

S001-01

A 会場 : 11/4 PM1 (13:45-15:30)

13:45~14:10

磁場閉じ込めプラズマを利用した統計加速の実験室模擬

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Experimental simulation for stochastic acceleration using magnetically confined plasmas

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Stochastic Fermi acceleration is commonly known as a mechanism for producing non-thermal high-energy particles in space. The acceleration mechanism is characterized as formation of power-law spectrum and longer heating timescale. In this study, we report on the stochastic acceleration observed in a magnetically confined torus plasma device, Heliotron J. The relativistic electrons circulating the Heliotron J torus (parallel to the magnetic field line) can be confined in the vacuum magnetic field, because a closed magnetic flux surface is formed only by the external coils. When non-resonant 2.45 GHz microwaves were launched in the vacuum magnetic field, the high-energy electrons with the energy exceeding 2 MeV were observed from the X-ray spectrum and the synchrotron radiation measurements. Since the normalized vector potential a_0 using the electric field of the microwave is less than 0.05, being much smaller than that for the laser plasma particle acceleration, the electrons need to be accelerated many times by the electric field to exceed the electron rest energy. The observed X-ray spectrum, taking the shielding effect of the vacuum vessel into account, has a power-law spectrum with exponent of -2.3. The electron acceleration simulation reveals (1) the formation of the power-law spectrum similar to the experimental observation, (2) the characteristics of the heating timescale (\sim ms) longer than the torus circulating period (\sim 100ns) and (3) the existence of the threshold energy for the initial electrons to produce the relativistic electrons.

S001-02

A 会場 : 11/4 PM1 (13:45-15:30)

14:10~14:25

宇宙線流によって駆動する宇宙空間での放電現象

#大平 豊¹⁾

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Discharge by streaming cosmic rays in the universe

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A new discharge process caused by streaming cosmic rays in the universe is proposed. The streaming CRs drive the return current of thermal electrons to compensate for the CR current. Then, electric fields are induced by the resistivity of the return current.

In this talk, we show that the resistive electric fields can accelerate secondary electrons generated by the streaming CRs. The discharge condition and the condition for runaway acceleration of secondary electrons are presented. In addition, we investigate the evolution of the energy spectrum of secondary electrons by solving the Boltzmann equation numerically. The discharge creates high-energy secondary electrons, resulting in enhancements of ionization and nonthermal emission including the K α emission line of neutral iron. After the discharge, the return current of thermal electrons is replaced by the electric current of secondary electrons. Since some generation and amplification of magnetic fields are driven by the return current of thermal electrons, the discharge can significantly influence them.

宇宙線流によって駆動される新しい放電過程を発見した。宇宙線流は、電流を中性化するために、背景の熱的電子の帰還電流を駆動する。その熱的電子の帰還電流は、背景のガスと相互作用するために、有限の抵抗性電場が発生する。本研究では、この抵抗性電場によって、宇宙線と背景ガスの衝突電離によって作られる2次電子が加速されることを示す。これは放電現象である。この放電現象が起きる条件、2次電子が暴走的に加速される条件を求めた。また、この放電現象によって加速される2次電子のエネルギースペクトルの発展もボルツマン方程式を数値的に解いて調べた。放電によって高エネルギーの2次電子が作られ、電離や中性鉄輝線を含む高エネルギー放射が増幅される。放電後は、熱的電子の帰還電流が、2次電子の帰還電流に置き換わる。熱的電子の帰還電流は、磁場の生成や増幅に重要であるため、本研究で発見された放電現象は、それらに大きな影響を与える。

S001-03

A 会場 : 11/4 PM1 (13:45-15:30)

14:25~14:40

高強度レーザーとプラズマの相互作用における陽電子の生成と加速機構について

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Positron generation and acceleration in self-organized photon collider by ultra intense laser pulse

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Femtosecond relativistic lasers, becoming available in many laboratories, open a high field science in quantum electrodynamic regime. One of challenges in the regime is confirmation of production of positrons via the linear Breit-Wheeler (BW) process, which is an electron-positron pair production simply by a photon-photon collision and thus believed as one of elementary processes of formation of matter in the universe. With a help of two-dimensional particle-in-cell simulations, we reveal the dynamics of positrons induced by the linear BW process which appears dominantly in a self-organized channel structure formed by the laser pulse traveling in a near-critical plasma. The self-organized channel accompanies a magnetic field which assists the direct laser acceleration of electrons in the forward direction. While a positive electrostatic field, which is excited by the laser photon pressure at the pulse front, accelerates electrons backward. This counter flow of energetic electrons emits photons opposite, thus realizing a photons collider for the linear BW process. The energies of positrons moving forward are boosted by surfing in the co-moving electrostatic field up to GeV with a narrow divergence angle of <10 degrees. The maximum positron energy in the surfing acceleration is speculated theoretically.

集光強度 10^{21} W/cm² を超えるフェムト秒の相対論的レーザー光は、世界の研究施設で利用できるようになった。このような超高強度レーザー光は、高エネルギーの X 線やガンマ線を輻射し、量子電気力学的な現象を含む高強度場科学が開かれた。この領域での課題の一つとして、線形ブライト・ウィラー過程による陽電子の生成の確認がある。この過程は、シンプルに光子と光子の衝突による電子・陽電子ペアの生成であり、宇宙における物質生成の素過程の一つと考えられている。私たちは 2 次元粒子コードに輻射輸送過程と電子・陽電子生成過程を組み込み、高強度レーザー光が臨界密度近傍のプラズマ中を相対論的效果によって伝播するときに、線形ブライト・ウィラー過程により陽電子ビームが生成される機構を明らかにした。この陽電子過程は、レーザーパルスが臨界プラズマ中を伝播することによって形成される自己組織化されたチャンネル構造の中で現れる。この自己組織化したチャンネル構造は磁場を伴い、高強度レーザーによる電子の直接加速を補助する。一方、パルス前面のレーザー光圧によって励起された正の静電場は、プラズマ電子を後方に加速する。この方向が反対の 2 つの加速により対向する高エネルギー電子流が生成され、それらが光子を輻射することで、光子衝突配位が出現し線形ブライト・ウィラー過程が起こる。前方に発生した相対論的エネルギーを持つ陽電子は、レーザー光よりもプラズマ中では早く進み、パルス先端に追いつき静電場に乗ることで GeV まで加速され、発散角 10 度以下の強い指向性を持って放出される。講演ではシミュレーションモデルと計算結果の詳細を紹介する。

S001-04

A 会場 : 11/4 PM1 (13:45-15:30)

14:40~14:55

#諫山 翔伍¹⁾, 松清 修一¹⁾, 高橋 健太¹⁾, 佐野 孝好²⁾

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Relativistic resonant particle acceleration by counter propagating Alfvén waves

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(¹⁾ IGSES, (²⁾ ILE, Osaka U

Since high energy cosmic rays were discovered by Hess, its origin has been a much controversial issue in astrophysics [Hess 1912]. Coherent large amplitude electromagnetic waves in a plasma should play crucial roles in the acceleration of high energy cosmic rays. In a space plasma large amplitude Alfvén waves are often generated. A number of models of large amplitude Alfvén wave generation accompanying cosmic ray acceleration have been proposed so far. More than decades ago, Matsukiyo and Hada [Matsukiyo and Hada 2009] showed that a relativistic Alfvén wave in a pair plasma is unstable to form the coherent standing wave form which consists of counter propagating Alfvén waves. In our recent studies, we found that the phase transitions of the behavior of particles trapped in a trough of magnetic envelope occur when wave amplitudes exceed critical values. In a supercritical regime, numerical simulations show that any particles irreversibly gain relativistic energy within a short time regardless of their initial energy. In this presentation, the particle acceleration in large amplitude counter propagating Alfvén waves is discussed by test particle and particle-in-cell (PIC) simulations.

S001-05

A 会場 : 11/4 PM1 (13:45-15:30)

14:55~15:10

高強度レーザー駆動多種イオンプラズマ中の無衝突静電衝撃波によるイオン加速

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High-intensity laser driven ion acceleration by collisionless electrostatic shock in a multicomponent ion plasma

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Shock waves observed in astrophysical systems, for example, supernova remnant shock and the bow shock of the earth, are shocks in collisionless plasmas. Such collisionless shocks are the most promising candidate for the generation mechanism of cosmic-rays. The interaction between the electric and magnetic fields, generated by the collective phenomenon of plasma, and charged particles is important for the generation of collisionless shocks. By using a high-intensity laser, an acceleration mechanism called ion acceleration by a laser-driven collisionless electrostatic shock is drawing attention [1-4]. In the collisionless electrostatic shock ion-acceleration (CESA), upstream ions of the shock are reflected by the shock potential and accelerated.

The CESA experiments are performed with high-intensity LFEX laser beams (pulse width = 1.5 ps, energy ~ 300 J, laser intensity $\sim (3-6) \times 10^{19}$ W/cm², and normalized laser intensity $a_0 \sim 2$) at the Institute of Laser Engineering, Osaka University. In order to generate an initial plasma with a near-critical density and a long scale-length on the rear-side of the drive-laser irradiated target, which is suitable for CESA [2-4], the rear surface of the target is irradiated with an ionization laser at 2.5 ps before the drive laser. As the ionization laser, one of the Gekko XII laser beams (pulse width = 1.3 ps, energy ~ 3 J, laser intensity $\sim 3 \times 10^{11}$ W/cm²) is focused on the back surface of the target (a thin foil of C₈H₇Cl with a thickness of 1 μ m). Thomson parabola spectrometer (TPS) and electron spectrometer (ESM), located on the rear-side of the target, are used to measure ion and electron spectrum, respectively. We observed clear evidences for the proton acceleration by the collisionless electrostatic shock.

[1] D. Haberberger, et al, Nature Phys. **8**, 95 (2012).

[2] R. Kumar, Y. Sakawa, et al, Phys. Rev. Accel. Beams **22**, 043401 (2019).

[3] R. Kumar, Y. Sakawa, et al, Phys. Rev. E **103**, 043201 (2021).

[4] Y. Sakawa, Y. Ohira, et al, Phys. Rev. E **104**, 055202 (2021).

S001-06

A会場 : 11/4 PM1 (13:45-15:30)

15:10~15:25

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Electron betatron and shock drift acceleration at reforming quasi-perpendicular shocks

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Energetic, non-thermal electrons are directly observed in the vicinity of Earth's quasi-perpendicular bow shock. While Shock Drift Acceleration (SDA) model has been considered important for producing non-thermal electrons out of the solar wind thermal population, SDA alone does not seem to explain all observed features. Here we show, using 1D PIC simulations of a quasi-perpendicular collisionless shock (Alfvén Mach number 7.1, shock angle 70 degrees, plasma beta 0.3, and ion-to-electron mass ratio 625), that there are additional electron acceleration mechanisms associated with the nonstationary self-reformation process of supercritical shocks. The analysis is performed by separating and quantifying all acceleration and deceleration processes including the effect of cross-shock potential. We found that incoming electrons, trapped in a thin, time-evolving magnetic trough embedded in the overshoot magnetic field, gains a perpendicular energy via non-adiabatic betatron acceleration. The electrostatic component of the phase standing oblique whistler wave in the overshoot is mainly responsible for the betatron acceleration. SDA still occurs simultaneously due to not only the motional electric field but also a time-varying electric field along the shock front generated in the overshoot. We will discuss the acceleration processes depending on the Alfvén Mach numbers of 3.5 -7.1 and shock angles of 65 and 85 degrees.

S001-07

A会場：11/4 PM1 (13:45-15:30)

15:25~15:40

磁化プラズマ衝撃波の長時間発展の大型レーザー実験

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High power laser experiment on the long time evolution of magnetized plasma shock

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A collisionless shock plays the role of an efficient energy converter in space. It is known also as a source of cosmic rays and large amplitude waves. However, the details of their energy conversion mechanism have not been clarified despite of the long term effort based on in-situ observational as well as theoretical and numerical simulation studies. We have tried to reproduce collisionless magnetized plasma shock in the laboratory to observe the long time evolution of its spatial and temporal structures separately. In particular, in a supercritical shock with Alfvén Mach number above a critical value (~ 3), the structure of a transition region with ion-scale is considered to play an important role in the energy conversion. Therefore, we have developed to establish an experimental platform to capture. The experiment is conducted using the Gekko XII laser facility (The Institute of Laser Engineering, at Osaka University). When the laser is irradiated onto the target aluminum plate in the chamber filled with 5 Torr nitrogen gas, the high-speed plasma flow originating from the target compresses the gas originated nitrogen plasma to generate a shock. By applying an external magnetic field (~ 4 T) to the volume of interest using a Helmholtz coil, a magnetized plasma shock wave is generated. The structure of a shock is observed by self-emission measurements and Thomson scattering measurement.

By FY2021, we observed the system evolution up to $t \sim 80$ ns by using the above method and confirmed that a front edge of the shock sharpens after $t \sim 50$ ns. The formation of such a structure on a time scale shorter than the gyro period of nitrogen ions (~ 220 ns) is not desirable for an experiment to reproduce a space plasma shock. As we considered that this may be caused by insufficient mass of the target plasma, which is an ejector, we increased laser energy and pulse duration in the experiment in FY2022. In addition, in order to investigate the development of the system for a longer period of time ($t \sim 200$ ns), the size of the system including the Helmholtz coil was expanded. When the pulse duration (and the laser energy) was doubled, we confirmed that the front of the shock was blunt. When the pulse duration was quadrupled, spatial fluctuations of the shock front were captured after $t = 110$ ns. The relationship between the wavefront structure and ion dynamics will be discussed in the presentation.

無衝突衝撃波は宇宙における効率的なエネルギー変換器の役割を担っており、宇宙線や大振幅波動の生成源として知られている。しかしながらエネルギー変換機構の詳細は未解明で、人工衛星によるその場観測や理論、数値シミュレーションによる研究が長年続けられている。我々は、無衝突磁化プラズマ衝撃波を実験室内に再現し、時空間構造を分離してその長時間発展をとらえることを目指した研究を進めている。特に、アルフベンマッハ数が臨界値 (~ 3) を超える超臨界衝撃波においては、イオンスケールの遷移層構造がエネルギー変換に重要な役割を果たすと考えられており、これを捉えるための実験プラットフォームの構築を進めてきた。激光 12 号レーザー (大阪大学レーザー科学研究所) を用いて、チャンバー内に 5 Torr の窒素ガスを充填した状態でターゲットのアルミ板にレーザーを照射すると、ターゲット由来の高速プラズマ流がガス由来の窒素プラズマを圧縮して衝撃波を生成する。ヘルムホルツコイルを用いて検査領域に外部磁場 (~ 4 T) を印加しておくことで、磁化プラズマ衝撃波が生成される。

2021 年度までに、上の方法で $t \sim 80$ ns までの系の時間発展を追跡したところ、 $t \sim 50$ ns 以降で衝撃波の先端部が先鋭化することが分かった。窒素イオンのジャイロ周期 (~ 220 ns) よりも短い時間スケールでこうした構造ができることは、宇宙プラズマ衝撃波の再現実験としては好ましくない。イジェクタであるターゲットプラズマの質量が不十分であることが原因の可能性があると考え、2022 年度はレーザー照射時間を昨年度の 2 倍、4 倍と変化させた実験を行った。また、より長時間 ($t \sim 200$ ns まで) の系の発展を調べるため、磁場生成コイルを含めた系の大型化を図って検査領域を拡大した。照射時間を 2 倍にした実験では先端部の先鋭化が抑えられることを確認した。さらに 4 倍にした実験では、 $t = 110$ ns 以降において衝撃波面が空間的に揺らぐ様子を捉えた。発表ではこの波面構造とイオンのダイナミクスの関係について議論する。

S001-08

A 会場 : 11/4 PM2 (15:45-18:15)

15:55~16:20

強磁場中における相対論的波動粒子相互作用

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Relativistic wave-particle interaction under strong magnetic fields

#Takayoshi Sano¹⁾

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Laser astrophysics, experimental astronomy using huge laser facilities, is attracting attention as the third research tool for astronomy to complement observation and theory. Conventionally, astronomical phenomena have been reproduced by plasma generated by lasers. However, with the recent discovery of high-luminosity celestial objects, a new type of laser astrophysics experiment in which intense laser beams can be regarded as an astronomical phenomenon is now being considered.

In the astronomical phenomenon called Fast Radio Bursts (FRBs), highly bright radio emissions of the frequency about 1 GHz with a short duration of nearly a millisecond are observed. The dimensionless amplitude of this electromagnetic wave corresponds to an intensity exceeding $a_0 = 10^4$, which is highly relativistic. Although the source and mechanism of FRB emission have not yet been understood, it has been suggested that they are related to neutron stars with magnetic fields of about 10^{15} Gauss, which are called magnetars. Assuming that the radio source is very close to the neutron star, this high-intensity electromagnetic wave must pass through the magnetosphere of the neutron star. In a strong magnetic field where the cyclotron frequency exceeds the radio frequency ($\omega_{ce} \gg \omega_0$), the scattering rate of relativistic electromagnetic waves will be high, and it is not apparent whether the transmission is possible or not. Such considerations can give a constraint on the theoretical model of the FRB. In the absence of a magnetic field, the propagation characteristics of intense electromagnetic waves have been studied in detail in the field of laser plasmas. However, our understanding of ultra-strong magnetic fields, which are not feasible in current high-intensity laser experiments, is still insufficient. Therefore, we have analyzed wave-particle interactions under extreme plasma conditions, such as those expected in FRBs, using PIC simulations. In this talk, we focus on the collision process of Alfvén waves.

We have shown theoretically that all electrons with non-relativistic velocities are accelerated to relativistic speeds due to the standing waves created by counter-propagating circularly polarized electromagnetic waves along magnetic field lines in an electron-ion plasma (Isayama et al. 2022; Sano et al. 2022). We then numerically verified whether a similar phenomenon occurs for Alfvén waves in electron-positron plasmas, which could be assumed in FRBs. As a result, it is found that both electrons and positrons are efficiently accelerated to energies above MeV in standing waves created by linearly polarized Alfvén waves if the amplitude of the electromagnetic wave is larger than the intensity of the background magnetic field. Furthermore, simulations considering radiation damping reveal that most of the energy of the original electromagnetic wave is converted to gamma-ray radiation by relativistic particles. This gamma-ray radiation is also expected to produce electron-positron pairs, suggesting that various energy conversion processes may be realized quickly. In this talk, we will introduce the details of such physical processes, the conditions under which they are realized, and their importance in the FRB model. We will also discuss the possibility of future proof-of-principle laser experiments as a new "laser astrophysics" topic.

S001-09

A 会場 : 11/4 PM2 (15:45-18:15)

16:20~16:35

ピックアップイオンを含む斜め衝撃波の運動論的2次元構造

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2D kinetic structure of PUI mediated oblique shock

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It is believed that pickup ions (PUIs) play crucial roles in the phenomena occurring in the heliospheric boundary region, since its relative density reaches dozens of percent. We previously showed that PUIs significantly alter the kinetic structure of a perpendicular heliospheric termination shock. It has been recognized that the shock angle of the termination shock is variable depending on longitude and latitude. Here, the shock angle is defined as the angle between the shock normal and upstream magnetic field vector. For instance, while the shock angle near the nose of the heliosphere is close to perpendicular, that in the region of flank of the heliosphere is thought to be oblique. Researchers think that the oblique termination shock may be an efficient accelerator of PUIs. Particle acceleration at a shock is closely linked with the kinetic structure of the shock. So far, the kinetic structure of a PUI mediated oblique shock has been seldom investigated numerically except for one-dimensional case. For an oblique shock, a back streaming plasma escape away from the shock along upstream magnetic field so that large system size in the shock normal direction is necessary. Because of this, higher dimensional simulations were difficult previously. In this study we perform two-dimensional full particle simulation of PUI mediated oblique shock by using the supercomputer Fugaku. The shock angle is 50 deg, Alfvén Mach number ~ 5.4 , upstream electron beta 0.25, solar wind ion temperature is the same as electron temperature, and relative PUI density is 25%, respectively. Complex multiscale structures reproduced in the simulation are discussed with particularly focusing the role of the PUIs.

S001-10

A 会場 : 11/4 PM2 (15:45-18:15)

16:35~16:50

Outer Heliosheath のリング分布の安定性における ion-Bernstein モードの影響

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Influence of ion-Bernstein modes on the stability of the ring distribution at the outer heliosheath

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The heliosphere is a bubble formed by the interaction of the solar wind and the interstellar medium, and its boundary is the limit of the influence of the solar wind. The Interstellar Boundary Explorer (IBEX) satellite observes energetic neutral particles called Energetic Neutral Atoms (ENAs) coming into the heliosphere from the outer heliosphere. IBEX observations have shown that the ENA forms a narrow band-like distribution on the sky maps, which is called the IBEX Ribbon. The most likely origin of the IBEX Ribbon is that the charge exchange occurs twice in the outer heliosheath. First, the protons in the solar wind and neutral particles of interstellar origin charge exchange in the heliosphere, and the protons become neutral particles. Some of these neutrals reach the outer heliosheath and become charged particles again through a second charge exchange. These charged particles are picked up by the interstellar magnetic field, and the pickup ions form a ring distribution in velocity space. The pickup ions with this ring distribution and the interstellar neutrals then charge exchange for the third time, and the solar wind-originated neutrals return to the heliosphere in this scenario. To explain IBEX Ribbon in this model, the ring distribution must remain stable from the second to the third charge exchange, but the ring distribution is generally known to be unstable and excites waves which make the original ring distribution isotropic through pitch angle scattering (e.g. Coates et al., 2009). In many cases, Alfvén ion-cyclotron (AIC) instability dominates and contributes significantly to the isotropization of the ring distribution; Florinski et al. (2016) showed that if the thermal velocity of the ring component is lower than that of the background protons, the AIC is stable in the linear phase and the ring distribution may be maintained. On the other hand, Min et al. (2018) performed simulations under conditions where AIC is stable. However, their results showed that even if the AIC is stable in the linear phase, the ring component is scattered by the mirror and the ion-Bernstein modes, which makes the AIC unstable in the nonlinear phase, and the ring distribution is not maintained stable. However, the hybrid simulation has low resolution and may not properly account for the effects of relatively short-wavelength ion-Bernstein modes. The ion-Bernstein modes may also be affected by the kinetic effects of electrons, and the validity of hybrid simulations that treat electrons as a fluid also needs to be examined.

We report the results of the study of the ion-Bernstein modes excited by ring distributions. Although the ring velocity and density differ from Min et al. (2018), high-resolution hybrid simulations show that short-wavelength and the near-perpendicular propagating ion-Bernstein mode were confirmed. This excitation of ion-Bernstein modes was not confirmed with the resolution used in Min et al. (2018), suggesting that high-resolution simulations are needed to accurately discuss the short-wavelength ion-Bernstein mode. In the hybrid simulation, the ion-Bernstein mode had a strong growth rate at an angle of 50 ~ 90 degrees relative to the background magnetic field. On the other hand, the propagation angles are 50 ~ 70 degrees in particle-in-cell (PIC) simulations with the same parameters and the growth rates obtained with PIC simulations are lower than that of the hybrid simulation. This difference may be attributed to the fact that the hybrid simulation ignores electron kinetic effects. We have indeed confirmed that the results of the linear analysis and the PIC simulation agree with each other, suggesting that the hybrid simulation does not accurately describe the ion-Bernstein mode.

In the future, we plan to investigate the influence of the ion-Bernstein mode and the validity of the hybrid simulation for parameters closer to the outer heliosheath.

