

R009-01

A 会場 : 11/24 PM1 (13:45-15:45)

13:45~14:00:00

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BepiColombo Mission Status and Overview of Mercury Flyby Results

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The ESA-JAXA joint mission BepiColombo is still on the cruise to Mercury. The BepiColombo mission consists of two spacecraft, Mio (Mercury Magnetospheric Orbiter: MMO) and Mercury Planetary Orbiter (MPO). The two orbiters will arrive at Mercury in November 2026. The 8-years interplanetary cruise of BepiColombo covers the heliocentric distance range of 0.3-1.2 AU and also includes 9 planetary flybys: once at the Earth, twice at Venus, and 6 times at Mercury. On 8 January 2025 we completed the last (6th) Mercury flyby successfully. Even before arrival, we already obtained fruitful science data from Mercury during the Mercury flybys. We performed science observations with almost all the instruments onboard Mio and successfully obtained comprehensive data of Mercury's magnetosphere such as magnetic fields, plasma particles, and waves. Here we present the updated status of the BepiColombo mission and the overview of the results from the science observations during the Mercury flybys.

R009-02

A 会場：11/24 PM1 (13:45-15:45)

14:00~14:15:00

BepiColombo/Mio 搭載 MPPE による第4回・第6回水星フライバイ時の水星磁気圏観測

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Observation of Mercury Magnetosphere During Mercury Flyby #4 and #6 by MPPE on BepiColombo/Mio

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BepiColombo Mio will arrive at Mercury in November 2026, after nearly 8 years' journey. To date, BepiColombo has completed six Mercury flybys. The first, second, third, fourth and sixth Mercury flybys were on 1 October 2021, 23 June 2022, 19 June 2023, 4 September 2024, and 8 January 2025, respectively. During the 4th flyby, BepiColombo approached Mercury's magnetosphere from the dusk-side northern part of the magnetotail, crossed the low-altitude regions in the dawn-side equatorial region with the closest approach altitude of about 165km and exited the magnetosphere at the dawn-side southern hemisphere. During the 6th flyby, BepiColombo approached Mercury's magnetosphere from the southern part of the magnetotail, crossed the low-altitude regions almost along the noon-midnight meridian with the closest approach altitude of about 295km and exited the magnetosphere at the dayside northern hemisphere.

The Mercury Plasma/Particle Experiment (MPPE) is a comprehensive instrument package on BepiColombo/Mio spacecraft for plasma, high-energy particle and energetic neutral atom measurements. It consists of 7 sensors: two Mercury Electron Analyzers (MEA1 and MEA2), Mercury Ion Analyzer (MIA), Mass Spectrum Analyzer (MSA), High Energy Particle instrument for electron (HEP-ele), High Energy Particle instrument for ion (HEP-ion), and Energetic Neutrals Analyzer (ENA).

Although the MOSIF (MMO Sunshield and Interface Structure) blocked most of the MPPE sensor's field of view during cruising phase, the MPPE sensors except HEP-ion were turned on in order to observe Mercury's magnetosphere during the 4th and 6th Mercury flybys. During Mercury flyby #4, MIA observed heavy ion pickup-like signatures outside magnetosphere both at inbound and outbound magnetopause. MSA observed asymmetric (north-south/dawn-dusk) ions including cold and energetic heavy planetary ions. During Mercury flyby #6, MEA observed a lot of sub-structures above the poles in 'auroral' regions. MSA detected Heavy ion dispersion signatures in the central plasma sheet region. They are interpreted as the consequence of sporadic proton injection and planetary ion injections leading to ion bouncing near Mercury. ENA observed natural ENA following the first natural ENA observation during Mercury flyby #2.

The observation with full performance of MPPE will start after Mio's arrival at Mercury in November 2026.

BepiColombo/Mio 衛星は、2026 年 11 月に約 8 年の水星への旅を経て、目的地である水星に到着する予定であり、現在までに、BepiColombo は 6 回の水星フライバイを完了した。第 1 回、2 回、3 回、4 回、6 回のフライバイは、2021 年 10 月 1 日、2022 年 6 月 23 日、2023 年 6 月 19 日、2024 年 9 月 4 日、2025 年 1 月 8 日であった。第 4 回目のフライバイの際、BepiColombo は水星磁気圏に、水星磁気圏尾部の北側・夕方側から近づき、朝側の赤道付近で再接近高度 165km で低高度領域を通過した後、朝側の南半球で磁気圏から出た。第 6 回目のフライバイの際は、BepiColombo は、磁気圏尾部に南側から近づき、水星磁気圏の殆ど真昼―真夜中を含む面内を再接近高度 295km の軌道に沿って飛行した後、昼側の北半球で磁気圏から出た。

MPPE(Mercury Plasma/Particle Experiment) は BepiColombo/Mio 衛星に搭載されたプラズマ、高エネルギー粒子、高速中性粒子の総合観測を行うための観測装置である。MPPE は 2 台の低エネルギー電子エネルギー分析器 (MEA1, MEA2)、低エネルギーイオンエネルギー分析器 (MIA)、低エネルギーイオンエネルギー質量分析器 (MSA)、高エネルギーイオン観測器 (HEP-ion)、高エネルギー電子観測器 (HEP-ele)、低エネルギー中性粒子分析器 (ENA) の 7 つのセンサーで構成されている。

水星に到着するまでの間、MOSIF と呼ばれる太陽光シールドが MPPE センサーの視野の殆どをブロックしているが、第 4 回、第 6 回のフライバイ時には、HEP-ion を除く全ての MPPE のセンサーが水星磁気圏の観測を行った。

第 4 回のフライバイ時には、MIA は磁気圏の外でピックアップされたと考えられる重イオンを磁気圏に入る時と出る時の両方で観測した。一方 MSA は、低いエネルギーと高いエネルギーの重イオンが、水星磁気圏中に南北非対称・朝夜非対称に存在していることを観測した。

第 6 回のフライバイ時には、MEA は、極地方のオーロラ領域上空で、複雑な電子分布の構造を観測した。MSA は、

プラズマシートの中央部で速度分散を持った重イオンが複数回繰り返して検出される現象を観測した。これらは、プロトンと水星起源の重イオンが、短い期間にインジェクションされた後、磁力線に沿って運動し、水星近傍で反射されて複数回バウンスした結果観測されたと解釈している。また、ENA は第 2 回目のスイングバイ時に続いて、自然の高速中性粒子を観測することができた。

MPPE は、2026 年 11 月の水星磁気圏到着後、本来の高性能を発揮した観測を開始する予定である。

R009-03

A 会場 : 11/24 PM1 (13:45-15:45)

14:15~14:30:00

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Significance of background electron temperature inferred from whistler-mode wave propagation in Mercury's magnetosphere

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In planetary magnetospheres, whistler-mode waves can be excited by free energy sources such as electron temperature anisotropies. Propagation characteristics of planetary whistler-mode waves are thought to reflect the properties of the background cold and cool plasmas. In this study, we focus on the propagation characteristics of Mercury's whistler-mode waves influenced by background electron temperature, proposing that such wave characteristics can serve as a remote-sensing tool to complement in-situ observations for identifying the finite temperature.

We particularly examine wave observations from the fourth flyby of Mercury by BepiColombo Mio Spacecraft. During the fourth flyby, the whistler-mode waves likely were detected with mid-latitude distribution. The Mio spacecraft's unique trajectory during the fourth flyby, which traversed along the north-south direction, provided a rare opportunity to study long-distance propagation away from the magnetic equator. Our analysis suggests that the background electron temperature significantly affects wave attenuation through Landau and cyclotron damping mechanisms. Numerical calculations show that when the background electron temperature exceeds approximately 100 eV, whistler-mode waves at frequencies around $0.45f_{ce}$ experience strong attenuation and are unable to propagate effectively within Mercury's magnetosphere, where f_{ce} is the electron gyrofrequency.

By investigating the dependence of wave propagation on the density and temperature of background cold electrons, we aim to assess whether such a cold and cool electron population can exist in Mercury's magnetosphere, which lacks a well-developed ionosphere due to its tenuous atmosphere. In this presentation, we utilize wave data from the flyby phase prior to Mercury orbit insertion and will discuss the potential presence of cold and cool background electrons in Mercury's magnetospheric environment.

R009-04

A 会場 : 11/24 PM1 (13:45-15:45)

14:30~14:45:00

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Study of Na source regions in the Mercury's magnetosphere based on systematic global MHD simulations

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One of important characteristics of Mercury is the absence of a collisional thick atmosphere, and it exhibits a weak global intrinsic magnetic field [e.g., Anderson et al., Science, 2011]. Consequently, the magnetosphere of Mercury is formed by the interaction between the solar wind and the planetary magnetic field. As demonstrated in the works of Yagi et al. [JGR, 2010; 2017] and Zurbuchen et al. [Science, 2011], sodium ions originating from the solid planet constitute a significant plasma source. Given that Mercury revolves around the Sun at a radial distance of 0.31-0.47 AU, the solar wind density (~50 1/cc on average) and interplanetary magnetic field (IMF) strength (~35 nT) at the Mercury's orbit are considerably larger than those at Earth. Previous studies have indicated that the configuration of the Mercury's magnetosphere depends on the solar wind conditions and the surface conductivity of the solid planet [e.g., Seki et al., JGR, 2013]. Changes in configuration can cause variations in the location of the cusp in the magnetosphere. The cusp is the source region of exospheric N, which is produced by sputtering from the surface of Mercury [e.g., Raines et al., JGR, 2022]. On the one hand, ground-based telescopes have been utilized to observe the exospheric Na distribution. These observations indicate that the spatial distribution of Na emission is subject to variation over time and can be categorized into eight distinct types. A comparison of in-situ IMF observations by MAG/MESSENGER reveals that Na emission patterns depend on IMF [Mangano et al., PSS, 2015]. However, the mechanisms that cause the IMF dependence remain to be fully elucidated. Consequently, the investigation of the solar wind and IMF effects on the cusp location is important to comprehend the planetary ion source in the Mercury's magnetosphere.

The objective of this study is to investigate how the cusp location changes with solar wind and IMF conditions based on global MHD simulations.. The CIP-based divB-free MHD model, which solves the vector potential instead of the magnetic flux [Yagi et al., JGR, 2017], is utilized for the simulations. A systematic simulation is conducted (24 cases) under Parker spiral IMF configurations with some Bz components added, for three solar wind dynamic pressure conditions. The results indicate that the locations of the high-pressure region in dayside (cusp-like region) systematically change with the IMF Bz and solar wind dynamic pressure under background Parker spiral IMF conditions. The simulation results are categorized into eight types of spatial distributions that were proposed by Mangano et al. [PSS, 2015]. The results indicate that 2P patterns, including 2PN and 2PS, are the dominant patterns. Different By polarity causes opposite longitudinal twist of the cusp location. As the solar wind dynamic pressure increases, the appearance of WP or EP patterns is particularly evident, especially during periods of negative Bz conditions. The results of the study indicate that exospheric Na distribution can systematically change in response to variations in the solar wind conditions.

R009-05

A 会場 : 11/24 PM1 (13:45-15:45)

14:45~15:00:00

放射線シミュレーションを用いた水星表層一宇宙線の相互作用による宇宙風化の評価

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Assessment of Cosmic-Ray-Induced Space Weathering on Mercury's Surface Using Radiation Simulations

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Understanding Mercury's evolution requires disentangling the effects of space weathering from remote sensing observations of the planetary surface. Space weathering processes fall into two broad categories: (i) stochastic micrometeoroid impacts and (ii) radiation effects from the solar wind and galactic cosmic rays (GCRs) (Mesick et al., 2018). This study focuses on the latter and aims to quantitatively evaluate GCR-induced space weathering using Geant4 radiation transport simulations (Allison et al., 2016).

GCRs consist mainly of protons with energies ranging from several hundred MeV to several GeV, originating from outside the solar system and accelerated by supernova explosions (Simpson, 1983). Previous work by Gurtner et al. (2004) explored GCR interactions with Mercury's surface using Geant4, but relied heavily on assumptions due to limited observational data from Mariner 10. With the advancements brought by MESSENGER and BepiColombo, a reassessment based on updated environmental and surface composition data is now necessary.

This study addresses two main objectives: (1) characterization of the near-Mercury GCR environment based on models and observations, and (2) simulation-based estimation of energy deposition by cosmic-ray protons into Mercury's surface. For (1), we assessed the effect of Mercury's magnetosphere on GCR penetration using the KT17 magnetic field model (Korth et al., 2017). We calculated Larmor radii and particle rigidity to estimate the shielding effect. We also analyzed high-energy particle data from the "SPM" radiation housekeeping monitor (Kinoshita et al., 2025) onboard BepiColombo/MMO (Murakami et al., 2020). The SPM continuously observes galactic cosmic rays (GCRs) during BepiColombo's cruise phase; in this study, we focus on measurements obtained during the Mercury swing-by. For (2), we constructed a model of Mercury-analog material in Geant4 and simulated incident proton trajectories (see Fig. 1). We recorded parameters such as incident energy, deposited energy, angle of incidence, and maximum penetration depth to examine their interdependencies. These results provide key insights for interpreting upcoming observations of Mercury's surface by X-ray, gamma-ray, and neutron spectrometers following BepiColombo's orbital insertion at the end of 2026.

水星のような大気が希薄で、小さく弱い磁気圏を持つ惑星の進化史を理解するうえで、宇宙風化の影響がどの程度の深さ・強度で及んでいるか把握し、惑星表層のリモートセンシングの結果から切り離して解釈することは重要である。宇宙風化プロセスは、(i) 太陽系全体に見られる小粒子やデブリによるランダムな衝突、または (ii) 太陽風、銀河宇宙線に関連する2つの大きなカテゴリーに大まかに分類することができる。本研究ではこのうち宇宙線に着目し、放射線シミュレーション (Geant4: Allison et al., 2016) を用いて宇宙線による水星表層の宇宙風化の定量的評価を目指す。

銀河宇宙線とは超新星爆発によって加速されて太陽系外から飛来する数百 MeV-数 GeV の高エネルギー粒子であり、ほとんどを陽子が占めている (Simpson, 1983)。Geant4 を用いた高エネルギー宇宙線と水星表層の相互作用の研究は Gurtner et al., (2004) が取り組んでいるが、当時はまだマリナー 10 号しか水星を観測しておらず、やむを得ず地球近傍の宇宙線のフラックスや地球磁気圏のモデルなどが使われており、かつ表面組成のモデルも仮定に基づいている。現在の MESSENGER & BepiColombo 時代においては、これらの情報を更新するための研究が必要である。

本研究では、(1) モデルと実測値に基づく水星近傍の宇宙線環境の評価と、(2) シミュレーションを元にした水星表層に模擬宇宙線が与えるエネルギーの概算、という2つの課題に取り組む。まず(1)に関して、水星磁気圏の宇宙線入射に対する影響を調査するため、KT17 水星磁場モデル (Korth et al., 2017) を用いて、宇宙線のラーマー半径を計算した。宇宙線フラックスとエネルギーの実測値としては、BepiColombo/MMO (Murakami et al., 2020) に搭載されている高エネルギー放射線観測機器"SPM" (Kinoshita et al., 2025) の時系列カウントデータを独自に較正して使用した。その結果、宇宙線は全球に渡って等方的に降り注ぐため、太陽風のような降下領域の地理的依存性 (e.g., Lavorenti et al., 2023) は生じえないことが分かった。次に(2)に関しては Geant4 のモデル空間に水星模擬物質のブロックを構築し、陽子を発射するシミュレーションを実施した (添付図)。入射エネルギー、Deposited Energy (粒子が侵入経路上に残すエネルギー)、最大侵入深度などのパラメータを記録し、それぞれの関係性を調べた。その結果、主に2次電子が最大で地下5 m まで影響を及ぼしうることが判明し、探査機のγ線観測機器などの観測深度と重複することから (e.g., Wurz et al., 2025)、観測結果から宇宙風化作用を取り除く必要性を定量的に示すことができた。これらの結果を通じて、2026 年末に迫る BepiColombo 水星軌道投入後に実施される水星表層観測の結果を解釈するうえで注意すべきポイントを整理する。

R009-06

A 会場 : 11/24 PM1 (13:45-15:45)

15:00~15:15:00

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Dependence of proton and magnetic field structures in Mercury's magnetotail on upstream IMF directions

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Mercury has a small magnetosphere owing to its weak intrinsic magnetic field and interactions with the solar wind. However, the dependence of global distributions of ions and magnetic fields in Mercury's magnetotail on upstream interplanetary magnetic field (IMF) directions remains unclear. A recent study has reported that proton number density sometimes shows a clear north – south asymmetry controlled by the IMF Bx component (Zhong et al., 2024). In this study, we used MESSENGER observations of magnetotail protons and interplanetary magnetic field directions, thereby analyzing the dependence of spatial distributions of magnetotail protons and magnetic fields on the IMF directions. As a result, we identified a dependence of cross-tail current sheet thickness on the IMF Bz component and a possible dependence of dawn-dusk asymmetry of proton distributions on the IMF By component in MSO coordinates. Based on these results, we discuss transport and energization processes of Mercury's magnetotail protons.

R009-07

A 会場 : 11/24 PM1 (13:45-15:45)

15:15~15:30:00

月・小型天体から放出される難揮発性イオンの質量分析

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Mass analysis of refractory ions emitted from the moons and small bodies

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Small bodies without atmospheres (such as the moon, comets, and asteroids) are directly ex-posed to sunlight and solar winds, causing them to emit neutral particles and charged particles (secondary particles). As a result, an exosphere forms around these small bodies. Since particles in the exosphere may contain information about the surface composition, it is conceivable that the mass of surface materials on small bodies could be analyzed using orbiting spacecraft without the need for landers. However, since the emission of secondary particles depends on the element, a comprehensive understanding of the emission mechanism is necessary. In this presentation, we will introduce a method for obtaining information on the composition ratio of surface materials in orbit, taking into account the secondary particle emission mechanism from the surface, using observation data from the mass spectrometer onboard the lunar orbiter “Kaguya.” Additionally, since the Mars Moon Exploration Mission (MMX) will also observe secondary ions from Phobos using a mass spectrometer (MSA), we will discuss the scientific outcomes of this mission as well.

大気を持たない小天体（月、彗星、小惑星など）は日光や太陽風に直接晒されるため、中性粒子と帯電粒子（二次粒子）を放出する。その結果、これらの小天体の周囲には外気圏が形成される。外気圏の粒子は表面の組成に関する情報を有する可能性があるため、着陸機を使用せずに軌道周回探査機で小天体の表面物質の質量を分析する可能性が考えられる。しかしながら、二次粒子の放出は元素の種類に依存するため、放出メカニズムの包括的な理解が必要となる。本発表では、月探査機「かぐや」に搭載された質量分析計の観測データを用いて、表面からの二次粒子放出メカニズムを考慮し、軌道上にて表面物質の組成比に関する情報を得る方法を紹介する。また、火星の衛星探査計画（MMX）では質量分析計（MSA）を用いてフォボスからの二次イオンの観測も行われるため、その科学的成果についても議論する。

R009-08

A 会場 : 11/24 PM1 (13:45-15:45)

15:30~15:45:00

Comet Interceptor 搭載 TOF 型イオン分析器における分子イオン識別手法の開発と模擬データによる適用評価

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(¹ 東京大学)

Development of a Molecular Ion Identification Method for a TOF Ion Mass Spectrometer on Comet Interceptor Using Simulated Data

#Ryo TAO¹⁾, Satoshi KASAHARA¹⁾

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Understanding the formation and evolution of the Solar System relies critically on comet observations. In particular, long-period comets are thought to originate from the Oort cloud at the outer edge of the Solar System and approach the Sun only rarely, making them primordial bodies that have undergone minimal physical and chemical alteration. Directly investigating the chemical composition of the gases and dust they contain provides essential insights into the properties of Solar System progenitor materials.

Comet Interceptor is a comet exploration mission jointly developed by ESA and JAXA. After launch, it will wait near the Sun – Earth L2 point and, upon selecting a target long-period comet, will perform a high-speed flyby to observe the comet's tenuous atmosphere, or coma. The onboard ion mass spectrometer CIMS measures the composition and dynamics of ions in the cometary coma.

The mass resolution of CIMS is approximately $m/\Delta m \approx 45$ for the LEF (Linear Electric Field) path and $m/\Delta m \approx 5$ for the ST (Straight Through) path, as verified by ion irradiation experiments. This resolution was incorporated into the simulated spectra as peak widths and used as a precondition for inverse analysis. In CIMS, ions pass through a carbon foil after electrostatic energy analysis, which provides the start signal for time-of-flight measurement and induces phenomena such as molecular ion dissociation into atomic ions and charge exchange at a certain probability. The post-foil charge state determines detection via the LEF or ST paths, with LEF generally measuring dissociated atomic ions and ST measuring intact molecular ions. Therefore, measurements in the high-resolution LEF path face the challenge that molecular ions are observed only in their dissociated states.

In this study, we developed an analysis method to identify multiple ion species from CIMS mass spectra, considering this detection mechanism and observational conditions. Simulated spectra were constructed using Gaussian functions reflecting the CIMS resolution, with predefined abundance ratios for known ion species. Observations near a comet (maximum ion density $\sim 100 \text{ cm}^{-3}$) were simulated with Poisson statistical fluctuations. Considering an observation time of 110 s, energy sweep (1/32), incidence angle sweep (1/8), carbon foil transmission (0.8), fraction of observable ions after passage (0.1), charge exchange to cations (0.01), and MCP transmission (0.6), the expected counts were approximately 210 for the LEF path and 6000 for the ST path.

Analysis was performed using both standard least squares and non-negative constrained least squares, under three data configurations: (1) LEF only, (2) ST only, and (3) LEF and ST combined with counts normalized by inverse-square weighting. Thus, each analysis generated six optimization results (2 methods $\times$ 3 data configurations). As LEF provides atomic ion information and ST provides molecular ion information, combining both enhances estimation accuracy from both molecular structure and atomic composition.

Optimization was conducted iteratively. For numerous random ion density patterns, the six analyses were applied, and the combination of path and method minimizing the sum of squared differences between reconstructed and true values was selected. Ion species with high reproducibility were then fixed in abundance for the next optimization step. However, for molecular ions with overlapping m/q values in the ST path (e.g., H_2O^+ vs. NH_4^+ , OH^+ vs. NH_3^+ , CO^+ vs. HCNH^+), ST results were not directly used before their abundances were fixed. This procedure was repeated until the abundances of all ion species were determined, suppressing misidentification while leveraging complementary information from LEF and ST, thereby improving overall identification accuracy.

