コードを用いてシミュレーションを行う．

BEN の低周波成分の励起メカニズムを明らかにするために昨年，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．この結果に基づいて本研究室で構築した PC-Cluster 上で 3 次元電磁粒子シミュレーションを行う．PC-Cluster のノード数は 4 台，１台当たりのメモリは 64Gbyte である．そして BEN の低周波成分の生成メカニズムを明らかにしていく．

プラズマ圏における弱相対論的プラズマに対する共鳴条件とホイスラーモード線形増幅率

池田 愼 [1]
[1] 武蔵大

Whistler-mode resonance condition and linear growth rate for equatorial weak relativistic electron in the plasmasphere

Makoto Ikeda[1]
[1] Musashi Univ.

http://www.musashi.ac.jp/modules/annai_education/

The author reports that Siple signals transmitted from the Siple station in Antarctica in 1975 and 1979 were amplified and observed inside the plasmapause by ISAS. Though these experiments have already been completed, he again checked those results and showed that the energetic electrons were accelerated to weak relativistic energy even in the plasmasphere and generated whistler mode signals inside and near L= about 4.0. These results are also reported by the new HAARP experiments, which excited VLF signals and VLF ducts by HF beam modulation above Alaska. In this report, the author further shows the comparison of non-relativistic growth rate and relativistic one of whistler mode, using the complete relativistic resonance condition.

終了したサイプル送信実験ではあるが、１９７５年と１９７９年に、宇宙研で行われたサイプル人工電波送信実験の観測の特徴を改めて検討し、プラズマ圏以内での人工電波の増幅が確認された事を報告する。この結果により、L～４．０付近のプラズマポーズの内側にまで高速電子が注入されている事も明らかになり、更に内側への加速侵入も予想されている。これらの結果は、最近の HAARP 送信実験でも明らかになっている。従って、放射線帯の安定捕捉領域以外にも高速電子は侵入可能で、ホイスラーモード波の増幅も、更には粒子降下も可能となると思われる。この時、高速電子は弱相対論的電子にまで加速されており、波動増幅や粒子降下に対しても相対論的扱いが必要になるであろう。この論文では、相対論的共鳴条件を近似なく導入して、弱相対論的電子の増幅率をプラズマ圏内で近似導出し、非相対論的電子の増幅率との比較を試みる。今後、よりエネルギーの高い相対論的粒子の拡散係数の導出も検討したい。

無衝突衝撃波の実験的研究：ジャンプ条件の検証

久保 聡一朗 [1]; 松清 修一 [2]; 羽田 亨 [3]
[1] 九大・総理工; [2] 九大・総理工; [3] 九大総理工

Experimental study of collisionless shocks : Verification of jump conditions

Soichiro Kubo[1]; Shuichi Matsukiyo[2]; Tohru Hada[3]
[1] ESST,Kyushu Univ; [2] ESST Kyushu Univ.; [3] ESST, Kyushu Univ

Recently, collisionless shocks have been successfully reproduced in a laboratory by using a high power laser facility. In contrast to in-situ or ground based observations in space, parameters can be actively controlled in a laboratory experiment. Hence, we expect that it can contribute to understand unresolved issues of collisionless shock physics, e.g., the mechanisms of energy dissipation, particle acceleration, etc,, if the laboratory experiment is established as a new tool of an empirical study.

We have started the experimental study of collisionless shocks in collaboration with the Institute of Laser Engineering at Osaka University. Last year, we reproduced spherical discontinuities expanding in a plasma by irradiating the Gekko XII laser to a spherical solid target in a gas. The observed discontinuities are not spherical symmetric because of unexpectedly large asymmetry due to directional irradiation of the main laser. It is found that a typical expansion velocity of the discontinuities reach several hundred km/s, which is supersonic, so that the discontinuities are likely to be shocks. In this study we examine the jump conditions across these discontinuities. By using an optical interferometer measurement, the spatial variations of electron density and the resultant compression ratios of the discontinuities are estimated. We will also report the result of forthcoming experiment in this fiscal year to reproduce a more planar shock by using a foil target in a gas.