太陽圏とは、太陽風と星間物質の相互作用によって形成される空間であり、その境界は太陽風の影響が届く限界で定義される。Interstellar Boundary Explorer (IBEX) 衛星は、outer heliosheath (太陽圏の外縁部) から太陽圏内に飛来する Energetic Neutral Atom (ENA) と呼ばれる高エネルギー中性粒子を観測する衛星である。IBEX の観測によって、ENA は天球図上で細い帯状の分布を形成することが分かっており、IBEX Ribbon と呼ばれている。この IBEX Ribbon の起源のメカニズムとして有力なものは、outer heliosheath で 2 回電荷交換が起こるというものである。まず太陽圏内で太陽風の陽子と星間空間起源の中性粒子が電荷交換をし、太陽風の陽子は中性粒子となる。この太陽風の陽子由来の中性粒子の一部が outer heliosheath に到達し、2 回目の電荷交換によって再び荷電粒子になる。この荷電粒子が星間磁場にピックアップされ、ピックアップイオンは速度空間上でリング分布を形成する。その後、このリング分布をしたピックアップイオンと星間中性粒子が 3 回目の電荷交換をし、太陽風由来の中性粒子が太陽圏に戻ってくるというシナリオである。このモデルで IBEX Ribbon を説明するには、2 回目の電荷交換から 3 回目の電荷交換までリング分布が安定に維持されていなくてはならないが、リング分布は一般には不安定であり、波動を励起し、その波動によってピッチ角散乱を受け等方化することが知られている (e.g. Coates et al., 2009)。多くの場合、Alfvén ion-cyclotron (AIC) と呼ばれる波動が支配的となり、リング分布の等方化に大きく貢献する。Florinski et al. (2016) では、リング成分の熱速度が背景プロトンの熱速度より低

ければ、線形段階において AIC は安定であり、リング分布が維持される可能性を示した。一方で Min et al. (2018) では、この AIC が安定となる条件でシミュレーションを行った。その結果、線形段階では AIC が安定となつていても、ミラーモードや ion-Bernstein モードによってリング成分が散乱されることによって、非線形段階では AIC が不安定となり、リング分布は安定に維持されないことが示された。しかし、このハイブリッドシミュレーションにおいては解像度が低く、比較的短波長の ion-Bernstein モードの効果が正しく考慮されていない可能性がある。また ion-Bernstein モードには電子の運動論効果が効いてくる可能性もあり、電子を流体として扱うハイブリッドシミュレーションの妥当性についても検討が必要である。

本発表では、リング分布が励起する ion-Bernstein モードについて調べた結果を報告する。Min et al. (2018) とはリング速度や密度が異なるが、高解像度のハイブリッドシミュレーションをすることで、短波長かつ垂直伝播に近い ion-Bernstein モードが確認された。この ion-Bernstein モードは Min et al. (2018) で用いられた解像度では確認できず、短波長の ion-Bernstein モードを正確に議論するには高解像度のシミュレーションが必要であることが示唆される。また、このハイブリッドシミュレーションでは ion-Bernstein モードは背景磁場に対して $50^\circ \sim 90^\circ$ の伝播角に、強い成長率を持っていたが、全く同じパラメータを用いた Particle-in-cell(PIC) シミュレーションでは $50^\circ \sim 70^\circ$ 程度となっており、ハイブリッドシミュレーションよりも成長率が低いことが分かった。この違いは、ハイブリッドシミュレーションが電子の運動論効果を見逃しているためだと考えられる。実際に、線形解析の結果と PIC シミュレーションの結果が一致することを確認しており、ハイブリッドシミュレーションは ion-Bernstein モードを正確に記述できていないことが示唆される。

今後はより outer heliosheath に近いパラメータにおける ion-Bernstein モードの影響・ハイブリッドシミュレーションの妥当性についても調査する予定である。

S001-11

A 会場 : 11/4 PM2 (15:45-18:15)

16:50~17:15

太陽フレアにおける磁気リコネクションと粒子加速の観測的研究

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Observational studies on magnetic reconnection and particle acceleration in solar flares

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A solar flare is one of the explosive phenomena driven by magnetic reconnection. Magnetic reconnection is a plasma process that releases energy stored in the magnetic field through the reconnection of magnetic field lines and converts it into kinetic energy, thermal energy, and particle acceleration energy. In solar flares, these converted energy forms have been observed as ejections of plasma blobs, super-hot plasma, accelerated particles, and so on. Of strong interest to us is the acceleration of particles. In a large-scale flare, particles accelerated somewhere in the corona enter the lower atmosphere called the chromosphere, are forced thermalized by the ultra-dense plasma there, and evaporate the plasma in the chromosphere. This evaporated plasma fills magnetic loops in the corona, and such loops are visualized in ultraviolet and X-rays, resulting in the well-known beautiful and dynamic appearance of solar flares. In other words, the generation and propagation of accelerating particles form solar flares, and they are an essential part of a complete understanding of flares. In addition, particle acceleration in solar flares is interesting from the perspective of plasma physics. The solar corona is an environment where initial acceleration is difficult because of its large density and the many obstacles for newly accelerated particles. Despite this, it is known from observations that particles are accelerated to several hundred keV or more in the order of seconds. This means that a very efficient acceleration mechanism exists. Perhaps the various plasma structures (shock waves, turbulence, plasmoids, etc.) produced by magnetic reconnection must hold the key to the acceleration. In addition to such interesting research subjects, solar flares also have an advantage as an observational target. Since they are magnetic reconnection phenomena that occur in the nearest stars from the Earth, it is possible to observe the various plasma structures produced by magnetic reconnection by spatially separating them. This has led to the discovery of locations where accelerated particles exist. However, at this point, due to observational limitations (mainly limitations of observation techniques), it is not fully understood where, when, and how particle acceleration is taking place.

In this talk, we will review observational studies of solar flares (magnetic reconnection) and the particle acceleration caused by them, and also introduce the next generation solar flare observations that will enable us to investigate accelerated particles in more detail than ever before.

太陽フレアは、磁気リコネクションが駆動する爆発現象のひとつである。磁気リコネクションは、磁力線のつながりによって磁場中に蓄えられたエネルギーを解放し、運動エネルギー、熱エネルギー、粒子の加速エネルギーなどに変換するプラズマプロセスである。太陽フレアでは、これら変換後のエネルギー形態に対応するものとして、プラズマの塊の噴出、超高温プラズマ、加速された粒子などが観測されている。このなかで我々が強い関心を持っているのが、粒子の加速である。大規模なフレアにおいては、コロナのどこかで加速された粒子が太陽表面付近（厳密には彩層と呼ばれる低層大気）に突入し、そこにある超高密度なプラズマによって強制熱化され、彩層のプラズマを蒸発させる。この蒸発したプラズマがコロナ中の磁気ループを満たすことで、紫外線・X線によって可視化され、一般によく知られる美しくダイナミックな太陽フレアの姿を見せる。つまり、加速粒子の生成と伝搬が太陽フレアを形成していると言え、フレアの完全な理解に不可欠なパーツである。また、太陽における粒子加速は、プラズマ物理の観点でも興味深い。太陽コロナは、密度が大きく、加速したての粒子にとっては障害物が多くある環境であり、初期の加速が難しい。にもかかわらず、秒のオーダーで数百 keV 以上にまで粒子が加速されていることが観測から知られている。すなわち、非常に効率のよい加速機構が存在することを意味する。おそらく磁気リコネクションが生成する様々なプラズマ構造（衝撃波、乱流、プラズモイドなど）が、加速の鍵を握っているに違いない。太陽フレアには、このような研究対象としての面白さに加え、観測対象としての利点もある。それは、地球から最も近い恒星で起きる磁気リコネクション現象であり、磁気リコネクションが生み出す多様なプラズマ構造を、空間分離して観測することが可能な点である。これにより、加速粒子が存在する箇所が見つかってきている。しかし、現時点では観測上の制限（主に観測技術の制約）もあり、粒子の加速が、どこで、いつ、どのように行われているかは完全に解明されていない。

本講演では、太陽フレア（磁気リコネクション）とそれによって生じる粒子加速の観測的研究をレビューするとともに、加速粒子の精査も可能な次世代の太陽フレア観測も紹介する。

S001-12

A 会場 : 11/4 PM2 (15:45-18:15)

17:15~17:30

パーカーソーラープローブとベピコロombo衛星を使った内部太陽圏の磁気ヘリシティ測定

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Measurements of magnetic helicity in the inner heliosphere using Parker Solar Probe and BepiColombo

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Magnetic helicity represents the topology of magnetic field such as rotation sense and its magnitude. The helicity is a crucial concept for understanding turbulence and dynamos in space and astrophysical systems. The Sun, as a prominent example, is a generator of magnetic helicity through the dynamo mechanism, and the helicity is considered as transported into the heliosphere not only by the convection with the solar wind but also by various plasma physical processes such as wave excitation due to unstable plasma conditions, wave-wave interactions, and turbulence cascade in the forward and inverse fashions. The detailed picture of helicity transport is still missing to date. We use two spacecraft of PSP and BC in a radially aligned configuration, and track the spectral evolution of magnetic helicity from a distance of 0.17 AU to 0.57 AU in the inner heliosphere. The helicity dynamics exhibits coherent components on larger spatial scales, damping of helicity on intermediate scales, and excitation of non-helical components on small scales. The solar magnetic field evolves scale-wise in to the heliosphere, and the helicity evolution is expected to be an important ingredient in the turbulent solar and stellar wind model.

磁気ヘリシティ量は宇宙空間の磁場構造（とりわけ螺旋度）を定量的に評価するのに有用で、宇宙空間・天体プラズマが乱流状態に発展したり天体系で磁場がダイナモ機構により発生する際に本質的な役割を果たす。太陽自身もヘリシティ磁場を生成しており、ヘリシティ量はプラズマの流れによって太陽圏へと輸送されていき、地球軌道近傍ではランダムな乱流状態へと発展していくことが知られている。近年では PSP、SO、BC による内部太陽圏の現場観測が運用されるようになり、多点観測を駆使して磁場のエネルギーだけでなく磁気ヘリシティ量の詳細な空間発展の様子が調べられるようになった。観測例として、太陽・PSP・BC が一列に並んだタイミングで磁気ヘリシティ量のスペクトルを 0.17AU から 0.57AU まで調べた研究を紹介する。内部太陽圏で磁気ヘリシティは MHD 的な長波長スケールでコヒーレントな磁場成分が輸送される一方で、中波長ではヘリシティの減衰が起こり、さらに短波長では非螺旋的な揺動成分の励起が起きていることが分かった。この結果は、太陽磁場がスケールごとに異なる描像で乱流状態へ発展していくことを示しており、太陽風および恒星風の乱流模型に向けて大事な要素となると考えられる。

S001-13

A 会場 : 11/4 PM2 (15:45-18:15)

17:30~17:45

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Physical properties of the solar corona derived from radio scintillation observations with the Akatsuki spacecraft

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The solar wind is a supersonic plasma flow streamed from the solar corona. The acceleration of the solar wind mainly occurs in the outer corona at heliocentric distances of about 5 – 20 solar radii, where the coronal heating by magnetohydrodynamic waves and the wave-induced magnetic pressure are thought to play major roles in the acceleration. The mechanisms have not been fully confirmed by observations because the acceleration region is too close to the Sun to be observed by in-situ probes.

The radio occultation observation covers the acceleration region fully and can obtain the large-scale process of the plasma complementary to in-situ observation. JAXA's Venus orbiter Akatsuki conducted the radio occultation observations on the opposite side of the sun as seen from the Earth. Key physical processes in the acceleration region can be observed with radio occultation. Coronal plasma traversing the ray path disturbs radio waves' amplitudes and frequency, from which we can derive physical parameters such as the flow speed and waves' amplitudes. We can derive roughly three types of physical quantities from the radio occultation data.

First, the radial velocity and the turbulence characteristics (power-law exponent, axial ratio, and inner scale) were retrieved from the intensity scintillation time-series by fitting a theoretical spectrum to the observed power spectra. In the radial distribution of the derived solar wind velocity, fast winds originating from regions near a coronal hole and slow winds from other regions were identified. Second, by applying wavelet analysis to the frequency time-series data, we can detect quasi-periodic fluctuations (QPC) that are thought to represent acoustic waves and quantify the amplitude, the period, and the coherence time of each wave event. The density amplitude and the wave energy flux were estimated following Miyamoto et al. (2014). Finally, we can derive the magnetic field's variations from circular-polarization data. Faraday rotation of a linearly polarized electromagnetic signal is the result of the magnetized plasma. Transmitted signals include the dual-circular polarization, and we can derive the Faraday rotation caused by magnetic fields variations from the phase shift between right and left circular polarization. We analyzed data taken by radio occultation observations using Akatsuki's radio waves during the superior conjunction periods in 2011, 2016, 2018, and 2021. Especially in 2021 campaign, Akatsuki and ESA's spacecraft BepiColombo had solar superior conjunction almost simultaneously in March. Both spacecraft continuously monitored the solar wind with radio occultation during this period. Furthermore, simultaneous measurements using BepiColombo and Akatsuki were conducted to observe the same stream of the solar wind on March 13-14. We will also conduct the cross-correlation analysis between the Akatsuki and BepiColombo's signals to derive the flow speed.

S001-14

A 会場 : 11/4 PM2 (15:45-18:15)

17:45~18:00

惑星間空間シンチレーション指数から求めたサイクル23-24における太陽風擾乱の発生頻度の長期変動

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Long-term variation in occurrence of solar wind disturbances during Cycles 23-24 derived from interplanetary scintillation indices

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The solar wind, which is a supersonic plasma flow from the Sun, ceaselessly changes over a wide range of spatial and temporal scales. This change imposes significant effects on the space environment and upper atmosphere near the Earth (space weather), and even on infrastructures in human civilization; therefore, continuous monitoring and prediction of the solar wind are an important subject. The high-speed solar wind and coronal mass ejection are known as a major driver to alter the space weather. Through the interaction with the ambient solar wind, the plasma in the leading portion (sheath region) of either the high-speed solar wind or fast CME is compressed, and enhancements in density, temperature, and turbulence are generated. The compressed plasma in the sheath region can be effectively detected from interplanetary scintillation (IPS) observations of radio sources. Namely, the strength of IPS represents integration of density fluctuations along the line of sight, and the g-value which is a measure for IPS strength increases when the compressed plasma associated with fast solar wind or CME intersects the line of sight. The collection of g-value data started in 1997 from 327MHz IPS observations at ISEE of Nagoya University, and the data which covers the period over 2 solar cycles (SCs 23 and 24) are available now. In this study, we analyzed ISEE g-value data to examine time variation in the occurrence rate of solar wind disturbances during SCs 23 and 24. There is no past study in which the g-value data over such a long period was analyzed, and this study enables to reveal how the occurrence rate of solar wind disturbances varies and how different those are between SCs 23 and 24. We calculated three kinds of IPS index from the g-value data to detect solar wind disturbances. The IPS indices, which are derived from the g-value data on a daily basis, act as a handy measure to indicate increase or decrease in the density fluctuation level of global inner heliosphere. In JpGU2022, we reported that IPS indices had weak but significant positive correlations with increase in the solar wind density and speed. This suggests utility of the IPS indices for detecting the compressed plasma associated with high-speed solar wind or CME. In this study, we counted the number of days when the IPS indices exceed threshold levels for each year to determine annual variation in the occurrence rates of solar wind disturbances. The threshold level for each IPS index was given by the average value plus +1 sigma. As the result, the occurrence rate for SC23 increased at the solar maximum, decreased at the declining phase, and increased again at the subsequent solar minimum. The highest rate occurred in 2009 (solar minimum), the next highest rate in 2001 and 1999 (solar maximum), and the lowest rate in 2004 (declining phase). On the other hand, the occurrence rate for SC24 was high for the period between SC23/24 minimum and the rising phase, dropped for the period from the solar maximum to the declining phase, and rose again at the next solar minimum. The highest rate was observed in 2011 (rising phase), and the lowest in 2014 (declining phase). The interesting point is that the minimum of the occurrence rate occurred in the declining phase just after the solar maximum for both cycles. A similar drop in the occurrence rate of transient streams at the declining phase was reported from in situ observations. Long-term variation of solar wind disturbances revealed from the IPS indices includes both effects of high-speed solar wind and CME, which may correspond to enhancements of the occurrence rate at solar minimum and maximum, respectively. The lower occurrence rate for SC24 (particularly at solar maximum), compared to that for SC23, is ascribed to the weaker solar activity of SC24.

太陽から噴き出す超音速のプラズマ流、太陽風は様々な時間・空間スケールで絶え間なく変動している。この変動は地球周辺の宇宙環境や超高層大気（宇宙天気）に大きな影響を与えており、その影響は現代社会の基盤設備にまで及ぶことから、太陽風の常時監視と予測が重要な課題となっている。宇宙天気を変動させる太陽風の主な要因として、高速風とCMEがある。特に、後者は磁気ロープと呼ばれる磁場構造を伴っており、これが長時間にわたって南向きIMFを生じ、さらに地磁気嵐を引き起こすことが知られている。しかし、南向きIMFは高速風や高速なCMEの前面に形成されるシース領域でも生じ、地磁気嵐の要因となる。シース領域では先行する太陽風との相互作用でプラズマが圧縮され、太陽風の高密度化、加熱、揺らぎ増大が起こる。ここで高速風の前面にできるシース領域は、Stream Interaction Region (SIR)、また複数の太陽自転にわたって存在する場合はCorotating Interaction Region (CIR)と呼ばれる。このプラズマの圧縮領域は、天体電波源の“またたき”現象、Interplanetary Scintillation (IPS)の観測から効率よく検出することができる。即ち、IPSの強度は視線に沿った密度揺らぎの積分量に比例するので、高速風やCMEに伴う圧縮領域を視線が横切るとIPS強度の指標であるg-valueの増大となって現れる。名大ISEEでは、1997年より周波数327MHzのIPS観測からg-valueデータが得られるようになり、g-valueデータの解析からCMEの3次元構造や伝搬特性の研究が行われてきた。ISEEにおけるg-valueデータ収集は現在も継続中で、これまでに2つの太陽活動周期（サイクル23-24）をカバーするデータが得られている。本研究では、ISEEのg-valueデータを使って、サイクル23-24における太陽風擾乱の発生頻

度の時間変動を調査した。このような長期間にわたって g-value データを解析した研究は過去にはなく、本研究からは太陽活動に伴って太陽風擾乱の発生頻度がどのように変化し、それが2つのサイクルでどの様に違うかが明らかにできる。本研究では、g-value データから3種類の IPS 指数を計算し、それを用いて太陽風の擾乱を検出した。g-value は1日に数多くの電波源について得られ、内部太陽圏の様々な場所の情報を伝えているが、このままでは情報量が多すぎて解析しづらい。IPS 指数は g-value データから日毎に計算され、内部太陽圏全体に対する密度揺らぎの増減を示す便利な指標となる。JpGU2022 では、IPS 指数は太陽風密度・速度の増加に対して弱い有意な正の相関があることを示した。このことは IPS 指数によって SIR または CME に伴う圧縮領域を捉えることができることを示している。我々は、IPS 指数が閾値を超えた日を年ごとに数えることで、太陽風擾乱の発生頻度の年変化を求めた。閾値は各 IPS 指数の平均値から $+1\sigma$ で与えた。その結果、サイクル 23 では発生頻度が極大期で増加し、下降期で減少し、続く極小期で増加していたことがわかった。最も高い頻度は 2009 年（極小期）、続くピークは 2001 年、1999 年（極大期）で起こっている。また、2004 年（下降期）で最小になった。一方、サイクル 24 では全サイクルから続く極小期～上昇期で高い発生頻度が見られ、極大期から下降期にかけて頻度が低くなり、次の極小期に再び増加した。発生頻度の最大値は 2011 年（上昇期）、最小値は 2014 年（下降期）で見られる。ここで、2つのサイクルに共通して極大を過ぎた直後の下降期で発生頻度が最小になっているのは興味深い。飛翔体観測でも同様な下降期における太陽風擾乱の発生頻度の低下がみられている。IPS 指数で検出された太陽風擾乱の変動は SIR と CME の影響を含んでおり、それぞれ極小期と極大期に増加する傾向に対応していると考えられる。サイクル 24 の発生頻度はサイクル 23 に比べ低いが（特に極大期）、これは太陽活動度を反映したものと考えられる。

S001-15

A 会場 : 11/4 PM2 (15:45-18:15)

18:00~18:15

日欧で観測された IPS 観測データを統合した CME の MHD シミュレーション

#岩井 一正¹⁾, Fallows, A Richard²⁾, Bisi, M Mario³⁾, 塩田 大幸⁴⁾, Jackson, V Bernard⁵⁾, 徳丸 宗利¹⁾, 藤木 謙一¹⁾

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Magnetohydrodynamic simulation of coronal mass ejections using interplanetary scintillation data observed from multiple stations

#Kazumasa Iwai¹⁾, Richard Fallows, A²⁾, Mario Bisi, M³⁾, Daikou Shiota⁴⁾, Bernard Jackson, V⁵⁾, Munetoshi Tokumaru¹⁾, Kenichi Fujiki¹⁾

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Interplanetary scintillation (IPS) is a useful tool for detecting coronal mass ejections (CMEs) throughout interplanetary space. Global magnetohydrodynamic (MHD) simulations of the heliosphere, which are usually used to predict CMEs, can be improved using IPS data. In this study, we demonstrate an MHD simulation that includes IPS data from multiple stations to improve CME modelling. The CMEs, which occurred on 09-10 September 2017, were observed over the period 10-12 September 2017 using the Low-Frequency Array (LOFAR) and IPS array of the Institute for Space-Earth Environmental Research (ISEE), Nagoya University, as they tracked through the inner heliosphere. We simulated CME propagation using a global MHD simulation, SUSANOO-CME, in which CMEs were modeled as spheromaks, and the IPS data were synthesised from the simulation results. The MHD simulation suggests that the CMEs merged in interplanetary space, forming complicated IPS g-level distributions in the sky map. We found that the MHD simulation that best fits both LOFAR and ISEE data provided a better forecast of the arrival of the CME to Earth. More IPS data observed from multiple stations at different local times in this study can help reconstruct the global structure of the CME, thus improving and evaluating the CME modelling. The time variation of the g-level of 3C147 observed by LOFAR can be explained by the passage of the CME front, although there are several hours of time difference between the observed and simulated g-level onset times. This time difference can be explained by the deformation of the CME caused by the interactions between the background solar wind and CME.

惑星間空間シンチレーション (IPS) 観測は、電波の散乱現象を利用することで、惑星間空間を伝搬中のコロナ質量放出 (CME) を効率よく検出することができる。そのため、太陽圏における CME の伝搬を計算するために一般的に使われる磁気流体 (MHD) シミュレーションは、より多くの IPS データを取り込むことによってより正確になり得る。特に地球上の異なる経度に設置された電波観測装置による協調した連続観測は CME を高頻度に観測できる利点が指摘されている。本研究では、名古屋大学 ISEE の IPS 観測装置と、欧州の電波干渉計 LOFAR で同時期に行われた IPS 観測データを組み合わせることで連続的な観測となった 2017 年 9 月 10 日から 12 日にかけて発生した CME 現象を、太陽圏の MHD シミュレーション (SUSANOO-CME) に取り込む実験を行った。本シミュレーションでは Spheromak を用いて CME がモデル化される。シミュレーション結果から得られる太陽圏の密度の 3 次元分布を用いて、地球から任意の方向に電波の散乱を解くことで疑似的な IPS データを計算できる。Spheromak の初期パラメータを変えたシミュレーションを多数行い、実際に観測された IPS データと最も近い疑似 IPS データが得られるシミュレーションを抽出した。対象となる CME は西のリムで発生したが、地球上の異なる経度に存在する ISEE のアンテナと LOFAR がほぼ同時刻に観測を行ったことで、IPS の反応を示す天体の分布は全天に広がっていたことが分かった。この IPS 分布は、広い角度幅を持った Spheromak を用いたシミュレーションによって再現され、そのシミュレーションは CME の地球への到来も再現できた。本結果は、多数の IPS 観測データを用いることで CME のグローバルな構造をより正確に再現できることを示唆している。LOFAR で観測された電波天体 3C147 の IPS 反応の時間変動は CME 前面が天体の前を通過することで説明できる。一方で、強い IPS 反応のオンセット時間は観測とシミュレーションで数時間の差があった。この差はシミュレーション中の背景太陽風がうまく再現されていないことで、太陽風と CME の相互作用が実際こと異なっていることを示唆している。

S001-16

A 会場 : 11/5 AM1 (9:00-10:30)

09:00~09:25

輻射磁気流体力学計算によるブラックホール近傍のプラズマ降着流・噴出流のダイナミクス

#朝比奈 雄太¹⁾, 大須賀 健¹⁾, 内海 碧人¹⁾, 井上 壮大¹⁾, 高橋 幹弥¹⁾, 高橋 博之²⁾

¹⁾筑波大,²⁾駒澤大

Dynamics of plasma accretion and outflow around a black hole by radiation magnetohydrodynamics simulations

#Yuta Asahina¹⁾, Ken Ohsuga¹⁾, Aoto Utsumi¹⁾, Akihiro Inoue¹⁾, Mikiya Takahashi¹⁾, Hiroyuki R. Takahashi²⁾

¹⁾Tsukuba Univ.,²⁾Komazawa Univ.