These results demonstrate that multiple overlapping ion species can be identified with high accuracy even under low resolution and low count conditions, and that the complementary use of LEF and ST is effective. Future work will experimentally evaluate ion-species-dependent dissociation efficiency and charge exchange probability at the carbon foil and refine the analysis method to incorporate noise characteristics, aiming for further improvements in accuracy.

太陽系の形成と進化を理解するうえで、彗星観測は極めて重要である。特に長周期彗星は太陽系外縁のオールトの雲を起源とし、太陽に接近する機会が限られるため、物理・化学的改変を受けにくい始原的天体と考えられている。これらに含まれるガスやダストの化学組成を直接調べることは、太陽系起源物質の特性解明に直結する。

Comet Interceptor は、ESA と JAXA が共同開発を進める彗星探査ミッションであり、打ち上げ後に太陽-地球系 L2 点付近で待機し、観測対象となる長周期彗星を決定後に接近して、高速フライバイにより彗星コマと呼ばれる希薄大気を観

測する。搭載されるイオン質量分析器 CIMS は、彗星コマ中のイオン組成や運動を計測する。

CIMS の質量分解能は LEF (Linear Electric Field) 経路で $m/\Delta m \approx 45$ 、ST (Straight Through) 経路で $m/\Delta m \approx 5$ であり、イオン照射実験によって検証済みである。この分解能は模擬スペクトル生成時のピーク幅として設定し、逆解析の前提条件とした。CIMS では、イオンは静電エネルギー分析後にカーボンフォイルを通過し、飛行時間計測のスタート信号を得るとともに、分子イオンが原子イオンへ分離する現象や一定確率での電荷交換が生じる。通過後の電荷状態により LEF 経路または ST 経路で検出され、一般に LEF では分離後の原子イオン、ST では分離前の分子イオンが観測される。したがって、高分解能の LEF 経路での計測は、分子イオンが分離後の状態で得られるという課題がある。

本研究では、この検出機構と観測条件を踏まえ、CIMS の質量スペクトルから複数イオン種を識別する解析手法を開発した。模擬スペクトルは既知の複数イオン種の存在比を設定し、CIMS の分解能を反映したガウス関数で構成した。彗星近傍（最大イオン数密度 $100 \text{ 個}/\text{cm}^3$ 程度）での観測を想定し、ポアソン統計に基づく揺らぎを導入した。さらに観測時間 110 秒に加え、エネルギー掃引 (1/32)、入射角度掃引 (1/8)、カーボンフォイル通過率 (0.8)、通過後の観測可能割合 (0.1)、陽イオンへの電荷交換率 (0.01)、MCP 通過率 (0.6) を考慮した結果、LEF 経路で約 210 カウント、ST 経路で約 6000 カウントと見積もられた。

解析は、通常の最小二乗法および非負制約付き最小二乗法の双方を用い、(1) LEF 経路のみ、(2) ST 経路のみ、(3) LEF・ST 経路をカウント値の逆二乗で正規化して同時利用、の 3 通りのデータ構成で実行した。したがって、1 回の解析で 2 種類の手法 $\times$ 3 通りの構成 = 計 6 通りの最適化結果が得られる。LEF は原子イオン、ST は分子イオンの情報を与えるため、両者を組み合わせることで分子構造と原子構成の双方から推定精度を高められる利点がある。

最適化は反復的に行い、多数のランダムなイオン数密度パターンに対して 6 通りの解析を適用し、復元値と設定値の差の二乗和が最小となる経路・手法の組み合わせを特定する。その結果から再現性の高いイオン種を選び、その存在量を次の解析ステップで前提条件として固定する。ただし、ST 経路で m/q が一致する異なる分子イオン（例： H_2O^+ と NH_4^+ 、 OH^+ と NH_3^+ 、 CO^+ と HCNH^+ ）については、存在量が固定される前の段階では ST 経路の結果を直接用いない。この手順を、すべてのイオン種の存在量が決定するまで繰り返すことで、誤同定の可能性を抑えつつ、LEF と ST を相補的に活用する解析を行い、全体の識別精度を向上させた。

以上により、低分解能・低カウント条件下でも複数の重なり合うイオン種を高精度に識別でき、LEF と ST の相補的利用が有効であることを示した。今後は、カーボンフォイル通過時の分離効率や電荷交換確率のイオン種依存性を実験的に評価し、ノイズ特性を含めた解析手法の改良により、さらなる精度向上を目指す。

R009-09

A 会場 : 11/24 PM2 (16:05-18:05)

16:05~16:20:00

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Spatial and temporal variability of low-energy lunar Ions: Insights from Kaguya/IMA observations

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We analyzed ~1 year of time-of-flight (TOF) data obtained from the Ion Mass Analyzer (IMA) on the Kaguya spacecraft to investigate the spatial and temporal variations of low-energy ions originating from the lunar surface and exosphere. In this study, we focused on the large-scale distribution and variability of ion fluxes of multiple species (He⁺, C⁺, O⁺, Na⁺, Al⁺, K⁺, Ar⁺). We assumed the low-energy ions (<300 eV) were accelerated along the motional electric field of the solar wind until the ions were detected by IMA. Mapping the observed fluxes at every footpoint of the motional electric field, we found that low-energy ions were more abundant on the dawnside than on the duskside. In addition, we examined possible drivers of temporal variations by categorizing the data according to meteor shower periods, solar wind flux levels, and solar EUV irradiance. We found that the low-energy ion fluxes during meteor shower periods increased compared to non-shower periods, whereas variations correlated with solar wind fluxes and EUV irradiance were less significant. These results suggest that micrometeoroid impacts are a major source of low-energy ions released from the lunar surface, while solar wind and EUV effects play secondary roles. This study demonstrates that ion measurements provide valuable insights into both surface composition and transient release processes, with implications for future observations by the Mass Spectrum Analyzer (MSA) on the MMX mission to study the Phobos surface.

R009-10

A 会場 : 11/24 PM2 (16:05-18:05)

16:20~16:35:00

月面空洞における流速・熱速度比に基づく局所的な正帯電形成メカニズムの解析

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Mechanisms of Ion-Driven Positive Charging in Lunar Cavities under Variable Flow-to-Thermal Speed Conditions

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The lunar surface, being almost entirely unshielded by an atmosphere, is directly exposed to the solar wind plasma and is therefore known to undergo significant surface charging. Previous studies have mainly discussed positive charging due to photoelectron emission under sunlight and negative charging caused by the dominant influx of electrons. However, the actual lunar surface is characterized by complex topography, including numerous craters, boulders, cracks, and deep cavities, where charging processes can differ significantly from those on flat surfaces.

In our earlier work, we reported an “ion-driven charging” mechanism, in which electrons are preferentially absorbed by the cavity sidewalls while ions readily reach the cavity floor, leading to a positive potential of several hundred volts at the bottom of deep cavities. In the present study, we aim to understand the general conditions under which such charging occurs by performing three-dimensional Particle-In-Cell (PIC) simulations, focusing on the relative magnitudes of the solar wind bulk flow velocity and the thermal velocities of ions and electrons.

Our analysis reveals that the potential at the cavity floor can be categorized into three regimes according to the flow-to-thermal speed ratio: (1) a negative potential forms when the flow velocity is lower than the ion thermal speed, due to dominant electron influx; (2) a pronounced positive potential develops when the flow velocity lies between the ion and electron thermal speeds, as electrons are lost to the sidewalls while ions penetrate to the floor; and (3) when the flow velocity exceeds the electron thermal speed, the enhanced electron supply drives the floor potential back toward near-zero values.

Furthermore, a semi-analytical free-fall model demonstrates that these charging characteristics, at spatial scales below the Debye length, can be consistently interpreted in terms of the flow-to-thermal speed ratio. Applying the results to typical solar wind conditions shows that, somewhat counterintuitively, positive charging is suppressed under fast-stream conditions and is instead more effectively induced under slow-stream conditions.

These findings provide important insights into the electrostatic environment of deep cavities and narrow gaps around landers or rocks on the lunar surface. They are also relevant to assessing charging risks for exploration hardware and predicting dust transport processes, while offering a basis for understanding surface charging on other airless bodies such as asteroids and Martian moons.

月面は大気による遮蔽をほとんど受けず、太陽風プラズマの直接的な影響を受けるため、表面帯電が顕著に生じることが知られている。従来研究では、太陽光に伴う光電子放出による正帯電や、電子流入優位による負帯電が主に議論されてきたが、実際の月面は多数のクレーターや岩塊、亀裂や深い空洞など複雑な凹地形を有しており、その内部では通常と異なる帯電現象が起こり得る。

我々はこれまでに、深い空洞内部において電子が側壁に失われやすい一方でイオンが底面に到達しやすくなるため、底面電位が数百ボルト規模で正に帯電する「イオン駆動帯電」機構を報告してきた。本研究では、この帯電がどのような条件で生じるかをより普遍的に理解するため、3次元 Particle-In-Cell (PIC) シミュレーションを用いて、太陽風の流速とイオン・電子熱速度の大小関係に着目した系統的解析を行った。

解析の結果、空洞底面の帯電状態は流速と熱速度の比により三つの領域に大別されることが分かった。すなわち、(1) 流速がイオン熱速度より低い場合には電子流入が支配的となり負電位を形成し、(2) イオン熱速度と電子熱速度の中間領域では電子が側壁に吸収される一方でイオンが底面に到達するため正電位が顕著に形成し、(3) 流速が電子熱速度を超える高流速領域では電子供給が増大し、底面電位がゼロ付近に収束した。

また、自由落下モデルに基づく半解析的な評価により、太陽風プラズマのデバイ長以下のスケールでのこの帯電特性が「流速／熱速度比」という指標によって統一的に説明できることを示した。さらに、典型的な太陽風条件に基づくパラメータマッピングを行った結果では、意外にも高速ストリームでは正帯電が抑制され、むしろ低速ストリーム条件において空洞底面の顕著な正帯電が誘発されやすいことが明らかとなった。

本成果は、月面の深部空洞や探査機周囲の狭隘部における帯電環境を理解する上で重要であり、探査機の帯電リスク評価や塵輸送現象の予測に資するだけでなく、小惑星や火星衛星といった他の無大気天体における電磁環境の理解にも寄与する。

R009-11

A 会場 : 11/24 PM2 (16:05-18:05)

16:35~16:50:00

太陽活動度変化に伴う月面からの光電子放出の変動

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Variations of photoelectron emission from the lunar surface with solar activity

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Since the Moon does not possess a dense atmosphere and a global magnetic field, the lunar surface directly interacts with its ambient charged particles. The imbalance between incoming and outgoing charged particles leads to surface charging. The lunar surface charging affects the motion of charged particles and the dust grains on the surface. Since the electrostatically lofted dust can be a hazard to future exploration, it is essential to determine the temporal and spatial distributions of the lunar surface potential. On the dayside lunar surface, photoelectron emission is dominant in interactions related to these charged particles. The characteristics of photoelectron emission depend on solar irradiation, which in turn is influenced by solar activity. However, it remains unclear how the energy spectra of photoelectrons vary with different levels of solar activity. We use a numerical model of photoelectron energy spectra emitted from the lunar surface and electron observations near the dayside lunar surface. First, we compare the model with ARTEMIS observations to constrain the free parameter in the model. Then we present variations in photoelectron energy spectra during solar minimum, solar maximum, and flare events. Our results show that larger fluxes of photoelectrons with higher energies are emitted from the surface under high solar activity conditions. We also discuss the implications for variations in lunar surface potential depending on the solar activity.

月は濃密な大気と全球的な磁場を持たない天体であるため、月面は周辺の荷電粒子と直接的に相互作用する。流出入する荷電粒子による電流が平衡となるように、月面の電位が変化する月面帯電が生じる。月面帯電は周辺の荷電粒子や表面のダスト粒子の運動に影響を与える。静電的な力によって浮揚したダストは将来の月面探査におけるリスクにもなるため、月面電位の時空間分布を決定することは重要な課題である。太陽光の当たる昼側の月面では、荷電粒子に関連する相互作用において光電子の放出が支配的である。光電子放出の特性は太陽放射に依存している。しかしながら、光電子のエネルギースペクトルが太陽活動度に応じてどのように変化するかについては理解が進んでいない。私たちは月面から放出される光電子のエネルギースペクトルの数値モデルと昼側月面付近での電子観測を用いる。最初に、月探査機 ARTEMIS の観測からモデル中のフリーパラメータを制約する。これを踏まえて太陽活動極小期、極大期、フレアイベントのそれぞれにおける光電子エネルギースペクトルの変化を示す。高い太陽活動度の際により高いエネルギーの光電子のフラックスが増加することがわかった。また、太陽活動に依存した月面電位の変化の可能性についても考察する。

R009-12

A 会場 : 11/24 PM2 (16:05-18:05)

16:50~17:05:00

高精度紫外線宇宙望遠鏡 LOPYUTA 計画の検討状況

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Status of ultraviolet space telescope LOPYUTA

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LOPYUTA is a ultraviolet (UV) space telescope mission, one of pre-project candidates for the JAXA M-class mission. The mission is dedicated to addressing two fundamental scientific themes: (1) the environments for life in the universe, and (2) the origin of structure and matter. To address the first goal, LOPYUTA will perform a comprehensive survey of the exospheres and ionospheres of various solar system objects and exoplanets, thereby enhancing our understanding of planetary systems and enabling the characterization of exoplanetary atmospheres. To address the second, the mission will probe the structure of the circumgalactic medium to verify star formation via gas inflows as predicted by models of cosmic structure formation. Furthermore, it will observe the high-temperature gas produced in the immediate aftermath of neutron star mergers to unravel the processes of heavy element nucleosynthesis. The measurement of the physical states of common elements such as hydrogen, oxygen, and carbon is central to these scientific objectives. As these elements are ubiquitous, their measurement is fundamental to understanding the structure and evolution of cosmic phenomena at wide spatial scales, from planetary atmospheres to stars and galaxies. LOPYUTA will leverage UV spectroscopy to pursue these scientific inquiries.

By optimizing its technical specifications for its scientific objectives, LOPYUTA is designed to surpass its predecessor, the Hisaki mission, by a factor of over 100 in sensitivity, spatial resolution, and spectral resolution, all within the constraints of a small satellite platform. The mission's goal is to achieve performance in the far-ultraviolet region that is comparable to the Hubble Space Telescope (HST). Its payload features a 60 cm aperture Cassegrain telescope equipped with four focal plane instruments: a Mid-Resolution Spectrograph (MRS, R=6,000), a High-Resolution Spectrograph (HRS, R=40,000), an Ultraviolet Slit Imager (UVSI), and a Fine Guidance Sensor (FGS). In order to realize an effective area of 350cm² and a spatial resolution of 0.1 arcseconds, a conceptual design study of the telescope is underway, in parallel with the development of three key technologies: high-reflectivity UV mirror coatings, large-format and high-precision detectors, and a pointing disturbance compensation system. These core UV observation technologies being developed for LOPYUTA are of global importance and will establish a foundation for Japan's contribution to the future flagship space telescope, the Habitable Worlds Observatory (HWO).

LOPYUTA は、宇宙科学研究所・公募型小型計画のプリプロジェクト候補として検討を進めている紫外線宇宙望遠鏡計画で、宇宙の生命生存可能環境(目標 1)と宇宙の構造と物質の起源(目標 2)の理解を目指す。目標 1 では、多様な太陽系天体・系外惑星の外圏・電離大気を網羅的に観測し、太陽系内天体の理解の深化と系外惑星大気の特徴づけを行う。目標 2 では銀河周辺物質の構造の観測から、宇宙構造形成の枠組みで予言されたガスの流入による星形成を検証する。また、中性子星合体直後の高温ガスの観測から重元素合成過程を解明する。これらの科学目標に取り組む上で鍵となるのが、水素、酸素、炭素などの物理状態の計測である。これらは宇宙にありふれた元素であるが故に、惑星大気から、恒星、銀河を構成するガスに至る、様々な空間スケールの構造とその進化の理解に関わっており、LOPYUTA は紫外線観測によって、これらの科学課題に取り組む。LOPYUTA は性能要求を科学目標に最適化することにより、先行ミッションである「ひさき」と同じ小型科学衛星規模でありながら感度、空間分解能、波長分解能をそれぞれ「ひさき」の 100 倍以上に向上し、真空紫外の波長域でハッブル宇宙望遠鏡 HST に匹敵する解像度と感度の実現を目指す。ミッション部は口径 60cm の主鏡を持つカセグレン望遠鏡と 4 つの焦点面装置、中分散分光器 MRS(分解能 6,000)、高分散分光器 HRS(40,000)、紫外スリットイメージャ UVSI、及び広視野ガイドカメラ FGS からなる。有効面積 350cm² と解像度 0.1 秒角を達成するため、紫外用ミラー成膜、大型高精度検出器、指向擾乱補正機能の 3 つのキー技術開発に加え、望遠鏡構造の概念検討を進めている。LOPYUTA で開発する紫外線観測のキー技術(高感度検出器や高い反射率を実現するミラー成膜技術)は世界的にも重要で、次世代旗艦宇宙望遠鏡 Habitable Worlds Observatory (HWO) への日本の参画の足掛かりともなる。

R009-13

A 会場 : 11/24 PM2 (16:05-18:05)

17:05~17:20:00

LAPYUTA 搭載に向けた紫外線高反射ミラーの開発

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Development of High-Reflectivity Ultraviolet Mirrors for LAPYUTA

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We are developing high-reflectivity ultraviolet mirrors to improve the detection efficiency of the focal plane instruments aboard the Life-environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly (LAPYUTA). Conventionally, ultraviolet mirrors are fabricated by vacuum-depositing aluminum (Al), which has high reflectivity in the UV range, onto polished glass substrates, followed by a magnesium fluoride (MgF₂) coating to prevent oxidation of the Al layer. In general, mirror reflectivity in the vacuum ultraviolet region is lower than in the visible and infrared. For one of LAPYUTA's primary science targets, the atomic oxygen emission line at 130.4 nm, the reflectivity of Al + MgF₂ mirrors is typically limited to about 85%. With four reflections in the optical path, the total efficiency would be reduced by half. Reducing the number of mirrors is an effective way to reduce this loss, but LAPYUTA requires three to five mirrors to achieve high imaging performance. Therefore, improving the reflectivity of each mirror is essential. In this study, we are fabricating mirrors while systematically varying deposition parameters—including the film thicknesses of Al and MgF₂, the substrate temperature during deposition, and the vacuum pressure—to determine the optimal conditions for maximizing reflectivity. Our current best process has achieved a reflectivity of 87.6%.

We have also begun investigating a new coating process. A recent study (Quijada et al., 2024) reported that introducing a small amount of xenon fluoride (XeF₂) between the Al and MgF₂ deposition steps allows Al to fluorinate before it oxidizes, thereby preventing a decline in reflectivity. Mirrors fabricated with this process have demonstrated reflectivity exceeding 90%. The reflectivity in this process also depends on multiple deposition parameters. Therefore, we aim to identify the optimal conditions and approach the theoretical maximum reflectivity of 95%. When this is realized, the overall efficiency with four reflective surfaces would improve to 81%. This presentation will also report on the preparation status of this coating process.

我々は、高精度紫外線宇宙望遠鏡 Life-environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly (LAPYUTA) の焦点面装置の検出効率向上に向けて、紫外線用の高反射ミラーの開発を行っている。従来の紫外線用ミラーは、研磨したガラス基板上に紫外線領域において反射率が高いアルミニウム (Al) を真空蒸着し、その上に Al の酸化防止コーティングとしてフッ化マグネシウム (MgF₂) を真空蒸着して作成する。一般に、真空紫外域でのミラーの反射率は可視・赤外域に比べて低く、LAPYUTA の観測ターゲットの 1 つである酸素原子輝線 130.4 nm における、Al + MgF₂ ミラーの反射率は通常 85 % 程度に留まる。反射が 4 回あると全体の効率が半分になるため、望遠鏡の効率低下を回避するにはミラーを減らすことが有効だが、LAPYUTA では高い結像性能を得るために 3-5 枚のミラーを使用する。このため、反射率の自体の向上が必須である。そこで、本研究では様々な蒸着パラメータ (Al・MgF₂ の膜厚、蒸着時の基板温度、蒸着時の真空度など) を制御してミラーを作成し、高い反射率を実現する最適な蒸着パラメータの決定に取り組んでいる。プロセスを改善した現状の最適蒸着パラメータでは、反射率 87.6 % に達している。

また、新しいコーティングプロセスにも着手している。近年、Al と MgF₂ の 2 回の蒸着の間に微量のフッ化キセノン (XeF₂) を封入することで、Al が酸化するより先にフッ化させ、反射率の低下を防ぐことができると報告された (Quijada et al., 2024)。このプロセスで作成したミラーの反射率は 90 % 以上である。このプロセスにも上述のように、様々なパラメータ依存性がある。そこで、我々はこのプロセスにおける最適蒸着パラメータを決定し、理論値の 95 % に近づく反射率を目指している。これが達成できれば、反射面が 4 枚の場合の効率は 81% まで改善する。本発表では、このプロセスの準備状況も報告する。

R009-14

A 会場 : 11/24 PM2 (16:05-18:05)

17:20~17:35:00

ひさき衛星の極端紫外分光データを用いたイオ軌道からエウロパ軌道にわたるプラズマ特性の導出

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Plasma properties from Io's to Europa's orbit estimated from the Hisaki observation

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Jupiter's inner magnetosphere contains the Io plasma torus with dense sulfur and oxygen ions originating from SO₂ gases emitted through volcanic activities in Io (at 5.9R_J from Jupiter). Europa (at 9.4 R_J) has a tenuous molecular oxygen atmosphere produced by magnetospheric plasma sputtering on its surface. It can also be a source of oxygen and hydrogen ions in the Jovian magnetosphere. Understanding the production and loss of Europa's atmosphere requires knowledge of plasma parameters around the satellite. However, measurements of the plasma properties outside 8 R_J remain limited. This study aims to estimate the electron density, electron temperature, and ion composition from Io's to Europa's orbit using Hisaki satellite data.

The ions in the torus emit ultraviolet light through electron impact excitation. The extreme ultraviolet spectrograph EXCEED aboard Hisaki, orbiting the Earth, measured the sulfur and oxygen ion emission lines in the wavelength range of 55 nm to 145 nm. In Europa's orbit, as the brightness is much weaker than that of Io's orbit, contamination from the terrestrial radiation belt and foreground geocoronal emissions was carefully removed. The data were integrated from March 1st to May 14th, 2015, which includes Io's volcanically active period (Hikida et al., 2020). We successfully identified sulfur and oxygen ion emission lines in Europa's orbit for the first time.

The intensity of emission lines is proportional to the local density of the torus ions and is affected by the electron density and temperature. Plasma parameters were obtained using the plasma diagnosis based on the CHIANTI atomic database, assuming exponential radial distributions of plasma parameters and fitting the observed spectra.