近年、高強度レーザーを用いて無衝突衝撃波を実験室に再現することができるようになってきた。パラメータを能動的に制御できる室内実験が、無衝突衝撃波の新たな実証的研究ツールとして確立すれば、遷移層でのエネルギー散逸過程や粒子の初期加速過程など、無衝突衝撃波の未解決物理の理解に大きく貢献できるはずである。

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を行っている。2013 年 8 月の実験では、激光 XII 号レーザーを用いて窒素ガス中の球状ターゲット（金でコーティングしたプラスティック球）に高強度レーザーを照射し、ガスプラズマ中に広がる球状の不連続構造を再現した。実験では不連続構造の異方性が見られた。これはレーザーの照射方向に起因する球対称性の破れの効果が予想以上に大きいためであることが分かった。不連続構造がガスプラズマ中を伝播する速度は数百 km/s の超音速に達しており、衝撃波である可能性が高い。ここでは、この不連続構造について衝撃波のジャンプ条件の検証を試みる。可視光による干渉計測を用い、プラズマの電子密度の空間変化を評価して不連続面における圧縮比を推定する。今年度の実験では、ターゲットを平板状の薄膜にして、より平面に近い形状の衝撃波を再現する予定であり、可能であればその結果についても報告する。

Sedov 期における超新星残骸衝撃波での宇宙線の加速

阿部 愛 [1]; 星野 真弘 [1]; 天野 孝伸 [1]
[1] 東大・理

Acceleration of the cosmic rays at SNR shocks in the Sedov phase

Megumi Abe[1]; Masahiro Hoshino[1]; Takanobu Amano[1]
[1] University of Tokyo

Galactic cosmic rays (CRs) are believed to be produced at supernova remnant (SNR) shocks and the maximum energy reaches up to $10^{15.5}$eV. The most plausible mechanism for the particle acceleration at the shock front is known as the Diffusive Shock Acceleration (DSA) process, in which the particles gain energy by bouncing back and forth across the collisionless shock front. According to DSA, the energy spectrum of CRs may be written by a power law with its index solely determined by the shock compression ratio. In the limit of a strong shock such as those of SNRs, the compression ratio approaches to the constant value, predicting a universal power-law index 2 as the CR source spectrum. Since the difference from the observed power-law index 2.7 of the galactic CRs may be attributed to propagation effect of CRs, DSA has been widely accepted as the standard theory of CR acceleration.

In this study, by adopting the Sedov solution as a more realistic model for evolving shocks with finite size, we investigate the energy spectrum of CRs accelerated by DSA. In a previous study, the power-law index of the energy spectrum is investigated with Monte Carlo simulations by changing the mean free path from $2*10^{17}$cm to 10^{18}cm. The index was predicted to be 3.4 that is much softer than the observation (Takahara1986). In order to bridge the gap between observations and theory, we incorporate phenomenologically several other effects in the diffusion coefficient in our model: the energy dependence of the diffusion coefficient, the increase in the gas compression due to back reaction from CRs, and the magnetic field amplification. During the Sedov expansion, the size of the shock wave becomes large, while the shock speed is decelerated. Then the acceleration efficiency may become worse. However, if the effects of the nonlinear shock and the magnetic field amplification are taken into account, the effective diffusion coefficient may decrease. As a result, the overall acceleration efficiency may be enhanced. The primary purpose of this study is to discuss quantitatively whether we can explain the observed CRs spectrum by the SNR shock scenario with the above phenomenological model.

銀河宇宙線は超新星爆発の際に発生する衝撃波で加速され、最大で $10^{15.5}$eV まで加速されると考えられている。その加速機構としては、無衝突衝撃波面を何度も往復することでエネルギーを得る Diffusive Shock Acceleration(DSA) 機構が最も有力視されている。DSA 機構では宇宙線のエネルギースペクトルが冪型分布で表され、その冪指数が衝撃波の圧縮比にのみ依存する。超新星残骸衝撃波のような強い衝撃波の極限では圧縮比が一定値となるため、対応するエネルギースペクトルの冪指数は 2 に漸近する。一方、観測される銀河宇宙線のべき指数は 2.7 程度であるが、この観測と理論の差は、宇宙線の伝播効果によると考えられる。よって DSA は宇宙線の基本的加速メカニズムとして最も有力であるため、加速の標準理論となっている。