Rotating plasma forms an accretion disk around a compact object like a black hole or neutron star. The released gravitational energy of the accreting plasma is converted to the kinetic energy, internal energy of plasma, and radiation energy. A part of the converted energy is ejected into interstellar space through an outflow and radiation. However, the structure of the accretion disk and the mechanism driving the outflow are not clear yet. The interaction between the radiation and magnetofluids cannot be ignored for a very bright object like ultra-luminous X-ray sources. Therefore, general relativistic radiation magnetohydrodynamics (GR-RMHD) simulations taking into account the effect of the radiation are needed.

In this presentation, we will introduce some results of GR-RMHD simulations. The approximate method is adapted for solving the radiation transfer to save the calculation costs in most previous studies. However, there is no guarantee that accurate radiation fields are obtained by the approximate method in the optically thin region. In addition, it is difficult to deal with anisotropic radiation. Thus, we have developed the INAZUMA code, which solves the radiation transfer equation to obtain a more accurate radiation field and apply INAZUMA to the black hole accretion disk. We obtain a more accurate radiation field in the optically thin region around the rotation axis of the accretion disk and report these results. Also, an important feature of the black hole is its rotation (spin). When the black hole has spin, the Blandford-Znajek mechanism, which is a mechanism for extracting the rotation energy from the black hole through the magnetic field, works. The extracted energy by the BZ mechanism can promote the acceleration of the outflow. We show the result for the dependence of the structure of the accretion disk and outflow on the spin of the black hole. X-ray pulse is observed for a part of ultra-luminous X-ray sources. A neutron star is considered the central object. We show the result of the simulations of the accretion plasma with the high-accretion rate into the neutron star.

ブラックホールや中性子星などのコンパクト天体の周囲には、回転しながら降着するプラズマによって降着円盤が形成される。プラズマが降着する際に解放された重力エネルギーはプラズマの運動エネルギーや内部エネルギー、輻射エネルギーに変換される。変換されたエネルギーの一部は輻射やアウトフローとして星間空間へと放出される。しかしながら、降着円盤の構造やアウトフローの駆動メカニズムの詳細は未だ解明されていない。超大光度 X 線源などの非常に明るい天体では輻射と磁気流体プラズマの相互作用を無視することができない。そこで輻射の効果を取り入れた一般相対論的輻射磁気流体 (GR-RMHD) シミュレーションが必須となる。

本講演ではいくつかの GR-RMHD シミュレーションの計算結果を紹介する。先行研究の多くは計算コストの削減のため近似解法を用いて輻射輸送を解いている。しかし、近似解法では光学的に薄い領域で正確な輻射場を得られる保証はない。さらに非等方的な輻射を取り扱うことは難しい。そこでより正確な輻射場を得るために輻射輸送方程式を直接解く INAZUMA コードを開発し、ブラックホール降着円盤に適用した。光学的に薄い降着円盤の回転軸付近でより正確な輻射場を得ることに成功したので、その結果について報告する。また、ブラックホールの重要な性質としてブラックホールの回転 (スピン) が挙げられる。ブラックホールが回転している場合、磁場を介してブラックホールの回転エネルギーが取り出される Blandford-Znajek (BZ) 機構が働く。BZ 機構によって抽出されたエネルギーはアウトフローの加速を促進する可能性がある。降着円盤やアウトフローの構造のブラックホールのスピン依存性を調べたシミュレーションを紹介する。さらに、一部の超大光度 X 線源では X 線パルスが観測されていることから、その中心天体は中性子星であると考えられている。そこで中性子星への質量降着率の高い降着流のシミュレーション結果についても紹介する。

S001-17

A 会場 : 11/5 AM1 (9:00-10:30)

09:25~09:40

恒星風を伴う低質量星への星間降着流の三次元シミュレーション

#田中 周太¹⁾, 田中 一詳¹⁾

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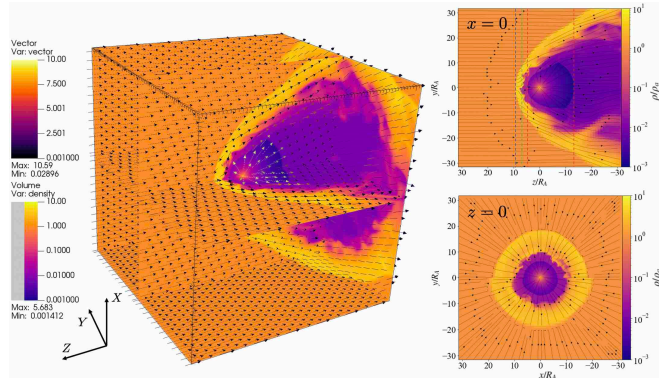
Three dimensional simulations of the interaction between interstellar accretion flow and stellar outflow

#Shuta Tanaka¹⁾, Kazuyoshi Tanaka¹⁾

¹⁾ AGU

Due to gravity, all celestial objects are subject to accretion of surrounding materials. On the other hand, most celestial objects form outflows using their gravity as an energy source. The coexistence of outflow and inflow is universal in various celestial bodies including blackholes. The simplest case of isotropic inflow and outflow solutions are the Bondi accretion and Parker wind solutions, which are known as spherically symmetric steady solutions, but they cannot coexist without singularities at a finite radius due to the nature of their solutions. Here, the interaction between the accretion inflow and the isotropic outflow with a three-dimensional hydrodynamic simulation is studied by three-dimensional hydrodynamic simulation. The figure shows the case when the isotropic outflow is far stronger than the accretion flow. The simulations of different sets of the relative strength between the outflow and inflow were performed. We explored how the isotropic outflow and the accretion inflow coexist and how they switch from one to the other.

重力によって、全ての天体は降着を伴う。一方で、ほとんどの天体はその重力をエネルギー源として、恒星風やジェットなどの流出流を形成する。流出と流入が共存する現象は様々な天体で普遍的である。最も単純な場合が球対称定常の解として知られているボンディ降着とパーカー風の解であるが、これらはその解の性質上共存できない。我々は、三次元の数値流体シミュレーションで降着流と等方的な流出流との相互作用を調べた。図は流出流が支配的であり、恒星圏が形成されている様子である。流出流と降着流の強度を帰ることでそれらがどのように共存し、どのようにして、それらが切り替わるのかを調べた。



S001-18

A 会場 : 11/5 AM1 (9:00-10:30)

09:40~09:55

プラズマ粒子シミュレーションのための相対論的カッパ分布の乱数生成法

#銭谷 誠司¹⁾, 中野 慎也²⁾

(¹ 神戸大学, ² 統数研)

Loading a relativistic kappa distribution in particle simulations

#Seiji Zenitani¹⁾, Shin ya Nakano²⁾

(¹Kobe U, ²The Institute of Statistical Mathematics)

A procedure for loading particle velocities from a relativistic kappa distribution in particle-in-cell (PIC) and Monte-Carlo simulations is presented. The algorithm is based on the rejection method and the generalized beta prime distribution. The rejection part extends earlier method by using additional parameters, and then the acceptance rate reaches >95%. Derivation of the procedure, mathematical properties, comparison with other procedures, and numerical tests are presented.

プラズマ粒子シミュレーションやモンテカルロ・シミュレーションにおいて、相対論的カッパ分布に従うプラズマ速度を乱数生成するためのアルゴリズムを提案する。このアルゴリズムは、ベータプライム分布（第2種ベータ分布）の乱数生成法と棄却法を組み合わせたものである。棄却法パートは、標準手法に追加パラメーターを導入して拡張することで、95%の採択率を達成している。本発表では、アルゴリズムの導出過程や他手法との比較、ベンチマーク結果などを紹介する。

S001-19

A 会場 : 11/5 AM1 (9:00-10:30)

09:55~10:10

パーカースパイラル磁場を持つ星風中を伝播する超新星残骸における宇宙線の逃走過程

#上島 翔真¹, 大平 豊¹

¹ 東大

Cosmic-ray Escape from Supernova Remnants in Circumstellar Media with Parker-spiral Magnetic Field

#Shoma Kamijima¹, Yutaka Ohira¹

¹U. Tokyo

It is believed that cosmic rays (CRs) below 3 PeV are accelerated by the diffusive shock acceleration (DSA) in supernova remnants (SNRs). In the DSA, the acceleration time depends on the angle between the shock normal direction and the magnetic field. It is suggested that perpendicular shocks rapidly accelerate CRs to PeV without upstream magnetic field amplification. In addition to acceleration, CR escape is important to determine the maximum energy and energy spectra of CRs. Previous studies about CR escape applied the diffusion approximation. Under the diffusion approximation, we cannot solve the gyration, which is important for the rapid perpendicular shock acceleration. Therefore, the escape process from perpendicular shocks is still unknown.

In this study, we performed test particle simulations to investigate the escape process from core-collapse SNRs in circumstellar media with Parker-spiral magnetic field. As for the upstream region of core-collapse SNRs, we consider the Parker-spiral magnetic field and the current sheet. The shape of the current sheet depends on which the rotation axis and the magnetic axis of progenitors are aligned or misaligned. We showed that injected particles concentrate on the equator or poles while drifting on the shock surface, and escape to the far upstream region along the equator or poles. Furthermore, we showed that there are two types of maximum energy. One is given by the characteristic length scale of the wavy current sheet. The other is given by the drift on the shock surface between the equator and pole. We revealed that the maximum energy becomes about 10-100 TeV. We will report the escape process from SNRs in the circumstellar medium and the escape-limited maximum energy.

3PeV 以下の宇宙線は、超新星残骸において衝撃波統計加速で加速されると考えられている。衝撃波統計加速の加速時間は、磁場と衝撃波法線のなす角に依存し、磁場と衝撃波法線が垂直な垂直衝撃波は、上流の磁場増幅なしで宇宙線を PeV スケールまで加速することが期待されている。加速過程に加え、宇宙線の逃走過程が宇宙線の最高エネルギーやエネルギースペクトルの決定に重要である。宇宙線の逃走過程の先行研究では宇宙線の運動を拡散運動と仮定する拡散近似が用いられてきた。しかし、垂直衝撃波ではジャイロ運動が加速に重要な場合があり、拡散近似下ではジャイロ運動を正確に解くことができない。そのため、垂直衝撃波領域からの宇宙線の逃走過程は未解明である。

本研究では、パーカースパイラル磁場を持つ星風中を伝播する超新星残骸からの宇宙線の逃走過程を調べるためにテスト粒子計算を実行した。衝撃波上流領域では、パーカースパイラル磁場と電流シートを考慮する。電流シートの形状は、爆発前の親星の磁軸と回転軸が揃っているか傾いているかで変化する。テスト粒子計算から、注入された粒子は赤道面または極域に向かってドリフト運動し、赤道面または極域に沿って衝撃波上流遠方に逃走することが明らかにした。最高エネルギーは逃走過程により決まり、親星の磁軸と回転軸が傾いている場合では、超新星残骸の年齢に応じて2種類の最高エネルギーが実現することを明らかにした。電流シートの典型的な空間スケールとジャイロ半径の釣り合いで最高エネルギーが決まる場合と極域と赤道面の間のポテンシャル差で決まる場合の2種類である。超新星残骸のほとんどの年齢における最高エネルギーは、約 10TeV から 100TeV であることを明らかにした。本発表では、星風中を伝播する超新星残骸からの宇宙線の逃走過程と逃走で決まる最高エネルギーについて報告する。

S001-20

A 会場 : 11/5 AM1 (9:00-10:30)

10:10~10:25

#蔵満 康浩¹⁾

⁽¹⁾ 阪大・工・電気

Laboratory astrophysics with relativistic laser pulses

#Yasuhiro Kuramitsu¹⁾

⁽¹⁾GSE, Osaka Univ.

We have been working on laboratory astrophysics, where space and astrophysical phenomena, such as collisionless shocks and magnetic reconnections, are experimentally investigated with high power, large laser facilities. However, the number of large laser facilities in the world is very limited, and the number of shots is also very small; the experimental opportunities are also very limited. Recently, we have been extending laboratory astrophysics from non-relativistic to relativistic regime using relativistic intense laser pulses with high repetition. In this talk, we introduce our recent efforts on sub-relativistic ion acceleration and the novel diagnostics for quantum beams, plasmas, and electric/magnetic fields. We are planning to create counterstreaming sub-relativistic plasma flows and address nonlinear evolution of the Weibel and filamentation instabilities under the influence of an external magnetic field in a controlled manner.

S001-21

A 会場 : 11/5 AM1 (9:00-10:30)

10:25~10:40

EHTによるSgrA*・1.3ミリメートル波電波の時間変動・周期性確認とデカメートル電波パルス観測に基づく超巨大ブラックホールバイナリー存在の可能性

#大家 寛¹⁾

¹⁾ 東北大・理・地物

Time Variation in EHT Data Analyzed with Results of Decameter Radio Wave from Sgr A* Suggesting the Existence of Black Hole Binary

#Hiroshi Oya¹⁾

¹⁾ Geophysics, Tohoku Univ.

Recently EHTC(Event Horizon Telescope Collaboration) published the results of the black hole shadow of SgrA* as a single stationary image. There remains, however, problem how they have solved the time varying feature of the mm wave intensity for SgrA* sources. In the present study we have analyzed public released EHT data and find the significant periodic time variations that are consistent with the time variation resulted by observation of the decameter radio wave pulses(ODWP) from SgrA*.

Before the present analyses of EHT data, we have analyzed the VLBI data observed in 2009 by Fish et al (2011) for the existing periodic time variation by comparing with the model of the binary supermassive black hole orbiting with the period of 2200+ - 50 sec that has been deduced by ODWP. The results have shown that the VLBI data observed by California and Arizona baseline reveal clear periodic time variation with 1075 sec due to eclipse of two black holes of the binary orbiting with period of 2150 +- 2.5 sec.

In the present study the public data provided by EHTC for the observation on April 5 and 6, 2017 made by 1.3 mm wavelength VLBI associated with globally distributed 6 stations with 8 antennas are analyzed for the time variation of the visibilities. Though the provided data are under the difficult situation because of the periodic sampling to avoid periodic time variation,

detections of the periodicity are successfully carried out applying the Fourier transformation. By applying the random noise at the data sampling moment for observation in parallel, we can separate the periodicity caused by artificially forced sampling of data from the periodicity of the physical origin. By comparison of the periodicity for physical component of observed data with that of the models that are constructed with parameter of super massive black hole binary based on the ODWP, the periodic time variation with periods around 1100sec associated with orbiting period 2180+ - 50 sec are clarified.

Based on this study we conclude that SgrA* consists of supermassive binary with masses of 2.27×10^6 Solar mass and 1.94×10^6 Solar mass, orbiting with period 2180+ - 50 sec.

2022年5月、天の川銀河中心 SgrA* の Event Horizon の影による電波像が EHT 国際共同観測グループ (EHTC) により発表されている。天の川銀河中心に降着してくるプラズマ運動による電子散乱効果が言われ、電波像構築の困難が指摘されていたが、5年間にわたる時間変動相殺の試みの結果として発表されている。しかし、本研究では、今回公表された public data の解析の結果、問題は解決されていないことが判明し、本研究で行って来たデカメートル電波観測結果に基づく超巨大ブラックホールバイナリー存在の可能性を述べる。

今回の研究に先立ち、本研究では、EHTC 発足の核となった Fish et al. (2011 年発表) による、波長 1.3 mm 電波 VLBI の観測研究結果に対し、デカメートル波 (波長 15m) で、SgrA* におけるブラックホールのスピン周期に同期するパルスの検出から結論されている結果 (2019 年出版 以降 DRWP と略称) と対比検討してきた。その結果は Fish et al の 観測結果で SgrA* の Event Horizon スケールで出現する強度の時間変動と、原因を SgrA* が、Super Massive Black Hole Binary (SMBHB) で周期 2200+- 50 秒で公転していることとする DRWP に基づくモデルの時間変動が一致することを示した。詳細には、DRWP により発表してきた公転周期 2200+-50 秒の下限に相当する 2150+-2.5 秒にて SMBHB が公転し、その半周期 1075 秒毎に二つのブラックホールが蝕を繰り返す場合の電波放射モデルとの一致となっている。

今回の EHTC による public data は全地球規模で展開された 6 局 8 アンテナで構成された 1.3mm 波 VLBI システムによる 2017 年 4 月 5、6 日観測によるもので、観測時間帯の異なるスペイン局を除いても 21 組のベースラインからなるデータ群が得られる。しかし、判明したのは Data 周期性を抑えるため 1000 秒前後の疑似周期性のある人工サンプリングが施されていて、周期的変動を究明する立場からは Fourier 解析には工夫を必要とされた。本研究では、サンプリング周期と物理的変動周期の分離のため並行してランダム雑音のサンプリングを観測データサンプリングと同期的に行って両者の分離を行っている。観測データの時間変動の中から分離された物理的周期変動はデカメートル電波観測に基づくモデルと対比し、干渉計の Visibility に 2180+- 50 sec の周期変動が 50 マイクロ秒角以下の領域を検出可能とするすべての基線の組み合わせでの Visibility に検出されることが判明した。結果は SgrA* が Binary Supermassive ブラックホールであることを強く示唆するものである。

S001-22

A 会場 : 11/5 AM2 (10:45-12:30)

10:55~11:10

ミュオン計ネットワークを用いた銀河宇宙線の南北異方性の研究

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(¹⁾PEDSC/ROIS-DS, (²⁾信州大・理, (³⁾極地研

Study of north-south anisotropy of galactic cosmic-rays using the muon detector network

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(¹⁾PEDSC/ROIS-DS, (²⁾Physics Department, Shinshu Univ., (³⁾NIPR

North-south (NS) anisotropy of galactic cosmic rays (GCRs) in the 10-100 GeV energy region reverses its polarity according to the sector structure of the interplanetary magnetic field. This is interpreted as the diamagnetic-drift phenomenon caused by the density gradient of GCRs. The spatial distribution of GCRs, which is an important factor to reveal the heliospheric transport of GCRs, can be estimated by analyzing this polarity reversal. However, the NS anisotropy is more difficult to detect than the diurnal anisotropy (anisotropy in the equatorial plane). Its quantified properties, such as energy dependence and temporal variation associated with solar activity, have been less understood.

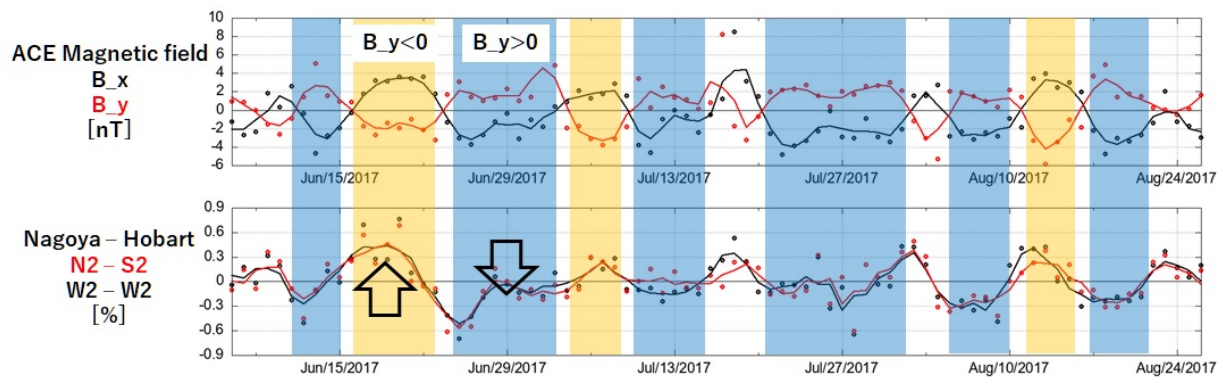
In recent years, a new correction method for atmospheric temperature effect on cosmic-ray muon intensities has been proposed. This method directly corrects the muon count rate by using the meteorological reanalysis data. The conventional analyses of the NS anisotropy have suffered from the correction of the temperature effect, but this new correction method will drastically relax the restrictions arising from the temperature effect. It will be possible to handle observation data at independent stations in an integrated manner. Using muon detectors in both the northern and southern hemispheres will enable us to analyze NS anisotropy with unprecedented accuracy. Focusing on this point, we are attempting a new analysis method for the NS anisotropy.

The attached figure shows (upper panel) the interplanetary magnetic field observed by the ACE satellite and (lower panel) the NS anisotropy derived from observation with the muon detectors. Each point is a daily value and the solid line represents a 3-day moving average. The interplanetary sector is represented by the GSE-x and y components of the magnetic field, and the positive and negative polarities of the NS anisotropy are reversed according to the sector polarity. Utilizing the new correction method for the temperature effect, the NS anisotropy was derived from an intensity difference between the muon detectors in the northern hemisphere (Nagoya) and the southern hemisphere (Hobart). "N2", "S2", and "W2" represent the directional components of the muon detector. "N2 - S2" is the difference between the Nagoya N2 component and the Hobart S2 component, and "W2 - W2" is the difference between the Nagoya W2 component and the Hobart W2 component. These pairs are formed considering the north-south symmetry of the geomagnetic effect.

10~100 GeV 領域の銀河宇宙線強度に現れる南北異方性は、惑星間空間磁場のセクター構造に伴い、南北極性を反転させることが知られている。これは宇宙線の密度勾配に起因する、反磁性ドリフト現象を示していると考えられる。その解析により、太陽圏内の宇宙線伝搬を解明する上で重要な、宇宙線密度の空間分布を推定することができる。ただし、赤道面内の異方性（日周異方性）と比べて南北異方性は解析が困難であり、エネルギー依存性や、太陽活動に伴う変動の定量的な理解は進んでいない。

近年、地上ミュオン計の新たな気温効果補正法が提案された。気象再解析データを用いることで、ミュオン計数率を直接補正する手法である。従来の南北異方性の解析方法では気温効果の補正による制約が大きかったが、この新たな補正法によりそれを大幅に緩和することができる。独立な地点の観測所データを統合的に扱うことが可能となり、南北半球のミュオン計を用いることで、南北異方性をこれまでになく精度で解析できる可能性がある。この点に着目し、南北異方性の新たな解析法の研究を進めている。

添付の図は、ACE 衛星で観測された惑星間空間磁場（上パネル）と、ミュオン計で観測された南北異方性（下パネル）である。各点が一日値で実線は3日間移動平均を表す。GSE 座標 x, y 成分で表される惑星間空間磁場のセクターに伴い、南北異方性の正負極性に反転が見られる。新たな気温効果補正法を活用し、北半球（名古屋）と南半球（ホバート）のミュオン計の強度差から南北異方性を導出した。N2, S2, W2 はミュオン計の方向成分を表しており、"N2 - S2" は名古屋 N2 成分とホバート S2 成分、"W2 - W2" は名古屋 W2 成分とホバート W2 成分の差を表している。地磁気効果の南北対称性を考慮したペアとしている。



S001-23

A 会場 : 11/5 AM2 (10:45-12:30)

11:10~11:35

ダイポール磁場中の電子・陽電子プラズマ生成計画と磁気圏現象の実験研究

#齋藤 晴彦¹⁾

¹⁾ 東大新領域

Electron-positron plasma creation and experiments on magnetospheric phenomena in dipole field

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¹⁾GSFS U.Tokyo

In this study we report the recent status and plan of laboratory experiments by using a dipole magnetic field configuration, which is globally equivalent to the geometry of a planetary magnetosphere. The Ring Trap Group of the University of Tokyo aims to (1) create antimatter plasmas using the excellent confinement properties of a dipole magnetic field, and to (2) understand the wave particle interactions as common phenomena in both magnetospheres and fusion-oriented plasma experiments, in an "artificial magnetosphere" created by a levitated superconducting magnet.