The estimated electron densities and core temperatures are consistent with Bagenal et al. (2015) and Yoshioka et al. (2018), but the hot electron fraction is approximately 4 times larger in both Io's and Europa's orbits. Both the hot electron fraction and the S³⁺ fraction increase with the radial distance, while the S⁺ fraction decreases. This indicates that electron impact ionization of sulfur ions proceeds as the ions are transported outward. Compared with the Cassini observations (Steffl et al., 2004), the S³⁺ fraction in Europa's orbit is approximately twice as large, likely reflecting an enhanced volcanic activity in 2015. Using Hisaki data with continuous observations of the torus, we will investigate variations in plasma properties in Europa's orbit during Io's volcanically quiet and active duration.

木星磁気圏は、木星から 5.9R_J 離れた衛星イオが主要なプラズマ源となっている。イオの火山性 SO₂ ガスが電離することで生じる硫黄イオンや酸素イオンは、木星の周囲でドーナツ状のイオプラズマトーラスを形成している。9.4 R_J に位置する衛星エウロパは、木星磁気圏のプラズマが衛星表面の水にスパッタリングすることで生じる希薄な酸素大気に覆われていて、水素イオンや酸素イオンの供給源となり得る。エウロパ大気の生成・散逸についての理解を深めるためには、衛星周辺のプラズマ状態を知ることが不可欠である。しかし、8R_J からエウロパ軌道にかけてのプラズマ特性の空間分布・時間変動に関しては、観測が依然として限定的である。そこで本研究では、ひさき衛星によって得られた極端紫外分光データを用いて、イオ軌道からエウロパ軌道にかけての電子密度、電子温度、イオン組成の動径方向分布を導出することを目的としている。

イオプラズマトーラスのイオンは電子衝突励起によって紫外線で発光し、イオンの種類やエネルギー準位に応じて特定の波長に輝線が現れる。地球周回軌道のひさき衛星に搭載された分光器 EXCEED によって、55nm~145nm の波長帯で硫黄イオンや酸素イオンの輝線を観測することができる。エウロパ軌道では、イオ軌道に比べてトーラスの発光強度が小さいため、地球の放射線帯やジオコ罗纳などの前景光の影響を丁寧に取り除く必要があった。また、輝線の S/N を向上させるため、2015 年 3 月 1 日から 5 月 14 日までの約 2.5 ヶ月分のデータを積分した。この期間は、2015 年 1 月のイオの火山噴火後で、火山活動が活発な時期を含んでいる (Hikida et al., 2020)。ひさき衛星の観測データから、エウロパ軌道における硫黄イオンと酸素イオンの輝線が初めて検出された。

観測される輝線の発光強度は、トーラスのイオンの密度、衝突電子の密度・温度によって決まる。本研究では、これらのプラズマ特性が動径方向に指数関数的に分布しているという仮定のもと、CHIANTI 原子データベースから計算された

モデルスペクトルを使って観測スペクトルのフィッティング（プラズマ診断）を行い、電子密度・電子温度・イオンの組成比を導出した。

推定された電子密度と電子温度は、Bagenal et al. (2015) によるエウロパ軌道の結果と Yoshioka et al. (2018) によるイオ軌道の結果の範囲内にそれぞれ一致した。一方、電子全体に対する高温電子の割合は、イオ軌道でもエウロパ軌道でも先行研究の約 4 倍の大きさとなった。イオン組成に関しては、高温電子の割合が動径方向外側ほど増加するにつれて、 S^{3+} の割合は増加し S^{+} の割合は減少した。これは、トーラスのイオンが動径方向外側へ輸送されるながら、電子衝突電離によるイオン化が進行していることを示している。また、Cassini の観測 (Steffl et al., 2004) に対し、エウロパ軌道における S^{3+} の割合はほぼ 2 倍高く、ひさき衛星のデータでは 2015 年の火山活動の活発化を反映している可能性がある。今後は、トーラスを連続観測しているひさき衛星のデータを用いて、イオ軌道からエウロパ軌道までのプラズマ特性が、火山の静穏期と活発期でどのように変動するかを調べる。

R009-15

A 会場 : 11/24 PM2 (16:05-18:05)

17:35~17:50:00

凝結による木星大気対流の抑制に関する流体力学数値モデル実験

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Hydrodynamic numerical experiments on condensation-inhibited convection in Jupiter's atmosphere

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1. Background and Objectives

The abundances and internal distributions of icy materials (hydrogen compounds of oxygen, nitrogen, carbon, sulfur, etc.) in giant planets such as Jupiter provide key information for understanding the formation of gas giants and the evolution of planetary systems. In the atmospheres of giant planets, these icy species condense to form clouds. When their abundance exceeds a certain threshold, convection is inhibited because their molecular weight is larger than that of major components (Guillot, 1995; Leconte et al, 2017). In such cases, convective energy transport is inhibited in the condensation layers, and observational estimation of composition and temperature structures may become more difficult. However, previous studies have mainly employed 1D vertical models, which cannot fully represent convective dynamics. Furthermore, the effects of material transport due to the precipitation of condensates in cloud convection and the associated latent energy transport have not been considered. On the other hand, employing a 2D cloud convection model for Jupiter that includes multiple condensable species and cloud microphysical processes, Sugiyama et al (2014) performed long-term integrations to investigate the spatiotemporal evolution of convection and the mean atmospheric structure. However, they didn't explore conditions where the abundance of condensable species exceed the threshold values for convective inhibition. In this study, we employ their 2D cloud convection model, deepconv, to investigate dynamical and energy transport structures under convection-inhibited conditions focusing on the role of precipitation processes.

2. Numerical Model

The 2D cloud convection model deepconv solves a set of equations based on Klemp and Wilhelmson (1978), coupled with conservation equations for condensable species. Cloud microphysical processes are represented by the warm-rain parameterization of Kessler (1969), and turbulent mixing is parameterized following Klemp and Wilhelmson (1978). The computational domain extends 512 km horizontally and 300 km vertically, with 2 km grid spacing. The bottom boundary is placed at pressure of 30 bar. A radiative cooling of -0.1 K/day, which is approximately one order of magnitude stronger than that for Jupiter's atmosphere, is imposed over the pressure range from 2 bar to 0.1 bar. The initial vertical temperature profile is adiabatic below 0.1 bar and isothermal above. For simplicity, we only consider water vapor as the condensable species, which contributes most strongly to convection inhibition.

3. Preliminary Results

Simulations were performed with water vapor mixing ratios of $1 \times$, $10 \times$, and $40 \times$ the solar composition (Grevesse et al, 2007), each integrated for ~ 1000 days. Fig.1 shows snapshots of vertical velocity, potential temperature deviation from the initial state, cloud mixing ratio, and rain mixing ratio at an active convective phase in the $40 \times$ abundance case. The atmosphere is separated into moist and dry convective layers above and below the condensation level. The regions around the condensation level become up to ~ 20 K colder than the initial state. This cooling results from evaporation of raindrops descending from the upper cloud layers, while upward convective heat transport is inhibited.

4. Future Work

The preliminary results suggest that cloud microphysical processes, neglected in conventional 1D models, can significantly affect atmospheric dynamics and energy transport. We will perform longer integrations to reach statistically steady state. To accelerate the approach to the statistically steady states, we plan to further enhance radiative cooling. Based on such extended experiments, we aim to quantitatively evaluate the contribution of material and energy transport associated with cloud microphysics to the atmospheric structure. Ultimately, we intend to clarify atmospheric dynamics, energy transport, and material cycles also under more realistic thermal forcing conditions.

1. 背景と目的

太陽系の木星をはじめとする巨大惑星における氷物質（酸素、窒素、炭素、硫黄などの水素化物）の存在度および惑星内部での分布は、ガス惑星の形成過程のみならず、惑星系全体の形成進化の推定においても重要な情報である。氷物質は

巨大惑星の表層大気中では凝結して雲を形成する。その存在度が閾値を超えると、その分子量が主成分であるガスの分子量より大きいと、対流が禁止されることが知られている (Guillot, 1995; Leconte et al, 2017)。そのような場合、凝結層において対流によるエネルギー輸送が阻害され、その結果、惑星内部の組成構造や温度構造の観測的推定は困難となる。しかし、過去の研究では鉛直 1 次元モデルが用いられており、運動の効果を十分に考慮できていない可能性がある。さらに、雲対流において必然的に生じる凝結物の落下による物質輸送、およびこれに伴う潜熱のエネルギー輸送の影響が考慮されていない。一方、Sugiyama et al (2014) は、木星大気における複数の凝結成分の雲生成と雲物理過程を含む 2 次元雲対流モデルを開発し、これを長時間積分することにより、対流運動の時空間構造と平均的大気構造を調査した。しかし、同研究では、対流が禁止されるほど凝結成分が極めて多い条件での計算は行われていない。そこで本研究では、杉山らと同じ 2 次元雲対流数値モデル deepconv を使用して、これまで 1 次元モデルでしか考察されてこなかった対流禁止条件における運動・エネルギー輸送構造を、降水過程の役割を含めて明らかにすることを目的とする。

2. 数値モデルの概要

2 次元雲対流モデル deepconv の基礎方程式系は、Klemp and Wilhelmson (1978) と凝結成分の保存の式からなる。雲微物理過程は Kessler (1969) の暖かい雨のパラメタリゼーション、乱流混合過程は Klemp and Wilhelmson (1978) のパラメタリゼーションで表現されている。計算領域は水平 512 km、鉛直 300 km、解像度は 2 km とする。2 - 0.1 bar には -0.1 K/day の放射冷却を与える（実際の木星の値より約 1 桁大きい）。初期の大気の鉛直温度分布は、0.1 bar までは断熱的分布、それ以上の高度は等温とする。また、問題を単純化するために、凝結成分としては対流禁止に最も強く寄与する成分である水蒸気のみを考えた。

3. 予備的な結果

太陽組成 (Grevesse et al, 2007) の 1, 10, 40 倍の水蒸気混合比を与え、それぞれ約 1000 日分積分した。図 1 は水蒸気混合比が太陽組成の 40 倍と非常に多い場合の実験の、対流活動が活発な時刻の鉛直速度、乾燥断熱状態からの温度偏差、雲の混合比、雨の混合比の分布のスナップショットである。水蒸気の凝結高度より上は湿潤対流層、下は乾燥対流層である。また、水蒸気混合比が多い場合、時間経過とともに凝結高度付近の冷却が顕著に進み、水蒸気混合比 40 倍実験においては、乾燥断熱状態と比べて最大約 -20 K 程低温の領域が生じた。これは大気上部の雲から降下する雨滴が蒸発して大気を冷却している一方、下からの対流熱輸送が禁止されているためである。

4. 今後の方針

予備的結果は、従来の 1 次元モデルでは考慮されてこなかった雲微物理過程が、大気の運動構造やエネルギー輸送に一定の影響を及ぼしうることを示唆している。今後は、さらに長時間の計算を行い、統計的定常状態を実現する設定を確立する。積分時間を短縮するために、放射冷却をさらに強めて計算を加速させる予定である。その上で、雲微物理過程による物質・エネルギー輸送が大気構造にどの程度寄与するのかを定量的に評価することを目指す。また、最終的には、より現実的な強さの熱強制条件下における運動構造、エネルギー輸送、および物質循環の特徴を明らかにしたい。

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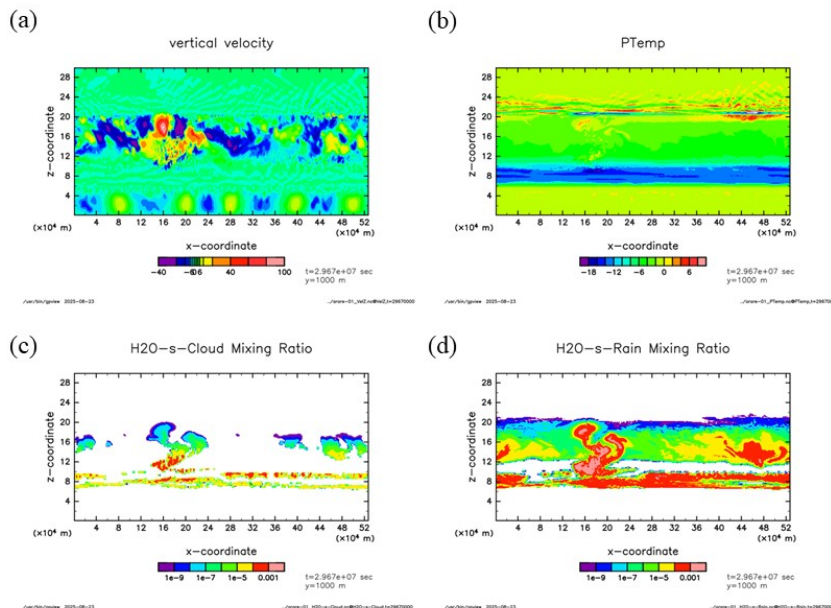


Fig. 1. Snapshots during an active convective phase in the $40 \times$ solar experiment: (a) vertical velocity, (b) potential temperature deviation from the initial state, (c) cloud mixing ratio, and (d) rain mixing ratio.

R009-16

A 会場：11/24 PM2 (16:05-18:05)

17:50~18:05:00

プラズマ照射実験に基づくエウロパ表層の塩化物塩の枯渇時間評価

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Lifetime of chloride salts on Europa estimated from plasma irradiation experiments

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Europa, one of Jupiter's moons, is thought to harbor an interior ocean beneath its icy crust and is considered one of the celestial bodies with potential for life. Near-infrared spectra obtained by the Galileo spacecraft (McCord et al., 2010) indicated the presence of sulfate and chloride salts, and spectral comparisons in laboratory experiments on these near-infrared reflection spectra (Poston et al., 2017; Trumbo et al., 2019) suggested that material from the interior ocean may have been transported to the surface. Determining the chemical composition of surface materials provides indirect clues to the properties of the interior ocean and its habitability (e.g., Carlson et al., 2001). Europa's surface is continuously irradiated by high-energy charged particles from Jupiter's magnetosphere, inducing space weathering that alters the chemical composition of materials through the ionization, dissociation, and recombination processes (Cooper et al., 2001). Consequently, the chemical state of fresh surface material before the space weathering is difficult to estimate. Sulfates and chloride salts are considered potential candidates for surface materials supplied from the interior ocean (e.g., Carlson et al. 2001). In a previous laboratory plasma experiment involving electron, oxygen ion, and hydrogen ion irradiation of MgSO_4 —one of the sulfates—Otsuki (Master's thesis, Tokyo University of Science, 2024) proposed that sulfates may originate from Europa's interior ocean. This study simulated chemical cycling driven by space weathering and estimated the depletion time of MgSO_4 to be approximately 1.1×10^3 years. This value is significantly shorter than Europa's average surface age ($\sim 1 \times 10^7$ years; Zahnle et al., 2003). Regions where hydrated materials such as sulfates are observed correspond to areas where material transport from the interior ocean to the surface is considered plausible (Carlson et al., 2009). Therefore, the experimental results suggest that MgSO_4 may be supplied from the interior ocean to the surface within 1.1×10^3 years, remaining present without complete depletion. Meanwhile, Ligier et al. (2016) conducted model calculations combining near-infrared observations from ground-based large telescopes with laboratory spectral data. Their results revealed spectral features consistent with chloride salts, including MgCl_2 , in regions where material transport from the interior ocean is expected. This suggests that MgCl_2 may also originate from the interior ocean. However, no prior studies have reproduced the depletion processes of chloride salts under space weathering conditions, and both the depletion time and mechanisms remain unclear. Consequently, the presence of chloride salts on Europa's surface has not yet been empirically demonstrated. As a result, the concentration of chloride salts in the interior ocean and the surrounding environmental conditions relevant to potential habitability remain unresolved.

In this study, laboratory plasma irradiation experiments targeting magnesium chloride (MgCl_2) were conducted under conditions like Otsuki (2024). Electron, oxygen ion, and hydrogen ion irradiations were performed at fluxes of 2.1×10^{14} , 1.9×10^{14} , and 5.3×10^{14} /cm²/s, respectively, over durations of 2.0 – 3.5 hours to simulate space weathering spanning 4.7×10^2 to 2.8×10^4 years in Europa. As a result, quadrupole mass spectrometry detected the release of gases such as Cl, Cl_2 , and HCl from chloride salt samples during irradiation. Based on the measured gas production rates, numerical simulations were conducted to estimate the depletion time of MgCl_2 under each irradiation condition. The estimated depletion times were 5.1×10^2 years for electron irradiation, 3.6×10^4 years for oxygen ion irradiation, and 1.3×10^4 years for hydrogen ion irradiation. Additionally, the depletion cross sections were estimated to be 2.4×10^{-18} , 4.8×10^{-18} , and 1.2×10^{-18} cm², respectively. Assuming Europa-like environmental conditions and applying these cross sections, the simulated depletion time of MgCl_2 under simultaneous irradiation by electrons, oxygen ions, and hydrogen ions was calculated to be 4.8×10^2 years. This depletion time is significantly shorter than Europa's average surface age ($\sim 1 \times 10^7$ years; Zahnle et al., 2003), which is inferred from crater chronology. Therefore, MgCl_2 is likely to be depleted by space weathering before the surface is renewed by geological processes. The model calculations by Ligier et al. (2016), which combined near-infrared observations with laboratory spectral data, suggest the presence of chloride salts, including MgCl_2 , in chaos regions where material transport from the interior ocean to the surface is expected. Assuming chloride salts are present in these regions, the results of this study indicate that a continuous supply of material from the interior ocean within the estimated depletion time (4.8×10^2 years) could allow chloride salts to persist on the surface despite ongoing space weathering. Furthermore, when compared to the depletion time of sulfates (1.1×10^3 years; Otsuki, Master's thesis, Tokyo University of Science, 2024), chloride salts appear to deplete more rapidly under space weathering conditions. This suggests that chloride salts may serve as a significant tracer of more recent material supply from the interior ocean than sulfates.

木星の衛星エウロパは、氷の地殻の下に液体の水からなる内部海を持つと考えられており、生命が存在する可能性が示

唆されている天体の一つである。ガリレオ探査機による近赤外分光観測 (NIMS) によって得られた表層スペクトルは、硫酸塩や塩化物塩などの存在を示しており (McCord et al., 2010)、これらの近赤外反射スペクトルに関する室内実験との比較 (Poston et al., 2017; Trumbo et al., 2019) により、内部海の物質が表層へ輸送されている可能性が示唆されている。表層物質の化学組成を理解することは、内部海の成分や生命存在可能性を間接的に探る手がかりとなる (e.g., Carlson et al. 2001)。一方、エウロパの表層は木星周辺の高エネルギー粒子によって継続的に照射されており、物質の組成変化を引き起こす「宇宙風化」が生じている (Cooper et al., 2001)。この風化過程では、物質が電離、分解、再結合を繰り返すことによって化学サイクルが形成される。その結果、風化前の物質組成を明らかにすることは困難である。

現在、内部海から供給される可能性のある表層物質の候補として、塩化物塩と硫酸塩が注目されている (e.g., Carlson et al. 2001)。硫酸塩の一つである MgSO_4 に対して、電子・酸素イオン・水素イオンを照射する室内プラズマ実験を通じて、硫酸塩が内部海由来である可能性を提示した先行実験 (大槻, 東京理科大学修士論文, 2024 年) では、宇宙風化による化学サイクルを模擬し、 MgSO_4 の枯渇時間を 1.1×10^3 年程度と推定した。この値はエウロパの平均表層年代 ($\sim 1 \times 10^7$ 年; Zahnle et al., 2003) よりも十分に短い。硫酸塩などの水和物が存在する領域は、内部海の物質が表層へ輸送されている可能性がある領域に対応している (Carlson et al., 2009) ことから、先行実験の結果は、 MgSO_4 が内部海から 1.1×10^3 年以内に表層へ供給され、枯渇せず表層に存在している可能性を示唆している。一方 Ligier et al. (2016) は、地上の超大型望遠鏡による近赤外観測と室内実験のスペクトルを組み合わせたモデル計算を実施した。その結果、内部海からの物質輸送が期待される領域において、 MgCl_2 を含む塩化物塩に由来すると考えられるスペクトルが検出され、 MgCl_2 が内部海由来である可能性を示唆している。しかし、宇宙風化による枯渇過程を再現した前例は報告されておらず、枯渇時間やその過程は未解明であり、表層における塩化物塩の存在の実証には至っていない。結果として、内部海における塩化物塩の濃度やそれを取り巻く生命存在可能性につながる環境も未解明である。

本研究では、塩化物塩の一つである塩化マグネシウム (MgCl_2) に対して、大槻 (東京理科大学修士論文, 2024 年) と同条件の室内照射実験を行った。電子・酸素イオン・水素イオンをそれぞれ 2.1×10^{14} , 1.9×10^{14} , 5.3×10^{14} / cm^2/s のフラックスで 2.0 - 3.5 時間照射し、宇宙風化による塩化物塩の枯渇過程を 4.7×10^2 - 2.8×10^4 年再現した。その結果、四重極質量分析器を用いて、照射中の塩化物塩サンプルからは Cl , Cl_2 , HCl などのガスの脱離が観測された。得られたガス生成データをもとに、各成分の生成率から MgCl_2 の枯渇までに要する時間 (枯渇時間) を数値シミュレーションした結果、電子照射では 5.1×10^2 年、酸素イオン照射では 3.6×10^4 年、水素イオン照射では 1.3×10^4 年と見積もられた。さらに各照射における枯渇断面積は 2.4×10^{-18} , 4.8×10^{-18} , 1.2×10^{-18} cm^2 と推定された。実際のエウロパ環境を想定し、得られた枯渇断面積を用いて電子・酸素イオン・水素イオンの同時照射による MgCl_2 の枯渇時間をシミュレーションした結果、 4.8×10^2 年と算出された。

この枯渇時間は、クレーター年代学に基づいて示唆されているエウロパの平均表層年代 ($\sim 1 \times 10^7$ 年; Zahnle et al., 2003) よりも十分に短く、地質学的プロセスにより表層が更新されるより前に、 MgCl_2 は宇宙風化により枯渇する可能性が高いと考えられる。Ligier et al. (2016) による近赤外観測と室内実験スペクトルを組み合わせたモデル計算は、内部海物質が表層へ輸送されたと示唆されるカオス領域に MgCl_2 を含む塩化物塩が存在する可能性を示している。当該領域に塩化物塩が存在すると仮定すれば本研究の結果は、推定された枯渇時間 (4.8×10^2 年) 以内に内部海から表層へ物質が継続的に供給されることで、宇宙風化を受けながらも、完全には枯渇せず塩化物塩が表層に安定して存在し続ける可能性を示している。また硫酸塩の枯渇年数 (1.1×10^3 年; 大槻, 東京理科大学修士論文, 2024 年) と比較すると、塩化物塩は宇宙風化により速く枯渇する傾向にある。塩化物塩は、硫酸塩よりも最近の物質供給を示す有意なトレーサーである可能性が示唆される。

R009-17

A 会場 : 11/25 AM1 (9:15-10:45)

9:15~9:30:00

Habitable Worlds Observatory (HWO) : プロジェクトおよび日本の参画の計画概要

#塩谷 圭吾¹⁾, 亀田 真吾²⁾, 住 貴宏³⁾, 宮崎 聡⁴⁾, 山崎 敦¹⁾, 村上 豪¹⁾, 米田 健太¹⁾, 高橋 葵¹⁾, 山田 亨¹⁾, 河原 創¹⁾, 宮崎 翔太¹⁾, 山崎 典子¹⁾, 近藤 依央菜¹⁾, 東尾 奈々¹⁾, 村上 尚史⁵⁾, 田村 元秀⁵⁾, 葛原 昌幸⁵⁾, 小谷 隆行⁵⁾, 西川 淳^{4,5,6)}, 大内 正己^{6,8)}, 生駒 大洋⁴⁾, 松尾 太郎³⁾, 伊藤 哲司⁷⁾, 成田 憲保⁸⁾, Guyon, Olivier⁹⁾

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Habitable Worlds Observatory (HWO): Overview of the project and Japan's participation plan

#Keigo Enya¹⁾, Shingo KAMEDA²⁾, Takahiro Sumi³⁾, Satoshi Miyazaki⁴⁾, Atsushi Yamazaki¹⁾, Go MURAKAMI¹⁾, Kenta Yoneta¹⁾, Aoi Takahashi¹⁾, Toru Yamada¹⁾, Hajime Kawahara¹⁾, Shota Miyazaki¹⁾, Noriko Yamasaki¹⁾, Iona Kondo¹⁾, Nana Higashio¹⁾, Naoshi Murakami⁵⁾, Motohide Tamura⁵⁾, Masayuki Kuzuhara⁵⁾, Takayuki Kotani⁵⁾, Jun Nishikawa^{4,5,6)}, Masami Ouch^{6,8)}, Masahiro Ikoma⁴⁾, Taro Matsuo³⁾, Satoshi Itoh⁷⁾, Norio Narita⁸⁾, Olivier Guyon⁹⁾

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The Habitable Worlds Observatory (HWO) is a proposed NASA's space telescope planned to be realized in the 2040s as a flagship space telescope following the James Webb Space Telescope and the Nancy Grace Roman Space Telescope, based on recommendations from the U.S. Decadal Survey (Astro2020). HWO is designed to have a 6 m class aperture for observations in the ultraviolet to near-infrared wavelength range.