本研究ではより現実的な衝撃波として Sedov 解を採用し、衝撃波パラメータの時間変化や加速領域の有限性を考慮したモデルで、DSA によって加速された宇宙線のスペクトル調べる。先行研究では、モンテカルロ法を用いて、平均自由行程を $2*10^{17}$cm から 10^{18}cm まで変えて調べられているが、得られたエネルギースペクトルは、観測とは程遠い冪指数 3.4 程度のソフトなものであった（Takahara 1986）。そこで本研究では、磁場増幅効果に伴う拡散係数の変化およびエネルギー依存性、宇宙線加速の非線形効果による圧縮率の増大などを組み込んだ現象論的なモデルで宇宙線の加速効率を考察する。Sedov 期の衝撃波では、年齢とともに加速領域のサイズは大きくなるが、衝撃波速度が下がり、断熱膨張の効果のため加速効率が悪くなると考えられる。その一方で現象論的に取り入れた圧縮率増大の効果や磁場増幅による拡散係数の減少は加速効率を上げると予想される。本発表では、このような現象論的モデルを採用し、観測される宇宙線スペクトルが超新星残骸衝撃波で説明できるかどうか定量的に評価する。

非ガウス統計にしたがう宇宙線の輸送

原田 大輔 [1]; 羽田 亨 [2]
[1] 九大・総理工・大海; [2] 九大総理工

Transport of cosmic rays with non-Gaussian transport

Daisuke Harada[1]; Tohru Hada[2]
[1] ESST, Kyushu Univ.; [2] ESST, Kyushu Univ

Diffusion of cosmic rays (energetic charged particles) have been discussed mainly using quasi-linear theories, which assumes presence of small amplitude, phase random magnetic fluctuations as scatterers. However, the magnetic fluctuations in space often have large amplitude (nonlinear), and are also often intermittent. Thus the diffusion of the cosmic rays may differ from normal, Gaussian diffusion, in which individual particles obey Brownian-type motion.

We analyzed anomalous diffusion of cosmic rays by performing test particle simulations and also by numerically solving the fractal diffusion equation. In the test particle simulation, we adopt the walk-stick model (Weeks et al., 1996), in which the walk and the stick time intervals are given by Levy distribution. The fractal diffusion equation is solved as an initial value problem (Podlubny, 1999; Shimamoto, 2012).

Perri and Zimbardo (2008) analyzed energetic particle flux observed by Ulysses, and suggested the presence of non-Gaussian scattering in the solar wind. However, the flux data they used in the analysis have large fluctuations, and thus statistical significance of their conclusions must be carefully examined. We numerically produce the cosmic ray flux using the model described above, and evaluate associated power-law index and its statistical error, for the cases of normal and non-Gaussian transport. Also, we analyze a model in which cosmic rays travel several distinct regions with different scattering properties.

これまで多くの場合、宇宙線の拡散過程はブラウン運動に代表される通常拡散と準線形理論で説明されてきた。準線形理論において、磁場揺らぎを構成する MHD 波動は平均場よりも十分小振幅であり、位相はランダムであると仮定されている。しかし宇宙プラズマ中の MHD 波動や磁場揺らぎ構造はしばしば大振幅、したがって非線形であり、その分布は間欠的である。したがって宇宙線の拡散は必ずしも通常拡散ではなく、異常拡散となっている可能性が指摘されている。

本研究では宇宙線の異常拡散について、テスト粒子計算およびフラクタル拡散方程式の数値解によって解析を行った。テスト粒子計算としては、歩行・停滞モデル (Weeks et al., 1996) を用い、歩行準拡散に対応する粒子運動を生成した。フラクタル拡散方程式（非整数階偏微分方程式）は初期条件として原点に宇宙線が集中している場合の時間発展を初期値問題として解いた (Podlubny, 1999; 島本, 2012)。

太陽観測衛星である Ulysses の観測データに基づき、Perri and Zimbardo (2008) は宇宙線フラックスを時間のベキ乗分布としてあらわし、そのベキ則指数の値より散乱が非ガウス的であると結論した。しかし、彼等の用いたデータにはかなり大きなフラクチュエーションが伴っており、結果の統計的有意性は慎重に検討する必要がある。先述の拡散モデルを用いて通常拡散と異常拡散の場合についてフラックスの時間変化を計算し、これをベキ則として記述した場合の結果の有意性を、観測点に到達する粒子数への依存性に注目しつつ議論した。また、散乱体の統計的性質が異なる領域が複数隣接する場合の統計についても解析を行った。