(1) It is predicted that electron-positron plasmas exist around high-energy astrophysical objects. Because of the mass symmetry, electron-positron plasmas exhibit unique stability and wave properties as one of "pair plasmas", plasmas consist of particles with equal mass. Experimentally, very few studies have been conducted on this topic so far. Based on recent drastic advances in beam technologies that have realized intense low-energy positron beams, several attempts are made to experimentally realize magnetically-confined electron-positron plasmas in a laboratory. Because the dipole magnetic field can trap charged particles independent of their charge signs according to the conservation of adiabatic invariants, this configuration is suitable for the confinement of electron-positron plasmas. In RT-1, a superconducting levitated dipole experiment, we have realized confinement of pure electron non-neutral plasma for more than 300 seconds. In a prototype dipole field trap with a permanent magnet operated at NEPOMUC slow positron facility, efficient injection and relatively long trapping of positron beams have been demonstrated. Based on these initial investigations, we plan to create electron-positron plasmas in a compact levitated dipole trap suitable for realizing high-density states of charged particles, to be operated with a pulsed positron source of AIST.

(2) Particle acceleration and transport phenomena due to the wave particle interactions are important research subjects that are common to plasmas in nature and laboratories. At RT-1 we investigate the principles of advanced fusion concept by taking a hint from high-beta plasmas observed around Jupiter. Several similarities are found between the transport properties and self-organization processes of structures caused by the wave particle interactions observed in RT-1 and in natural magnetospheres. In the hot-electron high-beta plasma of RT-1 generated by the electron cyclotron resonance heating, we observed spontaneous excitation of electromagnetic fluctuations in the Whistler wave frequency range, in addition to low-frequency fluctuations that drive the so-called inward diffusion. The fluctuation mode often shows frequency sweeping, which is similar to the planetary chorus mode emission. In the dipole magnetic field configuration of RT-1, electrons are efficiently accelerated by the circularly polarized electromagnetic fields and can take chaotic orbits, which may affect the transport properties of plasmas.

惑星磁気圏と大域的に等価なダイポール磁場を活用した実験室研究の現状と進行中の計画について報告する。東京大学 Ring Trap グループでは、磁気浮上した超伝導コイルにより人工磁気圏を生成し、(1) ダイポール磁場の優れた閉じ込め性能を活用した反物質プラズマの実現や、(2) 磁気圏現象と核融合プラズマの共通課題としての波動粒子相互作用の解明を目指す研究を進めている。

まず、(1) 高エネルギー天体の周辺等に存在すると考えられる電子・陽電子プラズマは、等質量の粒子から構成されるペアプラズマとして、特異的な安定性や波動特性を示すと予測されているが、実験研究の例は少ない。近年、粒子線技術の進展により大強度の低速陽電子ビームが入手可能となり、磁場閉じ込めによる電子・陽電子プラズマの生成プロジェクトが開始されている。ダイポール磁場は、断熱不変量の保存を介して電荷符号に依存しない荷電粒子の捕獲が可能であり、電子・陽電子プラズマに適した閉じ込め配位の一つである。超伝導磁気浮上装置 RT-1 では電子のみの非中性プラズマの 300 秒以上の閉じ込めが実現され、また、低速陽電子施設 NEPOMUC における永久磁石を用いた小型ダイポール装置による実験では、大強度陽電子ビームの高効率入射と捕獲が示された。これらの初期実験結果に基づき、産業技術総合研究所のパルス陽電子源を活用した電子・陽電子プラズマの実現に向け、希少粒子の高密度状態実現に適したコンパクトな磁気浮上ダイポール装置開発を進めている。

次に、(2) 波動との相互作用による粒子の加速や輸送現象は、ジオスペースなどの自然界や実験室のプラズマに共通して重要な研究課題である。RT-1 では、木星周辺に観測される高ベータプラズマをヒントに先進核融合の原理検証を実施しており、各種の波動粒子相互作用を介したプラズマの輸送や構造の自己組織化など、磁気圏と類似した現象が発見された。RT-1 において、内向き輸送を駆動すると考えられる低周波揺動の他に、電子サイクロトロン共鳴加熱により生成した高温電子が主として圧力を担う高ベータプラズマでは、ホイッスラー波帯域の電磁場揺動の自発励起が観測された。揺動は時間的な周波数変動を示し、コーラスモードとの類似性が認められる。RT-1 のダイポール磁場配位において、円偏

波した電磁場により加速される電子の軌道は容易にカオス化し、輸送に影響を与える可能性がある。

S001-24

A 会場 : 11/5 AM2 (10:45-12:30)

11:35~11:50

一様磁化プラズマ中でのホイッスラーモード・トリガードエミッション

#大村 善治¹⁾, 藤原 悠也¹⁾, 野儀 武志¹⁾

(¹⁾ 京大・生存圏, (²⁾ 京大・生存圏, (³⁾ 京大・生存研

Whistler-mode triggered emissions in a homogeneous magnetized plasma

#Yoshiharu Omura¹⁾, Yuya Fujiwara¹⁾, Takeshi Nogi¹⁾

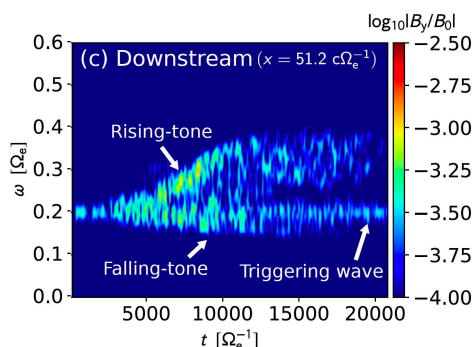
(¹⁾RISH, Kyoto Univ., (²⁾RISH, Kyoto Univ., (³⁾RISH, Kyoto Univ.

We perform a self-consistent one-dimensional electromagnetic particle simulation with a uniform magnetic field and open boundaries [1]. The plasma environment consists of cold electrons, energetic electrons, and immobile ions. The cold electrons are initialized with the bi-Maxwellian distribution function with a small thermal velocity, while the energetic electrons are initialized with subtracted-Maxwellian distribution with relatively large thermal velocities, resulting in a temperature anisotropy. By oscillating external currents with a constant frequency $0.2 f_{ce}$, where f_{ce} is the electron cyclotron frequency, a whistler-mode wave is injected as a triggering wave from the center of the simulation system, and we investigated the process of interactions between the triggering wave and energetic electrons. We find that both rising-tone and falling-tone emissions are triggered through the formation of an electron hole and an electron hill in the velocity phase space consisting of a parallel velocity and the gyro-phase angle of the perpendicular velocities [2]. The rising-tone emission varies from $0.2 f_{ce}$ to $0.4 f_{ce}$, while the falling-tone varies from $0.2 f_{ce}$ to $0.15 f_{ce}$. The generation region of the rising-tone triggered emission starts in the downstream region due to the triggering wave and moves upstream generating new subpackets. The generation region of the falling-tone triggered emission also moves upstream generating new subpackets [3]. The simultaneous formation of the electron hole and hill is identified by separating small and large wavenumber components corresponding to lower and higher frequencies, respectively, by applying the discrete Fourier transformation to the wave forms in space. When multiple waves are present as in the present result, it is essential to separate them in wavenumber and frequency for accurate analysis, and only after the separation, the correct resonant currents and relative gyro-phase angles can be obtained for comparison with the nonlinear wave growth theory. Based on the simulation results of the whistler-mode triggered emissions, we conclude that the mechanism of frequency variation of whistler-mode chorus emissions works even in a uniform magnetic field.

[1] Fujiwara, Y., Nogi, T., & Omura, Y. (2022). Nonlinear triggering process of whistler-mode emissions in a homogeneous magnetic field. *Earth, Planets and Space*, 74 (95).

[2] Nogi, T., Nakamura, S., & Omura, Y. (2020). Full particle simulation of whistler-mode triggered falling-tone emissions in the magnetosphere. *Journal of Geophysical Research: Space Physics*, 125 (10), e2020JA027953.

[3] Nogi, T., & Omura, Y. (2022). Nonlinear signatures of VLF-triggered emissions: A simulation study. *Journal of Geophysical Research: Space Physics*, 127 (1), e2021JA029826.



S001-25

A 会場 : 11/5 AM2 (10:45-12:30)

11:50~12:05

#中村 紗都子¹⁾, 三好 由純²⁾, 小路 真史²⁾, 北原 理弘²⁾

⁽¹⁾IAR&ISEE, ⁽²⁾名大 ISEE

Roles of ion hole and hill in a triggering process of EMIC rising-tone emissions

#Satoko Nakamura¹⁾, Yoshizumi Miyoshi²⁾, Masafumi Shoji²⁾, Masahiro Kitahara²⁾

⁽¹⁾IAR&ISEE, ⁽²⁾ISEE, Nagoya Univ.

Since the first report by Pickett et al., 2010, it has been recognized for the important role of EMIC rising-tone in the magnetospheric dynamics. We have investigated by in-situ observations and simulations, and roughly understood the generation mechanism of its rising-frequency spectrum based on the nonlinear wave growth theory. However, it has still been unclear what causes repetition of rising tones and its fine-structure such as sub-packets. We show EMIC rising tones detected by THEMIS, RBSP, and ARASE, and summarize the feature of its fine structure. We find some patterns in the time evolution of the starting frequency and the repetition period in a series of EMIC rising tones, and the starting frequency of EMIC rising tones gradually decreases below the initial frequency of the triggering wave. We discuss the possible mechanism on the pattern which may be caused by a simultaneous generation of the ion hill and hole. This study may contribute to the further understanding of the nonlinear wave-particle interaction in space plasma.

S001-26

A 会場 : 11/5 AM2 (10:45-12:30)

12:05~12:20

#小谷 翼¹⁾, 樋田 美栄子²⁾, 森高 外征雄²⁾, 田口 聡¹⁾

(¹⁾京大理, (²⁾核融合研

Simulation study of the harmonic structure of lower hybrid wave driven by energetic ions: comparison with observation

#Tsubasa Kotani¹⁾, Mieko Toida²⁾, Toseo Moritaka²⁾, Satoshi Taguchi¹⁾

(¹⁾Graduate school of Science, Kyoto Univ., (²⁾NIFS

In the cold plasma approximation, there are no perpendicularly propagating waves above the lower hybrid resonance frequency. However, unusual waves with an integer multiple of the lower hybrid resonance frequency have been recently observed in the Earth's magnetosphere [Huang et al., 2020, JGR]. These unusual waves propagate perpendicular to the magnetic field with linear polarization. Hereafter, we call these waves the harmonic lower hybrid waves. The excitation mechanism of the harmonic lower hybrid waves has not been fully understood because energetic ions, which can excite the lower hybrid wave, have not been found in the observation.

Using one-dimensional, electromagnetic, particle-in-cell simulations, we report the excitation mechanism and development of the harmonic lower hybrid waves driven by energetic ions. We investigate the parameter dependence, such as the ratio of the electron plasma frequency to the electron cyclotron frequency, on the development of the harmonic lower hybrid waves. We also compare the simulation results with the observation to discuss the condition where the harmonic lower hybrid waves are excited.

S001-27

A 会場 : 11/5 PM1 (13:45-15:30)

13:45~14:00

トラスプラズマ中の高エネルギーイオン分布の飽和現象

#永岡 賢一^{1,4)}, 藤原 大²⁾, 神尾 修治³⁾, 山口 裕之¹⁾

(¹核融合科学研究所,²NTT 宇宙環境エネルギー研究所,³カリフォルニア大アーバイン校,⁴名古屋大学理学研究科)

Saturation of Energetic particle profile in a torus plasma

#Kenichi Nagaoka^{1,4)}, Yutaka Fujiwara²⁾, Shuji Kamio³⁾, Hiroyuki Yamaguchi¹⁾

(¹National Institute for Fusion Science,²NTT Space Environment and Energy Laboratories,³University of California, Irvine,⁴Graduate School of Science,

Experimental studies on the interaction between energetic particles and Alfvén waves in a magnetic confined fusion plasma are presented. A phenomenon is observed in which the pressure gradient of energetic particles in a plasma relaxes when the pressure gradient exceeds a threshold value, which excites Alfvén waves, resulting in real-space transport of energetic particles and relaxation of the pressure gradient [1]. In plasmas that satisfy the resonance condition with Alfvén waves, a saturation of the fast ion pressure gradient is observed, and verification of the physical process that determines the nonlinear saturation level is an issue. In this presentation, we will introduce examples of experimental observations of pressure gradient saturation of energetic particles resulting from wave-particle interactions and discuss attempts to control the saturation level externally.

[1] K. Nagaoka, "Progress of Wave-Particle Interaction Study in High-Temperature Plasmas", J. Plasma Fusion Res. Vol.97, No.5 (2021)281-285.

磁場閉じ込め核融合プラズマ中の高エネルギー粒子とアルベン波の相互作用に関する実験研究を紹介する。プラズマ中に高エネルギー粒子の圧力勾配が、閾値を超えるとアルベン波を励起することで、高エネルギー粒子の実空間の輸送が起こり、圧力勾配を緩和させる現象が観測される [1]。アルベン波との共鳴条件を満たすプラズマでは、この高速イオン圧力勾配が飽和する現象が観測され、非線形飽和レベルを決める物理過程の検証が課題となっている。本発表では、波動粒子相互作用の結果の圧力勾配の飽和現象の実験観測例を紹介し、その飽和レベルを外部から制御する試みについて議論する。

[1] 永岡賢一、「高温プラズマにおける波動粒子相互作用研究の進展」J. Plasma Fusion Res. Vol.97, No.5 (2021)281-285 (http://www.jspf.or.jp/Journal/PDF_JSPF/jspf2021_05/jspf2021_05-281.pdf).

S001-28

A 会場 : 11/5 PM1 (13:45-15:30)

14:00~14:15

#星野 真弘¹⁾

⁽¹⁾ 東大・理

Energy Partition between Thermal and Nonthermal Plasmas during Magnetic Reconnection

#Masahiro Hoshino¹⁾

⁽¹⁾University of Tokyo

The nonthermal particle acceleration during magnetic reconnection remains a fundamental topic in several astrophysical phenomena, such as solar flares, pulsar wind, and magnetars, for more than half a century, and one of the unresolved questions is its efficiency. Recently, nonthermal particle acceleration mechanisms during reconnection have been extensively studied by particle-in-cell simulations, yet it is an intriguing enigma as to how the magnetic field energy is divided into thermally heated plasmas and nonthermal particles. Here, we study both non-relativistic and relativistic magnetic reconnections using large-scale particle-in-cell simulation for a pair plasma and indicate that the production of the nonthermal particle becomes efficient with increasing the plasma temperature. In non-relativistic plasma case, most of the magnetic energy can be converted into the thermal plasma heating, while in the relativistic hot plasma case, the nonthermal particle acceleration becomes dominant rather than the thermal plasma heating. Furthermore, we determine that the heated plasmas by reconnection can be approximated by a kappa distribution function with the kappa index of approximately 3 or less (equivalent to 2 or less for the power-law index), and the nonthermal energy density of reconnection is approximately over 95% of the total internal energy in the downstream exhaust.

S001-29

A 会場 : 11/5 PM1 (13:45-15:30)

14:15~14:30

高出力レーザーを用いた磁気リコネクション実験における電子アウトフローの大域・局所計測

#境 健太郎¹⁾, 蔵満 康浩¹⁾

¹⁾ 阪大・工・電気

Global and local observations of electron outflow in magnetic reconnection using high power lasers

#Kentaro Sakai¹⁾, Yasuhiro Kuramitsu¹⁾

¹⁾Osaka Univ.

Magnetic reconnections are ubiquitous in various space and astrophysical plasmas, which converts the magnetic field energy to the kinetic and thermal energies in plasmas. The microscopic electron dynamics plays an important role in the onset of magnetic reconnection, while the macroscopic magnetic field topology changes. We experimentally investigate magnetic reconnection in laser produced plasmas to study its multiscale nature. We irradiate a thin plastic target with high power laser beams to generate a plasma flow interacting with the externally applied magnetic field. Controlling the strength of the external magnetic field, we magnetize the electrons but not the ions so that only the electrons are directly coupled with the magnetic field. The global images with optical self-emission imaging show the plasmoid and cusp resulting from the reconnection. These structures propagate at the electron Alfvén velocity [1]. The local velocity measurements with collective Thomson scattering show the electron Alfvénic outflow that is not accompanied with the ion outflow [2].

[1] Y. Kuramitsu, et al., Nat. Commun. 9, 5109 (2018).

[2] K. Sakai, et al., Sci. Rep. 12, 10921 (2022).

S001-30

A 会場 : 11/5 PM1 (13:45-15:30)

14:30~14:45

#Law King Fai Farley¹, 安部 勇輝¹, Morace Alessio¹, 有川 安信¹, 森田 大樹², 余語 寛文¹, 尾崎 哲³, 千徳 靖彦¹, Korneev Phillip⁴, 藤岡 慎介¹

(¹ 阪大レーザー研, (² 宇都宮大, (³ 核融合研, (⁴ ロシア国立原子力研究大学

Particle acceleration from semirelativistic magnetic reconnection experiment by petawatt laser

#King Fai Farley Law¹, Yuki Abe¹, Alessio Morace¹, Yasunobu Arikawa¹, Hiroki Morita², Akifumi Yogo¹, Tetsuo Ozaki³, Yasuhiko Sentoku¹, Phillip Korneev⁴, Shinsuke Fujioka¹

(¹ ILE, Osaka U, (² Utsunomiya U, (³ NIFS, (⁴ MPhI, NRNU,

Magnetic reconnection, the process of magnetic field topology rearrangement that results in the conversion of magnetic field energy into kinetic energy of energetic particles, is recently accounted for various phenomena in astronomical plasmas. Examples of such situations include solar phenomena and planetary magnetosphere. In this work, we performed an experimental demonstration of magnetic reconnection under relativistic electron magnetization, where magnetic field energy density is about 100 times of electron rest mass density. This is an intermediate situation between the highly relativistic case in electron-positron pair plasma, in which magnetic reconnection is also accounted for its contribution to gamma-ray flares, and the typical non-relativistic situation mentioned above. In terms of astrophysical settings, this situation shows similarity to plasma in accretion disks of black holes, which also requires an efficient particle acceleration mechanism to fulfill the constraints from recent observations.

In this experiment, the magnetic reconnection plasma was generated by laser-irradiation on the inner surface of a curved target fabricated from a thin metal foil, which produces 2.2 kilo-tesla magnetic field on picosecond time scale. Firstly, we characterized the magnetic field amplitude in the reconnection plasma by proton deflectometry method. After that, we observed a pair of outflow, driven by the reconnection, was accelerated from the irradiated target and particle spectrum in the outflow was measured. A hard ($p = 1.535 \pm 0.015$) power-law non-thermal component was observed in the electron spectrum, which showed consistency with 3-D particle in cell simulation results. Our results reveal the capability of magnetic reconnection as an efficient particle acceleration in semirelativistic magnetized proton-electron plasma.

S001-31

A 会場 : 11/5 PM1 (13:45-15:30)

14:45~15:00

レーザー生成プラズマ中の磁気リコネクションにおける磁気拡散領域の時間・空間分解計測

#森田 太智¹⁾, 松清 修一¹⁾, 諫山 翔伍¹⁾, 前之園 凱夫²⁾, 村本 裕耶²⁾, Yiming Pan²⁾, 富田 健太郎³⁾, 竹崎 太智⁴⁾, 蔵満 康浩⁵⁾, 境 健太郎⁵⁾, 江頭 俊輔⁶⁾, 東 力也²⁾, 高橋 健太²⁾, 有川 安信⁷⁾, 前田 亘佑⁶⁾, 坂和 洋一⁷⁾, 小口 拓哉⁴⁾, 山崎 了⁸⁾, 田中 周太⁸⁾, 佐藤 雄飛⁸⁾, 塩田 珠里⁸⁾

(¹⁾ 九大・総理工, (²⁾ 九大・総理工, (³⁾ 北大・工, (⁴⁾ 富山大・工, (⁵⁾ 阪大・工・電気, (⁶⁾ 阪大・理, (⁷⁾ 阪大・レーザー研, (⁸⁾ 青学・理工

Space-time resolved measurement of magnetic diffusion region of magnetic reconnection in laser-produced plasma

#Taichi Morita¹⁾, Shuichi Matsukiyo¹⁾, SHOGO ISAYAMA¹⁾, Yoshio Maenosono²⁾, Yuya Muramoto²⁾, Pan Yiming²⁾, Kentaro Tomita³⁾, Taichi Takezaki⁴⁾, Yasuhiro Kuramitsu⁵⁾, Kentaro Sakai⁵⁾, Shunsuke Egashira⁶⁾, Rikiya Higashi²⁾, Kenta Takahashi²⁾, Yasunobu Arikawa⁷⁾, Kosuke Maeda⁶⁾, Youichi Sakawa⁷⁾, Takuya Oguchi⁴⁾, Ryo Yamazaki⁸⁾, Shuta Tanaka⁸⁾, Yuhi Sato⁸⁾, Juri Shiota⁸⁾

(¹⁾ Faculty of Eng. Sci., Kyushu Univ., (²⁾ Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, (³⁾ Faculty of Engineering, Hokkaido University, (⁴⁾ Faculty of Engineering, University of Toyama, (⁵⁾ GSE, Osaka Univ., (⁶⁾ Graduate School of Science, Osaka University, (⁷⁾ ILE, Osaka Univ., (⁸⁾ Department of Physical Sciences, Aoyama Gakuin University

Strong magnetic field is spontaneously generated in the interaction of high-power laser with a solid. By the interaction between two ablation plasmas, anti-parallel magnetic field structure is formed. We investigated a magnetic reconnection of these magnetic fields between two plasma plumes. In the present study, we performed experiment with a high-power laser, Gekko, at Osaka University, and we measured plasma parameters in the diffusion region by using laser Thomson scattering method. In the direction perpendicular to the magnetic field, ion-acoustic resonant peaks show different strength, indicating different ion and electron drifts and current sheet formation formed in anti-parallel magnetic field. On the other hand, asymmetric ion-feature with different width is detected in the direction parallel to the magnetic field. This asymmetry can be explained with non-Maxwellian ion velocity distribution as the superposition of low-temperature and slow ions and high-temperature and fast ions, indicating that ion thermalization and acceleration via magnetic reconnection.

In this talk, we will discuss the time and space resolved plasma measurement in the magnetic diffusion region of magnetic reconnection in laser-produced plasma with optical diagnostics such as laser Thomson scattering and self-emission imaging. Also, we will discuss a reconnection rate and energy conversion process from the magnetic field to ion and electron thermal and kinetic energies.

高強度レーザーを固体に照射することでアブレーションプラズマ中に強磁場が自発的に生成される。アブレーションプラズマ同士を相互作用させることでプラズマ間に反平行磁場構造を形成し、磁気リコネクションを検証した。本研究では、大阪大学の大型レーザーである激光を用い、磁気拡散領域に対してレーザートムソン散乱計測を適用した。リコネクション磁場に垂直方向について計測したイオン音波共鳴スペクトルは左右異なる強度分布を示した。これは電子・イオン流速度が異なることを示し、反平行磁場間に形成される電流シートを意味する。一方、磁場に平行方向については、左右非対称なスペクトル幅を示し、これは Maxwellian 分布からずれたイオン速度分布から説明される。低温・低速度イオンと高温・高速度イオンの重ね合わせの速度分布を仮定することで本実験で得られたスペクトルは良く再現され、磁気リコネクションに伴うイオン加熱・加速を計測したものと考えられる。

本講演では、レーザートムソン散乱法や発光イメージング計測を用いて、磁気リコネクションにおける磁気拡散領域のパラメータ変化を検証し、リコネクション率や、磁場から電子・イオンへのエネルギー変換について議論する。

S001-32

A 会場 : 11/5 PM1 (13:45-15:30)

15:00~15:15

#凡 雨萌¹⁾, 松清 修一²⁾, 銭谷 誠司³⁾, 森田 太智⁴⁾

(¹⁾九州大学, (²⁾九大・総理工, (³⁾神戸大学, (⁴⁾九大総理工

Mass ratio dependence of microinstability in a magnetic island formed through magnetic reconnection

#yumeng fan¹⁾, Shuichi Matsukiyo²⁾, Seiji Zenitani³⁾, Taichi Morita⁴⁾

(¹⁾Kyushu Univ., (²⁾Kyushu Univ., (³⁾Kobe U., (⁴⁾Faculty of Eng. Sci., Kyushu Univ.,

Magnetic reconnection is known as an explosive event through which magnetic energy is rapidly converted into the kinetic energy of a plasma. It occurs when anti-parallel magnetic field configuration accompanying a current sheet is realized. When there are two X-lines, a magnetic island is formed so that the particles accelerated near the X-lines are trapped in it. It is known that the accelerated particles drive instabilities inside a magnetic island leading to further acceleration and/or heating. Electron Weibel instability was discussed in Lu et al. (2011) as a mechanism of an instability seen inside a magnetic island in their simulation. However, parameter dependence of the instability has not been studied so far. We investigate the nature of instabilities in a magnetic island especially focusing on ion to electron mass ratio dependence by performing two-dimensional particle-in-cell simulations.