HWO is planned to be equipped with a coronagraph instrument that will conduct direct observations of Earth-like planets orbiting solar-type stars, studying their atmospheric and surface characteristics, and searching for signatures of life. It is also planned to carry a high-resolution imager and an ultraviolet multi-object spectrograph, with other instruments also being considered. A mission concept review for HWO is scheduled for 2029, and it is planned to improve the maturity of the concept and technology by then. Japan's contributions to HWO currently being considered are hardware for the coronagraph and ultraviolet observation instruments, as well as participation in scientific study.

In December 2024, a task force was established at JAXA/ISAS with the aim of promoting Japan's participation in HWO. The role of the ISAS HWO Task Force is to act as the point of contact with NASA, promote technology frontloading, and collaborate with the community. The HWO Community Science & Instrument Team (CSIT) has been established in 2025, with plans to send CSIT members from Japan in the future.

In the presentation, we will provide an overview of HWO (science, instruments, schedule, program status etc., and then an overview of Japan's participation plans.

Habitable Worlds Observatory (HWO) は、米国のディケイダルサーベイ (Astro2020) の提言を受け、NASA がジェームズ・ウェッブ宇宙望遠鏡、ローマン宇宙望遠鏡に続く旗艦宇宙望遠鏡として、紫外線から近赤外線にわたる波長域で観測を行う口径 6 m 級の宇宙望遠鏡を 2040 年代に実現しようとする超大型計画である。

HWO には太陽型星を周回する地球型惑星の直接観測を行い、その大気や表面の特徴を調べるとともに、そこに生命の兆候を探索するコロナグラフ装置や、高解像度撮像装置、紫外線多天体分光器を搭載する予定であり、更にその他の装置の搭載も検討されている。HWO では 2029 年にミッションコンセプトレビューを予定しており、それまでにコンセプト及び技術の成熟度を高めることが計画されている。HWO に対する日本からの寄与として、コロナグラフ装置および紫外線観測装置の開発、そして科学研究への参画が検討されている。

2024 年 12 月、HWO への日本の参画に向けて、宇宙研にタスクフォースが設立された。宇宙研 HWO タスクフォースが担う役割は、NASA に対する日本側の窓口となること、技術フロントローディングの推進、コミュニティとの連携等である。その前段階では、2023-2024 に 2 名の JAXA representative が活動してきた。

講演では HWO の全体概要 (科学目標、観測装置、スケジュールや米国・NASA 予算等のプログラムの状況等) および日本の参画計画の概要を示す。

R009-18

A 会場 : 11/25 AM1 (9:15-10:45)

9:30~9:45:00

HWO 搭載に向けた紫外線面分光器・高分散分光器の検討状況

#亀田 真吾¹⁾, 村上 豪²⁾, 桑原 正輝¹⁾, 山崎 敦²⁾

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Conceptual study of UV Integral Field Spectrograph and High-Resolution Spectrograph onboard Habitable Worlds Observatory

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Earth-like planets have been detected in the habitable zone of low-mass stars. However, no atmospheres of terrestrial exoplanets have been detected at present possibly because transit spectroscopy requires extremely high accuracy to observe the thin layer of lower atmosphere of a small terrestrial planet. On the other hand, strong XUV radiation of low-mass stars may cause the far-extended upper atmospheres. We investigate the possibility of detecting the upper atmospheres of terrestrial exoplanets by transit spectroscopy with future ultraviolet space telescopes, LAPYUTA and Habitable Worlds Observatory (HWO). There are several atomic and ionic emission lines (H, C, N, and O) in the far UV spectral range which will be helpful for understanding the surface environment of the exoplanet especially in case the lower atmosphere cannot be detected. In addition, icy moons in the solar system have water plumes. H and O atoms are generated by dissociation and could be detected by far UV imaging spectroscopy.

We performed a conceptual design study on a high-resolution spectrograph (HRS) and an integral field spectrograph (IFS) for far UV as potential contribution to HWO by JAXA. We are developing a large-format high-efficiency funnel microchannel plate (MCP) for photon counting for LAPYUTA mission, 60-cm FUV space telescope under study in JAXA. In design, HRS is composed of a collimator mirror, an echelle grating, a cross disperser, and a large MCP detector. The spectral resolution of HRS can be $>120,000$ with the spectral range of 100-180 nm, which covers H, C, N, and O atomic emission lines and C and N ionic emission lines. IFS is composed of an image slicer, 80 gratings and 4 MCP detectors, which enables the field of view is >1.6 arcsec $\times$ 3.6 arcsec with the spatial resolution of 0.01-0.02"/pix and $R >5000$ with the spectral range of 94-174 nm.

In this presentation, we introduce our study on exoplanets and solar system bodies, conceptual design study of IFS and HRS for HWO, and current status of UV technology development.

Earth-like planets have been found around low-mass stars, but detecting their thin lower atmospheres via transit spectroscopy remains difficult. However, strong XUV radiation from these stars may expand the upper atmospheres, making them more detectable. This study explores observing such upper atmospheres using future ultraviolet space telescopes like LAPYUTA, a 60-cm Far UV telescope, and the Habitable Worlds Observatory (HWO). Far UV emission lines from H, C, N, and O may provide key insights, even when lower atmospheres are undetectable. Similar techniques may also detect H and O atoms from water plumes on icy moons. JAXA is studying a high-resolution spectrograph (HRS) and an integral field spectrograph (IFS) as potential contributions to HWO, along with developing a high-efficiency funnel microchannel plate (MCP) detector for LAPYUTA.

R009-19

A 会場 : 11/25 AM1 (9:15-10:45)

9:45~10:00:00

#アサ サティアグラハ¹⁾, 木村 智樹¹⁾, 藤井 友香²⁾, 埜 千尋³⁾, 原 亮太¹⁾

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Development of a Simplified Analytical Model for Exoplanetary Auroral Radio Emission

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Planetary auroral radio emissions are considered a promising tool for the direct detection of planetary magnetic fields and atmospheres. Their circular polarization (Wu & Lee, 1979) allows them to be distinguished from other radio sources, and their emission frequency is theoretically proportional to the magnetic flux density at the source region. Therefore, auroral radio observations can directly constrain the magnetic field strengths without relying on complex model assumptions. However, auroral radio emissions have not yet been observationally detected from any exoplanet, except for a marginal detection (Turner et al., 2021). Previous modeling efforts have focused on magnetosphere-ionosphere (M-I) coupling (Nichols, 2011) and star-planet interaction (SPI) mechanisms (Saur et al., 2013), but these models have not successfully explained emissions across diverse exoplanetary systems simultaneously.

We present a newly developed simplified analytical model of the M-I coupling that predicts the auroral radio power across various star-exoplanet systems, based on the pioneering exoplanetary M-I coupling model by Nichols (2011). The model uses only magnetospheric velocity distribution, excluding parameters difficult to constrain observationally, such as flux function and mass loading rate. Plasma velocity profiles are used to calculate the dynamo electric field and latitudinal currents, from which total Joule heating is then estimated. Validation against Jupiter and Saturn shows that our model accurately estimates the total auroral energy dissipated via Joule heating in their ionospheres—approximately 450 TW for Jupiter and 15 TW for Saturn. These values agree with observational estimates within an uncertainty of one order of magnitude and are consistent with previous modeling studies. Assuming a 0.01% conversion efficiency from auroral Joule heating to radio emission, our model predicts radio powers of ~10 GW for Jupiter and ~1 GW for Saturn, consistent with observations (Cowley et al., 2004; Zarka, 2007). When applied to ultracool dwarfs (UCDs), the model suggests that their observed radio emissions—up to ~1 TW (Hallinan et al., 2008; Kao et al., 2023)—indicate weak atmospheric ionization, with electric conductance estimated between 0.1 and 10 mho (cf. ~0.5 mho at Jupiter; Nichols et al., 2016). We also applied our model to the tentative LOFAR detection of the hot Jupiter Tau Boö b. According to our modeling, the magnetospheric size of Tau Boö b must be approximately 3 – 23 planetary radii to reproduce the observed signal of 10^{14} - 10^{16} W (Turner et al., 2021). This is significantly more compressed than Jupiter's magnetosphere (extends from 42 planetary radii; Kivelson et al., 2006), which is plausible given Tau Boö b's close orbital distance of 0.0462 AU (Butler et al., 1997). These results support the validity of our model. We plan to apply it to a broader range of UCDs and hot Jupiters, with the ultimate goal of extending it to Earth-like planets. Here, we summarize the current status of our model development and validation.

R009-20

A 会場 : 11/25 AM1 (9:15-10:45)

10:00~10:15:00

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Ray Tracing for Titan's Ionospheric Occultation of Saturn Radio Emissions: Implications for JUICE Mission

#Rikuto Yasuda^{1,2)}, Hiroaki Misawa¹⁾, Baptiste Cecconi²⁾, Corentin Louis²⁾, Tomoki Kimura³⁾, Takeru Kato¹⁾, Yasumasa Kasaba¹⁾, Fuminori Tsuchiya¹⁾, Thomas Gautier^{2,4)}, Shotaro Sakai⁵⁾

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Titan possesses a highly variable and complex ionosphere influenced by both solar radiation and interactions with Saturn's magnetosphere. While previous estimates of Titan's ionospheric electron density have been derived from radio occultation and in situ measurements, photoionization by solar UV radiation is considered the dominant ionization mechanism. The accumulation of new observational data is expected to further advance our understanding of its detailed structure and temporal variability.

Yasuda et al. (2024) proposed a new method for deriving ionospheric electron densities of planetary satellites using planetary auroral radio emissions. This method was successfully applied to Galileo Plasma Wave Investigation (PWS) data of Jovian radio emissions, providing new insights into the ionospheric structures of Ganymede and Callisto, both of which have tenuous neutral atmospheres.

In this study, we extend this method to Titan, which has a dense atmosphere, by analyzing the occultation of Saturn Kilometric Radiation (SKR) using data from the Cassini Radio and Plasma Wave Science (RPWS) instrument. The SKR emission was modeled using Exoplanetary and Planetary Radio Emission Simulator (ExPRES) developed at Paris Observatory, and the propagation paths of the radio waves were computed with ray tracing simulations.

As a result, we successfully constrained both the peak electron density and the width of Titan's ionosphere from data acquired during the Cassini Titan-15 (T15) flyby. The peak densities were estimated to be 3200 cm^{-3} on the dayside and 1090 cm^{-3} on the nightside, consistent with previously reported day-night asymmetries. Additionally, by comparing the frequency range of the observed SKR with ExPRES model predictions, we provided a new constraint on the beaming angle of Saturn's radio emissions.

The polarization data from RPWS played a critical role in this analysis. It not only allowed us to constrain the beaming angle, but also enabled us to determine whether the radio sources were located in Saturn's northern or southern hemisphere. This represents a major advancement over previous applications to Jovian satellites based on Galileo observations, which lacked polarization measurements. Since the upcoming JUICE mission will carry the Radio & Plasma Wave Investigation (RPWI) instrument with polarization capabilities, our methodology can be directly applied to future Jupiter Icy Moons Explorer (JUICE) observations.

We are currently extending this analysis to other Titan occultation events. This study highlights the potential of planetary auroral radio emissions as a new diagnostic tool for probing the ionospheres of icy moons and contributes to the development of observation strategies for the JUICE mission.

R009-21

A 会場 : 11/25 AM1 (9:15-10:45)

10:15~10:30:00

3次元磁気流体力学シミュレーションを用いた土星風及び太陽風によるタイタン大気 の非熱的散逸過程の比較

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Comparison of Titan's atmospheric escape processes driven by the Kronian and solar winds using 3D magnetohydrodynamic simulations

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Titan is the only body in our solar system moons with an abundant atmosphere, maintaining a pressure of 1 atm at its surface. Titan's atmospheric composition resembles that of the early Earth's nitrogen-rich atmosphere before the rise of oxygen produced by life (nitrogen: 94%, methane: 5%, hydrogen: 1%; Magee et al., 2009). Therefore, understanding the evolutionary processes of Titan's atmosphere is essential for elucidating the atmospheric evolution of early Earth. In the upper atmosphere, the energy deposition to the atmosphere by Saturn's magnetospheric plasma precipitation, responsible for the non-thermal atmospheric ion pickup and sputtering, is likely more dominant than the solar EUV (Micheal et al., 2005), which is important for elucidating atmospheric evolution.

Titan is typically located within Saturn's magnetosphere, where it is exposed to plasma composed of O^+ and H^+ ions originating from Enceladus' subsurface ocean (hereafter, we refer to the plasma as the Kronian wind). However, solar wind protons should significantly affect Titan's atmosphere when Saturn's magnetosphere shrinks as the solar wind dynamic pressure increases, and Titan moves out of the magnetosphere (Bertucci et al., 2008). Because spacecraft in-situ observations are insufficient to capture the global extent of non-thermal escape driven by the external plasma flows, such as the Saturn and solar winds, numerical simulations have been employed alongside observations to understand it (Modolo et al., 2008; Strobel, 2009; Gu et al., 2019). However, previous studies have not sufficiently addressed non-thermal escape processes for hydrogen, which is the abundant atmospheric component in the upper atmosphere. Furthermore, because the Kronian and solar winds have not been treated with the same method, there is no discussion of the differences in escape rates for the two external plasma flows. Therefore, the differential impact of the Kronian and solar winds on Titan's atmospheric evolution remains unresolved.

In this study, we employed 3D multi-component ion magnetohydrodynamic (MHD) simulations (Terada et al., 2009) to model the non-thermal escape of nitrogen and hydrogen globally, the primary constituents of Titan's atmosphere, and to compare escape rates induced by the solar and Kronian winds for the first time. The non-thermal atmospheric escape was simulated under the Kronian wind conditions of O^+ :0.2[cm^{-3}] density, H^+ :0.1[cm^{-3}] density, 120 [km/s] velocity and 7.0 [nT] magnetic flux density (Sittler et al., 2009), resulting in an escape rate of 4.2×10^{23} [/s] for nitrogen-associated ions and 5.2×10^{24} [/s] for hydrogen-associated ions. Under the solar wind conditions of density: 0.35 [cm^{-3}], velocity: 360 [km/s], magnetic field strength: 0.5 [nT] (Bertucci et al., 2015), the escape rates were estimated to be 2.3×10^{23} [/s] for nitrogen-associated ions and 2.0×10^{24} [/s] for hydrogen-associated ions. These results suggest that the Kronian wind is more effective than the solar wind in driving the escape for both nitrogen and hydrogen. An investigation of the spatial structure of escape revealed that this difference in escape rate is due to the structure of the external plasma flow near Titan. In the case of the Kronian wind, the ion escape region expanded in altitude because of no bow shock formation due to its low velocity, while in the case of the solar wind, the bow shock was formed, which made the escape region shrink toward lower altitudes compared to that of the Kronian wind. Therefore, the escape rate under Saturn wind conditions is considered to exceed that under solar wind conditions.

We estimated the non-thermal escape rates for nitrogen- and hydrogen-based ions, which are the major components of Titan's atmosphere, by determining their sums, respectively. In future work, we plan to quantitatively evaluate the escape rates and investigate the underlying mechanisms for each ion species individually. In this presentation, we report the current status of our study.

土星の衛星タイタンは、太陽系惑星の衛星の中で唯一豊富な表面で1気圧の大気を持つ。タイタン大気の組成は、生命起源の酸素が増え始める直前の初期地球の窒素大気と類似している(窒素:94%、メタン:5%、水素:1% Magee et al., 2009)。タイタン大気の進化過程を明らかにできれば、初期地球の大気進化の解明に寄与すると考えられる。特にイオンピックアップやスパッタリング等によって駆動される非熱的散逸過程は、大気粒子へのエネルギー付与率が太陽のEUV照射よりも上層大気で優位であることが示唆されている(Micheal et al., 2005)ため、大気進化解明の上で重要である。

タイタンは通常土星磁気圏内に位置し、エンセラダスの内部海起源の O^+ や H^+ で構成されるプラズマ(以下、土星風)に吹き付けられている。しかし太陽風動圧が強くなると磁気圏が縮小し、タイタンが土星磁気圏界面の外に出て(Bertucci et al., 2008)、大気は太陽風 H^+ の影響を大きく受けるはずである。土星風や太陽風といった外部プラズマ流による非熱的散逸への影響を解明するには、断片的な探査機観測では困難であるため、数値シミュレーションによる再現が観測と併用

されてきた (Modolo et al., 2008; Strobel, 2009; Gu et al., 2019)。しかし先行研究では、タイタン上層大気で豊富な水素について非熱的散逸の取り扱いがない。また、土星風と太陽風を同じ手法で扱っていないため、2つの外部プラズマ流に対する散逸率の相違点等は議論はなされていない。そのため、土星風と太陽風による大気進化の違い等については未解明である。

そこで本研究は、3次元多成分イオン MHD シミュレーション (Terada et al., 2009) を用いて、大気の主成分である窒素と水素について非熱的散逸を全球的に模擬し、太陽風と土星風による散逸率の比較を初めて行った。カッシーニのその場観測データをもとに、土星風条件を O^+ : 密度 $0.2[cm^{-3}]$ 、 H^+ : 密度 $0.1[cm^{-3}]$ 、速度 $120[km/s]$ 、磁場強度 $7.0[nT]$ (Sittler et al., 2010) として散逸率を見積もった結果、散逸率が、窒素系イオン: $4.2 \times 10^{23}[s]$ 、水素系イオン: $5.2 \times 10^{24}[s]$ であった。一方、太陽風条件を密度 $0.35[cm^{-3}]$ 、速度 $360[km/s]$ 、磁場強度 $0.5[nT]$ (Bertucci et al., 2015) として、散逸率を見積もった結果、窒素系イオン: $2.3 \times 10^{23}[s]$ 、水素系イオン: $2.0 \times 10^{24}[s]$ となった。これらの結果から、土星風は窒素、水素の両方において太陽風よりも散逸を促進する働きがあるとわかった。散逸の空間構造を調査した結果、この散逸率の違いは、タイタン付近の外部プラズマ流の構造に起因している事がわかった。土星風の場合、速度が遅いためにバウショックが形成されずイオンの散逸領域が拡大した一方、太陽風はバウショックが形成され、土星風に比べて散逸領域が低高度にむかって縮小した。このため、土星風による散逸率が、太陽風による散逸率を上回る結果になったと考えられる。

本研究ではタイタン大気の主要成分である窒素系イオン、水素系イオンについてそれぞれ総和を求めて非熱的散逸率を推定したが、今後は、イオン種ごとに分けて散逸率の定量評価や散逸メカニズムを議論する予定である。本発表では、上記の現状を報告する。

R009-22

A 会場 : 11/25 AM1 (9:15-10:45)

10:30~10:45:00

3次元多成分イオン磁気流体力学シミュレーションによる初期地球における膨張水素大気の非熱的散逸モデリング

#草野 百合¹⁾, 木村 智樹¹⁾, 堺 正太郎²⁾, 吉田 辰哉³⁾, 前田 優樹⁴⁾, 中田 英太郎⁵⁾, 高田 亮馬¹⁾, 寺田 直樹³⁾

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Non-thermal escape of hydrogen atmosphere on early Earth by a 3D multispecies MHD simulation

#Yuri Kusano¹⁾, Tomoki KIMURA¹⁾, Shotaro SAKAI²⁾, Tatsuya Yoshida³⁾, Yuki Maeda⁴⁾, Eitaro Nakada⁵⁾, Ryoma TAKADA¹⁾, Naoki TERADA³⁾

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The presence of an atmosphere is crucial for a planet—such as Earth—to retain surface oceans. Part of Earth's primordial atmosphere, formed during its accretion, is believed to have originated from nebular gas composed mainly of hydrogen and helium. Over time, this atmosphere evolved to its present form as a result of the balance between the supply of gas from Earth's interior and atmospheric loss to space. Previous studies have used global numerical simulations to estimate the magnitude of thermal escape, which likely played a key role in the loss of hydrogen from the early atmosphere, while nonthermal escape mechanisms—such as ion pickup—have been considered negligible for the atmospheric escape (Tian et al., 2005; Johnson et al., 2013). In contrast, Lichtenegger et al. (2010) investigated the relationship between the exobase and the magnetopause from 4.4 billion years ago to the present and proposed that strong solar XUV radiation may have made the ancient atmosphere expand beyond the magnetopause. This suggests nonthermal escape could have been significant in the past. However, no quantitative evaluation of nonthermal escape rates from the early hydrogen-rich atmosphere has been conducted (Wang, Zhou, and Liu, 2022).