非平衡プラズマにおける協同トムソン散乱：高強度レーザー実験への応用

藤野 亮佑 [1]; 松清 修一 [2]; 羽田 亨 [3]
[1] 九大・総理工・大海; [2] 九大・総理工; [3] 九大総理工

Collective Thomson scattering in non-equilibrium plasma: Applications to high power laser experiment

Ryosuke Fujino[1]; Shuichi Matsukiyo[2]; Tohru Hada[3]
[1] ESST,Kyushu Univ.; [2] ESST Kyushu Univ.; [3] ESST, Kyushu Univ

In space and astrophysical plasma physics, satellite based in-situ observation and ground and satellite based remote sensing have been the typical methods of empirical studies. While the in-situ observation can directly measure local electromagnetic fields and plasma distribution functions with quite high resolution, it is difficult to capture the global structure of the corresponding system. In contrast, the remote sensing can capture a global structure of the system, although the resolution for local structures is often insufficient. On the other hand, numerical simulations reveal that multi-scale phenomena, in which a global and a local structure of a system affect each other, often play decisive roles in a variety of high energy phenomena in space. Recently, high power laser experiments have reproduced various high energy phenomena as seen in space and astrophysical plasmas like a collisionless shock, magnetic reconnection, etc. Since in the experiment we can access both global and local structures of the corresponding phenomenon in principle, it is expected to be a new tool of the empirical study of space and astrophysical plasma physics.

The collective Thomson scattering is often utilized to measure local quantities of a plasma in laboratory experiment. It is the application of the elastic scattering of low frequency electromagnetic waves by free electrons in a plasma. In the measurement, one observes scattered waves which are radiated through the interaction between an incident probe laser light and collective motions of electrons in a plasma. The characteristics of the scattered waves enable us to infer local electron density, plasma temperature, and valence of ions. Details of the scattering theory are complex. In particular the theory of the collective Thomson scattering in a non-equilibrium plasma has not been established.

In this presentation, an experiment of a collisionless shock is taken as an exapmle. The wave equation of the scattered waves for a plasma containing arbitrary density fluctuations is numerically solved to discuss how the non-equilibrium plasma seen in a shock transition region scatters an incident probe laser light. In the past collective Thomson scattering measurement in a laboratory plasma, the so-called ion feature is often paid attention, since the spectral intensity of scattered waves is relatively high. Here, we suggest that the electron feature, whose spectral intensity is usually very weak, can be observed in a highly non-equilibrium plasma as in the shock transition region.

従来、宇宙・天体プラズマ諸現象の実証的研究手法としては、人工衛星を用いたその場観測や、地上観測を含めたリモートセンシングなどが主流である。その場観測の場合、局所的な電磁場の微細構造やプラズマ分布関数の直接計測が可能な反面、衛星経路上以外の大域的な系の構造を同時にとらえることは難しい。反対に、リモートセンシングでは、系の大域的構造を端的にとらえられるが、局所的構造の解像度はしばしば不十分である。その一方で、数値シミュレーションによると、系の大域的構造と局所的な微細構造が互いに影響を与えあう多スケール結合が、宇宙のさまざまな高エネルギー現象を理解する上で本質的に重要であることが示唆されている。近年、無衝突衝撃波やリコネクションなど、宇宙・天体プラズマ中で見られる高エネルギー現象を、高強度レーザー実験を用いて再現することができるようになってきた。実験では、現象の大域的構造と局所的構造に同時にアクセスすることが原理的に可能であるため、レーザー実験が今後宇宙・天体プラズマ諸現象の新たな実証的研究ツールとして整備されることが期待されている。

実験での局所的プラズマパラメータの計測に、協同トムソン散乱計測がしばしば用いられる。プラズマの自由電子による光の弾性散乱を応用したもので、プラズマに入射したプローブ光がプラズマ電子の集団運動の影響で変調された散乱光を計測し、その特徴から局所的な電子密度やプラズマの温度、イオン価数などを推定する（宇宙では電離層プラズマの計測などに用いられている）。散乱理論の詳細は複雑で、プラズマが比較的平衡状態に近い場合についてはよく調べられているものの、非平衡な場合の理論の整備は遅れている。