S001-33

A 会場 : 11/5 PM2 (15:45-18:15)

15:30~15:55

太陽放射スペクトルの変動による地球上層大気への影響

#陣 英克¹⁾, 埜 千尋¹⁾, 三好 勉信³⁾, 渡邊 恭子²⁾, 北島 慎之典²⁾, 品川 裕之¹⁾, 藤原 均⁴⁾

(¹⁾ 情報通信研究機構, (²⁾ 防衛大, (³⁾ 九大・理・地球惑星, (⁴⁾ 成蹊大学

Effect of variations in solar radiation spectrum on the Earth's upper atmosphere

#Hidekatsu Jin¹⁾, Chihiro Tao¹⁾, Yasunobu Miyoshi³⁾, Kyoko Watanabe²⁾, Shinnosuke Kitajima²⁾, Hiroyuki Shinagawa¹⁾, Hitoshi Fujiwara⁴⁾

(¹⁾NICT, (²⁾NDA, (³⁾Dept. Earth & Planetary Sci, Kyushu Univ., (⁴⁾Seikei University,

The outermost part of the Earth's atmosphere is called the thermosphere, and its ionized part is called the ionosphere. In those regions, the atmospheric state parameters such as density and temperature vary by tens of percent to by a factor both on short and long terms, and such changes can have influence on satellites' orbits at LEO and on ground-to-satellite radio communications. One of the major sources for the thermospheric and ionospheric variations is the solar radiation. The incident solar EUV/X ray flux acts on different layers of the Earth's atmosphere depending on its wavelength, by heating, dissociating and ionizing the atmospheric particles. On the other hand, the solar radiation flux is generated at different layers of solar atmosphere depending on its wavelength. The connection between both the ends and the resultant variations in the thermosphere and ionosphere have not been fully understood. In this study, we use a whole atmosphere-ionosphere coupled model called GAIA and investigate the effects of variation in the input solar radiation spectrum on the simulated thermospheric and ionospheric variations.

地球大気のもも外側には中性大気領域の熱圏とそれが電離してプラズマ状態となった電離圏が存在する。熱圏と電離圏では、密度や温度などの状態が短期・長期的に数十%から数倍も変動し、低軌道衛星に対する大気抵抗や衛星-地上間の通信電波の伝搬状況を左右するため、宇宙天気の見点で重要な領域とされている。その熱圏・電離圏の変動をもたらす主要因の一つは太陽放射である。太陽から地球大気に入射する X 線・紫外線は、その波長に応じて異なる高度の地球大気の加熱や解離、電離に寄与する。一方、太陽側でも放射光の波長によって太陽の光球からコロナまで異なる領域から発せられることが知られる。この両者すなわち熱圏・電離圏での加熱・電離過程とそれらをもたらす太陽放射源の変動との結びつきはあまり詳細に調べられておらず、十分な理解のためには太陽と地球超高層大気の見専門家の知見が必要と思われる。

本研究では、地球の全大気領域と電離圏プラズマ領域を統合した数値モデル GAIA[Jin et al., 2011] を利用し、GAIA への入力となる太陽放射スペクトルの変動と熱圏・電離圏の変動過程との対応を調べ、太陽放射源との関連を議論する。これまで太陽放射スペクトルとして、太陽電波観測から得られる F10.7 指数と連動する EUVAC モデル [Richards et al., 1994] が広く用いられてきたが、近年 F10.7 だけでなく X 線や太陽紫外光の観測に対応して変動するモデル FISM[Chamberlin et al., 2007; 2008; 2020] が開発されている。

本発表では、FISM を導入した GAIA による地球大気・電離圏のシミュレーションから波長ごとに異なる太陽放射変動の熱圏・電離圏への影響を解析し、太陽研究者との協力により太陽面の活動と熱圏・電離圏の各高度の加熱・電離との対応を議論する。

S001-34

A 会場 : 11/5 PM2 (15:45-18:15)

15:55~16:10

X線天文衛星を用いた地球超高層大気密度鉛直構造の測定～長期トレンドの調査～

#勝田 哲¹⁾, 榎戸 輝揚²⁾, Lommen Andrea³⁾, 森 浩二^{4,7)}, 望月 優子²⁾, 中島 基樹⁵⁾, Ruhl Nathaniel³⁾, 佐藤 浩介¹⁾, Gunter Stober⁶⁾, 田代 信^{1,7)}, 寺田 幸功^{1,7)}, Wood Kent⁸⁾

(¹ 埼玉大学, (² 理化学研究所, (³ ハベフォード大学, (⁴ 宮崎大学, (⁵ 日本大学, (⁶ ベルン大学, (⁷ 宇宙航空研究開発機構, (⁸ コロラド在住

Measuring vertical density profiles of the Earth's upper atmosphere using X-ray astronomy satellites

#Satoru Katsuda¹⁾, Teruaki Enoto²⁾, Andrea Lommen³⁾, Koji Mori^{4,7)}, Yuko Motizuki²⁾, Motoki Nakajima⁵⁾, Nathaniel Ruhl³⁾, Kosuke Sato¹⁾, Stober Gunter⁶⁾, Makoto Tashiro^{1,7)}, Yukikatsu Terada^{1,7)}, Kent Wood⁸⁾

(¹Saitama University, (²RIKEN, (³Haverford College, (⁴University of Miyazaki, (⁵Nihon Universtiy, (⁶University of Bern, (⁷ISAS/JAXA, (⁸Colorado,⁹⁾

We present new measurements of the vertical density profile of the Earth's atmosphere at altitudes between 70 and 200 km, based on atmospheric occultations of the Crab Nebula observed with X-ray astronomy satellites. We established the method by using recent Japanese X-ray astronomy satellites Suzaku and Hitomi (reference 1). After that, we investigated long-term density trends of the Earth's upper atmosphere at altitudes between 71 and 116 km, based on atmospheric occultations of the Crab Nebula observed with X-ray astronomy satellites, ASCA, RXTE, Suzaku, NuSTAR, Hitomi, and NICER. The period covered by our analysis ranges from 1994 to 2022. We take into account variations due to a linear trend and the 11-yr solar cycle using linear regression techniques. We find a negative density trend of roughly -5 %/decade at every altitude. This is in reasonable agreement with inferences from settling rate of the upper atmosphere. In the 100–110 km altitude, we found an exceptionally high density decline of about -12 %/decade. This peak may be the first observational evidence for strong cooling due to water vapor and ozone near 110 km, which was first identified in a numerical simulation by Akmaev et al. (2006, J. Atmos. Sol. Terr. Phys., 68(17), 1879).

References:

1) Katsuda et al. 2021, JGR: Space Physics, 126(4), e28886

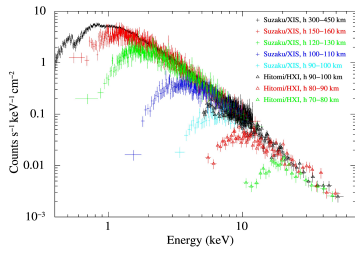
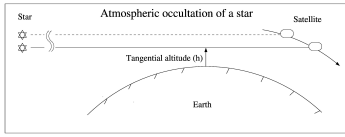
2) Katsuda et al. 2022, JGR: Space Physics, under review

X線天文衛星による地球超高層大気密度計測について紹介する。多くのX線天文衛星は地球低軌道を固定姿勢で周回しており、全観測時間の3割ほど、視線が地球に遮られている。天体が地面に沈む瞬間と地面から出る瞬間、天体からのX線は大気減光を受ける(大気掩蔽現象)。大気密度は地表から上空に向け指数関数的に減少するため、天体が地表に近づくにつれX線の減衰が激しくなる。我々は、この減衰の様子から、地球超高層大気(高度70–200 km)の密度プロファイル測定することに成功した。手始めに、日本のX線天文衛星「すざく」「ひとみ」がカニ星雲を観測した際の大気掩蔽データを使って、密度計測を行い、観測手法を確立した。この解析で得られた密度プロファイルは、概ね標準的な大気密度モデルと一致していたが、高度100 km付近で測定値がNRL-MSISE-00モデルの予想値より数割低いことが判明した。密度モデルを構築する際に参照された観測データが数十年前に取得されたことを踏まえると、地球温暖化に伴う超高層大気の寒冷化・低密化によって、データ(2010頃)とモデル(1970-1980年ごろ)に食い違いが生じたのかもしれない。

そこで我々は、超高層大気密度の長期変動を調査するため、1993年打ち上げの「あすか」衛星から、現在も稼働しているX線天文衛星「NuSTAR」「NICER」まで、合計6つの衛星に搭載された8つの観測機器のデータを包括的に解析した。背景X線源としては、カニ星雲を選定した。カニ星雲はX線天文衛星の標準的な較正用ターゲットであり、全てのX線天文衛星が多数のデータを取得しているため、長期トレンドを追うには打ってつけの天体である。このデータから過去30年間にわたる大気密度の時間変動を調査した結果、上空70-120 kmのほとんどの領域で、0.5%/年のペースで密度が減少していることが明らかになった。この密度低下率は、温室効果ガスの増大に伴う超高層大気の寒冷化・収縮の最新のモデルで説明可能である。さらに我々は、高度100-110 kmにおいて密度減衰率が-12%/10年まで増大することを発見した。この密度減衰ピークは、Akmaev et al. (2006, J. Atmos. Sol. Terr. Phys., 68(17), 1879)らのシミュレーションで最初に指摘された水蒸気とオゾンに起因する構造と考えられる。以上の結果は2本の論文にまとめられている:

1) Katsuda et al. 2021, JGR: Space Physics, 126(4), e28886

2) Katsuda et al. 2022, JGR: Space Physics, under review



S001-35

A 会場 : 11/5 PM2 (15:45-18:15)

16:10~16:25

双極子磁場におけるフィードバック不安定性の線形安定性解析

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Linear stability analysis of feedback instability in dipole magnetic field

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The aurora observed in the ionosphere has curtain-like or vortex structures. The feedback instability in a magnetosphere-ionosphere coupling system is a theoretical model explaining such structure formation of the aurora. The feedback instability occurs when the fluctuation in the ionosphere resonates with the Alfvén wave in the magnetosphere via the geomagnetic field. From the satellite observations, it is shown that the Alfvén wave in the magnetosphere is categorized into the kinetic Alfvén wave, where effects such as the electron Landau damping, the electron inertia effect, and the finite ion Larmor radius effect are important. In our preceding study, a dispersion relation of the kinetic Alfvén wave derived from the gyrokinetic model in the magnetosphere approximated by a slab magnetic field is used to construct a Landau closure, and a gyrofluid model of the magnetosphere is introduced. It is desirable to extend the background magnetic field to a more realistic dipole magnetic field. However, with such an extension, it is not possible to derive the dispersion relation of the kinetic Alfvén wave from the gyrokinetic model due to the non-uniformity along the magnetic field, and the gyrofluid model cannot be introduced. Therefore, we need to directly deal with the gyrokinetic model. In this study, we revisit the linear stability analysis of the feedback instability using the reduced MHD model. We use a linear dipole magnetic field, i.e., a coordinate system with equal intervals along the magnetic field is introduced, where the curvature effect is neglected. The linear stability in the presence of the non-uniformity of the Alfvén velocity along the magnetic field line is investigated as an eigenvalue problem and an initial value problem. As a result, it is found that the linear growth rate is enhanced and the frequency becomes higher in comparison with a case with uniform Alfvén velocity. In the presentation, we will also discuss how to extend the magnetosphere model from the reduced MHD model to the gyrokinetic model.

電離圏において観測されるオーロラは、カーテン状や渦状の構造を持つ。このようなオーロラの構造形成を説明する理論の一つが、磁気圏-電離圏結合系におけるフィードバック不安定性である。フィードバック不安定性は、電離圏の揺らぎと電離圏のアルフベン波が地磁気を介して共鳴する場合に発生する。観測衛星によるデータからは、磁気圏のアルフベン波は、電子ランダウ減衰、電子慣性効果、有限イオンラーマ半径効果などの効果が重要となる、運動論的アルフベン波であることが示されている。我々の先行研究においては、スラブ磁場であると近似された磁気圏において、ジャイロ運動論モデルから導出された運動論的アルフベン波の分散関係を用いてランダウクロージャを構成し、ジャイロ流体モデルを導入した。背景磁場をより現実的な双極子磁場へと拡張することが望ましい。しかし、このような拡張を行うと、磁力線に沿った非一様性のため、ジャイロ運動論モデルから運動論的アルフベン波の分散関係を導出することができなくなり、ジャイロ流体モデルを導入することができなくなる。従って、ジャイロ運動論モデルを直接取り扱う必要がある。本研究においては、簡約化 MHD モデルを用いたフィードバック不安定性の線形安定性解析を再訪問した。ただし、磁力線に沿った等間隔の座標系を導入して曲率の効果を無視する直線双極磁場を用いた。磁力線に沿ったアルフベン速度の非一様性が存在するときの線形安定性を、固有値問題および初期値問題として調べた。解析の結果、アルフベン速度が一様である場合に比べて、線形成長率が促進されること、および、周波数が高くなることを見出された。講演では、磁気圏モデルを簡約化 MHD モデルからジャイロ運動論モデルへ拡張する方法についても議論を行う。

S001-36

A 会場 : 11/5 PM2 (15:45-18:15)

16:25~16:40

磁気座標系を用いた磁気圏-電離圏結合系におけるフィードバック不安定性の非局所解析

#榊 剛志¹⁾, 渡邊 智彦¹⁾

¹⁾ 名大・理・物理

Nonlocal analysis of the feedback instability in the magnetosphere-ionosphere coupling system using a flux coordinate system

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A variety of simulation studies of auroral structure formation through the feedback instability in the magnetosphere-ionosphere coupling (M-I coupling) system have been performed. The local analysis, formulating the magnetospheric dynamics by means of the reduced magnetohydrodynamics (MHD) equations, have revealed that the auroral vortex structure develops and makes transition to a turbulent state because of nonlinear effects. However, no global analysis dealing with the time evolution of auroral fine structures has been conducted, and the previous studies have been limited to discussions on characteristics of nonlocal development of auroral arcs (Watanabe+, JGR 1993, Hasegawa+, JGR 2010).

In order to study the auroral dynamics in the global M-I coupling, we have developed the flux coordinates adapted to a spherical surface boundary, combining two coordinate systems, that is, the non-orthogonal dipole coordinates (Lysak, JGR 2004) and the modified dipole coordinates (Kageyama+, Comput Geosci 2006). By means of the new coordinate system, we have performed linear analyses of the feedback instability in the dipole field configuration. It is found that the initial density perturbation given on the ionosphere propagates with the group velocity, while satisfying the local dispersion relation, and that the growth of the auroral wave packet is saturated during the propagation on the ionosphere because of the nonuniform field line length. In addition, we have extended the linear analysis to cases with a finite longitudinal wavenumber, and identified the feedback instability growth. Extensions incorporating nonlinear effects will also be discussed in the presentation.

これまで磁気圏-電離圏結合系 (M-I 結合系) フィードバック不安定性によるオーロラ構造形成のシミュレーション研究が数多く行われてきた。磁気圏を簡約化磁気流体方程式によって定式化した局所的な解析 (Watanabe+, NJP 2016)) では、非線形効果によって渦構造が発達し、乱流状態へ遷移することが示された。一方で、オーロラの微細構造の時間変化を取り扱った大域的な解析は行われておらず、オーロラアークの非局所的な発達特性についての議論にとどまっている (Watanabe+, JGR 1993, Hasegawa+, JGR 2010)。

M-I 結合系におけるオーロラ発達の大域的なダイナミクスを説明するために、非直交双極子座標 (Lysak, JGR 2004) と修正双極子座標 (Kageyama+, Comput Geosci 2006) を元に、球面適合磁気座標系を開発した。また、その座標系を用いて双極子磁場配位の下でフィードバック不安定性の解析を行なった。電離層上に与えた密度の初期揺動は局所分散関係を満たしながら群速度を持って伝播し、不安定性の成長は磁力線長不均一性の効果で減衰することを確認した。さらに、有限の経度方向の波数を持つ場合についても拡張を行い、フィードバック不安定性の成長を同定した。講演では、非線形効果を取り入れた拡張についても議論する。

S001-37

A 会場 : 11/5 PM2 (15:45-18:15)

16:40~16:55

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Development of Quantum Algorithm for Clarifying Auroral Electron Acceleration Mechanism by Collisional Boltzmann-Maxwell Equation

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The magnetosphere-ionosphere coupling system, where auroras are generated, is characterized by the coupling of high magnetic field weak ionized gas system and collisionless plasma system through magnetic field lines, and the plasma density gradient, etc. occurs on a much smaller scale than in MHD, requiring first principles equations that can be applied to multiple scales. In the space plasma physics research field, including auroral electron acceleration mechanism research, studies using kinetic equations such as the Vlasov equation (collisionless Boltzmann equation), which follows the motion of 3-D plasma particles with a 6-D state distribution function (e.g. [Shi. R. et al.,2018]), have become popular owing to advances in computer technology. To reproduce the auroral electron acceleration mechanism in a magnetosphere-ionosphere coupling system, collisional interactions between particles as well as three-dimensional wave-particle interactions are essential. However, high-order numerical calculations of the collisional Boltzmann equation, first principles method for describing them, are not realistic even with state-of-the-art supercomputers due to the huge computational cost.

Recently, advancements in quantum computer research have shown that quantum algorithms can provide exponential speedups compared to classical algorithms (e.g., P. W. Shor, 1994). For the solution of advection-diffusion equations, the superiority of quantum algorithms for Navier-Stokes equations has also been demonstrated (Budinski Lj., 2021). It shows that by using a high-dimensional solution space treated as a quantum state, speedups can be expected and multiple types of simulations can be performed without the need for additional quantum gates. At the same time, however, it also shows that the algorithm can only handle relatively simple collisionless and uniform force field categories. We have developed a quantum algorithm for the collisional Boltzmann-Maxwell equation and applied it to the magnetosphere-ionosphere coupling system, thus unraveling all aspects of the auroral electron acceleration mechanism. In this presentation, We integrate the Splitting algorithm (C.Z. Cheng and G. Knorr, 1976] of the classical Vlasov solution based on the framework of the quantum algorithm for the Navier-Stokes equations (Budinski Lj., 2021) and optimize the collisionality term to obtain the collisional An attempt to construct a quantum algorithm for the Boltzmann-Maxwell equations is discussed.

オーロラが発生する磁気圏-電離圏結合系は、強磁場弱電離気体系と無衝突プラズマ系が磁力線を通じて結合している領域であり、プラズマ密度勾配等が MHD よりも遥かに小さいスケールで生じているため、マルチスケールに対応可能な第一原理的方程式を要求する。オーロラ電子加速機構研究を含めた宇宙プラズマ物理分野では、計算機の発達に伴い 3 次元プラズマ粒子の運動を 6 次元状態分布関数で追う Vlasov 方程式 (無衝突 Boltzmann 方程式) などの運動論的方程式を用いる研究 (e.g., Shi. R. et al.,2018) が主流となりつつある。磁気圏-電離圏結合系のオーロラ電子加速機構を再現するには、3 次元波動粒子相互作用に加えて粒子間の衝突作用も不可欠である。しかし、それらを第一原理的に記述する衝突性 Boltzmann 方程式の高次数値計算には莫大な計算負荷がかかるため、現代のスーパーコンピュータを持ってしても現実的ではない。

近年、量子コンピュータ研究の進歩により、量子アルゴリズムは古典的アルゴリズムと比べて指数関数的な高速化をもたらす事が示された (e.g., P. W. Shor, 1994)。移流-拡散方程式の解法についても、ナビエ-ストークス方程式の量子アルゴリズムの優位性が明らかにされている (Budinski Lj.,2021)。これによると、高次元の解空間を量子状態として扱うことで高速化が期待でき、量子ゲートを追加することなく複数種のシミュレーションが可能となる。しかしながら、同時に比較的単純な無衝突かつ均一力場の範疇でしか扱えないアルゴリズムであることも示されている。我々は、衝突性 Boltzmann-Maxwell 方程式の量子アルゴリズムを開発し、磁気圏-電離圏結合系に適用することで、オーロラ電子加速機構の全容解明を目指した研究を進めている。本講演では、「ナビエ-ストークス方程式の量子アルゴリズム (Budinski Lj.,2021) の枠組みを基に古典的 Vlasov 解法の Splitting アルゴリズム (C.Z. Cheng and G. Knorr, 1976] を融合し、衝突項を最適化することで、衝突性 Boltzmann-Maxwell 方程式の量子アルゴリズムを構築する試みについて議論する。

S001-38

A 会場 : 11/5 PM2 (15:45-18:15)

16:55~17:20

MAVEN 衛星による火星プラズマダイナミクスの観測と今後の展望

#原田 裕己¹⁾

¹⁾ 京大・理

MAVEN Observations of Plasma Dynamics at Mars and Future Directions

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As Mars lacks an intrinsic global magnetic field of internal dynamo origin, the upper atmosphere of Mars interacts directly with the solar wind. Consequently, the near Mars space provides a unique plasma environment characterized by (i) small spatial dimensions of the entire interaction region, (ii) multi-component plasmas consisting of a mixture of plasma of solar wind origin and heavy ions and photoelectrons of ionospheric origin, (iii) complex magnetic field morphology and topology generated by contribution from the interplanetary magnetic field and crustal magnetization of Mars, and (iv) a wealth of dynamic plasma phenomena driven by the ever-changing upstream solar wind and rotation of the crustal magnetic fields with the planetary body.

Since the orbit insertion in 2014, the MAVEN spacecraft has been obtaining high quality data with its comprehensive plasma package. The simultaneous measurements of charged particles and fields by MAVEN have greatly advanced our understanding of the plasma environment and aeronomy of Mars.

In this talk, I review recent advances in our understanding of the plasma dynamics at Mars with a particular focus on MAVEN observations. I first provide a brief overview of the Martian plasma environment, followed by a series of topical reviews on recent MAVEN observations of plasma processes such as magnetic reconnection and wave-particle interaction. I conclude with a summary of current understanding and discussion on future directions.

S001-39

A 会場 : 11/5 PM2 (15:45-18:15)

17:20~17:45

宇宙プラズマ観測用質量分析装置の開発：太陽系探査への展開

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Development of Mass Spectrometer for Space Plasma Observation and Solar System Exploration

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(¹⁾Osaka Univ., (²⁾ISAS, (³⁾ISAS/JAXA, (⁴⁾The University of Tokyo, (⁵⁾RIKEN BDR

In the interplanetary space of the solar system, supersonic plasma (solar wind) blowing from the sun is dominant, and each planet and moon in the solar system is affected by it in its own way. As a result, plasma phenomena such as shock and magnetic reconnection are formed in a wide range of parameter space. Thus, the solar system has been treated as a "natural" giant experimental facility for plasma research, an ideal location for in-situ observations by spacecraft. Since the establishment of spacecraft technology, many spacecraft plasma observation programs have been carried out, and plasma measurement technology has progressed along with the research of the space plasma, extending the observation area from the near-Earth to the inner planets and deep space.