In this study, we assess the nonthermal escape of ionized atmospheric hydrogen using a multi-species ion MHD model (Terada et al., 2009). We assume a hydrogen-rich atmosphere simulating early Earth's composition (Yoshida and Kuramoto, 2021), which is heated by the solar XUV at a flux 100 times greater than today, extending at 1,000-185,000 km in altitude. The model distinguishes between atmospheric-origin and solar wind-origin hydrogen, enabling separate evaluations of their escape rates. We assume a non-magnetized Earth, as might occur during geomagnetic reversals, with solar wind parameters with a velocity of 1,800 km/s, density of 2100/cm³, and IMF strength of 7 nT. Under these conditions, atmospheric escape fluxes at 1000R_p downstream (where R_p is Earth's radius) were estimated as 3.5×10^{31} /s for H⁺ and 1.1×10^{31} /s for H₂⁺. These values correspond to 5-19% of the thermal escape rate of 2.4×10^{32} /s- 9.2×10^{32} /s estimated by Yoshida and Kuramoto (2021) at <30R_p. This indicates that a part of the atmosphere heated by thermal processes reaches higher altitudes, where it interacts with the solar wind and escapes via nonthermal mechanisms. Based on the ratio of nonthermal to thermal escape rates, 5-19% of hydrogen may have escaped through solar wind interactions, while the remaining 81-95% escaped thermally as neutral particles at altitudes greater than 30R_p. We are planning to evaluate the effects of IMF strength, XUV flux variation, and solar wind dynamic pressure on these escape ratios. In this presentation, we report the current progress on our study.

地球を含む惑星が表層に海洋を保持するためには、大気が存在が極めて重要である。集積時に形成された地球の初期大気の一部は、水素とヘリウムを主成分とする星雲ガス由来のものであったと考えられており、地球内部からのガス供給と、宇宙空間への散逸にその収支を制御されながら現代の大気へと進化してきた。先行研究では初期地球の水素大気で主要な役割を果たしたとされる熱的散逸の大きさを、数値シミュレーションを使って全球的に推定してきた。これとは対照的に、イオンピックアップ等の非熱的散逸は、影響が非常に小さく、無視できる程度であった可能性が指摘されている (Tian et al., 2005; Johnson et al., 2013)。一方 Lichtenegger et al. (2010) では、44 億年前から現代までの地球の外圏底と磁気圏界面の位置関係を調べ、強い太陽 XUV(X 線及び極紫外線) 放射によって過去の大気は膨張し、磁気圏界面の外側まで広がっていた可能性を示した。これにより、イオンピックアップ等の非熱的散逸が顕著に生じていた可能性が指摘されている。ただし、初期地球における水素大気の非熱的散逸率の定量化は、未だ行われていない (Wang, Zhou and Liu, 2022)。

そこで本研究は、現代の 100 倍の太陽 XUV フラックスを想定し、形成直後の地球における組成を反映した水素大気 (Yoshida and Kuramoto, 2021, 高度 1000~185000km、最大密度 3×10^{12} /cm³) について、多成分イオン MHD モデル (Terada et al., 2009) を使って大気起源イオンの非熱的散逸率を評価した。本研究では、多成分イオンモデリングの利点を活かし、大気起源の水素と太陽風起源の水素を分離しつつ非熱的散逸率を評価した。初期地球は地磁気反転時等で太陽風の影響が大きいと思われる非磁化の時代を想定し、地球の固有磁場は無し、太陽風は速度 1800km/s、密度 2100/cm³、IMF 強度を 7nT に設定した。その結果太陽風下流 1000R_p、(R_p は地球の半径、地表を 1R_p とする。) での大気散逸率は H₂⁺ が 1.1×10^{31} /s、H⁺ が 3.5×10^{31} /s と推定された。これは、Yoshida and Kuramoto(2021) が 30R_p 以下の高度領域で推定した水素大気の熱的散逸率 (2.4×10^{32} /s- 9.2×10^{32} /s) の 5-19% に相当する。これは熱的散逸によって上昇してきた大気の一部が、高高度での太陽風との相互作用を受けさらに非熱的過程で散逸していることを示唆している。非熱的

散逸率と熱的散逸率の比率から、高度 $30R_p$ 以上では、5-19% が太陽風との相互作用を受けて非熱的に散逸し、残りの 81-95% が中性粒子のまま熱的に散逸していく可能性がある。今後は、これらの比率に対する IMF の影響と XUV フラックス、太陽風動圧による変化を評価する予定である。発表では、本研究の現状を報告する。

R009-23

A 会場 : 11/25 AM2 (11:05-12:35)

11:05~11:20:00

#原田 裕己¹⁾, Cravens Thomas E.²⁾, Brain David A.³⁾, Halekas Jasper S.⁴⁾, Luhmann Janet G.⁵⁾, Fowler Christopher M.⁶⁾, Hanley Gwen⁵⁾, McFadden James P.⁵⁾

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MAVEN Observations of Collisional Effects on Magnetic Reconnection in the Martian Ionosphere

#Yuki Harada¹⁾, Thomas E. Cravens²⁾, David A. Brain³⁾, Jasper S. Halekas⁴⁾, Janet G. Luhmann⁵⁾, Christopher M. Fowler⁶⁾, Gwen Hanley⁵⁾, James P. McFadden⁵⁾

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We study collisional effects on magnetic reconnection in the Martian ionosphere by analyzing MAVEN data. Although much work has been done regarding collisional reconnection in solar and laboratory plasmas, few studies, if any, have addressed collisional effects on magnetic reconnection with in-situ spacecraft measurements in space and planetary environments. Our results show that current sheets with large magnetic shear are frequently observed even in the collisional region of the Martian ionosphere, yet reconnection ion jets are rarely detected in the collisional regime. This suggests that reconnection ion jets could be slowed down by ion-neutral friction effects with increasing collisionality. Based on in-situ parameters measured by MAVEN, we propose that the Martian ionosphere allows us to explore multiple regimes of magnetic reconnection, thereby offering a unique natural laboratory to study the transition of reconnection processes from collisionless to collisional plasmas with in-situ spacecraft measurements.

R009-24

A 会場 : 11/25 AM2 (11:05-12:35)

11:20~11:35:00

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Eleven-ion multifluid simulation study on the effects of crustal magnetic fields at Mars

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Mars lacks a global intrinsic magnetic field but has highly localized crustal magnetic fields, resulting in a unique configuration of the magnetosphere. The crustal magnetic fields also have complicated influences on ion outflow and escape. Numerous studies have investigated the effects of crustal magnetic fields, but they mainly focused on the dominant ion species in the ionosphere (O^+ , O_2^+ , CO_2^+). Some recent studies investigated distributions and outflows of minor ion species such as C^+ and NO^+ . However, the detailed process of these ions' escape and the effects of the crustal magnetic fields remain poorly understood.

The purpose of this study is to investigate the escape of carbon- and nitrogen-bearing ions (C^+ , CO^+ , HCO^+ , N^+ , N_2^+ , NO^+) and the effects of the crustal magnetic fields using a three-dimensional global multifluid MHD model, MAESTRO (Sakata et al., 2024). We implemented photochemical and collisional processes for these ions, extending the original set of five ions (H^+ , O^+ , O_2^+ , CO_2^+ , H_{SW}^+) to eleven in total. We conducted eleven-ion multifluid simulations under typical solar wind conditions ($n = 3 \text{ cm}^{-3}$, $V = 400 \text{ km s}^{-1}$, $B = 2.5 \text{ nT}$), with both “away” and “toward” sectors of the Parker spiral interplanetary magnetic field (IMF) considered. The strongest crustal magnetic field region at around 180-degree longitude was placed at four local times (noon, dusk, midnight, dawn). A simulation without crustal magnetic fields was also conducted for comparison.

The results show that the crustal magnetic fields reduce ion escape except for O_2^+ , and the dependence on the crustal field location is different among ion species. NO^+ , which is abundant in the nightside ionosphere, shows a unique trend compared to other ions. The IMF polarity also influences the escape rate because it controls the direction of the solar wind convection electric field. The effects are also seen in the magnetotail, as the current sheet twist significantly weakens under specific conditions of the crustal field and IMF polarity. These results suggest a role of magnetic reconnection in regulating the magnetospheric configuration and ion escape. On average, the six additional ions account for approximately 10% of the total escape rate. Notably, the C^+ escape rate is about 70% higher than that of CO_2^+ , implying that “minor” ion species have a non-negligible contribution to atmospheric escape from Mars.

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R009-25

A 会場 : 11/25 AM2 (11:05-12:35)

11:35~11:50:00

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Effects of magnetic field structures on Martian diffuse auroras based on MAVEN observations

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Mars lacks a global intrinsic magnetic field, and crustal magnetic fields exist mainly in the southern hemisphere. In such an environment, solar wind magnetic fields drape around Mars and form an induced magnetosphere, which is variable due to the variation of solar wind conditions. The nightside structures of the draped magnetic fields during extreme solar events are especially not well understood, despite the importance of these periods for understanding the ion loss from Mars. During extreme solar events, global diffuse auroras are observed. The Martian diffuse auroras are global ultraviolet emissions including CO₂⁺ ultraviolet doublet (UVD) on the nightside, caused by solar energetic particles (SEPs) consisting of electrons and protons (Schneider et al., 2015; Schneider et al., 2018; Nakamura et al., 2022). The auroral emissions caused by the electrons can vary with nightside magnetic fields around Mars, while those by protons are less affected by the magnetic fields due to the larger Larmor radii than electrons. We investigated the relationship between the Martian diffuse auroral emissions and magnetic fields based on the newly developed Monte Carlo model and the MAVEN observations (Okuyama et al, 2025). Our model study indicates that the more horizontal magnetic fields lead to brighter mean auroral intensities for the higher altitude, where the SEP electron contributions are dominant compared to the SEP protons, with the same incident electron flux in the uniform magnetic field assumption. However, the effects of nightside magnetic fields on the electron-induced Martian diffuse auroras were not confirmed by observations.

We investigated the dependence of diffuse auroral emissions on the nightside magnetic field structure with MAVEN observations. We selected the December 2014 SEP event because the diffuse auroras were observed in the northern hemisphere, where the crustal magnetic field effects are relatively weak, and MAVEN observed upstream solar wind magnetic fields during this event. The observed mean auroral intensities at 90-110 km altitude normalized by the SEP electron flux increased as the angles from the current sheet on the Martian nightside increased. The MHD simulations indicate that the magnetic fields tend to be more horizontal with the larger angles from the current sheet (Xu et al., 2018). Therefore, the observed dependence of mean auroral intensities on the angle from the current sheet might be consistent with our model predictions. Future missions will increase the proper observational conditions, where the solar wind magnetic fields and the precipitated SEP fluxes will be observed at the same time as the auroras, which will help us to analyze more events to validate statistical significance.

R009-26

A 会場 : 11/25 AM2 (11:05-12:35)

11:50~12:05:00

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Study of global SEP precipitation into Martian atmosphere based on PTRIP and MAESTRO models

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The study of aurorae extends beyond Earth to other planets, including Mars, where the diffuse aurora emission is considered to be driven by the precipitation of solar energetic particles (SEPs) into the Martian atmosphere (e.g. Schneider et al., 2015). Jolitz et al. (2021) demonstrated that while SEP protons are minimally affected by magnetic fields, the precipitation of SEP electrons is reduced by both the Martian intrinsic crustal and solar wind induced magnetic fields. Okiyama et al. (2025) recently showed that the magnetic field orientation can alter the vertical profile of diffuse auroral emissions at 75-100 km altitudes caused by the SEP electrons. However, the precipitation mechanism of SEP electrons into the Martian atmosphere during interplanetary coronal mass ejection (ICME) events with disturbed induced magnetospheric conditions is poorly understood. In our study, we combine the PTRIP test particle model (Nakamura et al., 2022) with the MAESTRO Global MHD model for solar wind-Mars interaction (Sakata et al., 2024), employing a strategy of the back tracing of test electrons.

This approach allows for the efficient simulation of the SEP electron precipitation with a good coverage in the phase space. In our simulations, electrons with uniformly distributed initial pitch and phase angles, latitude, and longitude were launched upward from an altitude of 300 km, simulating a September 2017 event (Schneider et al., 2018). The electrons were traced under the influence of magnetic fields obtained from the MAESTRO global MHD simulations until they reached upper or lower altitude boundaries. The results of the back tracings identified three main consequences: upstream escape, tailward escape, and precipitation onto the surface. It implies that we can estimate the global distribution of incident SEP electrons from the results by combination with upstream SEP observations. The estimated distribution of global SEP electron precipitation patterns showed a qualitative match with aurora emission distribution observed by IUVS onboard MAVEN. In the presentation, validation of these results by comparison with observations and estimation of incident SEP electron distribution functions at 300 km altitude will be reported.

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R009-27

A 会場 : 11/25 AM2 (11:05-12:35)

12:05~12:20:00

探査機 Mars Express と MAVEN の観測に基づく火星夜側電離圏の全球的な傾向と上流太陽風・IMF 及び地殻磁場依存性

#竹内 直之¹⁾, 原田 裕己¹⁾, Sánchez-Cano Beatriz²⁾

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Global trends of the martian nightside ionosphere and the effects of upstream drivers and crustal fields based on MEX and MAVEN

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Understanding the behavior of the Martian plasma is essential for understanding magnetospheric dynamics and ion escape processes. In particular, ion escape through the magnetotail is thought to be one of the main channels, but observations of the nightside ionosphere remain limited, and its formation processes and variability are still poorly understood.

In this study, we derived a huge database of the Martian nightside ionosphere using observations from Mars Express (MEX) and MAVEN spanning from October 2014 to November 2022. This enabled not only a global statistical investigation but also detailed analyses of localized regions such as mini-magnetospheres. Furthermore, we performed a comprehensive survey that combined upstream solar wind and interplanetary magnetic field (IMF) conditions with crustal magnetic field configurations, which had not been sufficiently examined in previous studies.

Our results show that in regions of weak crustal fields, with few exceptions, the maximum electron density tends to be low while the detection rate is high, and the solar wind dynamic pressure and the orientation of the solar wind electric field are the primary controlling factors. In contrast, in regions of strong crustal fields, the maximum electron density is generally high while the detection rate is low, and the relative orientation between the crustal field and the draped IMF plays a key role. These tendencies are consistent with the recently highlighted characteristics of Martian “electron aurora,” supporting the idea that electron precipitation is a primary production mechanism of the nightside ionosphere. Further constraints on its formation processes are expected through analysis of ionospheric ion data from MAVEN.

火星プラズマの挙動を理解することは、磁気圏ダイナミクスやイオン散逸過程の解明に不可欠である。特に、磁気圏尾部からのイオン散逸は大きな割合を占めると考えられているが、その供給源となりうる夜側電離圏の観測例は限られており、生成過程や変動性の理解は十分に進んでいない。

本研究では、Mars Express (MEX) および MAVEN による 2014 年 10 月から 2022 年 11 月までの観測データを用い、夜側電離圏の大規模データベースを構築した。これにより、全球的な統計解析に加え、ミニ磁気圏など局所領域における詳細な調査も可能となった。また、これまで十分に検討されてこなかった上流太陽風・IMF 条件と地殻磁場条件を組み合わせた解析を実施した。

その結果、地殻磁場の弱い領域では、例外を除き、最大電子密度が低く検出率が高い傾向が確認され、太陽風動圧や太陽風電場の方向が主要因であることが示唆された。一方、地殻磁場の強い領域では、最大電子密度が高く検出率が低い傾向が見られ、地殻磁場とドレイプした IMF の相対的な方向が重要な役割を果たすことが分かった。これらの傾向は近年注目される火星「電子オーロラ」の特徴と整合的であり、いずれも電子降り込みが夜側電離圏の主要な生成機構であることを支持する。今後、MAVEN による電離圏イオン観測データを解析することで、生成機構に対する更なる制約が期待される。

R009-28

A 会場 : 11/25 AM2 (11:05-12:35)

12:20~12:35:00

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Statistical study of ion escape from Mars during CIR events based on MAVEN observations

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Mars, lacking a global intrinsic magnetic field, is directly exposed to the solar wind, making its atmosphere vulnerable to escape. This study investigates ion escape driven by solar activity events such as Interplanetary Coronal Mass Ejections (ICMEs) and Corotating Interaction Regions (CIRs), to better understand atmospheric evolution. Both ICMEs and CIRs often facilitate high solar wind dynamic pressure condition and disturb the Martian induced magnetosphere and influence atmospheric escape. MAVEN observations and their comparison with global MHD simulation results show that atmospheric escape rates increased significantly during an ICME event in March 2015[1]. On the other hand, other results of statistical analysis show that the ion escape rate from Mars does not have clear dependence on the solar wind dynamic pressure[2]. These contradictory observations indicate the need for careful investigation of effects of ICMEs and CIRs on the ion loss from Mars. Observationally there are two major escape channels for ions from Mars: polar plumes accelerated by the convective electric field of the solar wind and the tailward escape, a bulk ion outflow through Martian magnetotail[2]. Statistical studies of the polar plumes[3] and tailward escape[4] both indicate that the spatial distributions of the ion escape flux are highly localized in terms of the MSE coordinates determined by the direction of the solar wind electric field. In this study, we aim to evaluate the impact of solar wind on the ion escape from Mars especially during CIRs by carefully investigating the localization effects of both ion escape channels.

Utilizing observations by SWIA and MAG onboard MAVEN from 2015 to 2023, we identified CIRs. The solar wind data satisfying the following criteria were selected: (1) the difference in velocity over two days was greater than 100 km/s. (2) Among the selected data, events where velocity increased following a density rise were classified as CIRs. As a result, we found 131 CIRs over the nine-year period. Because the apoapsis of MAVEN's orbit during the early period (2015 – 2019) was higher than during the later period (2020 – 2023), the frequency of the solar wind observations and thus the number of events were decreased during the later period. The “before” and “CIR” periods relative to CIR arrivals were defined as follows: for each event, a quiet period was visually identified, and the “after” period was defined as 48 hours from the time when the solar wind density first exceeded 1.5 times the average value during that quiet period. We also used median values of all data when upstream solar wind observations were available from 2015 to 2021 as the “normal” dataset to compare with “CIR”. Utilizing data from STATIC onboard MAVEN, distributions of heavy ion fluxes are separately examined both in the Mars-Solar-Orbital (MSO) coordinates and the Mars-Solar-Electric field (MSE) coordinates to differentiate the effects of the crustal magnetic field and acceleration by solar wind electric field. We then calculated the differences between the medians of heavy fluxes during “normal” and “CIR” datasets, and ratio of the differences normalized by the median of the “normal”. The results show that in the $-Z_{MSE}$ hemisphere, the escaping flux in the optical wake region increased by approximately 50%. The structure of the polar plume tends to shift toward the nightside. Based on these statistical results, we will discuss the effects of CIRs on the spatial distributions of the ion loss from Mars.

References

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R009-29

A 会場 : 11/25 PM1 (13:45-15:45)

13:45~14:00:00

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Martian water loss to space driven by a rocket dust storm

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Mars almost certainly possessed substantial water in the past. During southern summer, warm and dusty conditions can loft water vapor directly to high altitudes without condensation, promoting escape. In this study, we identify an additional, off-season pathway: during northern summer, a strong local dust storm drove significant vertical transport, yielding widespread increases in ~50-km water vapor within a few days across northern high latitudes, followed by a rise in exobase hydrogen. These observations show that water loss can occur whenever intense local dust activity is present, not only under canonical southern-summer conditions, implying that cumulative loss may be larger than previously thought.

R009-30

A 会場 : 11/25 PM1 (13:45-15:45)

14:00~14:15:00

白金フィラメントを用いた水素/重水素吸収セルの開発

#遠藤 まどか¹⁾, 田口 真¹⁾, 桑原 正輝¹⁾, 吉岡 和夫²⁾

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Development of Hydrogen/Deuterium Absorption Cells Using Platinum Filaments

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Hydrogen/deuterium absorption cells were developed as a device for observing D/H in celestial atmospheres [Kawahara et al., 1997]. The cell consists of a cylindrical glass container weighing several tens of grams and several centimeters in width, containing hydrogen or deuterium gas and filaments, with both ends sealed by MgF₂ windows. In the case of the hydrogen absorption cell, when the filament is heated, hydrogen molecules inside the cell dissociate and are adsorbed, then thermally desorbed to form hydrogen atoms that cause resonance scattering with the hydrogen Lyman-alpha emission. This is referred to as the selective absorption of the cell, because only the hydrogen Lyman-alpha emission cannot pass through the cell. The same applies to deuterium.

The tungsten filaments currently used in the absorption cells have the highest melting point among metals but stability issues due to filament degradation. Specifically, the lifetime of a single filament is at most several tens of hours. The degradation is caused by the formation and sublimation of tungsten oxide due to the oxidation of tungsten. Therefore, in this study, we aimed to develop an absorption cell with high durability and absorption efficiency by using a platinum filament instead of tungsten, as platinum is a metal with high oxidation resistance. However, since pure platinum lacks the hardness required to form filament shapes, a platinum alloy containing 10% rhodium or 10% iridium was used. Hydrogen at 300 Pa was sealed in a stainless-steel cell, and filaments were applied electric power for a long time, recording the time until they broke. During this process, voltage and current were continuously measured using a digital multimeter. We also measured the absorption efficiency of the hydrogen Lyman-alpha emission by the filaments using a VUV experimental setup which consists of a hydrogen Lyman-alpha light source, a VUV spectrometer and an MCP at the University of Tokyo, Kashiwa Campus.

The results of durability tests show that the platinum-rhodium filaments feature durability longer than 30 days at around a temperature of 1450 K, which is comparable or better than that of a tungsten filament. However, at temperatures above 1750 K, the filament melted and broke within a few hours after the power was applied. This was probably caused by the filament bending, causing adjacent coils to come into contact, shortening the filament length, and increasing the current. The current through the filament under constant voltage showed no significant fluctuations except a stepwise increase immediately before the breakage.