本研究では、非平衡性の強いプラズマによる協同トムソン散乱の理論的枠組みを構築することを目的とする。無衝突衝撃波の実験を例に、任意のプラズマ密度揺動に対する散乱光の波動方程式を数値的に解き、衝撃波遷移層近傍での様々な非平衡プラズマが、入射プローブ光をどのように散乱するかを議論する。従来の実験室プラズマにおける協同トムソン散乱計測では、散乱光としてスペクトル強度の強いイオン光と呼ばれる成分に注目することが多かった。衝撃波遷移層などの非平衡性の強いプラズマでは、これまでスペクトル強度が低いため観測しにくいとされてきた電子光と呼ばれる成分が優位に計測される可能性があることを示す。また、可能であれば今年度予定している実験での計測結果を報告する。

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

Kenya Shimizu[1]; Masaki Fujimoto[2]; Iku Shinohara[3]
[1] Earth and Planetary Science, Tokyo Univ.; [2] ISAS, JAXA; [3] ISAS/JAXA

We have inspected how the electric field structure around an X-line varies according to reconnection rate. In a very simple simulation of 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 will 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. When reconnection rate hits a peak, the normal magnetic field is rapidly ejected from inner electron diffusion region, causing a downward convex profile of the electric field. This feature is also seen when overshoot of reconnection rate due to a plasmoid ejection occurs. On the other hand, when reconnection is about to terminate, the gradient of the electric field caused by increasing normal magnetic field becomes attached at the edge of the electron diffusion region, causing a barrier to set-up of electron outflow from the diffusion region. An analysis from the same perspective allows us a better understanding of how a retreating X-line, which is an X-line that retreats from a wall against which one of the jets from the X-line is ejected, can maintain high reconnection rate during its retreat motion.

低ベータ磁気リコネクションジェットでのアルフベン乱流生成

東森 一晃 [1]; 星野 真弘 [1]
[1] 東大・理

Generation of Alfvenic turbulence in low beta magnetic reconnection jets

Katsuaki Higashimori[1]; Masahiro Hoshino[1]
[1] University of Tokyo

Magneto-hydro-dynamic (MHD) turbulence is often observed in solar wind and magnetosphere. As one of possibilities of the turbulence generation, this study focus on non-linear reconnection dynamics. For example in the Earth's magnetotail where reconnection greatly affects macroscopic dynamics, MHD to ion scale turbulence is observed in the current sheet [1]. Also, since the turbulence is observed during plasma flow, the importance of reconnection dynamics is implied [2]. On the other hand, as generation mechanism of turbulence in reconnection, some possible candidates such as the fire-hose and Kelvin-Helmholtz coupling mode have been suggested [3], however, there exist open issues such as the condition for the turbulence evolution.

We specifically focus on MHD to ion scale dynamics and investigate generation of turbulence in reconnection outflows using an electromagnetic hybrid code. We choose the ion beta in the initial lobe regions as a simulation parameter. Results show that turbulence develops with decreasing the beta value and the fluctuations consist of outgoing Alfven wave packets. As probable clues to generate the Alfven waves, we discuss ion kinetic effects in the plasma sheet boundary layer (PSBL) and a global unstable mode driven by ion bulk flow. And the linear analyses for reconnection jets show that damping rate of waves becomes large beyond beta = 0.1–0.2 in PSBL and it is consistent with non-linear simulation results where waves cascade down only in low beta cases. In this presentation, we specifically focus on conditions required for development of turbulence and discuss self-generation processes in reconnection jets.

[1] M. Hoshino, et al., "Turbulent magnetic field in the distant magnetotail: Bottom-up process of plasmoid formation?", JGR, (1994)
[2] J.P. Eastwood, "Observations of Turbulence Generated by Magnetic Reconnection.", PRL, (2009)
[3] K. Arzner and M. Scholer, "Kinetic structure of the post plasmoid plasma sheet during magnetotail reconnection.", JGR, (2001)

磁気流体 (MHD) 乱流は太陽風中や磁気圏でしばしば観測される。本研究では乱流生成の一つの可能性として、磁気リコネクションの非線形発展に着目する。例えばリコネクションがマクロなダイナミクスに大きく影響する地球磁気圏尾部では、電流シートで MHD からイオンスケールまで発達した乱流スペクトルが観測される [1]。またプラズマフローを伴って乱流スペクトルが観測されることから、リコネクションダイナミクスの重要性が示唆されている [2]。一方でリコネクションにおける乱流（波）の励起過程として、Fire-hose 不安定と Kelvin-Helmholtz 不安定のカップリングモデルなどの有力な理論的提案があるが [3]、乱れの発展条件など、未解決の問題がある。