In the charged-particle measurement of in-situ plasma observation, it is required to obtain three-dimensional velocity distribution functions of electrons and ions with appropriate resolution at first. However, solar wind ions contain not only H⁺ but also He⁺⁺ and multi-charged heavy ions, although their abundance ratios are small. Therefore, mass spectrometers have been used in plasma observation programs from a relatively early stage. Plasma observations in the lunar and planetary neighborhoods have revealed that many kinds of heavy ions are flying around, and the importance of mass spectrometers has only increased.

In in-situ observations of plasmas, mass spectrometry is first of all important to capture the plasma physics accurately. Energy analysis alone treats everything as H⁺, which leads to errors in moment calculations, etc., depending on the ratio of heavy ions present. It has also been reported that different acceleration and heating occurs depending on the ion species (mass) in the interaction with the surrounding waves.

The second importance of mass spectrometry is to know the origin of the plasma. In planetary (magnetospheric) observations, mass information plays a major role in identifying the entry of solar wind plasma into the magnetosphere and the ejection of planetary plasma into the solar wind region (atmospheric escape).

Here, we introduce the principles of mass spectrometers onboard spacecraft and their scientific results, including KAGUYA (Moon), BepiColombo/MIO (Mercury), and Arase (Earth radiation belt), in which we have participated from instrument development. We are also developing high-resolution mass (isotope) spectrometers to elucidate the age and origin of materials and the evolution of atmosphere, based on our past development experience. We will introduce mass spectrometers for Mars Moons eXploration, Comet Interceptor, and LUPEX.

太陽系惑星間空間では太陽から吹き付ける超音速プラズマ（太陽風）が支配的であり、太陽系を構成する月惑星はそれぞれ独自の影響を受けている。その結果、広範囲に及ぶパラメータ空間で衝撃波や磁気リコネクション等のプラズマ現象が引き起こされているため、太陽系はプラズマ研究において「天然の」巨大実験施設として宇宙機による「その場 (in-situ)」観測を行う絶好の場所として扱われてきた。宇宙機技術が確立されて以来数多くの宇宙機によるプラズマ観測計画が実施され、研究と共にプラズマ計測技術も進展し、観測領域は地球近傍から内惑星や深宇宙へと広がっていった。

プラズマ「その場」観測のうち荷電粒子計測では電子・イオンの三次元速度分布関数を適切な分解能で取得することが始めに求められる。しかしながら、太陽風イオンには H⁺ に加えて He⁺⁺ も存在し、存在比は僅かだが酸素等の重イオンも混在している。そのため、プラズマ観測計画では比較的早い段階から質量分析器も利用されてきた。月惑星近傍の観測では多くの種類の天体起源重イオンが飛び交っている状況も明らかになり、質量分析器の重要性は高まる一方となった。

プラズマの「その場」観測において質量分析は、第一にプラズマ物理を正確に捕捉するために重要である。エネルギー分析のみの場合は全てを H⁺ として処理するため、モーメント計算などで重イオンの存在比に応じた誤差が生じてしまう。波動との相互作用においてイオン種（質量）に依存して異なる加速加熱が起きていることも報告されている。

質量分析の第二の重要性としてはプラズマの起源を知ることが挙げられる。惑星近傍（磁気圏）での観測では、太陽風プラズマの惑星圏への侵入や惑星起源プラズマの太陽風領域への放出（大気散逸）の同定において、質量情報が大きな役割を果たしている。

ここでは、これまでの太陽系探査の中でプラズマ観測衛星に搭載された質量分析器の原理やその科学成果を、私たちが機器開発から参加した「かぐや」（月）、「ベピコロombo/MMO」（水星）、「あらせ」（地球放射線帯）、などを例に紹介する。また、私たちは太陽系探査計画への展開として、天体物質の年代・起源、天体大気の進化の解明を目的とした高分解能質量（同位体）分析器も現在開発中である。搭載を予定している将来計画 Mars Moons eXploration, Comet Interceptor, LUPEXなどを例として紹介する。

S001-40

A 会場 : 11/5 PM2 (15:45-18:15)

17:45~18:00

「ひさき」衛星による惑星間空間のヘリウム光学観測

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EUV observation of neutral helium distribution in interplanetary space by Hisaki

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Interstellar medium flows into the heliosphere due to relative motion of the heliosphere and interstellar medium as interstellar wind. The main components of interstellar medium are neutral hydrogen and helium, and neutral particles can penetrate the heliosphere beyond the heliopause. Once neutrals are ionized by the solar ultraviolet light in the heliosphere, they are picked up by the solar wind and return back to the heliopause. Only neutral helium, however, can penetrate deep near the sun, because the ionization rate is low due to the high ionization energy.

The motion of neutral particles in the heliosphere is determined by solar gravity and solar radiation pressure. The orbits of helium atoms show Keplerian motions because the term of radiation pressure can be negligible. As a result, dense regions are formed on the downwind side of the interstellar wind. This is called a helium cone. The neutral helium distribution in the helium cone is dependent on the velocity and direction of the interstellar wind and the density and temperature of helium atoms in the interstellar medium. Although optical observation of neutral helium is a traditional study that has been done since the 1970s, it is a valuable method because it is possible to estimate the parameters of interstellar medium from the observation in interplanetary space.

The "Hisaki" (SPRINT-A) satellite has an extreme ultraviolet spectrometer to detect resonant scattering of helium atoms in interplanetary space. It is noted, however, that the resonant scattering emission is absorbed by the neutral helium in earth's exosphere, where the "Hisaki" orbit is located. By considering the Doppler effect, it is possible to estimate the speed and temperature of interplanetary space helium atoms. We will compare and discuss the differences between the results of EUVE satellite observations (Vallerga+2004) and of the HISAKI satellite.

太陽圏と星間物質には相対速度があり、星間物質が星間風として太陽圏に衝突している。星間物質の主成分は水素とヘリウムであり、そのうち中性成分はヘリオポーズを超えて太陽圏に侵入することが可能である。太陽圏内で太陽の紫外線を受けてイオン化すると太陽風にヒックアップされヘリオポーズへ戻されるが、イオン化エネルギーの高いヘリウムはイオン化率が低く、ほとんどが中性のまま太陽近傍にまで深く侵入することができる。

太陽圏内での中性粒子の軌道は太陽重力と太陽光放射圧によって決まるが、放射圧の項はほとんど無視できるためヘリウム原子はケプラー運動をする。その結果、太陽の星間風の風下側に密度の濃い領域が形成され、ヘリウムコーンと呼ばれる。ヘリウムコーンのヘリウム分布は、星間風の速さと方向、星間空間でのヘリウム原子の密度と温度によって決定づけられる。1970年代から実施されている伝統的な研究方法であるが、惑星間空間に滞在しながら星間物質のパラメータ推定が可能であり、貴重な観測方法である。

「ひさき」(SPRINT-A)衛星は極端紫外分光装置を搭載しており、惑星間空間に分布するヘリウム原子の共鳴散乱光を検出することが可能である。しかしながら、地球外圏中を飛翔しているため、その共鳴散乱光は地球外圏の中性ヘリウムに吸収される。ドップラー効果を考慮することにより、惑星間空間ヘリウム原子の移動速度、温度などを推定することが可能となる。過去のEUVE衛星の観測結果(Vallerga+2004)と、「ひさき」衛星の観測結果を比較し、その差異を議論する。

S001-41

A 会場 : 11/5 PM2 (15:45-18:15)

18:00~18:15

月面近傍プラズマ・静電気環境研究の最近の動向と今後の展望

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Recent Progress of the Lunar Plasma and Electrostatic Environment Research and Future Prospects

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Mission preparation for lunar exploration using landers has been rapidly increasing, and strong demand should arise toward precise understanding of the electrostatic environment. The lunar surface, which has neither a dense atmosphere nor a strong magnetic field, gets charged electrically by the collection of surrounding charged particles of the solar wind or the Earth's magnetosphere. As a result of the charging processes, the surface regolith particles behave as "charged dust grains". Dust particles have been suggested to have adverse effects on exploration instruments and living organisms during the lunar landing missions, and their safety evaluation is an issue to be solved for the realization of sustainable manned lunar explorations. It is necessary to develop comprehensive and organized understanding of lunar charging phenomena and the electrodynamic characteristics of charged dust particles.

It is widely accepted that the surface potential of the lunar dayside is, "on average", several to 10 V positive due to photoelectron emission in addition to the solar wind plasma precipitation. Recent studies, however, have shown that insulating and rugged surfaces of the Moon tend to make positive and negative charges separated and irregularly distributed, and intense and structured electric fields can be formed around them. This strong electric field lies in the innermost part of the photoelectron sheath and may contribute to mobilizations of the charged regolith particles. Since this strong electric field develops on a spatial scale of less than the Debye length and can take various states depending on the lunar surface geometry, it is necessary to update the research approach. In this paper, we will discuss the direction of the near-surface plasma, electrostatic, and dust environment for upcoming lunar landing missions.

着陸機を用いた月探査計画に向け、月面近傍の静電気環境を精確に理解する必要性が高まっている。濃い大気や強い磁場を持たない月の表面は太陽風や地球磁気圏内のプラズマの衝突により帯電し、表層のレゴリス粒子は「帯電ダスト」としての振る舞いを発現する。ダスト粒子は月着陸時の探査機器や生体への悪影響が示唆されており、その安全性評価は持続的な有人月探査実現に向けて解決すべき課題として挙げられている。このことから月面帯電現象と帯電ダストの電気力学的特性に関してこれまでに得られている学術的知見を整理し、その理解を体系化する必要がある。

月昼側の表面電位は太陽風プラズマの降下に加えて光電効果による電子放出が加わることにより、平均的には数 V~10 V の正電位になることが広く知られている。しかし近年の検討により、月面のように絶縁性の凹凸表面上には、正と負の電荷が分離した状態で不規則に分布し、その間に強力かつ複雑な構造を持つ電場が発生していることを示す結果が得られている。この強電場が一般によく知られたプラズマシースの最深部に横たわっており、表層の帯電レゴリス駆動に深く関与している可能性がある。この強電場はデバイ長未満の空間スケールで発達しており、また月面形状に依存して多様な状態をとり得るため、研究アプローチのアップデートを含めた検討が必要である。本発表では本格的な月着陸探査を見据えた月面近傍プラズマ・静電気・ダスト環境の方向性について議論を行う。

S001-42

A 会場 : 11/6 AM1 (9:00-10:30)

09:00~09:25

#松本 仁¹⁾

¹⁾ 慶應義塾大学理工学部

Role of helicities in core-collapse supernova explosions

#Jin Matsumoto¹⁾

¹⁾ KiPAS, Keio University

Massive stars explode at the final phase of their evolution. These explosions are called core-collapse supernovae (CCSNe) and are very energetic and bright events in the Universe. A shock wave is excited after the bounce of the core due to the gravitational collapse of the massive star. The explosion occurs when this outwardly propagating shock wave reaches the surface of the massive star. However, it stalls in the Fe core because of the ram pressure for the shock surface in the upper stream. Although the neutrino-heating is considered to be a key process to explode the massive star, the explosion mechanism of the CCSN is not completely understood yet. In this process, neutrinos from a protoneutron star that is born at the center of the massive star after the bounce heat the matter behind the stalled shock wave. The turbulence behind the shock that originates from convection due to the negative gradient of the entropy and/or hydrodynamic instabilities drastically enhances the efficiency of the neutrino-heating. This is because if the turbulence fully develops, the matter is effectively exposed by neutrinos and can gain substantial thermal energy to overcome the ram pressure due to the mass accretion. Helicities may play an important role in the properties of the turbulence and then the explosion itself.

Our group has investigated the impact of the magnetic field on the explosion mechanism of CCSN through magnetohydrodynamics simulations with spectral neutrino transport. We have performed three-dimensional simulations for the evolution of non- and slowly-rotating stellar cores focusing on the difference in the magnetic field of the progenitors. We find that the neutrino-driven explosion occurs in both strong and weak magnetic field models. The neutrino heating is the main driver for the explosion in our models, whereas the strong magnetic field supports the explosion. In this presentation, we will introduce our results focusing on the role of helicities and magnetic fields.

S001-43

A 会場 : 11/6 AM1 (9:00-10:30)

09:25~09:40

人工的な球偏波アルヴェン擾乱の生成について

#成行 泰裕¹⁾

¹⁾ 富山大・教育学系

On generating synthetic spherically polarized Alfvenic fluctuations

#Yasuhiro Nariyuki¹⁾

¹⁾ Faculty of Education, Univ. Toyama

Spherical Alfvenic fluctuations in the solar wind have been investigated over the past quarter century [Tsurutani et al, JGR, 2018; and references therein]. Magnetic switchbacks, which is now being watched with interest by recent observations of Parker Solar Probe (PSP), also indicate the spherical Alfvenic motion [e.g., McManus et al, ApJ, 2022]. The spherical Alfven wave is an exact solution of ideal MHD system and generating synthetic data of such fluctuations has also been investigated [e.g., Primavera et al, ApJ, 2019; Valentini et al, ApJ, 2019; and references therein]. In this presentation, we revisit the way of generating synthetic spherically polarized Alfvenic fluctuations. It is shown that arc-polarized waves[e.g., Vasquez, JGR, 1996; DelZanna, GRL, 2001], which is a class of spherical Alfven waves, with nonmonochromatic spectra can be generated in several ways. We also discuss Langevin modeling of particles which describes the deviation from the ideal Alfvenic state.

S001-44

A 会場 : 11/6 AM1 (9:00-10:30)

09:40~09:55

宇宙再電離期における宇宙線による磁場生成

#横山 将汰¹⁾, 大平 豊¹⁾

(¹⁾ 東大, (²⁾ 東大)

Magnetic Field Generation Induced by Cosmic Rays at Cosmic Dawn

#Shota Yokoyama¹⁾, Yutaka Ohira¹⁾

(¹⁾The University of Tokyo, (²⁾U. Tokyo)

Magnetic fields are known to pervade the current Universe: galaxies and clusters of galaxies commonly have magnetic fields of micro-gauss level. However, the origin of large-scale magnetic fields is not fully understood. Here, we focus on the role of cosmic rays on the magnetic field generation in the early Universe. Cosmic rays (CRs) are high-energy charged particles and are known to have a significant influence on the plasma environment in the current Universe: they can generate and amplify magnetic fields and alter the degree of ionization. Although the origin of CRs is also a mystery, a recent study suggests that the first generation of CRs is produced in supernova remnants of the first stars. Based on this expectation, we discuss the magnetic field generation induced by CRs at cosmic dawn, that is, the epoch where the formation of astrophysical objects such as stars and galaxies begins and they start to reionize the Universe.

We propose a new mechanism to generate magnetic fields: the Biermann battery driven by resistive heating induced by streaming CRs. We estimate the strength of magnetic fields achieved by this mechanism and show that it is sufficient to be the "seeds" of magnetic fields in the current galaxies. We compare this mechanism to the previously proposed ones. We conclude that our new mechanism works efficiently in relatively small-scale, low-temperature, and strongly ionized regions.

現在の宇宙において、磁場はいたるところに存在し、銀河や銀河団ではマイクロガウス程度の磁場が普遍的に観測されている。しかし、磁場の起源の理解は不十分である。本講演では宇宙線が初期宇宙での磁場生成に果たす役割を議論する。宇宙線とは高エネルギーの荷電粒子であり、現在の宇宙では、磁場を生成・増幅したり電離度を変えたりとプラズマ環境に大きな影響を及ぼすことが知られている。宇宙線の起源もまた未解明であるが、最近の研究では初代星の超新星残骸において最初の宇宙線が生成されるという可能性が提案された。この可能性に基づいて、我々は宇宙再電離期における、宇宙線による磁場生成に注目する。

我々は、宇宙線が伝播することで生じる抵抗性加熱により Biermann battery 効果が駆動されるという、新しい磁場生成過程を提案する。この過程により生成する磁場強度を見積もり、それが現在の銀河磁場の種として十分であることを示す。さらに先行研究で提案された他の磁場生成過程との比較を行い、新しい磁場生成過程が比較的小スケールで、温度が低く、電離度の高い環境で有利に働くことを示す。

S001-45

A 会場 : 11/6 AM1 (9:00-10:30)

09:55~10:10

#寺境 太樹¹⁾, 天野 孝伸²⁾

(¹ 東大, ² 東大)

Role of magnetized electrons in Weibel-dominated collisionless shocks

#Taiki Jikei¹⁾, Takanobu Amano²⁾

(¹UTokyo, ²Univ. Tokyo)

It is known that Weibel instability is the dominant instability in high Mach number collisionless shocks. These Weibel-dominated shocks are promising candidates for cosmic ray accelerators and have been studied extensively by theory, simulation, and laser experiments.

Since the kinetic energy is sufficiently larger than magnetic energy, most studies ignore the background magnetic field. However, PIC simulation results of collisionless shocks, in which a finite background magnetic field is imposed, show that the shock dynamics depend on background magnetic field strength. Whether the electron is magnetized or not could drastically change the magnetic field structure and electron heating efficiency in linear and nonlinear evolution.

In this study, we investigate the Alfvén Mach number dependence on the ion Weibel instability by theory and 2D PIC simulations. The magnetized electrons increase the growth rate of the Weibel magnetic field, especially at long-wavelength and near parallel propagation angles. In nonlinear stages, the magnetized electrons create a strong beam-aligned magnetic field which leads to spontaneous magnetic reconnection in the nonlinear stage, which was found in previous 2D shock simulations.

By performing 2D PIC simulations with periodic boundary conditions, we confirmed the larger magnetic field amplification, reconnection, and more efficient electron heating in the Weibel instability with magnetized electrons.

S001-46

A 会場 : 11/6 AM1 (9:00-10:30)

10:10~10:25

高エネルギー原子核衝突におけるプラズマ物理学的課題：磁気流体力学の応用

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Plasma physics issues in high-energy heavy-ion collisions: Applications of magnetohydrodynamics

#Takahiro Miyoshi¹⁾, Kouki Nakamura²⁾, Kei Nishida³⁾, Chiho Nonaka^{1,2)}, Hiroyuki Takahashi⁴⁾

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Quarks and gluons are fundamental constituents of matter and are normally confined within hadrons by the strong interaction. However, quantum chromodynamics which is the theory of the strong interaction predicts that, in the very early universe with extremely high temperature, the quarks and gluons were deconfined and freely moved exceeding the size of the hadrons. This extreme state of matter is called as quark-gluon plasma (QGP).

High-energy heavy-ion collisions are a unique experiment producing states above the critical temperature required for the phase transition to the QGP. Indeed, huge international collaborations at the Relativistic Heavy Ion Collider (RHIC) or the Large Hadron Collider (LHC) succeeded in creating the QGP. Those experiments suggested that the dynamics of the QGP is described by relativistic hydrodynamics with a very small viscosity. However, the detailed space-time evolution of the high-energy heavy-ion collisions is still unclear. In this study, we discuss plasma physics issues in the high-energy heavy-ion collisions, and aim to develop an interdisciplinary field of plasma physics and high-energy physics.

In the high-energy heavy-ion collisions, extremely strong magnetic fields are generated since charged particles pass each other at nearly the speed of light, and the fields may affect the dynamics of the QGP. Therefore, this talk focus on applications of magnetohydrodynamics (MHD). In particular, we will briefly present our projects, an analysis of chiral MHD describing the dynamics of chirally imbalanced matter and an attempt to apply relativistic resistive MHD to the high-energy heavy-ion collisions.

クォークとグルーオンは物質の基本的な構成要素であり、通常、強い相互作用によってハドロン内部に閉じ込められている。しかし、超高温状態の極初期宇宙においては、クォーク、グルーオンは閉じ込めから解放され、ハドロンのサイズを超え自由に移動し得ることを、強い相互作用を支配する量子色力学は预言する。この極限的な物質状態をクォーク・グルーオンプラズマ (QGP) と呼ぶ。

高エネルギー原子核衝突は、QGP 相への相転移に必要な臨界温度以上の超高温状態を作り出す唯一の実験手段である。実際に、相対論的重イオン衝突型加速器 (RHIC) や大型ハドロン衝突型加速器 (LHC) を利用した国際共同実験によって QGP の生成に成功した。これらの実験から、QGP のダイナミクスは粘性の極めて小さい相対論的流体力学によって支配されることが示唆された。しかし、高エネルギー原子核衝突の時空間発展の詳細は未解明である。そこで本研究では、高エネルギー原子核衝突におけるプラズマ物理学的課題を検討し、プラズマ物理学と高エネルギー物理学の学際領域の開拓を目指す。

高エネルギー原子核衝突では、荷電粒子群がほぼ光速ですれ違うため、極めて強い磁場が発生し、磁場が QGP のダイナミクスに影響を与える可能性がある。そこで本講演では、磁気流体力学 (MHD) 的な課題に注目する。特に、我々が推進するカイラル不均衡物質のダイナミクスを記述するカイラル MHD の基礎的な解析と高エネルギー原子核衝突に相対論的抵抗性 MHD を適用する試みについて紹介する。

S001-P01

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

高階微分項を用いた陽的 FDTD 法のクーラン条件の緩和

#関戸 晴宇^{1,2)}, 梅田 隆行²⁾, 三好 由純²⁾

(¹ 名大, ² 名大 ISEE)

Relaxation of the Courant Condition in the Explicit Finite-Difference Time-Domain Method with Higher-Degree Differential Terms

#Harune Sekido^{1,2)}, Takayuki Umeda²⁾, Yoshizumi Miyoshi²⁾

(¹Nagoya Univ., ²ISEE, Nagoya Univ.)

The Finite-Difference Time-Domain (FDTD) method (Yee 1966) is a numerical method for solving the time development of electromagnetic fields by approximating Maxwell's equations in both space and time with the finite difference of the second-order accuracy. A higher-order version of the FDTD method is known as FDTD(2,4), which uses the finite difference of the fourth-order spatial difference (Petropoulos 1994). However, the Courant condition of FDTD(2,4) is more restricted than that of the standard FDTD method. In the present study, a new explicit method is developed by using higher-order spatial difference terms. The new method relaxes the Courant condition and reduces the numerical error in the phase velocity of electromagnetic waves.

FDTD (Finite-Difference Time-Domain) 法は、Yee (1966) によって開発された、電磁界の時間発展を解く数値計算手法であり、空間と時間ともに 2 次精度の差分で Maxwell 方程式を近似することで求められる。不連続波形で数値振動が発生するほか、連続波形でも傾きが大きいと数値振動や振幅の減衰が起こるといった欠点が存在する。これらの欠点を改善するため、Petropoulos (1994) は空間微分項の差分精度を 4 次精度とした FDTD(2,4) 法を提案したが、数値不安定が生じないクーラン数 C の上限値が小さくなるという問題を抱えている。本研究では電界および磁界のそれぞれの時間発展方程式に高階空間微分項を付加することにより、新たな陽的時間発展式を導出した。その結果、従来の手法では数値不安定が生じ、計算することができなかった範囲においても計算が可能となることを確認した。また、従来の手法で計算が可能であった範囲においては、位相速度の誤差を抑えることができた。

S001-P02

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

#坪内 健¹⁾

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Property of the heliosheath plasma associated with the compression at the termination shock

#Ken Tsubouchi¹⁾

⁽¹⁾The University of Electro-Communications

The interaction between the solar wind and local interstellar medium forms the termination shock (TS) and the heliopause (HP). Voyager 1 and 2 have already crossed both the TS and HP. Their crossing positions show that the TS is asymmetric in a radial distance, while the HP is almost symmetric. The thickness of the heliosheath (HS), the region between the TS and HP, is consequently asymmetric. The MHD modelings suggested that the effect of the interstellar magnetic field can account for this asymmetry. In this study, we focus on another factor that affects the HS thickness. The Voyager 2 measurements showed that the compressional ratio at the TS is smaller than expected from the MHD theory. The presence of pickup ions (PUIs) modifies the compression property at the TS. We performed the one-dimensional hybrid simulation and investigated the correlation between the PUI density and the plasma properties in the HS. We especially pay attention to the variability of the specific heat ratio which controls the plasma heating at the TS. Associations with the HS thickness are further discussed.