As a result of the absorption efficiency experiments, it was confirmed that the hydrogen Lyman-alpha line was absorbed at a filament temperature of 1600 K with tungsten and platinum alloy filaments. Absorption efficiencies were around 21-26 %, 10-18 % and 21-24 % for the filaments made of tungsten, platinum-rhodium and platinum-iridium, respectively, though the temperature estimation of the platinum-iridium filament was not accurate. The absorption efficiency for the tungsten filament reached its upper limit at approximately 1600 K and did not increase when the filament was heated at higher temperatures. The platinum alloy filaments began to bend at around 1500 K, making accurate temperature calculations difficult. Based on the experimental result, higher-strength platinum-alloy filaments are being developed by increasing the rhodium content and diameter of filament.

Kawahara et al, "Glass-type hydrogen and deuterium absorption cells developed for D/H ratio measurements in the Martian atmosphere", Appl.Opt.,1997.

天体大気の D/H を観測するための装置として、水素・重水素吸収セルが開発された [Kawahara et al.,1997]。セルは、質量数十グラム、幅数センチの円筒型ガラス容器の中に水素または重水素ガスとフィラメントが内蔵されており、両端は MgF₂ 窓で閉じられている。水素吸収セルの場合、フィラメントを昇温するとセル内部の水素分子が解離吸着し熱脱離することにより水素原子に熱解離する。この水素原子と天体大気から放射された水素ライマン α 線が共鳴散乱を起こし、水素ライマン α 放射のみがセルを通過できない。これをセルの選択的吸収という。重水素の場合も同様である。

吸収セルに現在用いられているタングステンフィラメントは、金属で最も高い融点を持つ一方でフィラメントの消耗に

よる安定性に課題があり、1本のフィラメントで数十時間の使用が限界である。消耗の原因はタングステンの酸化により酸化タングステンが形成され昇華するためであると考えられている。そこで、本研究ではタングステンの代わりに、酸化耐性の高い金属である白金のフィラメントを用いることにより、耐久性が高く吸収効率の良い吸収セルの開発を目指した。ただし、純白金ではフィラメント形状を形成するための強度が弱すぎるため白金ロジウム(イリジウム)10%合金を用いた。ステンレスセルに水素 300 Pa を封入し、フィラメントを長期間通電し、断線するまでの時間を記録した。その際、デジタルマルチメータで電圧、電流を継続して測定した。また、水素ライマンα光源、紫外分光器、マイクロチャンネルプレートを用い、東大柏キャンパスで水素ライマンα線の吸収効率測定を行った。

耐久試験の結果、1450 K 程度で 30 日以上耐久性を確認した。しかし、1750 K 以上では通電開始から数時間以内にフィラメントが断線した。この原因は、フィラメントのたわみにより隣同士のコイルが接触し、フィラメントの長さが短くなり、電流がより多く流れることであると考えている。白金ロジウムフィラメントを定電圧で通電中の電流は、断線の直前を除いて大きな変動は見られなかった。

吸収効率測定の結果、タングステンと白金フィラメントどちらも 1600 K で水素ライマンα線の吸収を確認できた。1600 K での吸収効率は、タングステン、白金ロジウム、白金イリジウムそれぞれ、21~26 %, 10~18 %, 21~24 % であった。ただし、白金イリジウムは正確な温度計算が出来ていない。タングステンフィラメントは、1600 K 程度で吸収効率が上限に達し、それ以上温度を上げても吸収効率は上がらなかった。白金合金フィラメントは 1500 K 程度からたわみはじめ、正確な温度計算が出来なくなるという課題があった。実験の結果をもとに、ロジウムの含有率やフィラメント径を変えた、強度の高い白金合金フィラメントを試作中である。

R009-31

A 会場 : 11/25 PM1 (13:45-15:45)

14:15~14:30:00

OMEGA/MEx の 2.77 μ m と 2.01 μ m を用いた火星高高度・低高度ダストの分類と広域解析

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Classification and Global Analysis of High- and Low-Altitude Dust on Mars Using 2.77 μ m and 2.01 μ m from OMEGA/MEx

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Martian dust plays a crucial role in climate and meteorology through horizontal and vertical transport in the atmosphere. Previous nadir observations in the ultraviolet, visible, and infrared wavelengths provided insights into the dust horizontal distribution (e.g., Smith et al., 2001; Montabone et al., 2015; Battalio and Wang, 2021; Leseigneur and Vincendon, 2023). Previous solar occultation and limb observations provided valuable information on dust vertical distribution, but uncertainties persist regarding its spatial variability and transport mechanisms. Conventional limb and solar occultation observations can retrieve dust altitude information directly, but their spatial and temporal coverage is limited. This study aims to obtain new insights into the dust vertical distribution by applying the spectral synergy method to nadir observations.

The spectral synergy method estimates the altitude of atmospheric constituents by leveraging differences in absorption characteristics at multiple wavelengths (Pan et al., 1995; Pan et al., 1998; Edwards et al., 2009). This method is applied in Earth remote sensing for retrieving the vertical distributions of CO₂ (Christi & Stephens, 2004), O₃ (Landgraf & Hasekamp, 2007), and CH₄ (Razavi et al., 2009) and has recently been used to analyze water vapor in the Martian atmosphere (Knutsen et al., 2022). However, no studies have applied this approach to Martian dust yet.

To address this gap, we propose a new method to estimate the vertical distribution of dust using dust optical depth (DOD) data at two wavelengths (2.77 μ m and 2.01 μ m) obtained by the OMEGA near-infrared imaging spectrometer onboard Mars Express. The 2.77 μ m band in the CO₂ saturated absorption region, with sensitivity to altitudes around ~30 km, and its corresponding DOD database is described in Kazama et al. (under review). The 2.01 μ m band is a weaker CO₂ absorption band with a sensitivity peak at 10 – 20 km (Leseigneur & Vincendon, 2023). We calculated a normalized difference index ($\Delta \tau_{\text{norm}}$) between the DOD at the two wavelengths and classified dust clouds with $\tau > 1.5$ into “high-altitude” (≥ 30 km) and “low-altitude” (≤ 20 km) categories. Radiative transfer simulations using the DISORT model (Stamnes et al., 1988) demonstrated that a threshold of $\Delta \tau_{\text{norm}} > 0.6$ effectively distinguishes dust layers with centroid altitudes above and below ~30 km.

Applying this method to ~4,000 observations from MY27 – 29, including the MY28 global dust storm, revealed pronounced seasonal and spatial variations in dust vertical distribution. High-altitude dust was frequently detected over Hellas Basin, Acidalia – Chryse Planitia, and around the Amazonis region, suggesting that these areas are “hotspots” where local circulation and topographic effects promote vertical dust transport. In contrast, low-altitude dust was found to be widely distributed across Mars, indicating the persistent presence of background dust near the surface. Interestingly, in the region south of Elysium, despite being a major dust storm pathway (Battalio & Wang, 2021), high-altitude dust was not detected, and low-altitude dust dominated. This suggests the existence of mechanisms that inhibit dust lofting into the upper atmosphere for certain storms.

Moreover, high-altitude dust tended to appear and disappear within only a few degrees of solar longitude, whereas low-altitude dust exhibited more stable distributions. This implies that high-altitude transport is driven by short-timescale dynamical processes such as thermal convection, while low-altitude background dust remains in the atmosphere for longer periods. During the MY28 global dust storm, high-altitude dust persisted over a broader latitude range (60° S – 60° N) and for a longer duration than in quiescent periods, indicating global-scale vertical transport.

Our method provides a new large-scale diagnostic for dust vertical distribution that is effective even when high-resolution vertical profiles are unavailable, offering valuable constraints for understanding dust transport and its interactions with atmospheric circulation.

火星のダストは、大気中での水平および鉛直方向の輸送を通じて火星の気候に大きな影響を与える重要な要素である。これまでの紫外・可視・赤外の直下視観測によって、ダストの水平分布に関する知見は広く得られている (e.g., Smith et al. 2001; Montabone et al., 2015; Battalio and Wang, 2021; Leseigneur and Vincendon, 2023)。一方で、鉛直方向のダスト分布については、太陽掩蔽観測やリム観測により一定の情報が得られているものの、その水平方向の広がりや輸送メカニズムには依然として不明な点が多い。従来のリム観測や太陽掩蔽観測では、ダストの高度情報を直接取得できるが、時間・空間分解能が限られるという課題があった。本研究では、直下視観測におけるスペクトルシナジー法を活用し、ダストの鉛直分布に関する新たな知見を得ることを目的とする。スペクトルシナジー法とは、異なる波長での吸収特性の違い

を利用することで、直下視観測から大気成分の高度情報を推定する手法である (Pan et al., 1995; Pan et al., 1998; Edwards et al., 2009)。この手法は地球観測において CO₂ (Christi & Stephens, 2004) や O₃ (Landgraf & Hasekamp, 2007)、CH₄ (Razavi et al., 2009) の高度分布推定に活用され、近年では火星大気中の水蒸気分布解析にも適用されている (Knutsen et al., 2022)。しかし、火星のダストに対して適用する試みは未だに行われていない。

本研究ではこの課題を克服するため、Mars Express に搭載された近赤外分光撮像装置 OMEGA によって取得された 2 つの波長帯 (2.77 μ m と 2.01 μ m) のダスト光学的厚さ (DOD) を用いた新しい鉛直分布推定手法を提案する。高度約 30 km に感度を持つ 2.77 μ m の CO₂ 吸収飽和帯を用いた DOD データベース (Kazama et al., under review) と、10 – 20 km に感度ピークを持つ 2.01 μ m の CO₂ 吸収帯を用いた DOD データベース (Leseigneur and Vincendon, 2023) を利用した。2.01 μ m と 2.77 μ m の DOD から規格化差分指標 ($\Delta \tau_{\text{norm}}$) を計算し、 $\tau > 1.5$ のダスト雲を「高高度 (≥ 30 km)」と「低高度 (≤ 20 km)」に分類した。放射伝達モデル DISORT (Stamnes et al., 1988) を用いたシミュレーションにより、 $\Delta \tau_{\text{norm}} > 0.6$ という閾値が、ダスト重心高度が約 30 km を境に高低を分ける有効な指標であることを実証した。

この手法を MY27 – 29 (MY28 全球ダストストームを含む) の約 4000 観測に適用した結果、ダスト鉛直分布の季節的・空間的変動が明らかになった。高高度ダストはヘラス盆地、アシダリア・クリュセ平原、マゾニス周辺に頻繁に検出され、これらの地域が局所的な大気循環や地形効果により鉛直輸送が促進される「ホットスポット」である可能性が示唆された。一方、低高度ダストは火星全球に広く分布しており、背景ダストが常時低高度に存在していることを示している。興味深いことに、エリシウム南側ではダストストーム主要経路 (Battalio and Wang, 2021) にもかかわらず、高高度ダストはほとんど見られず低高度ダストが優勢であった。これは特定のストームが上層大気へダストを輸送しにくいメカニズムの存在を示唆する。さらに、高高度ダストは Ls 数度程度の短期間で出現・消失する傾向があるのに対し、低高度ダストはより安定した分布を示した。これは、高高度輸送が熱対流などの短周期的動的プロセスに駆動される一方、低高度の背景ダストは長期間大気中に滞留することを示す。また、MY28 の全球ダストストーム期間には、高高度ダストが南緯 60° から北緯 60° まで平穏期より広い緯度範囲で長期間持続し、全球規模での輸送が生じていた。

本手法は、高解像度鉛直プロファイルが得られない場合でも、ダスト輸送や大気循環との相互作用の解明に有効な広域指標を提供する可能性がある。

R009-32

A 会場 : 11/25 PM1 (13:45-15:45)

14:30~14:45:00

#柿沼 希泉¹⁾, 青木 翔平¹⁾, 今村 剛¹⁾, 野口 克行²⁾, Kleinböhl Armin³⁾

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Aerosol transport by traveling waves in the Martian atmosphere studied with MRO/MCS data

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Traveling waves in the Martian atmospheres are considered to play a significant role in determining the climate at mid-to-high latitudes, as is the case with Earth. Previous observations from landers have revealed that these waves become particularly prominent from early autumn to late winter in the northern hemisphere (Barnes, 1981). Their behavior near the surface and in the middle atmosphere had been revealed by analyzing the measurements taken by infrared sounders on several spacecraft. Waves with a zonal wavenumber of 1 exhibited amplitudes of up to 20 K and were extended vertically through the atmosphere, whereas waves with higher zonal wavenumbers showed smaller amplitudes (Banfield et al., 2004). Gong et al. (2023a, 2023b) further characterized traveling waves in both the troposphere and mesosphere, identifying a vertically separated double-peak structure in temperature amplitude for waves with zonal wavenumber of 1. These peaks were observed in the upper troposphere and the mesosphere.

Dust storm is one of the notable features of the Martian meteorology. Their interaction with traveling waves has been explored using spacecraft measurements. Wang et al. (2005) revealed that the occurrence of dust storms is linked to the development of traveling waves, based on imagery from the Mars Orbiter Camera onboard the Mars Global Surveyor.

However, their impact on the transport of dust and water ice clouds has not been studied quantitatively. Examining how traveling waves influence the transport of aerosols provides valuable perspectives into the climatology of Mars. This study aims to quantitatively assess the relationship between traveling waves and the transport of atmospheric substances, such as dust and water ice clouds.

In this study, we utilize the data taken by the Mars Climate Sounder (MCS) onboard the Mars Reconnaissance Orbiter (MRO) in MY30 and MY31. MCS is an infrared radiometer which provides vertical profiles of temperature, dust opacity, and water ice opacity. Its vertical resolution is ~5 km, which provides a better vertical information than other infrared sounders of Mars. Observations revealed eastward-propagating waves during the northern autumn and winter, which were identified as Rossby waves. A pronounced zonal wavenumber-1 mode was detected in the regions where the zonal-mean temperature exhibits a steep meridional temperature gradient, consistent with a baroclinic origin. Our analysis further revealed distinct phase relationships among fluctuations in temperature, dust opacity, and water ice opacity within the region and season characterized by a strong zonal wavenumber-1 mode. Specifically, we identified a positive correlation between temperature and dust opacity, and a negative correlation between temperature and water ice opacity. The amplitudes of the temperature, dust, and water ice variations, when normalized by their respective meridional gradients, yield comparable horizontal displacement scales. This consistency suggests that these variations are driven by the meridional advection associated with traveling waves. These findings suggest that traveling waves play a crucial role in the transport of dust and water ice clouds in the Martian atmosphere.

R009-33

A 会場 : 11/25 PM1 (13:45-15:45)

14:45~15:00:00

火星大気観測を見据えたテラヘルツヘテロダイナミック分光装置の 0.9THz 帯高調波ミキサ検出器の開発

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Development of a 0.9-THz-band harmonic mixer detector of THSS for Martian Atmospheric Observations

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The Mars Aqueous-environment and Space Climate Orbiter (MACO) Working Group is advancing a mission concept to investigate the sustainability of habitable environments on Mars and other terrestrial planets. The program aims to comprehensively explore Martian space weather, climate, and the water cycle through demonstrations of orbital and exploration technologies. In particular, orbiter observations of water vapor in the atmospheric boundary layer will address surface – atmosphere interactions, material cycles, and vertical coupling processes relevant to Martian climate and hydrology. As one of the key candidate payloads, a Terahertz Heterodyne Spectroscopy Sensor (THSS) is under study.

The THSS is currently designed to operate in multiple frequency bands (Band 1: 460 GHz, Band 2: 560 GHz, Band 3: 890 GHz). By combining transitions and isotopologues with different optical depths, the instrument will probe lower-atmosphere water vapor and HOx species, high-altitude (>100 km) water vapor, and carbon monoxide lines for atmospheric dynamics. The baseline architecture foresees two antennas for limb-sounding of meridional and zonal circulation, while a single-antenna configuration is also feasible depending on mission constraints. In this study, we report on the development of the Band 3 (~890 GHz) receiver.

The receiver employs a harmonic mixer detector integrating Schottky barrier diodes (SBDs) provided by Virginia Diodes Inc. A 24-GHz phase-locked dielectric resonator oscillator (PLDRO) is frequency multiplied by 36 to generate the local oscillator (LO) signal for heterodyne spectroscopy, producing the intermediate frequency (IF) output. The detector can operate at room temperature and has already achieved TRL 9, with flight heritage from NASA CubeSat missions at similar frequencies. Laboratory evaluation showed a single-sideband conversion loss of approximately – 22 dB. A high-pass filter was also tested to suppress PLDRO harmonics.

To further enhance sensitivity, radiative cooling of the harmonic mixer element is being investigated to reduce thermal noise, together with optimization of applied bias conditions. In addition, a custom thermally isolated waveguide has been implemented between the mixer and the multiplier to reduce both LO signal loss and thermal inflow.

Mars Aqueous-environment and Space Climate. Orbiter (MACO) ワーキンググループは、地球型惑星や火星のハビタブル環境の持続性解明に向け、周回・探査技術の実証を通じて、火星の宇宙天気・気候・水環境を包括的に探査する計画を推進している。特に周回機では、大気境界層における水蒸気分布の観測により、地表・表層水と大気の相互作用や物質循環、宇宙気候・水環境に関わる大気上下結合のメカニズムの解明も視野にいられている。その搭載候補の重要測器の1つとして、テラヘルツ分光装置 (Terahertz Heterodyne Spectroscopy Sensor: THSS) が検討されている。

THSS では、Band1(460 GHz 帯)、Band2(560GHz 帯)、Band3(890GHz 帯) など複数帯域を用い、光学的厚みの異なる遷移・同位体を組み合わせることで、低高度の水蒸気や HOx 種、高高度 (100km 超) の水蒸気、一酸化炭素輝線による大気ダイナミクスの観測を狙う。子午面循環、東西方向をリムサウンディングするために2基のアンテナ構成を想定するが、ミッションに合わせてアンテナ1基の構成にも対応可能である。本研究では、Band3 の 890GHz 帯受信機の開発について報告する。

検出器は、ショットキーバリアダイオード (SBD) を集積した高調波ミキサ検出素子 (Virginia Diode Inc.) を採用している。局発振器 (LO) には 24 GHz 帯の位相固定誘電体発振器 (PLDRO) を 36 通倍した信号を導入し、ヘテロダイン検出によって IF 信号を生成する。本検出器は常温動作が可能であり、同波長域で NASA のキューブサットに搭載実績があり、すでに TRL9 を達成している。SBD ミキサのシングルサイドバンド変換損失は約 – 22 dB である。また、PLDRO 信号由来の高調波をハイパスフィルタで抑制する手法も検討した。さらに観測効率の向上を目指し、放射冷却を活用して高調波ミキサ部のみを冷却することで熱雑音低減による高感度化を図り、最適な印加バイアスの探索も進めている。高調波ミキサ部と通倍器の間は熱的に切るため、独自開発した断熱導波路を実装し、LO 信号の損失や熱流入を低減している。

R009-34

A 会場：11/25 PM1 (13:45-15:45)

15:00~15:15:00

金星雲層における二酸化硫黄 (SO₂) 混合比の高度分布の導出

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Derivation of vertical profiles of sulfur dioxide (SO₂) in the Venus cloud layer from Akatsuki radio occultation measurements

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Vertical profiles of the sulfur dioxide (SO₂) volume mixing ratio (VMR) near the Venusian cloud layer were derived from Akatsuki radio occultation data, extending the method of Oschlisniok et al. [2021]. The analysis used 42 occultation events obtained between 2016 and 2023, covering 60° S – 60° N and the altitude range of 47 – 60 km. Assuming that sulfuric acid vapor is not supersaturated, any absorption exceeding the saturation vapor pressure was attributed to SO₂.

The results show that the SO₂ VMR decreases monotonically from about 260 ppm at 47 km to about 55 ppm at 54 km. Above this altitude, the VMR fluctuates between about 40 and 140 ppm, within the error range. These values and their vertical variations are consistent with those obtained from the VEGA probes [Bertaux et al., 1996] and Venus Express radio occultation [Oschlisniok et al., 2021].

金星の高度 45 – 70 km には硫酸からなる雲が存在し、惑星全体を覆っている。この雲は、太陽光入射の約 78% を宇宙空間に反射する一方で、地表面や下層大気からの赤外線を吸収・放射することで温室効果を引き起こす。そのため、金星の雲に関する知見は大気の熱収支や大気循環を知る手掛かりとなる。金星の雲の主材料である硫酸蒸気の生成には SO₂ が不可欠であると考えられているため、SO₂ の高度分布に関する情報は金星の雲物理を理解する上で重要である。

SO₂ 混合比を観測した例として、欧州宇宙機関 (ESA) が実施した Venus Express ミッションの太陽掩蔽観測 (SOIR) や赤外分光観測 (SPICAV) が挙げられる。Belyaev et al. [2012] は多数の観測データを用いて、高度 65km から 80km までは減少し、逆に高度 85km から 100km までは増加する傾向を示した。高度下端の値は、0.1ppm から最大でも 1ppm のオーダーである。一方でそれよりも下の高度域では、過去に旧ソ連が実施した VEGA 探査機による 2 本の降下プローブ観測と、Venus Express の電波掩蔽観測に限られる。前者は、下層から高度 60 km までの SO₂ 混合比を取得し、高度 40 – 60km において 150 – 200ppm 程度の極大を示した [Bertaux et al., 1996]。後者は、高度 51 – 54 km における SO₂ 混合比の平均値として 90 – 160ppm を示した [Oschlisniok et al., 2021]。

本研究では、Oschlisniok et al. [2021] の手法を発展させ、あかつき電波掩蔽観測によるデータを用いて雲層付近の SO₂ 混合比の高度分布を導出した。電波掩蔽観測では、探査機が惑星の背後に隠れる際や背後から出てくる際に地上局に向けて電波を送信し、惑星大気を通過してから地上局に到達した電波の周波数や電波強度の時系列データを解析することで、その惑星大気の鉛直構造に関する情報を得る。金星の場合は、周波数の時系列データを解析することで気温と気圧の高度分布を、電波強度の時系列データを解析することで大気に含まれる硫酸蒸気混合比の高度分布をそれぞれ得ることができる。

我々は、雲層においては硫酸蒸気が過飽和していないという仮定を導入することで、硫酸の飽和蒸気圧を上回る吸収は全て SO₂ によるものとみなし、SO₂ 混合比の高度分布の推定を試みた。解析対象は、2016 – 2023 年までに取得された 42 例の観測データで、緯度範囲は 60° S – 60° N、高度範囲は 47 – 60km である。SO₂ 混合比のばらつきが大きかったため、高度 1km ごとに中央値を算出した。

その結果、SO₂ 混合比は高度 47 km (約 260ppm) から 54km (約 55ppm) までは単調減少し、それ以上の高度では誤差の範囲内でばらつきを示しながら 40 – 140ppm 程度であった。本研究で得られた高度分布の特徴や混合比の値は、VEGA プローブ観測や Venus Express 電波掩蔽観測の結果とおおよそ整合的であった。

R009-35

A 会場 : 11/25 PM1 (13:45-15:45)

15:15~15:30:00

金星極域大気雲層における温度と対流圏界面高度の数日周期変動をもたらす波

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Waves driving the temperature and tropopause height variations with time scales of several days in the Venusian polar cloud layer

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In the Venusian atmosphere at altitudes of 50-70 km, a cloud layer composed mainly of H_2SO_4 exists. Around the cloud base, infrared absorption from the lower atmosphere drives convection in the lower and middle clouds (at altitudes of about 50 – 55 km), forming the troposphere. Based on the analysis of temperature data from radio occultation observations by the Venus Express spacecraft, Ando et al. (2017) found temperature variations on timescales of several Earth days in the polar region and proposed that these are caused by planetary-scale waves. By further analyzing a larger set of radio occultation data, we have shown that the tropopause height also varies on a similar timescale, and that there is a strong positive correlation between the temperature below the tropopause and the tropopause height. These may be explained by meridional advection of the background atmospheric structure associated with planetary-scale waves (presented at SGEPS 2024 Fall Meeting). However, meridional wind data cannot be directly obtained from radio occultation observations, so this mechanism remains a hypothesis. In this study, we investigate meridional advection of the temperature field associated with waves using numerical solutions of the global non-hydrostatic Venus atmospheric model SCALE-GM. The model results suggest the presence of a prominent wavenumber-2 structure in both the temperature and meridional wind fields at mid-to-high latitudes below the tropopause, which may give rise to north-south oscillations of temperature. In future work, we plan to conduct a more detailed analysis of the model to identify the waves responsible for the wavenumber-2 structure and to examine whether meridional advection can quantitatively explain the observed temperature and tropopause height variations.