我々は特に MHD からイオンスケールまでに注目し、電磁ハイブリッドコードを用いてリコネクションアウトフロー中での乱流生成について調べた。初期ローブ領域でのイオンのベータ値をパラメータとして実験を行った。その結果、ベータ値が低いほど (beta < 0.1–0.2) リコネクションジェットは乱れ、またその乱れは外向きに伝搬するアルフベン波束からなることがわかった。またアルフベン波を生成する要因として、プラズマシート境界層でのイオンの運動論効果と、ジェットのバルク速度をエネルギーとするグローバルな不安定モードによる波の励起を議論する。そしてリコネクションジェットに関する線形解析から、波の減衰率がプラズマシート境界層で beta = 0.1–0.2 を境として大きくなり、低ベータのみでカスケードする非線形シミュレーション結果とコンシステントであることを示す。発表では特に乱流への発展条件に重点を置き、リコネクションジェットでの自発的な乱れの生成過程を議論する。

[1] M. Hoshino, et al., "Turbulent magnetic field in the distant magnetotail: Bottom-up process of plasmoid formation?", JGR, (1994)
[2] J.P. Eastwood, "Observations of Turbulence Generated by Magnetic Reconnection.", PRL, (2009)
[3] K. Arzner and M. Scholer, "Kinetic structure of the post plasmoid plasma sheet during magnetotail reconnection.", JGR, (2001)

磁気リコネクションの拡散領域についてのいくつかの考察

銭谷 誠司 [1]; 梅田 隆行 [2]
[1] 国立天文台; [2] 名大 STE 研

Some remarks on the diffusion regions in magnetic reconnection

Seiji Zenitani[1]; Takayuki Umeda[2]
[1] NAOJ; [2] STEL, Nagoya Univ.

The structure of the diffusion regions in antiparallel magnetic reconnection is investigated by means of a theory and a Vlasov simulation. The magnetic diffusion is considered as relaxation to the frozen-in state, which depends on a reference velocity field. A field-aligned component of the frozen-in condition is proposed to evaluate a diffusion-like process. Diffusion signatures with respect to ion and electron bulk flows indicate the ion and electron diffusion regions near the reconnection site. The electron diffusion region resembles the energy dissipation region. These results are favorable to a previous expectation that an electron-scale dissipation region is surrounded by an ion-scale Hall-physics region.

磁気リコネクション研究では、磁力線の繋ぎ変わるＸ点近傍の「磁気拡散領域」の物理が重要だとされている。運動論プラズマでは、この磁気拡散領域の範囲／物理を議論することが非常に難しいことが知られている。我々は、この問題を「磁気拡散」の意味に立ち返って再検討した。抵抗性磁気流体力学（resistive MHD）では、磁場の時間発展を記述する誘導方程式に電気抵抗由来の拡散項が現れ、磁束の凍結条件を破っている。運動論ではこの関係は自明ではなくなるが、我々は同じ磁束凍結項に注目して実効的な「拡散」を議論することにした。また、理想条件／磁束凍結条件／磁気拡散は、基準場の取り方に依る相対的な概念だと考える。こうすると、イオン拡散領域・電子拡散領域の範囲と意味も明確になる。本発表では、これらのアイデアをブラソフプラズマシミュレーションで検証するとともに、磁力線の繋ぎ変え条件（Newcomb 1958）との関係を議論する。

MHD simulation of the magnetorotational instability using the compact difference scheme and LAD method with the shearing box model

Kenichiro Hirai[1]; Yuto Katoh[1]; Naoki Terada[2]
[1] Dept. Geophys., Grad. Sch. Sci., Tohoku Univ.; [2] Dept. Geophys., Grad. Sch. Sci., Tohoku Univ.