S001-P03

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

オーロラ加速領域における電界構造の計算機シミュレーション

#池羽 良太^{1,2)}, 梅田 隆行²⁾, 三好 由純²⁾

(¹名古屋大学,²名大 ISEE)

Computer simulation on the structure of double layer in the auroral acceleration region

#Ryouta Ikeba^{1,2)}, Takayuki Umeda²⁾, Yoshizumi Miyoshi²⁾

(¹Nagoya Univ.,²ISEE, Nagoya Univ.)

The existence of electric fields in the auroral region was predicted by Alfvén (1957). Rocket observations of aurora in 1960's showed the precipitation of high energy electrons, possible due to electric fields in the acceleration region (McIlwain 1960). Evans (1974) reproduced the result of rocket observation by a model calculation, which demonstrated the existence of the auroral acceleration region. Electric fields due to the electric double layers in the auroral acceleration region were first observed by spacecrafts in 1970's (Mozer et al. 1977). The FAST observation showed detailed multi-dimensional structures of the auroral double layer (Ergun et al. 2001). The previous one-dimensional Vlasov-Poisson simulation of a current-carrying plasma showed that a double layer was generated by a strong density depression (Newman et al. 2001). However, multi-dimensional kinetic simulations have not been performed yet due to both computational resources and computational techniques. In the present study, we first perform a two-dimensional particle-in-cell simulation of a current-carrying plasma with a density depression. It is demonstrated that a double layer is driven generated in the two-dimensional system with a weak ambient magnetic field. An electrostatic wave is excited inside the double layer at the frequency around the ion plasma frequency and at the phase velocity around the ion acoustic speed, which propagates in the direction oblique to the ambient magnetic field.

オーロラ領域における加速電場の存在は Alfvén (1957) によって予言された。1960 年代にはロケットによるオーロラ観測が行われ、加速電場により生成したと思われる高エネルギー粒子の降下を観測した (McIlwain 1960)。Evans (1974) はモデル計算によりロケット観測結果を再現し加速電場の存在を裏付けた。オーロラ領域における電気二重層による加速電場は 1970 年代の科学衛星によりはじめて観測された (Mozer et al. 1977)。また、FAST 衛星観測によってオーロラの電気二重層の詳細な多次元構造が明らかとなった (Ergun et al. 2001)。1 次元 Vlasov-Poisson シミュレーションにより、沿磁力線電流が存在するプラズマ中に強い密度降下を与えることによって電気二重層が成長することを示された (Newman et al. 2001)。しかし、計算資源や計算技術の不足により多次元的な運動論的シミュレーションはこれまで行われてこなかった。本研究では沿磁力線電流中の密度降下による電気二重層形成モデルの 2 次元 Particle-In-Cell シミュレーションを世界に先駆けて行った。その結果、2 次元空間において背景磁場が弱い場合において電気二重層が成長することを確認した。また、周波数がイオンプラズマ周波数、伝搬速度がイオン音速に近くで磁力線に対して斜めに伝搬する静電波動が電気二重層内に励起した。

S001-P04

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

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Magnetic field structure and non-thermal velocity in the plasma upflow region

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Plasma upflows have been detected by Hinode's Extreme Ultraviolet Imaging Spectrometer (EIS). They are usually observed in the transition regions or corona above the active region. Some studies have suggested that the upflow is the source of the slow solar wind. However, the relationship between upflows and the slow solar wind has not been understood. The global structure of the magnetic field associated with upflows, in particular, whether the magnetic field lines above the upflow are open or closed, will be an important point to investigate the relationship between the upflows and slow solar wind.

In this study, we analyzed EIS data obtained from Hinode observations to identify upflow events. We calibrated the EIS data using the `eis_prep` routine available in the Solar SoftWare (SSW) library and obtained Doppler velocity maps from a single Gaussian fit of the FeXIII 202.04 angstrom line with the `eis_auto_fit` routine. We also corrected the orbital variation using the `eis_update_fitdata` routine. We used potential field source surface (PFSS) extrapolation to study the configuration of the coronal magnetic field around the upflow region. The PFSS extrapolation was performed using the synoptic magnetogram of the ADAPT model 0. For comparison, we analyzed non-thermal velocities of the upflow regions connected to open/closed magnetic field lines. In this analysis, we chose AR 11271 (2011 Aug 21), AR 12685 (2017 Oct 26), and AR 12713 (2018 Jun 17), where both upflows associated with open and closed field lines are observed. Non-thermal velocity is a broadening of the spectral linewidth that cannot be explained by thermal or instrumental broadening, that can be an important observational constraint for coronal heating models based on nanoflares and wave dissipation (Brooks 2016).

Our analysis showed that only three of the thirteen upflows were connected to an open magnetic field line. This result is similar to that of Edward et al. 2016, where only one of the seven was connected to an open magnetic field line. This result indicates that not all upflows can be the source of solar wind. In addition to this result, our analysis shows that the open upflow regions had smaller line widths than the closed upflow regions. This result means that the thermal temperatures or non-thermal velocities are smaller in the open upflow regions. In the latter case, open and closed upflow may have different generation mechanisms.

S001-P05

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

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Multicolor reordering for computing moments in particle-in-cell plasma simulations

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Thread parallelism in the computation of the current density/charge density in particle-in-cell plasma simulations has been performed by using the reduction operation conventionally, which is known to have a larger computational overhead with a larger number of threads. In the present study, two types of multicolor reordering, i.e., loop striding loop tiling/blocking are introduced for a particle shape function with an arbitrary degree, which is free from the reduction operation. The present performance measurement result suggests that the loop tiling is superior to the loop striding.

衛星帯電と光電子からの電場計測への干渉

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Interference with electric field observation caused by spacecraft charging and photoelectrons

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Spacecraft charging and photoelectrons disturb the electric field observation in space. The Electric Field Detector (EFD) of the Plasma Wave Experiment (PWE) instrument onboard the Arase satellite measures the magnetospheric electric field with two sets of double probes. We found in some cases, that the electric field measured in a low-density plasma environment continually points to the subsolar direction in the spin plane, due to an electric potential between the positively charged spacecraft and the photoelectrons primarily emitted on the subsolar side. A model calculation was carried out to simulate the electric potential measured at the probes spinning with the satellite body. In the model, positive and negative charges were employed to represent the spacecraft charging and photoelectrons slightly separated in the subsolar direction. The resultant waveform of simulated probe potential under the strong influence of photoelectrons has a significant depression near the peak, consistent with the Arase observations.

地球磁気圏中で DC 電場を計測することは、磁気圏プラズマ対流を知るうえで有用と期待されている。しかし電場計測は、衛星本体の帯電や光電子放出、衛星下流のウェイクなど、衛星が存在することによって生じる諸現象の影響を受けやすく、特にデバイ長が長くなる希薄なプラズマ中での電場観測は容易ではない。

ジオスペース衛星「あらせ」のプラズマ波動・電場観測器 (Plasma Wave Experiment / Electric Field Detector, PWE/EFD) は 2 対の電位プローブによって磁気圏内の DC 電場を計測しているが、プラズマポーズの外のおおよそ 10 個/立方 cm 以下の低密度プラズマ中で、計測された電場が継続的に太陽方向を向いてしまうことがある。これは真の磁気圏電場ではなく、衛星本体の正の帯電と、衛星より太陽側にずれた位置にある光電子雲が周辺に作り出す電位構造のためと考えることができる。電子雲の中心が衛星の帯電の中心よりも太陽側にずれていると、プローブが太陽側に回り込んだ時に電子雲に近いため電位が低くなり、その結果太陽向きの電場として観測されてしまう。衛星のスピン軸が太陽方向と完全に一致していればこのようなことは起きないが、機上での衛星姿勢計測のために、「あらせ」のスピン軸は通常、太陽方向から 5 度以上大きくなるような運用がされている。

これを確認するため簡単なモデル計算を行った。衛星の帯電の中心をプローブのスピン中心より太陽側にややずれた位置 (1m) に置き、電子雲の中心をさらに太陽側にずれた位置 (例、10m) に設定し、衛星のスピンに伴うプローブの軌道 (半径 15.7m) 上の電位を計算した。電子雲の電荷量を衛星の帯電と同程度ないし 3 割程度とすると、予想通り太陽向きの電場が得られる。(光電子量をさらに減らしていくと衛星本体の作る電位が優勢となり電場は逆転する。) 衛星帯電による電位構造も、電子雲によってできる電位構造も、スピンするプローブから見ると正弦波に似た波形となるが、電荷の中心がプローブのスピン中心から偏心しているため、正確には正弦波ではない。そのため両者を合成すると、ピークにへこみのある特徴的な波形が得られた。この波形のへこみの大きさはスピン軸方向、衛星帯電中心位置、電子雲の中心位置、電子雲の電荷と衛星帯電量の比によって変わる。実際に偽太陽向き電場の観測された時刻前後を見ると、直前まではほぼ正弦波だった波形が、偽太陽向き電場となった時から、ピークにへこみのある特徴的な波形となっていた。この波形の情報から逆に、電子雲の電荷量や中心位置などの情報を得ることが出来ると考えられる。これを用いて周辺の温度などの物理量の推定に利用できるのではないかと期待している。

S001-P07

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

シア磁場を考慮した非対称磁気リコネクションの三次元効果

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Three dimensional MHD simulation of the asymmetric magnetic reconnection with the shear field component

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Using two and three-dimensional MHD simulations, the asymmetric magnetic reconnection structures are examined. The reconnection x-line with the finite length causes three-dimensional in-flows, and these flows weaken the evolution of the magnetic reconnection. However, the reconnection rate in the self-similar phase reaches almost the same level as that in the two-dimensional simulations. In addition, the asymmetric magnetic reconnections with this finite x-line in the shear field case produce the sheared plasmoids. This result means that the actual in-situ probes may cross only one side of a pair.

IPS 観測による g-value の日平均値を用いた地球での太陽風擾乱予測の可能性

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Possibility of predicting the solar wind disturbances with daily-averaged IPS g-value

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IPS (interplanetary scintillation) is a phenomenon in which radio waves from radio sources are scattered by solar wind plasma. IPS observations have the advantage of providing information on the solar wind over a wide area in a relatively short period because they include information on solar wind velocity and density fluctuation. The g-value, an index of electron density fluctuation obtained from IPS observations, is particularly useful for detecting solar wind disturbances, and we are currently conducting basic research on its application to space weather forecasting. Here, g-value is the normalization of the IPS intensity observed daily for each radio source to the average IPS intensity that changes with the solar elongation angle, and it is an index to evaluate the increase or decrease of solar wind density fluctuations along the line of sight. As solar wind disturbances pass through the line of sight, they appear as an increase in g-value. In a previous study, the correlation between g-value and the magnetospheric disturbance index A_p obtained from IPS observations at 81 MHz in Cambridge during 1990-1992 was studied. The results show a slightly better correlation coefficient between g-value calculated to the east of the Sun and A_p , which is comparable to the correlation coefficient with the Space Environment Service Center (SESC) A_p prediction. However, it has been pointed out that IPS data may show higher correlations during periods of low solar activity, as they are better suited to predict disturbances arising from co-rotating structures (Lucek et al, 1996).

In this study, we analyze g-value data obtained from IPS observations by ISEE at Nagoya University for the period 1997-2020 and compare them with solar wind data near Earth orbit. The solar wind data used in this study are daily averaged proton density and bulk velocity data from OMNI (https://pdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/omni_m_daily.dat). ISEE g-value data are obtained from multiple radio sources each day, so daily mean, maximum, and minimum values were calculated for the entire sky, east of the Sun, and west of the Sun, respectively. The OMNI data were then shifted with respect to the g-values by ± 7 days, for a total of 15 days, and their correlations were examined. In order to evaluate the solar activity cycle dependence, the analysis was performed separately for two solar activity cycles (SC23 and SC24). First, in comparison with the density data in SC23, the largest positive correlation was found with OMNI leading by 0 day. The maximum and minimum values show a similar trend, but there is a large variation. A similar comparison between east and west of the sun showed the same trend, but the west showed more variation in correlation. In the east, the maximum of the positive correlation was shifted to 1 day, and the change in correlation was less clear. Then, for the velocity data, the correlation became negative with OMNI leading by -2 days, followed by a maximum positive correlation on 1 day. A similar analysis was performed for SC24, which showed a slight trend similar to that of SC23, but little correlation. From the present analysis, we can't confirm that the correlation coefficients are better when only the east side is used, as reported by Lucek et al. (1996). However, it should be noted that the correlation coefficient of the present results is very small. We plan to examine the periodicity from the Fourier analysis in the future.

Reference: Lucek et al, Ann. Geophysicae 14, 139-148 (1996) (issue 2) "The use of various interplanetary scintillation indices within geomagnetic forecasts"

IPS (interplanetary scintillation) とは、電波天体からの電波が太陽風プラズマによって散乱される現象である。地上で観測すると強度変動として現れるため、地上から太陽風の情報を得ることができる。IPS 観測データは太陽風速度、密度擾乱の情報を含むため、比較的短時間に広範囲の太陽風の情報を取得することができるという利点がある。特に IPS 観測から得られる電子密度擾乱の指数である g-value は、太陽風擾乱の検出において有効であり、現在、我々は宇宙天気予報へ応用するための基礎研究を行っている。ここで g-value とは、電波源ごとに日々観測された IPS の強度を太陽離角とともに変化する IPS 強度の平均値に対して規格化したもので、視線に沿った太陽風密度揺らぎの増減を評価する指標となる。太陽風擾乱が視線を通過すると、g-value の増加となって現れる。先行研究では 1990~1992 年のケンブリッジにおける 81MHz での IPS 観測から得られた g-value と磁気圏擾乱指数 A_p の相関について研究が行われている。その結果は、東側のみの g-value と A_p の相関係数はやや良くなるが、これは宇宙環境サービスセンター (SESC) の A_p 予測との相関係数と同程度であった。しかし、IPS データは共回転構造から生じる擾乱を予測するのにより適しているため、太陽活動が低い時期により高い相関を示す可能性が指摘されている (Lucek et al, 1996)。

本研究では長期間の地球での太陽風擾乱と g-value の相関を調べるために 1997 年から 2020 年までの期間に名古屋大学 ISEE の IPS 観測から取得した g-value データを解析し、地球軌道付近の太陽風観測データと比較した。本研究で用いた太陽風データは OMNI (https://pdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/omni_m_daily.dat) のプロトン密度、バ

ルク速度の1日平均値である。ISEEのg-valueデータは毎日複数の電波天体から得られるため、日ごとの平均・最大・最小値を全天、太陽の東側、西側それぞれで計算した。続いてOMNIデータをg-valueに対して日付を±7日間、合計15日間ずらし、それぞれの相関を調べた。なお、太陽活動周期依存性を評価するため、2つの太陽活動周期(SC23、24)に分けて解析を行った。まず、SC23における密度データとの比較では、両者のずれが0日の場合に最も大きな正の相関が見られた。最大値、最小値は同様な傾向があるものの、ばらつきが大きい。太陽の東西で同様な比較をすると、同じ傾向がみられたが、西は相関の変化がより大きく出ていた。東は正の相関の最大が1日目にずれこんでおり、なおかつ相関の変化がはっきりとは出なかった。続いて速度データについては、-2日で相関が負の相関となり、その後1日にかけて正の相関の最大値になった。同様に東西で比較すると、密度と同様、西の方がはっきりとした相関がみられた。SC24についても同様な解析を行った。SC23と同様な傾向はわずかに見られたものの、ほとんど相関はなかった。今回の解析より、Lucek et al. (1996)の東のみの値を使用すると相関係数が良くなることを確認することは確認できなかった。しかし、今回の結果の相関係数は非常に小さいことに留意する必要がある。今後、フーリエ解析より周期性の検討を行う予定である。

参考文献：Lucek et al, Ann. Geophysicae 14, 139-148 (1996) (issue 2) “The use of various interplanetary scintillation indices within geomagnetic forecasts”

Grad-Shafranov 方程式による太陽風磁気ロープの再構築の新方式

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A New Method for Grad-Shafranov Reconstruction of Interplanetary Magnetic Flux Ropes

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INTRODUCTION: The interplanetary magnetic flux ropes (IFRs) have long been studied from the viewpoints that they are main drivers of strong geomagnetic storms, and that they provide information on the generation mechanism of CMEs. It is a key in such studies to determine the 3-D geometries and the internal magnetic field structures of IFRs. In order to challenge the problem, the following two analysis methods are commonly used: (1) fitting of observed magnetic fields to force-free models (FF method), and (2) reconstruction of IFRs based on the Grad-Shafranov equation (GS method). These analysis methods were developed from different view-points, and thus have both merits and demerits of each. We present here a new method for significant improvement of the GS method, which have been developed with the aid of knowledge from the FF method.

OUTLINE OF THE METHOD: The GS method is attractive in that no assumption is needed for the shape of the IFR cross-section. However, it needs magnetic field distribution along a line which is used as a boundary condition for calculating the spatial structure of the IFR. This raises a difficulty in analyzing the observed IFRs, because the data obtained from spacecraft are generally combination of spatial and temporal variations. While a theory was published to resolve this difficulty by Hasegawa et al. (JGR, 2014), the method has not been applied to sufficient number of IFR events. On the other hand, the FF method is designed aiming to reproduce the observed spatial-temporal variations by using time-varying IFR model structure. Therefore, it is expected that the results from the FF method can provide the purely spatial variations of IFR magnetic fields at any fixed time. We developed a method to derive the spatial field change along the spacecraft orbit for IFRs expanding in a self-similar fashion.

RESULT: We applied the new method to a test data-set: the field variation to be observed when the spacecraft passes through the expanding axisymmetric IFR model. The result shows the axisymmetric structure is retrieved from the virtually asymmetric time-variation of the test data-set.

CONCLUSIONS: We need to test the applicability of the method to data from real observations. Judging from the fact that there are many IFR events which can be reproduced by the expanding cylindrical model, the applicability should be assured by such tests. (While such an attempt is not made as of now, some results will be shown in the presentation in the conference.)

(序) 太陽風磁気ロープ (IFR) は、強い磁気嵐の駆動源として、またコロナガス噴出機構の手がかりをあたえるものとして、広く関心をもたれている研究課題である。IFR の 3 次元形状と内部磁場構造を決めることが重要なカギである。太陽風磁場の観測からこの問題にとりくむ二つの代表的な解析法として (1) force-free 磁場モデルを使った model-fitting (FF モデル法) と (2) 二次元的な磁場に適用される Grad-Shafranov (GS) 方程式から磁場構造を再構築する解析 (GS 法) がある。この二つの解析法はそれぞれ少し異なる視点から考案されたものであり、それぞれ優れた部分と劣った部分がある。この講演では、FF モデル法の知見をとり入れて新方式の GS 法を開発する試行結果について発表する。

(新方式の概略) GS 法は IFR の断面形状を仮定しない魅力的な方法であるが、空間構造を求めるには、ある時刻における磁場の 1 次元空間変化が必要である。しかしながら、IFR の構造が時間的に変化している場合、衛星観測では時間的変化と空間的変化の合成である。この問題に対処する理論が考案されているが (Hasegawa et al., JGR, 2014) 十分な成果をあげていない。これに対して FF モデル法は、観測される時間的・空間的変化を再現するように、時間的に変化する IFR 構造を求めている。この結果が正しければ、その結果を利用して GS 法に必要なある瞬間における 1 次元空間変化のスナップショットを算定することができる。ここでは、適当な FF モデルを衛星が通過したときに観測する磁場変化を仮想観測データとして扱い、新方式の適用性を確認する。新方式は IFR が自己相似的に膨張しているとの想定で、その効果を差し引くことで時間的変化を除去するものである。

(結果) IFR の膨張は観測される磁場構造の時間的非対称性の説明として一般に受け入れられているが、非対称性の強い IFR の解析は GS 法では扱いにくいものである。新方式によって膨張の効果を除去した結果、軸対称な磁場構造が再現され、はじめに仮想データによく一致する結果になる。

(結言) force-free の IFR からつくった仮想的な IFR 磁場変化に対して新方式を採用した結果、はじめに与えたモデルがうまく再現された。実際に観測された IFR の事例についての解析にはまだ着手していないが、FF モデル法で観測結果がうまく再現できる IFR の事例が多い事実から考えて、新方式の有用性が確認されると期待している。

S001-P10

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

エクサ計算時代に向けた PIC コード開発と天体衝撃波シミュレーションへの応用

#松本 洋介¹⁾

¹⁾ 千葉大理

Development PIC simulation code for the exascale computing and its application to astrophysical shock simulations

#Yosuke Matsumoto¹⁾

¹⁾Chiba University

Using massively parallel supercomputer systems with a parallelized particle-in-cell (PIC) code is a powerful way to elucidate nonlinear phenomena, including particle accelerations. Indeed, we have elucidated important acceleration mechanisms in collision-less shocks using the Japanese flagship supercomputer system with hundreds of thousands of processor cores (e.g., Matsumoto et al., 2017).

Here we report the current development status of our PIC simulation code and its application to astrophysical shocks. Due to time evolution, the load imbalance among MPI processes in PIC simulations arises if particles were in-homogeneously distributed in the simulation domain. This imbalance becomes problematic when using huge numbers of MPI processes (say more than millions of cores), and we met this situation when we used the supercomputer Fugaku. We have adopted the recursive multi-section algorithm which has been successfully implemented in the cosmological N-body simulations (Makino, 2004; Ishiyama et al., 2009). We successfully implemented this method to the PIC code for the first time with benchmark tests of the Weibel instability and collision-less shock simulations. Then we applied this new PIC code to collision-less shock simulations. With the new code, we can take a long upstream domain to track accelerated particle evolution for a long time. In this presentation, we report initial results from long-term simulations of high-Mach number oblique shocks and discuss primary to subsequent electron acceleration mechanisms.

ジャイロ運動論的シミュレーション GKV の磁気圏-電離圏結合への適用

#渡邊 智彦¹⁾, 前山 伸也¹⁾

¹⁾ 名大・理・物理

Application of the gyrokinetic simulation GKV to the magnetosphere-ionosphere coupling

#Hiko Watanabe Tomo¹⁾, Shinya Maeyama¹⁾

¹⁾ Dept. Physics, Nagoya Univ.

The feedback instability has been discussed as a possible mechanism to elucidate the auroral growth via Alfvén waves in the magnetosphere-ionosphere coupling. The conventional models employ the (extended) MHD equations for the magnetosphere and the two-fluid equations for the ionosphere. However, it is widely known that the kinetic approach is indispensable to deal with the auroral particle acceleration in collisionless magnetospheric plasma.

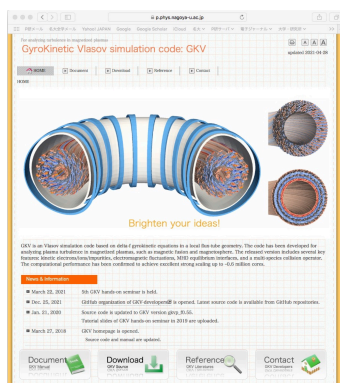
We have successfully derived formulation of the feedback instability by means of the gyrokinetics [1], which simultaneously explains the auroral growth and the electron acceleration by the kinetic Alfvén waves. In this study, we have constructed a gyrokinetic simulation model of the magnetosphere-ionosphere coupling. The GKV code (see the figure), which has been widely used for analyses of turbulent transport in fusion plasma, is adopted as the base code, and is implemented with a module of the ionospheric solver. The preliminary study confirms the dispersion relation of the feedback instability.

[1] Watanabe, T.-H. (2014), A unified model of auroral arc growth and electron acceleration in the magnetosphere-ionosphere coupling, *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL061166.

アルヴェン波を介した磁気圏-電離圏結合系におけるオーロラ発達を説明する理論として、フィードバック不安定性が議論されてきた。従来は、磁気圏を（拡張）MHD 方程式、電離圏を二流体方程式で記述するモデルが広く用いられてきた。一方、よく知られているように、磁気圏プラズマはほぼ無衝突であり、オーロラ粒子加速などを扱うには運動論的取り扱いが必須である。

我々は、これまでにジャイロ運動論を用いたフィードバック不安定性の定式化に成功しており [1]、オーロラ成長と運動論的アルヴェン波による電子加速を同時に説明する理論を導出した。本研究では、ジャイロ運動論を用いた磁気圏-電離圏結合のシミュレーションモデルの構築を進めた。核融合プラズマの乱流輸送解析に広く用いられてきた GKV コード（図参照）を基盤コードとして採用し、そこに電離圏ソルバーをモジュールとして導入する。予備的な解析では、フィードバック不安定性の分散関係をほぼ再現する結果が確認された。

[1] Watanabe, T.-H. (2014), A unified model of auroral arc growth and electron acceleration in the magnetosphere-ionosphere coupling, *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL061166.