金星大気の高度 50~70 km には、硫酸を主成分とする雲層が存在する。雲底付近では、下層大気からの赤外線放射が吸収されることにより、下層・中層雲 (高度約 50~55 km) で対流が駆動され、対流圏が形成される。Ando et al. (2017) は金星探査機 Venus Express の電波掩蔽観測による温度データの解析から、極域において数日 (地球日) の時間スケールの温度変動を見出し、その原因は惑星規模波動であると提唱した。我々はさらに、より多くの電波掩蔽データを用いた解析により、対流圏界面の高度も同様の時間スケールで変動していること、対流圏界面より下の温度と対流圏界面高度との間に強い正の相関があることを明らかにし、これらは惑星規模波動に伴う背景大気構造の南北移流によって説明できる可能性を示した (SGEPS 2024 年秋季大会)。しかし、電波掩蔽観測では南北風データを直接得ることができず、上のメカニズムはあくまで推定にとどまる。そこで本研究では、金星大気の全球非静力学モデル「金星 SCALE-GM」の数値解を用いて、波動に伴う温度場の南北移流を検証する。金星 SCALE-GM の数値解では対流圏以下の温度と南北風の分布に中高緯度において顕著な波数 2 の構造が存在しており、これによって温度の南北振動が生じている可能性が見出された。今後は、数値解を詳細に解析し、波数 2 の構造をもたらす波動を同定するとともに、南北風による温度移流が温度変動や対流圏界面高度の変動を定量的に説明するかどうかを検討する。

R009-36

A 会場 : 11/25 PM1 (13:45-15:45)

15:30~15:45:00

外惑星探査小型実験機 OPENS-0 が目指すサイエンス

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Science Goals of OPENS-0: Outer Planet Exploration by Novel Small Spacecraft

#Takeshi Imamura¹⁾, Hajime Yano²⁾, Kazuyoshi Arai³⁾, Shun-ichi Kamata⁴⁾, Hajime Kawahara⁵⁾, Naoya Sakatani²⁾, Shuji Matsuura⁷⁾, Yuhito Shibaike⁶⁾, Hiroshi Kobayashi⁵⁾, Haruna Sugahara¹¹⁾, Hiroki ANDO⁸⁾, Katsuyuki NOGUCHI⁹⁾, Shota CHIBA⁵⁾, Ryu Funase^{2,10)}

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Japan, being a latecomer in outer planet exploration, is planning a realistic approach to conduct missions under limited resources. The OPENS (Outer Planet Exploration by Novel Small Spacecraft) program has been conceived to make use of Japan's heritage in ultra-small deep space probes and to enable outer planet exploration. The concept envisions the frequent launch of small spacecraft in the 100 – 200 kg class, utilizing the Epsilon-S rocket and rideshare opportunities.

As its first step, a mission concept named the “Outer Planet Exploration by Novel Small Spacecraft – Experimental Mission (OPENS-0)” has been proposed under the ECO & FAST class of competitively selected small missions. In the original proposal, OPENS-0 is planned for launch in 2028 by an Epsilon-S rocket, to reach the Saturnian system in 2039 via Venus and Earth swing-bys. OPENS-0 is currently under consideration as a pre-project candidate, with studies ongoing toward the mission definition review.

While the primary goal of OPENS-0 is to demonstrate engineering technologies required for Japan's independent outer planet exploration, the mission also aims to produce scientific returns by making effective use of onboard instruments originally intended for spacecraft operations during the decade-long cruise to Saturn and the flyby within the Saturnian system. Potential observations during the cruise include:

- Earth photometry as reference data for exoplanet observations
- Radio occultation of Venus' atmosphere
- Radio occultation of the solar corona
- Observations of zodiacal light and cosmic background scattered light between 0.7 and 10 AU from the Sun
- In-situ measurement of interplanetary dust spatial distribution between 0.7 and 10 AU
- Asteroid flyby observations

During the Saturn system flyby, OPENS-0 plans to conduct integrated observations of the rings by combining multiple methods across different physical parameters and spatial scales, aiming to advance understanding of ring formation and evolution. Candidate observations include high-resolution imaging of ring fine structures and constituent particles with a visible camera, large-scale and locally resolved studies of ring structures via radio occultation, and in-situ measurements of dust distribution from the ring region outward to interplanetary space. Radio occultation of Saturn's atmosphere may also be conducted in addition to ring studies.

This presentation will outline the scientific objectives of OPENS-0, with emphasis on the planned observations, and report on the current status of the mission.

外惑星領域の探査において後発である日本が現実的なリソースのもとでミッションを実施するため、超小型深宇宙探査機の実績を活かして外惑星探査を可能にする OPENS (Outer Planet Exploration by Novel Small Spacecraft) 探査プログラムが構想されている。これはイプシロン S ロケットや相乗り打上げなどを活用して 100~200 kg 級の小型探査機を高頻度で送り出すというものである。その第 1 弾として、公募型小型計画の ECO&FAST クラスでの実施を目指して、「外惑星探査小型実験機 (OPENS-0)」が提案された。提案時の計画では OPENS-0 はイプシロン S ロケットにより 2028 年に打ち上げられ、金星と地球のスイングバイを経て、2039 年に最終目的地である土星圏に到達する。OPENS-0 は現在、プリプロジェクト候補であり、ミッション定義審査に向けて検討を進めているところである。

OPENS-0 は日本独自の外惑星探査に必要な工学技術の宇宙実証を主目的とするが、打上から土星圏到達までの十年超に及ぶクルージング期間と土星圏フライバイにおいて、探査機本体の運用に関わる工学機器を科学目的にも活用することを基本として、科学成果創出を狙う。クルージング中には以下の観測を行う可能性がある。

- ・地球測光による系外惑星観測の参照データ取得
- ・金星大気電波掩蔽観測
- ・太陽コロナ電波掩蔽観測

- ・太陽距離 0.7AU～10AU における黄道光/宇宙背景放射散乱光の観測
- ・太陽距離 0.7AU～10AU における惑星間ダスト空間分布の直接計測
- ・小惑星フライバイ観測

土星圏フライバイに際しては、異なる物理量や空間スケールを対象とする複数の手段を組み合わせ、土星リングの統合観測を実施し、リングの形成と進化の理解進展を図る。可視カメラによるリング微細構造やリング構成粒子の観測、電波掩蔽によるリングの広域構造把握と局所高分解能観測、リング周辺から惑星間空間にかけてのダスト分布の直接計測などが候補である。リング観測に加えて土星大気電波掩蔽観測も実施する可能性がある。

講演では OPENS-0 の科学観測を中心に、ミッションの狙いと現状を報告する。

ハワイ・ハレアカラ東北大 T60 望遠鏡による水星カリウム外圏大気の観測

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Observation of Mercury's Potassium Exosphere using the Tohoku 60-cm Telescope at Haleakala Observatory in Hawaii

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We report on observation of Mercury's potassium exosphere using the Tohoku 60-cm telescope (T60) at the Haleakala Observatory in Hawaii, equipped with a visible adaptive optics (AO) system and a high-dispersion two-dimensional spectrograph. Our current goal is to provide ground-based support observations for the ESA-JAXA joint Mercury mission, BepiColombo, which will be in orbit around Mercury in 2026.

Mercury is known to have an exosphere consisting of alkali metals. The resonance scattering emissions of neutral sodium (Na D2 589.0 nm, D1 589.6 nm) and potassium (K D1 769.9 nm) are bright enough to be observable from the ground with high-dispersion spectroscopy, enabling studies of their spatial distribution and velocity fields. Sodium and potassium, both alkali elements, are expected to share common release and transport processes from Mercury's surface. However, previous studies have shown that the Na/K abundance ratio exhibits very large spatiotemporal variability, ranging from 30 to 400, and their emission distributions differ as well. Particularly, Na often shows enhancements at cusp regions, whereas K has been reported to increase at low latitudes and small solar zenith angles (Lierle et al., 2022), drawing attention to the differences in their source and transport processes. Nevertheless, because the potassium exosphere is about two orders of magnitude fainter than that of sodium, observations are still very limited, and its variabilities remain unclear. Our study aims to monitor the potassium exosphere continuously during daytime ground-based observations with AO, achieving unprecedented spatial resolution.

The observations employed the T60 telescope at Haleakala, combining with the visible AO system and a high-dispersion spectrograph ($R = 60,000$) equipped with a fiber integral-field unit (IFU, $\text{fov} = 15 \times 18''$). These instruments are operated remotely and in automated mode from Japan, contributing to long-term monitoring of solar system bodies.

Observations of Mercury's potassium exosphere were conducted on May 1 and August 19, 2025. In May, the best AO performance achieved a spatial resolution of $\text{FWHM} = 1.2''$, while in August the resolution was degraded to $\sim 2''$ due to poor weather conditions, preventing the entire Mercury disk from fitting within the IFU field of view. Mercury was observed in sets of 24 consecutive exposures (datasets) with 1-minute integration each. A total of six datasets were obtained in May, and four in August. Background sky spectra and flat-field calibration source were also acquired for each dataset.

Preliminary analysis showed that the disk-averaged intensity of the K D1 line emission was derived to be 80 ± 50 kR in May. In contrast, no statistically significant emission was detected in August with an upper limit of 40 kR at $S/N = 1$. Additionally, sodium exosphere observations conducted on May 3 show a disk-averaged Na D2 emission intensity of 5.0 MR. The disk-averaged abundance ratio $\text{Na/K} = 90$ was obtained from the observation in May. Those emission intensities and the Na/K ratio fall within the variability ranges reported in previous studies. In this presentation, we will discuss the spatial distributions of both potassium and sodium emissions in detail.

東北大ハワイ・ハレアカラ観測所 60cm 望遠鏡 (T60) に搭載した可視補償光学と高分散 2 次元分光器による水星カリウム外圏大気観測の試みについて報告する。本開発は、日欧合同 BepiColombo 水星探査機の周回観測 (2026-2029) に対する地上観測支援を直近の目標としている。

水星は、アルカリ金属による外圏大気が存在が知られ、特に中性ナトリウム (Na D2 589.0nm, D1 589.6nm) とカリウム (K, D1 769.9nm) の共鳴散乱発光は地上からの高分散分光により、その分布と速度場の観測が可能である。共にアルカリ金属元素であるナトリウムとカリウムは、水星表面からの放出や輸送過程に共通点が多いと考えられている。しかし先行研究では両者の存在量比 (Na/K) の時空間変動幅は 30~400 と非常に大きく、発光分布にも違いが見られる。特に両極カスプ域で強い発光を示すナトリウムに対して、カリウムでは低緯度・低太陽天頂角での増大が報告されており (Lierle et al. 2022)、両者の生成・輸送プロセスの違いに注目が集まっている。しかしナトリウム大気より 2 桁程度暗いカリウム大気の観測例は非常に限られており、時空間変動の特徴は未だ明らかではない。本研究では補償光学を用いた日中の地上観測により、カリウム大気をこれまでにない空間分解能で連続してモニター観測することを目指している。

観測にはハワイ・ハレアカラ観測所の T60 望遠鏡と可視補償光学 (AO)、およびファイバー視野集積装置 (IFU, 視野 15×18 秒角) を備えた高分散分光器 ($R=60,000$) を用いた。これらの観測装置は日本からの遠隔操作・自動運転によって主に太陽系天体の継続的観測に寄与している。

水星カリウム大気の観測は 2025 年 5 月 1 日と 8 月 19 日に実施した。5 月の観測では AO による最良時の空間分解能 (FWHM) は $1.2''$ を達成したが、8 月の観測では天候不良により空間分解能は $2''$ 程度となり、IFU の視野に水星全体を捉えることができなかった。水星観測は 1 分の積分を連続して 24 枚取得したものを 1 データセットとし、5 月の観測では

6 データセット、8 月の観測では 4 データセットを取得した。1 データセット取得の前後で背景光（スカイ）や波長校正のためのフラット光源データも取得した。

解析の結果、5 月の観測では、水星ディスク平均の K D1 線発光強度が $80 \pm 50 \text{ kR}$ と導出された。一方、8 月の観測では、 40 kR で $S/N=1$ に相当する検出限界を超える発光は検出できなかった。また、5 月 3 日に観測した Na D2 線発光強度の水星ディスク平均は 5.0 MR であった。5 月の観測から、水星ディスク平均の存在量比 $\text{Na/K} = 90$ が求められた。これらの発光強度と Na/K は、先行研究で示された変動の範囲に含まれている。本公演ではカリウムおよびナトリウム発光の分布の詳細について報告する。

水星近傍宇宙環境における粒子ダイナミクスの数値モデル化：初期結果

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Numerical modeling of particle dynamics in the near-Mercury space environment: Initial results

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Mercury, the closest planet to the Sun, possesses a weak dipole-shaped magnetic field. It is generally assumed that such a weak field cannot sustain long-term particle trapping. Nevertheless, the extent to which particles may experience trapping or quasi-trapping remains an open question.

To investigate particle dynamics in Mercury's space environment, we developed a three-dimensional relativistic test particle simulation code. This code computes particle trajectories across a wide range of energies, pitch angles, and L-shells. It incorporates two tracing approaches: the Tao – Chan – Brizard guiding center model and full Lorentz motion, with transitions between the two determined through evaluation of the adiabaticity condition. In the current research phase, Mercury's magnetic field is represented using the KT17 model. In particular, we are investigating the initial pitch angle distribution on particle dynamics.

In this presentation, we will report the initial results of numerical results, which will clarify the fundamental aspects of particle dynamics in Mercury's magnetosphere and provide a comparative planetary study by comparing the dynamics on Earth.

太陽に最も近い惑星である水星は、弱い双極子磁場を有している。一般的に、このような弱い磁場では、長期間にわたる粒子の捕捉は維持されないと考えられている。しかしながら、粒子の捕捉や準捕捉がどの程度可能であるか、その範囲はいまだ明らかになっていない。

水星近傍の宇宙環境における粒子ダイナミクスを解明するため、高度な三次元相対論的テスト粒子シミュレーションコードを開発した。本コードは、エネルギー、ピッチ角度、L 値の広い範囲に通じて粒子の軌道を計算する。さらに、本コードでは Tao – Chan – Brizard の旋回中心軌道モデルと Newton – Lorentz の螺旋軌道モデルの両方を取り入れており、断熱捕捉条件に応じて切り替えが行われる。現時点での研究フェーズでは、KT17 モデルを用いることによって水星の磁場を再現している。具体的には、初期条件として与えるピッチ角分布が粒子ダイナミクスにどのような影響を及ぼすのかを明らかにする。

本発表では、数値実験の初期結果について報告する。水星磁気圏の粒子ダイナミクスの基本的な様相を明らかにするとともに、地球でのダイナミクスの対比による比較惑星考察を行う予定である。

R009-P03

ポスター 3 : 11/26 PM2/PM3 (14:50-18:25)

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Development of the ion mass spectrometer for the Comet Interceptor mission

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Comets are pristine small bodies and thus provide key information about the solar system's evolution. Remote observations by ground observatories have characterized various comets, while in-situ observations by spacecraft have brought much more detailed information on several comets. However, the direct observations by spacecraft fly-by or rendezvous have been limited to the short-period comets, which neared the sun many times in the past and thus lost some of (or even most of) their primitive characteristics. The Comet Interceptor mission, led by ESA, aims at a long-period comet or an interstellar object. JAXA will provide an ultra-small (35 kg) daughter spacecraft (probe B1), whose closest approach will be less than 1,000 km, allowing the first-ever multi-spacecraft fly-by observations of a comet. Here we report our recent progress on the development of the ion mass spectrometer onboard probe B1. After the verification of the performance and endurance, we delivered the engineering model to the B1 system for further tests in the assembled state. The design of the flight model is ongoing in parallel.

彗星探査機 Comet Interceptor における人工磁場ノイズを利用した磁力計センサアライメント推定手法の開発

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Examination of the Method to Estimate the Magnetometer Sensor Alignment on Comet Interceptor Using Artificial Magnetic Noise

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Comets are samples of small celestial bodies retaining the characteristics at the early era of the solar system and providing essential information to understand the origin and evolution of the solar system. Previous missions to explore the comets have targeted short-period ones with orbital period of less than 200 years. However, these comets have approached the Sun many times, making it difficult to distinguish whether their surface features are original or affected by the solar illumination. The European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) are planning the Comet Interceptor mission, the first-ever mission to explore a long-period comet whose characteristics have not been affected by the solar illumination. In this mission three spacecraft will be launched to observe a comet simultaneously, aiming to gain new insights into the formation and evolution of the solar system and the interaction between the solar wind and the comet. The spacecraft are scheduled to launch in 2029; ESA provides the main spacecraft (A) and one of the daughter spacecraft (B2), while JAXA provides the other daughter spacecraft (B1).

All these three spacecraft are equipped with magnetometers. On Spacecraft B1, to prevent artificial magnetic noise generated by the spacecraft itself from degrading the precise measurement of natural magnetic fields, the magnetometer sensor is mounted at the tip of a 1.5-meter-long boom. The boom, which is compactly stored at the launch, will be deployed after the launch. However, there are concerns that the magnetometer sensor might not be correctly aligned as designed, because the boom could be distorted after the deployment. Since this alignment error directly impacts the accuracy of magnetic field data, the boom distortion is a significant issue. In previous missions such as the Selenological and Engineering Explorer (SELENE) and the Jupiter Icy Moons Explorer (JUICE), two coils are implemented inside the spacecraft to generate a known magnetic field for the calibration of the magnetometer sensor alignment (Shimizu et al., 2008; Takahashi et al., 2009). However, for the Comet Interceptor mission, it is not realistic to install coils since the weight restraint is the high priority. Therefore, we are aiming to develop an alternative method to estimate the magnetometer sensor alignment using magnetic noise generated by the instruments originally installed.

In this study, we use artificial magnetic noise from the spacecraft, which is normally a hindrance to measurements of natural magnetic fields, for the estimation of the sensor alignment after boom deployment. For the calibration, we treat the three reaction wheels used for spacecraft attitude control as noise sources, and extract only the magnetic field variations induced by their rotation for the alignment estimation. In this estimation, it is also necessary to determine the exact displacement of the magnetometer sensor. This is because the boom distortion may shift not only its alignment but also its location, and this positional uncertainty can degrade the accuracy of alignment estimation. The outline of the proposed procedure is as follows: First, before launch, we conduct a ground experiment to construct a model to calculate the magnetic field generated by the reaction wheels at any position around the wheels. After launch and the boom deployment, we compare the magnetic field variations generated by the wheels with the pre-constructed model and estimate the position and alignment of the sensor. To validate this approach, we conducted an experiment in the Magnetic Shielding Room at ISAS/JAXA to measure the magnetic field generated by the flight-model reaction wheels. Based on the acquired magnetic field data, we constructed a model in which the magnetic potential generated by the wheels is represented by a spherical harmonic expansion of the dipole term. The time variations of the Gauss coefficients are assumed to follow sinusoidal functions having the rotational frequencies of the wheels. Using this model, we carried out the alignment estimation procedure. We will discuss the achievable alignment estimation accuracy based on the results.