The magnetorotational instability (MRI) is one of the most important phenomena in the accretion disk. Turbulence generated by MRI causes the turbulent viscosity in the disk and is a strong candidate of the driver of mass accretion. Recent study suggested that the turbulence induced by MRI also plays an important role in the planetesimal formation in the protoplanetary disk. In the planetesimal formation process, both the ionized gas and dust coexist in the disk and the motion of dusts is strongly affected by the motion of gas through the collisional and/or frictional effects. Kato et al. (2010;2012) showed the result of the local MHD + dust simulation with the inhomogeneous MRI occurrence region and meter-sized dusts treated as test particles in the simulation system. They showed the possibility that meter-sized dusts are gathered locally due to the modification of the disk gas distribution through the evolution of MRI and that the situations favored for the planetesimal formation are created in the localized region. On the other hand, the computational domain used in this simulation corresponds to the spatially limited region in the disk. In order to study the dust motion in the disk globally, we should take into account the effects of the Kelvin-Helmholtz instability (Sekiya, 1998; Barranco, 2009) and the streaming instability (Youdin & Goodman, 2005) generated by the dust-gas interaction and the effect of the time evolution of the global disc structure (Suzuki et al., 2010). In order to carry out the MHD simulation considering these effects, we need to develop the scheme that can accurately resolve both waves of short wavelength in turbulence and discontinuity appeared in the evolution of instabilities.

In the present study, we develop the MHD simulation code using an 8th-order compact difference scheme with the local artificial diffusivity (LAD) method (Kawai, 2013). The compact difference scheme proposed by Lele (1992) has an advantage for solving turbulent flow because it has the property for resolving short wavelength. The LAD method for MHD simulation proposed by Kawai (2013) enables us to reduce unphysical oscillations generated in the compact difference scheme. We carry out a series of standard test problems for MHD simulations and clarify pros and cons of the developed MHD code for the study of MRI. In spatially 2-dimentional test problems, we find that the maximum value of the numerical error appeared in the computation of the divergence of the magnetic field is the order of 10^{-12}, which is approximately consistent with the results of Kawai (2013).

We then carry out the 2-dimensional MHD simulation of MRI by the developed code. We initially set the uniform vertical magnetic field and assume the perturbation of the radial magnetic field whose amplitude is 1% of the background magnetic field and wavelength corresponds to that of the maximum growth rate of MRI. We perform simulations with the different spatial resolution. In the linear growth phase, we find that the maximum growing mode of MRI is resolved in all simulation runs. By comparing the simulation results, we find that the saturation level of MRI increases as we increase the spatial resolution. We show the results of detailed analysis of the 2D-MRI growth and discuss the obtained dependence of the saturation process. In addition to the characteristics of the developed code, we report the current status of the development of 3-dimentional MHD simulation code and its first results.

磁気回転不安定性が駆動する磁気流体乱流計算の収束性について

簑島 敬 [1]; 廣瀬 重信 [2]
[1] JAMSTEC; [2] なし

On the convergence of numerical simulations of magnetohydrodynamic turbulence induced by the magnetorotational instability

Takashi Minoshima[1]; Shigenobu Hirose[2]
[1] JAMSTEC; [2] JAMSTEC

Magnetohydrodynamic (MHD) turbulence plays an important role in space and astrophysical plasmas. For example, weakly magnetized accretion disks are subjected to the magnetic turbulence induced by the magnetorotational instability (MRI; Balbus & Hawley 1991, 1998). The MRI-induced turbulence is believed to contribute to the outward angular momentum and subsequent mass accretion toward a central star (Hawley et al. 1995, 1996). Nonlinear stage of the magnetic turbulence has been extensively studied by means of MHD simulations.

When the (magnetic) Reynolds number in space and astrophysical plasmas is expected to be very high, ideal MHD equations are often adopted to study their dynamics. In ideal MHD simulations, the viscous and resistive dissipation scales are numerically determined, and are not necessarily identical. Kritsuk et al. (2011) have carried out turbulence decay simulations to compare the numerical resolution of MHD simulation codes, and have shown that a code with high velocity spectral bandwidth does not necessarily have high magnetic spectral bandwidth, and vice verse. Therefore, the numerical convergence of MHD turbulence simulations is no longer guaranteed among simulation codes.

In this study, we examine the numerical convergence of the MHD turbulence to assess the effect of numerical dissipation scales on a practical problem. To this end, we conduct a large set of numerical simulations of the MRI with various schemes. Our ideal MHD simulations do not achieve the numerical convergence. We show that the nonlinear saturation level is very sensitive to the numerical magnetic Prandtl number, indicating the importance to use explicit viscosity and resistivity to control the magnetic Prandtl number in MRI-induced turbulence simulations. Viscoresistive MHD simulations of the MRI are then carried out to examine the parameter dependence of the saturation level. The saturation level is found to intricately depend on the viscosity, resistivity, and gas pressure.