S001-P12

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

円偏波プラズマ波動による荷電粒子捕捉に関する統一モデル

#北原 理弘¹⁾, 三好 由純²⁾, 中村 紗都子^{2,3)}, 小路 真史²⁾, 加藤 雄人¹⁾, 北村 成寿²⁾

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A comprehensive model of the particle-trapping in a circularly polarized plasma wave

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Wave-particle interactions play a crucial role in the plasma dynamics such as particle acceleration, pitch angle scattering, and wave growth in space plasmas. For quantitative evaluation of the effectiveness of wave-particle interactions, we should estimate the size of a trapping region of charged particles encountering plasma waves. The trapping region in wave-particle interaction is expressed as a set of closed trajectories in the phase space and involves conserved quantities. By applying the method used in Albert et al. (2021) to the two conserved quantities introduced by Berchem and Gendrin (1985), we classified the motion of non-relativistic electrons on the wave-particle interaction and constructed a new model that can specify the exact trapping regions in the velocity space. This model predicts that the normal trapping region of the conventional cyclotron resonance seamlessly connects with the trapping region of the non-resonant interactions at the low pitch angle region. The trapping region predicted by our model corresponds to that of the conventional single pendulum model asymptotically at a high pitch angle region. We also found that this model is a general form that includes other models developed in previous studies, such as the two-valley motion model and efficient trapping at low pitch angles. Additionally, this model predicts the existence of a new trapping region in the velocity space in the direction opposite to the resonance velocity. We calculated the trapping regions by using our model with the parameters of lion roar in the magnetosheath, and we found that lower wave frequencies and larger wave amplitudes tend to yield larger trapping regions at low pitch angles. This new model for the exact trapping regions is expected to be applied to observation data of various wave-particle interactions on the cyclotron resonance.

S001-P13

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

#銭谷 誠司¹⁾

⁽¹⁾ 神戸大学

A plasma activation function for deep neural networks

#Seiji Zenitani¹⁾

⁽¹⁾Kobe U

The activation function is one of the most important building blocks in neural networks. Since it brings nonlinearity and complexity, the deep neural networks have a rich variety of applications. Owing to its simplicity and backpropagation ability, the Rectified Linear Unit (ReLU) function is a de-fact-standard activation function. However, it may not be the best choice for some applications, because its derivative has a singularity at the origin. For this reason, modern functions have been recently proposed, such as GELU, Swish, and Mish functions. They are more favorable, but often computationally more expensive than the ReLU function.

The Kappa distribution is a popular form of plasma velocity distribution. It contains both a thermal Maxwellian core and a power-law nonthermal tail. It has long been discussed in heliospheric plasmas, but it draws growing attention in various settings throughout the Universe. Its mathematical properties have been extensively studied accordingly.

In this contribution, inspired by the Kappa distribution, we propose a new family of activation functions for deep neural networks. We call them t-Linear Units (tLUs), as the kappa distribution is equivalent to Student's t distribution. The new function exhibits favorable properties as other modern functions, whilst its mathematical form remain relatively simple. Results of benchmark tests will be presented.

2次元アルフベン波乱流中での相対論的粒子加速

#高橋 健太¹⁾, 諫山 翔伍²⁾, 松清 修一³⁾, 佐野 孝好⁴⁾

⁽¹⁾ 九大・総理工, ⁽²⁾ 九大総理工, ⁽³⁾ 九大・総理工, ⁽⁴⁾ 阪大レーザー研

Relativistic particle acceleration in 2D Alfvén wave turbulence

#Kenta Takahashi¹⁾, SHOGO ISAYAMA²⁾, Shuichi Matsukiyo³⁾, Takayoshi Sano⁴⁾

⁽¹⁾IGSES, Kyushu Univ., ⁽²⁾IGSES, ⁽³⁾Kyushu Univ., ⁽⁴⁾ILE, Osaka U,

Large-amplitude MHD waves are ubiquitous in space, and they are considered to play key roles in particle acceleration. In the solar wind, large amplitude magnetic fluctuations are frequently observed. It is also known that the magnetic field is amplified in the vicinity of collisionless shocks associated with gamma-ray bursts, supernova remnants, and other high energy astrophysical events. The interaction between a monochromatic wave and a charged particle, and that between well developed turbulent fields and a particle have been well studied [1]. However, there are relatively few studies on particle acceleration through the interaction with developing turbulence. In space, many astrophysical events have long relaxation time so that we often observe developing turbulence and well accelerated particles simultaneously.

In 1D Particle-in-Cell (PIC) simulation, it has been shown that particles are efficiently accelerated to relativistic energy by two counter-propagating Alfvén waves which are locally enhanced in the course of successive decay instabilities [2]. Recent studies have also shown that when the amplitude of the two counter-propagating Alfvén waves exceeds critical amplitude any particles irreversibly gain relativistic energy within a short time regardless of their initial energy. In this research, we investigate the particle acceleration process in 2D Alfvén turbulence where the long time evolution of parametric instability could be different from that in 1D. In this talk, by using 2D PIC simulation, we discuss the particle acceleration process by counter-propagating Alfvén waves as well as the parametric decay process when the amplitude of the initial Alfvén wave is sufficiently large.

[1] M.Oka et al., ApJ, 886,53 (2019)

[2] S.Matsukiyo & T.Hada, ApJ, 692,1004 (2009)

大振幅 MHD 波動は宇宙のいたるところで励起され、粒子加速に寄与すると考えられている。太陽風中では背景磁場と同程度の磁場揺らぎが常時観測されており、またガンマ線バーストや超新星残骸等に付随する無衝突衝撃波近傍では、磁場が星間空間に比べてはるかに強く増幅されることが知られている。従来、単色波と荷電粒子の相互作用や十分発達した乱流場中での粒子加速についてはよく研究されているが、発展途上乱流における粒子加速の研究は比較的少ない。現象の緩和時間が長い宇宙では発展途上乱流がしばしば観測され、コヒーレントな波動とともによく加速された高エネルギー粒子が見られる [1]。

これまでの1次元粒子シミュレーションでは、パラメトリック崩壊過程によって発達するアルフベン乱流中で、局所的に発達した2つの対向伝搬アルフベン波による相対論的な粒子加速が見られている [2]。また最近の研究から、2つの対向伝搬するアルフベン波の振幅がある閾値を超えると、粒子が初期エネルギーによらず短時間で相対論的エネルギーにまで加速されることが分かっている。本研究では、2次元アルフベン乱流中における粒子加速過程について調査する。2次元系でのパラメトリック不安定性の長時間発展は1次元系のそれとは異なることが予想され、1次元系で見られた粒子加速過程が2次元系でも起こるかは自明ではない。本講演では初期のアルフベン波の振幅が十分大きい場合について、波の崩壊過程及び対向伝搬するアルフベン波による粒子加速過程を2次元粒子シミュレーションにより議論する。

[1] M.Oka et al., ApJ, 886,53 (2019)

[2] S.Matsukiyo & T.Hada, ApJ, 692,1004 (2009)

物理法則に基づいた深層学習によるプラズマパラメータの推定

#宮村 勇生¹⁾, 松清 修一²⁾, 諫山 翔伍³⁾

⁽¹⁾ 九大・総理工, ⁽²⁾ 九大・総理工, ⁽³⁾ 九大総理工

Estimation of plasma parameters by deep learning based on physical laws

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⁽¹⁾IGSES, Kyushu Univ., ⁽²⁾Kyushu Univ., ⁽³⁾IGSES

In general the data observed in space and laboratory is only a part of the physical quantities which are needed to understand a physical phenomenon. In recent years, the machine learning technique has been intensively investigated to predict the physical parameters from a small number of observed parameters. In the method called Physics-Informed Neural Network (PINN), the spatio-temporal evolution of some physical parameters is learned as a training data and the other unknown parameters are estimated so that they satisfy the governing equations [1]. Unlike the conventional parameter prediction technique such as a pattern recognition, this method predicts a parameter based on the law in physics. Therefore, the prediction model is less likely to become a black box and a physical interpretation of the predicted data becomes clearer. Furthermore, in contrast to usual numerical simulation in which one has to solve a forward problem, this method has an advantage to be able to predict parameters without setting initial and boundary conditions.

In this study, the PINN is applied to Magnetohydrodynamics (MHD) phenomena. The MHD model considerably helps to understand various plasma phenomena in space and laboratory. We treat the MHD equations as the governing equations in the PINN and predict the spatio-temporal evolution of plasma parameters from the observed spatio-temporal training data sets of the magnetic fields and some plasma parameters. Firstly, this method is applied to the MHD shock tube problem to predict the evolution of the density, the velocity, and the pressure of a plasma from the training data set of the magnetic fields. When this method is established, the PINN is expected to make a significant contribution to understand MHD phenomena as a new parameter determination method. In this talk, we report the development status of the prediction model and discuss its future prospects.

[1]M. Raissi, A. Yazdani, and G. E. Karniadakis, “Hidden Fluid Mechanics: A Navier-Stokes Informed Deep Learning Framework for Assimilating Flow Visualization Data,” arXiv:1808.04327 (2018).

宇宙や実験室での観測で得られるデータは、現象を理解するのに必要な物理量の一部であることが一般的である。近年、少数パラメータを教師データとしてその他の物理パラメータを機械学習によって予測する手法が盛んに研究されている。中でも Physics-Informed Neural Network(PINN) と呼ばれる手法では、あるパラメータの時空間発展を教師データとして学習し、その他のパラメータが支配方程式を満たすように推定される [1]。本手法は従来のパターン認識等によるパラメータ推定とは違い、物理法則に基づくパラメータ推定であるため、予測モデルがブラックボックス化しにくく予測データの物理的解釈が得られやすい。また本手法では初期条件や境界条件を設定しなくてもパラメータを推定することができるため、ある初期条件と境界条件のもと順問題を解く数値シミュレーションと比べて、効率よく観測データから未知パラメータを推定できる。

本研究では PINN を電磁流体現象 [Magnetohydrodynamics (MHD)] に適用する。MHD モデルは宇宙および実験室における多様なプラズマ現象の理解に大いに貢献している。本研究の目的は、観測される磁場やあるプラズマパラメータの時空間データをトレーニングデータとして、PINN を用いてその他のプラズマパラメータの時空間発展を MHD 方程式を満たすように予測する事である。まずは MHD 衝撃波管問題に本手法を適用し、磁場の時空間発展データから不連続面を持つプラズマの密度、速度、圧力の時空間発展を予測する。本手法が確立されれば、新たなパラメータ同定手法として MHD 現象の解明に大きく貢献することが期待される。本講演では予測モデルの開発状況および今後の展望について述べる。

[1]M. Raissi, A. Yazdani, and G. E. Karniadakis, “Hidden Fluid Mechanics: A Navier-Stokes Informed Deep Learning Framework for Assimilating Flow Visualization Data,” arXiv:1808.04327 (2018).

S001-P16

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

相対論的電子・陽電子プラズマ中の大振幅電磁波のパラメトリック不安定性の数値実験

#山田 鳳仁¹⁾, 松清 修一²⁾, 諫山 翔伍³⁾, 岩本 昌倫⁴⁾

¹⁾ 九大・総理工,²⁾ 九大・総理工,³⁾ 九大総理工,⁴⁾ 九大総理工

PIC simulation on parametric instability of a large amplitude electromagnetic wave in a relativistic electron-positron plasma

#Takahito Yamada¹⁾, Shuichi Matsukiyo²⁾, SHOGO ISAYAMA³⁾, Masanori Iwamoto⁴⁾

¹⁾IGSES, Kyushu Univ,²⁾Kyushu Univ.,³⁾IGSES,⁴⁾ESST, Kyushu University,

A pulsar wind is relativistic flow of a plasma composed mainly of electrons and positrons. The ratio of the Poynting flux of the electromagnetic field carried by the pulsar wind to its kinetic energy is expressed as σ . The value of σ near the terminal shock (upstream) is estimated as $\sigma \sim 10^{-3}$. In the vicinity of a neutron star, on the other hand, σ is considered to exceed 1 due to the strong magnetic field. Such significant decrease in σ cannot be explained by the adiabatic expansion of the pulsar wind, suggesting that a highly efficient energy conversion mechanism from the magnetic field to the plasma is at work in the pulsar wind. However, its mechanism has not been understood yet, and this is called the σ problem of pulsar winds.

In this study, we aim to understand the mechanism of energy conversion by conducting two-dimensional full particle simulations of parametric instability of a large amplitude electromagnetic wave, which is thought as a candidate of efficient energy conversion mechanism in a pulsar wind. In a periodic system, a relativistic large amplitude electromagnetic wave is given as a parent wave. We discuss the long time evolution of wave spectrum and the mechanism of particle acceleration and heating.

パルサー風は電子・陽電子を主成分とする相対論的なプラズマ流である。パルサー風が運ぶ電磁場のポインティングフラックスとプラズマの運動エネルギーの比は σ で表され、終端衝撃波近傍（上流）での値は概ね $\sigma \sim 10^{-3}$ と見積もられている。一方、中性子星近傍は磁場優勢の環境であり σ は1を超えると考えられている。この σ の大幅な減少はパルサー風の断熱膨張の効果では説明がつかず、パルサー風中で磁場からプラズマへの高効率のエネルギー変換機構が働いていることを示唆する。しかしこれを満足に説明する理論はいまだ確立されておらず、パルサー風の σ 問題と呼ばれている。

本研究では、パルサー風における電磁場からプラズマ粒子への高効率のエネルギー変換機構の候補として知られるパラメトリック不安定性を数値シミュレーションによって再現し、エネルギー変換機構の詳細を明らかにすることを目的とする。相対論的大振幅電磁波を親波として与えた2次元フル粒子シミュレーションを行い、波動の多次元発展と粒子の加速・加熱機構について議論する。

#深澤 伊吹¹⁾, 三宅 洋平²⁾, 白井 英之³⁾, 草地 恒史郎²⁾, 栗田 怜⁴⁾, 小嶋 浩嗣⁴⁾

(¹⁾ 京都大学, (²⁾ 神戸大学, (³⁾ 神戸大・システム情報, (⁴⁾ 京都大学 生存研, (⁵⁾ 京都大学 生存研

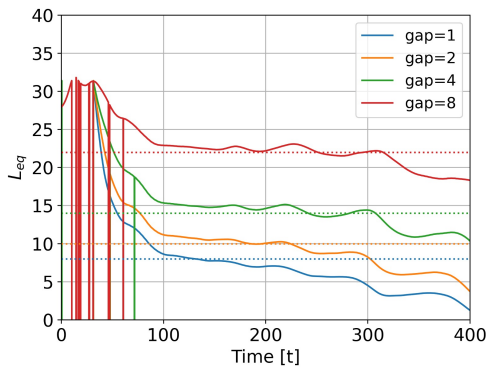
Particle Simulations on Characteristics of Electric Field Sensors applied to the Interferometry technique in Space Plasmas

#Ibuki Fukasawa¹⁾, Yohei Miyake²⁾, Hideyuki Usui³⁾, Koshiro Kusachi²⁾, Satoshi Kurita⁴⁾, Hirotsugu Kojima⁴⁾

(¹⁾Kyoto University, (²Kobe Univ., (³System informatics, Kobe Univ., (⁴RISH, Kyoto Univ., (⁵RISH, Kyoto Univ.

One of the most important parameters of plasma waves is phase velocities. The interferometry technique is one of the methods to obtain phase velocities in space based on satellite observations. The method utilized for a single satellite measurement uses electric field signals picked up by two individual monopole electric field sensors. From the time difference and the distance between the observation points, the phase velocity can be calculated. The problem here is the uncertainty in the distance, because of the length of sensors is not negligible relative to wavelengths. In this study, we use the full-PIC simulation to evaluate the interferometry technique and determine the equivalent length L_{eq} . A 3D simulation model is used in this paper. Three objects were used to realize the interferometry technique. Two of them were placed on the conductor rod as sensors and the last one was placed in the center of the conductor rod as a satellite.

The figure shows the time variation of L_{eq} in the dependence of the gap between the end of a sensor and a satellite body as shown in the figure. The dashed lines in the figure indicate the sensor's center-to-center distance. The figure shows L_{eq} is almost equal to the sensor's center-to-center distance when the gap is equal to 8. On the other hand, when the gap is small, it is found to be shorter than the sensor center-to-center distance. We found that this stem from the changes in the potential structures of the Langmuir wave around the satellite because of the effect of the satellite body.



S001-P18

ポスター 3 : 11/6 AM1/AM2 (9:00-12:30)

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Dynamic Load Balancing for Particle-based Plasma Simulations

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Numerical modeling of collisionless and weakly collisional plasma dynamics is becoming more and more important for a variety of applications in laboratory, space, and astrophysical plasmas. An efficient parallelization strategy is indispensable to fully exploit the advantage of the modern supercomputing capability. Conventional plasma kinetic numerical simulations employ the Particle-In-Cell (PIC) scheme for some of the particle species. In other words, a large number of particles are distributed over the computational domain, whereas the electromagnetic field or some fluid quantities are defined on the mesh. While mesh-based simulations can easily be parallelized using the domain-decomposition approach, the use of computational particles makes it problematic because the inhomogeneity in the particle distribution introduces a significant load imbalance between different processes. The PIC simulations have been used for investigating elementary plasma processes, including magnetic reconnection and collisionless shocks. However, the load imbalance may become a major obstacle for those simulations at the largest scale available with modern supercomputers.

Furthermore, the ever-increasing computational resource is now allowing us to perform kinetic modeling of more complicated problems both in terms of physics as well as initial and boundary conditions. For instance, global modeling of the solar wind interaction with a planetary magnetosphere (or a more general celestial body) involves various different plasma parameters such as composition, collisionality, and ionization rate. Whereas a fluid approximation may be reasonable at high density (or highly collisional) regions close to the planet, the kinetic effect has to be taken into account at least partially for realistic modeling, particularly in dilute regions far from the planet. It may be reasonable to adopt a hybrid model in which only some of the species are represented as particles, whereas the rest may be approximated as fluids. This makes the issue of load imbalance even worse because regions without particles will arise naturally in a simulation box. Since a significant density inhomogeneity is intrinsic to these problems, the load imbalance problem has to be solved for the efficient use of parallel computers even as small as hundreds of cores.

To resolve the issue of load imbalance in particle-based numerical plasma modeling, we adopt an approach that has been used in some of the existing PIC simulation codes [Germaschewski et al., 2016, Derouillat et al., 2018, Rowan et al., 2021]. Namely, the computational domain is divided into smaller chunks, which are then distributed over the computational nodes. The size of a chunk is chosen to be sufficiently small such that each process can accommodate multiple chunks. The computational load is balanced by distributing chunks so that loads of different processes become as close as possible. Since the algorithm itself is quite general and can be applied to more general particle-based simulations, we try to develop a code in C++ as a general framework that can be utilized in different applications with different basic equations. In other words, the dynamic load balancing capability is separated from the rest of the code as much as possible. This report will discuss the initial results obtained with the code, including the basic algorithm, implementation, and comparison with other approaches [e.g., Nakashima et al. 2009, Ishiyama et al. 2012].

木星衛星イオの環境を想定した SO₂ 霜の紫外線照射実験及び中間赤外測定

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UV radiation experiment of SO₂ frost based on Jupiter moon's environment

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Jupiter's moon Io is covered with a tenuous sulfur oxide atmosphere ($\sim 10^{-3}$ Pa) consisting mainly of SO₂ ($\sim 90\%$) and SO₂ surface frost. This atmosphere is produced by direct eruption from volcanic vents and sublimation of SO₂ surface frost due to an increase in the surface temperature on the day side. Features that appear to be inhomogeneities in the size of frost on the Io surface and absorption of diverse solid molecules (e.g. ClSO₂, Cl₂SO₂, H₂S) have been observed by the Galileo and JUNO spacecraft. However, it is not clear whether the "solid" SO₂ frost on the surface is decomposed or promoted to grow by UV radiation. If we can obtain spectra obtained from laboratory measurements reproducing a tenuous and cold atmosphere, surface frost, and UV irradiation that can be compared with ground-based observations, we can step into the relationship between SO₂ frost morphology, spatio-temporal changes in Io's various volcanic activities, and solar irradiation. It also can contribute to a complementary understanding of planetary science and condensed matter physics and chemistry.

The following procedure is used to clarify the relationship between UV intensity/wavelength and chemical denaturation of SO₂ condensed particles by mid-infrared spectroscopy. We use a cryostat with a small chamber connected to a liquid nitrogen dewar. Inside of the small chamber is maintained at pressure of 10^{-3} Pa and temperature of 110-130 K, which are similar to the environment at the dayside surface of Io. SO₂ gas is sprayed onto the CsI plate, which is attached to a dewar sample holder, and then the frost is deposited. A UV chip with a peak wavelength of 270 nm and a xenon lamp with a continuous spectrum from the far UV to the visible region are used as light sources to irradiate the SO₂ frost. By adjusting the duration of the UV irradiation, the experiment will also reveal the relationship between the intensity and age of the UV irradiation and the change in SO₂ frost. For in-situ observation of the experiment, an imaging Fourier transform mid-infrared spectrometer based on the near-common-path wavefront-division phase-shift interferometry (Qi et al., 2015) is used to obtain the spatial two-dimensional transmission and absorption spectra. In this presentation, we will discuss how the morphological change of SO₂ frost occurs during UV irradiation through the change of the obtained 2D mid-IR absorption spectrum.

木星衛星イオは火山活動が活発な天体であり、SO₂ を主成分 ($\sim 90\%$) とした希薄な硫黄酸化物大気 ($\sim 10^{-3}$ Pa) と SO₂ の霜に覆われている。この SO₂ ガスは昼夜面の表面温度の変化によって昇華と凝結を繰り返す。SO₂ の霜の形態とイオの多様な火山活動の時空間変化及び太陽光照射の関係性に踏みこむことができれば、惑星科学と物性物理・化学の相補的な理解に寄与することが期待できる。これまでにガリレオ及び JUNO 探査機によって、イオ表面の霜の大きさの不均一性、および多様な固体分子 (ClSO₂, Cl₂SO₂, H₂S など) の吸収と思われる特徴が観測された。その一方で、表面の"固体"の SO₂ 霜は紫外線の照射によって、分解されるか、成長を促進されるか、また他の微量分子・原子と化学反応を起こす過程は明らかになっていない。この研究では希薄かつ低温の大気、表面霜、紫外線照射を再現した実験室測定を行い、将来的に地上観測結果と比較することが可能な中間赤外スペクトルが得ることを目的とする。

本研究では以下の手順で中間赤外分光測定を行う。液体窒素デュアーに小型の真空チャンバー内が接続しているクライオスタットを用いる。小型のチャンバー内をイオの昼面の環境に近い 10^{-3} Pa, 110-130 K の状態に保ちつつ、デュアーのサンプルホルダーに取り付けられている CsI プレート上に SO₂ ガスを吹き付けて、凝縮微粒子を堆積させる。その後、270 nm の波長帯をもつ紫外線チップ、及び遠紫外から可視域まで連続スペクトルを持つキセノンランプを光源にして、紫外線を照射しつつ、in-situ で中間赤外線領域に現れる振動スペクトルの変化を測定する。実際の赤外線照射変成実験では紫外線の照射時間を調整することで、紫外線照射の強度・年数と SO₂ 霜の構造変化との関係性を明らかにする。実験のその場観測には准共通光路波面分割型位相シフト干渉法 (Qi et al., 2015) に基づくイメージングフーリエ変換中間赤外分光器を用い、空間二次元の透過吸収スペクトルを取得する。得られた赤外吸収 2D スペクトルの時空間変化を通して、紫外線照射時における SO₂ 霜の形態変化を議論する。また、イオ火山噴出物として想定される NaCl などのサンプルをホルダーに載せた後、SO₂ ガスを導入し、紫外線を照射することで新たな分子を生成する実験も構想中である。