彗星は太陽系の形成初期における微小天体のサンプルであり、太陽系の起源や進化を理解するための重要な手がかりである。これまでの探査ミッションでは、周期が 200 年未満の短周期彗星がターゲットであったが、それらは太陽に何度も接近しているため、表面の特徴が元々のものか、太陽に接近する過程で変化したものかを見分けるのが難しいという問題がある。このため、ESA と JAXA により、史上初めて長周期彗星の探査を目指す Comet Interceptor ミッションが計画

されている。このミッションでは、3機の衛星を用いて彗星を同時に観測することにより、太陽系の形成や進化、太陽から吹き出す荷電粒子である太陽風と彗星との相互作用について、新しい知見が得られることが期待されている。衛星は2029年に打ち上げ予定であり、ESAが親機（A衛星）と子機の一つ（B2衛星）を、JAXAが残りの子機一つ（B1衛星）を提供する予定である。

JAXAが担当するB1衛星では、探査機本体が発する人工的な磁場ノイズが自然界の磁場の観測に影響を与えることを防ぐため、長さ1.5mの「ブーム」と呼ばれる棒状の伸展物の先に磁力計のセンサが設置される。打ち上げ時にはブームは小さく収納されているが、打ち上げ後にセンサが衛星本体から離れる方向に伸ばされる。しかし、保管時のブームの経時特性変化や機構部ガタ、熱変形などに起因した不確定性によりセンサの方向（アライメント）が変化することが懸念されており、そのアライメント誤差が磁場データの誤差に直結するため、重要な課題となっている。従来の磁力計を搭載した探査ミッションのうち、月周回衛星「かぐや」や木星氷衛星探査衛星「JUICE」などでは、アライメントを正確に推定するために、衛星本体内部に既知の磁場を発生させるコイルを装備し、その磁場をセンサで計測することでアライメントのずれを検証していた(Shimizu et al., 2008; Takahashi et al., 2009)。しかし、今回のミッションでは探査機の小型化の優先度が高いため、アライメント校正磁場を生成するコイルを搭載することができず、新たな校正手法の開発が求められている。

そこで本研究では、通常は自然磁場観測の妨げとなる探査機由来の人工磁場ノイズを逆に利用し、ブーム伸展後の磁力計センサのアライメントを推定する手法の開発を目指す。本手法では、校正に用いる磁場ノイズの発生源として衛星の姿勢制御に使用される3つのリアクションホイールを想定しており、ホイールの回転によって生じる磁場変動成分のみを抽出して利用する。なお、アライメント推定の際にはセンサの位置も同時に推定する必要がある。これはブームの歪みにより、センサのアライメントだけでなく位置も変化する可能性があり、その位置の不確かさがアライメント推定精度に大きく影響を及ぼすためである。アライメント推定の基本的な流れは以下の通りである。まず、打ち上げ前の地上試験において、ホイールが任意の位置に生成する磁場をモデル化する。打ち上げ後、ブームが伸展された状態で取得されるリアクションホイール由来の磁場変動と、この事前に構築したモデルとを比較することで、磁力計センサの位置およびアライメントを同時に推定する。この手法の検証のため、実際に衛星に搭載されるリアクションホイールを用いて、JAXA宇宙科学研究所の磁気シールドルームにて磁場測定実験を実施した。得られた磁場データに基づき、ホイールが発する磁場ポテンシャルをダイポール成分までの球面調和関数で表現し、各ガウス係数の時間変動がホイールの回転数に対応した周期的な正弦波で記述できると仮定してモデルを構築した。このモデルを用いてアライメント推定処理を一連で実施し、得られた結果をもとに、本手法によって達成可能なアライメント推定精度について議論する。

Comet Interceptor/Hydrogen Imager による長周期彗星観測に向けた彗星コマの高分解能紫外線スペクトルデータの解析

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Analysis of high-resolution ultraviolet spectral data of comet comas for observation of Comet Interceptor/Hydrogen Imager

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Hydrogen Imager: HI is an ultraviolet imaging device that will be installed on the Comet Interceptor long-period comet exploration mission. There are examples of long-period comet observations using similar wavelength bands, such as SOHO/SWAN and HST/STIS. In this study, we analyzed high-resolution ultraviolet spectral data from HST/STIS to understand the brightness distribution of the hydrogen coma of comets prior to HI observations.

Comets are highly active celestial bodies with high gas and dust emission rates. As they approach the Sun, volatile substances are released from the comet nucleus, forming structures such as comas and tails. By observing their composition and spatial distribution, it is possible to clarify the composition of the comet nucleus, spatiotemporal variations in activity and interactions with the solar wind. Long-period comets often have periods of more than 10,000 years, so they have been less affected by the Sun than short-period comets and are thought to retain the pristine features of solar system environment at the time of comet formation and to be highly active.

However, in-situ observations of long-period comets have never been conducted and are limited to short-period comets. This is because long-period comets have very long orbital periods, so when they approach Earth and are newly discovered, they are new comets whose orbits are unknown. In addition, the period from discovery to Earth flyby is generally only a few years, making it extremely difficult to develop instruments based on assumptions about the orbit and environment of a specific comet using conventional methods.

Therefore, in the Comet Interceptor mission led by European Space Agency (ESA), equipment is being developed based on the typical environment of long-period comets known from remote observations, and in-situ observations will be realized by parking in the vicinity of Earth after launch for comets suitable for observation.

One of the two sub-probes, Probe B1, will carry “Hydrogen Imager: HI”, which will capture images of the Lyman-alpha (121.6 nm) of the comet’s hydrogen coma to understand the spatial structure of hydrogen, derive the water release rate based on the assumption that hydrogen atoms are generated by the photodissociation of water molecules, and measure the ratio of hydrogen to deuterium (D/H ratio) using a glass cell filter, which has a slightly different emission wavelength.

HI primarily has two observation modes: one is to capture two-dimensional images of the Ly- α emission from hydrogen atoms, and the other is to measure the hydrogen-deuterium ratio based on brightness ratios. The influence of the “multiple scattering region” is of particular interest when analyzing these data.

Multiple scattering occurs in regions near the nucleus where the hydrogen column density is high, making the optical thickness greater, which disrupts the normal proportional relationship between column density and brightness (Suzuki et al. 2025). As a result, in HI, this leads to an underestimation of the hydrogen atom abundance near the nucleus and an overestimation of the D/H ratio due to differences in the optical thickness of the coma for hydrogen Ly- α and deuterium Ly- α .

Suzuki et al. (2025) used observational data from “Hisaki” satellite for C/2013 US10 (Catalina) and others, and there are a few other examples of long-period comets being spectroscopically observed in the far-ultraviolet region, like Hisaki. Among these, the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST) is equipped with an Echelle-type spectrograph with extremely high wavelength resolution ($R \sim 30,000 - 114,000$), such as E140H, enabling the separation of hydrogen Ly- α (121.567 nm) and deuterium Ly- α (121.534 nm). Weaver et al. (2008) analyzed observational data of C/2001 Q4 (NEAT) obtained with STIS/E140H and presented the spectral shape, deriving a D/H ratio of $\sim 3.2 \times 10^{-4} - 6.0 \times 10^{-4}$; however, the derivation method is unclear.

Since this is one of the few examples where the D/H ratio of a long-period comet can be calculated from the atomic abundance ratio, this study analyzed the same data. Considering the effect of multiple scattering on the apparent D/H ratio, the D/H ratio of C/2001 Q4 was derived and compared with previous analysis results. Additionally, by examining the effect of multiple scattering from the analysis results, this study also suggests the feasibility of observations using Comet Interceptor/HI.

In addition, the same observation data also shows an emission line originating from oxygen atoms (130.4 nm). The intensity of this emission line makes it possible to examine the state of water molecules not only from hydrogen atoms but also from oxygen atoms. Furthermore, since HI is designed to exclude light other than Ly- α using a bandpass filter, it is

important to consider the influence of oxygen emission lines, and the results also contribute to the performance evaluation of HI.

Hydrogen Imager: HI は長周期彗星探査ミッション Comet Interceptor に搭載される紫外線撮像装置である。同様の波長帯による長周期彗星観測は SOHO/SWAN や HST/STIS などの例がある。本研究では HI の観測に先立ち彗星の水素コマの輝度分布を把握するべく、HST/STIS の高分解能紫外線スペクトルデータを解析した。

彗星は高いガス放出率やダスト放出率を持った活動性の高い天体で、太陽に近づいて揮発性物質が彗星核から放出されることでコマやテイルなどの構造を形成する。これらの組成や空間分布を観測すれば、彗星核の組成や活動の時空間的な変動・太陽風との相互作用などを明らかにすることができる。特に、長周期彗星は 1 万年以上の周期をもつものが多いため、短周期彗星に比して太陽による変質を受けた回数が少なく、彗星形成時の始原的な太陽系環境を保持しており、活動度も高いと考えられている。

しかし、長周期彗星のその場観測は行われたことはなく、短周期彗星に限られている。というのも、長周期彗星は周期が非常に長いため、地球に近づいてきて新たに発見されるのは軌道の分からない新規の彗星であり、一般的に発見から地球近傍通過までの期間も数年と短いので、特定の天体の軌道や環境を想定して装置開発を行う従来の方法では実現が極めて困難であった。

そこで欧州宇宙機関 (ESA) が主導する Comet Interceptor では、リモート観測などからわかっている典型的な長周期彗星の環境を参考に装置を開発し、打ち上げ後は地球周辺で観測に適した彗星を待ち受けることでその場観測を実現する。

探査機の 2 つの子機の一つ、Probe B1 に搭載される「Hydrogen Imager: HI」は彗星の水素コマの Lyman- α (121.6 nm) 撮像から水素の空間構造を把握し、水素原子が水分子の光解離によって生成するという仮定により水の放出率を導出したり、ガラスセルフィルターを用いて発光波長がわずかに異なる水素と重水素の存在比 (D/H 比) を測定したりする。

HI は主に 2 つの観測モードがあり、1 つは水素原子が発する Ly- α の 2 次元画像を撮影し、もう一方は輝度比から望遠鏡視野内の水素・重水素比を計測する。これらのデータを解析する上で「多重散乱領域」の影響が注目される。

多重散乱は核近傍の水素柱密度が高い領域で光学的に厚いために生じ、柱密度と輝度が比例する本来の関係が崩れてしまう (Suzuki et al. 2025)。そのため HI では、核近傍の水素原子存在量の過小評価や、水素 Ly- α と重水素 Ly- α それぞれにとってコマの光学的厚みに差があるために D/H 比の過大評価につながる。

Suzuki et al. (2025) では「ひさき」による C/2013 US10 (Catalina) 等の観測データを用いているが、ひさきと同様に遠紫外領域で長周期彗星を分光観測した例は他にも少数存在する。中でもハッブル宇宙望遠鏡 (Hubble Space Telescope: HST) の Space Telescope Imaging Spectrograph: STIS は波長分解能が非常に高い ($R \sim 30,000$ -114,000) Echelle 型分光器を搭載しており、水素 Ly- α (121.567 nm) と重水素 Ly- α (121.534 nm) を分別可能である。Weaver et al. (2008) は STIS/E140H による C/2001 Q4 (NEAT) の観測データを解析している。スペクトル形状が示されており、 $D/H \sim 3.2 \times 10^{-4} - 6.0 \times 10^{-4}$ が導かれているが、その導出方法は不明確である。

長周期彗星の D/H 比を原子の存在比から計算できる数少ない例のため、本研究では同データを解析した。そこで多重散乱による見かけの D/H 比への影響を考慮した上で C/2001 Q4 の D/H 比を導出・過去の解析結果と比較し、逆に解析の結果から多重散乱の影響を考察することで Comet Interceptor/HI による観測の実現可能性についても示唆を与える。

加えて、同観測データには酸素原子由来の発光輝線 (130.4 nm) も見られている。この輝線強度により水素原子だけでなく酸素原子からも水分子の様子を考察することが可能である。また、HI はバンドパスフィルターを用いて Ly- α 以外の光を排するよう設計されているため酸素輝線の影響を考慮することは非常に重要であり、HI の性能評価につながる結果も示す。

かぐや MAP-PACE 観測データを用いた月面磁気異常領域における H₂O 存在量解析

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Analysis of H₂O abundance in the lunar magnetic anomaly region using KAGUYA MAP-PACE data

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Understanding when and how water was delivered to or generated on the Moon is crucial for deciphering the history of the Moon's formation and evolution. Several previous missions suggested the presence of water on the lunar surface. Infrared spectroscopic observations with the M3 onboard Chandrayaan-1 indicated the existence of water ice in the permanent shadow of the polar regions. Furthermore, observations by the Stratospheric Observatory for Infrared Astronomy (SOFIA) have detected a water molecule emission line at 6.1 μm in the high-latitude surface layers of the Moon. These observations highly suggest the presence of water in the permanent shadows of the Moon. One hypothesis for the origin of lunar water is the chemical reaction between solar wind protons and oxygen atoms in the surface minerals. Surface minerals irradiated by protons are thought to form hydroxyl (OH) groups, and with further proton irradiation, H₂O is generated.

While the Moon does not have a global intrinsic magnetic field like Earth's, numerous localized regions of strong magnetic fields, known as magnetic anomalies, are known to exist, as discovered by the Lunar Prospector electron reflectometer and the MAP-LMAG magnetometer onboard the KAGUYA satellite. In these magnetic anomaly regions, it is suggested that the motion of ions and electrons is separated due to their interaction with the magnetic anomalies, leading to the formation of an upward-pointing electric field. This upward electric field is inferred to suppress the amount of solar wind protons reaching the lunar surface. Consequently, it is speculated that the water production rate decreases in magnetic anomaly regions.

In this study, we attempt to clarify the difference in H₂O abundance on the lunar surface by directly comparing the amount of H₂O ions above lunar magnetic anomaly regions and non-magnetic anomaly regions, using the data obtained by MAP-PACE onboard the lunar orbiter KAGUYA. This aims to verify whether the solar wind shielding effect by magnetic anomalies on lunar water generation can be detected through in-situ ion observations. We used MAP-LMAG data to classify observational points of KAGUYA's low-altitude (~50km) MAP-PACE data into magnetic anomaly and non-magnetic anomaly regions. In order to confirm the direct influence of the solar wind, we limited our data to the dayside with a specific range of solar zenith angles. Furthermore, we selected data from periods when the Moon was not within the Earth's magnetotail, allowing us to analyze the pure interaction between the solar wind and magnetic anomalies. Using these filtered datasets, we compared the counts corresponding to the time-of-flight of H₂O ions inside and outside the magnetic anomalies. The analysis revealed that the counts of H₂O ions and many other ion species were significantly reduced in magnetic anomaly regions compared to non-magnetic anomaly regions. This result is consistent with previous research, indicating that the magnetic anomalies either deflect or reflect the solar wind ions, which generate lunar surface-origin ions, thereby suppressing their interaction with the surface, or that low-energy ions generated within the magnetic anomaly are unable to escape. On the other hand, it was also confirmed that the ratio of counts observed in non-magnetic anomaly regions to those in magnetic anomaly regions changes at specific time-of-flights. In future work, we will consider the origin of the counts corresponding to the time-of-flight of H₂O ions detected above magnetic anomaly regions, as well as identify the particle species with differing count ratios between magnetic anomaly and non-magnetic anomaly regions and investigate their origins. We also plan to apply filters for latitude and longitude in order to investigate location dependency.

月の水がいつ、どのようにして月面に供給・生成されたかを理解することは、月の形成と進化の歴史を解明する上で重要な情報となる。先行する複数のミッションにより、月面に水が存在することが示唆されている。Chandrayaan-1 搭載の M3 による赤外分光観測によって、極域の永久影での水氷の存在が示唆されている他、成層圏赤外線天文台 SOFIA による観測では水分子特有の 6.1 μm 輝線スペクトルが月の高緯度の表層で検出されている。これらの観測によって月の永久影における水の存在可能性が高まっている。月の水の起源の一つとして、太陽風中のプロトンと表層鉱物中の酸素原子の化学反応が考えられている。プロトン照射を受けた表層鉱物が OH 基を形成し、さらにプロトンが照射されることにより H₂O が生成される。

月は地球のようなグローバルな固有磁場は持たないが、Lunar Prospector の電子反射計や「かぐや」衛星に搭載された月磁場観測装置 MAP-LMAG により、局所的に磁場の強い領域である磁気異常領域が多数存在することが知られている。これらの磁気異常領域では太陽風プラズマとの相互作用によりイオンと電子の運動が分離され、上向きの電場が形成されることが示唆されている。この上向き電場は、月面に到達する太陽風プロトンの量を抑制し、結果として磁気異常領域では水の生成率が減少すると推測されている。

本研究では、月周回衛星「かぐや」に搭載されたプラズマ粒子観測装置 MAP-PACE の観測データを用いて、月面磁気

異常領域上空と非磁気異常領域上空における H₂O イオンの検出量を直接比較し、それぞれの領域における月表面の H₂O 存在量の差異を明らかにすることを試みる。これにより、磁気異常による太陽風遮蔽効果が月面での水生成に与える影響を、イオンの in-situ 観測によって検出することができるかどうかを検証する。「かがや」が低高度 50km で取得した MAP-PACE 観測データに対して、磁力計 MAP-LMAG データを用いて、観測点を磁気異常領域と非磁気異常領域に分類した。次に、太陽風の直接的な影響を確認するため太陽天頂角が一定範囲内の日中側のデータに限定した。さらに、月が地球の磁気圏尾部に入っていない期間のデータを選択し、太陽風と磁気異常の相互作用を解析できるようにした。これらのフィルターを適用したデータセットを用いて、質量分析中のイオンの飛行時間が H₂O イオンの飛行時間に相当する部分の count を比較した。解析の結果、磁気異常領域における H₂O を含む多くの粒子種の count は、非磁気異常領域と比較して有意に減少していることがわかった。これは、磁気異常が、月表面起源のイオンを生成する原因となる太陽風を偏向・反射させ、月表面層との相互作用を抑制するか、あるいは、磁気異常中で生成された低いエネルギーのイオンが、磁気異常から抜け出せないことを示しており、先行研究と矛盾しない結果である。一方で、特定の飛行時間において非磁気異常領域で観測された count と磁気異常領域で観測された count の比率が変化しているデータもあることが確認された。今後は、磁気異常領域上空において検出された H₂O イオンの飛行時間に相当する count の起源について考察するとともに、磁気異常領域と非磁気異常領域で count の比率が異なる粒子種の同定とその成因について考察する。また、緯度・経度についてもフィルターをかけ、場所依存性についても調査する予定である。本発表では上記の現状を報告する。

かぐや衛星の波形捕捉器で観測されたダスト衝突波形の研究

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Study on the dust impact signals observed by the WFC aboard KAGUYA

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Dust particles ranging in size from nanometers to micrometers are widely distributed in space, and it has been suggested that there exists a large number of dust particles around the moon in particular [1]. When such particles collide with spacecrafts, they generate plasma clouds around the spacecraft, which will affect electric field measurements[2]. The WFC (Waveform Capture) onboard the lunar orbiter KAGUYA has detected numerous waveforms believed to originate from dust impacts[3]. Horie et al. have extracted pulse-like waveforms, to be plausibly caused by dust impacts, from the WFC waveform data using pattern matching techniques and have statistically analyzed their characteristics. A notable feature of the KAGUYA observations is that such waveforms have been detected not only in monopole measurements, but also in dipole measurements, where the detection of dust impact signals is theoretically less likely. Horie et al. have suggested that in dipole mode, dust-related waveforms are observed due to sensitivity imbalances between the two antennas caused by partial shading from the satellite body. However, the detailed physical mechanism remains insufficiently understood. Therefore, in this study, we investigate the conditions under which dust impact waveforms are more likely to be detected and explore why such signals can be observed even in dipole mode, primarily based on monopole measurement data. Characteristic features of dust impact waveforms include their asymmetric shapes and the simultaneous appearance of similar waveforms across multiple antennas. However, due to contamination of the internal artificial noise, it is difficult to distinguish true dust signals from the monopole measurements data. To address this issue, we improved the detection accuracy by focusing on parameters such as the time intervals and the polarity consistency among the detected pulse signals. As a result, we found that the amplitudes of dust impact signals detected in monopole mode varied depending on the antenna, and that the amplitude ratio exhibited a correlation with the direction of the Sun as seen from the spacecraft. In this presentation, we discuss the relationship between these amplitude ratios and the solar direction, as well as the possible mechanism behind the generation of these waveforms.

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ナノメートルからマイクロメートルサイズのダスト粒子は宇宙空間に広く分布しており、特に月周辺にはダスト粒子が数多く存在する可能性が指摘されている [1]。これらの粒子が人工衛星に衝突すると、衛星周囲にプラズマ雲が生成され、電場観測に影響を及ぼすことが知られており [2]、月探査衛星「かぐや」に搭載された電場計測器（WFC: Waveform Capture）でも、ダスト起源と考えられる波形（ダスト衝突波形）が多数検出されている [3]。

堀江らは、かぐや衛星で観測されたダスト衝突波形と考えられるパルス波形を WFC 波形データからパターンマッチングを用いて抽出し、その特徴を統計的に研究している。かぐや衛星では、モノポール観測のみならず、原理上はダスト衝突波形が観測されにくいと考えられるダイポール観測で数多くのパルス波形が検出されていることが特徴である。堀江らは、かぐや衛星がダイポール観測時にもダスト衝突波形が多数検出されたのは、衛星の影がアンテナに部分的に落ちることで、左右のアンテナ感度のアンバランスが生じることが原因と結論付けているが、詳細な物理機構は十分解明されていない。そこで本研究では、どのような条件下でダスト衝突波形がより多く検出されるのか、また、なぜダイポールモードでも検出できるのかを、主にモノポール観測の結果を用いて検証する。

ダスト衝突波形の特徴として、非対称なパルス形状に加え、複数アンテナで同時刻かつ同形状の応答が観測されることが挙げられる。しかし、モノポール観測では人工ノイズが混入し、ダスト衝突波形との識別が難しいという課題がある。そこで本研究では、波形の検出時間間隔や前後の信号との極性の一致などに注目し、検出精度をさらに高める改良も行った。

解析の結果、モノポール観測時のダスト衝突波形の振幅値が、アンテナごとに異なる事例が観測され、その振幅比が衛星から見た時の太陽方向と相関があることが明らかになった。このことは、ある一定条件下でダイポール観測でダスト衝突波形が観測される結果と整合的であり、本研究では、これらの振幅比と太陽方向の関係を詳細に解析することで、波形発生メカニズムについて議論を行う。

月での太陽放射線予測適用に向けた説明可能な AI による予測根拠の分析

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Analysis of Prediction reasons using Explainable AI for the Application of Solar Radiation Prediction on the Moon

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We are advancing the development of solar radiation prediction technology for lunar and Martian exploration. This is a joint research project adopted under the "Moon to Mars Innovation" program, a research initiative promoted by the Space Exploration Innovation Hub Center, JAXA. Solar Energetic Particles (SEPs) are a type of space radiation that occurs with sudden solar phenomena such as solar flares (SFs) and coronal mass ejections (CMEs), propagating through space. They are known to affect human health and space systems not only around Earth but also in space, including the lunar surface. Therefore, SEPs are crucial prediction targets when considering activities on the lunar surface.

We have constructed a SEP event prediction model for the Moon using Wide Learning, an explainable AI developed by Fujitsu. This prediction model forecasts whether a SEP event will occur within a certain period from the prediction time as a binary classification task. Wide Learning is characterized by its ability to make highly accurate predictions even with small amounts of data, and its comprehensive discovery of combinations of categorical and numerical variable ranges that are characteristic of the phenomenon to be predicted. This allows us to explain the reasons for predicting the occurrence of SEP events.

In constructing the lunar SEP event prediction model, we used observational data from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument aboard the Lunar Reconnaissance Orbiter (LRO). The LRO orbits the Moon in a polar orbit at an altitude of 50 km, and CRaTER measures cosmic radiation, including SEPs. First, to clearly identify the flares associated with the target SEP events, we performed event detection and solar flare identification using LRO/CRaTER observational data from June 2010 to May 2025. Furthermore, we trained Wide Learning using 88 solar flares linked to detected SEP events as positive examples and other flares as negative examples, thereby constructing the SEP prediction model. In this presentation, we report on the analysis of important factors for SEP event prediction, derived from the prediction reasons for SEP event occurrences provided by the SEP prediction model.

我々は、JAXA 宇宙探査イノベーションハブが推進する研究制度 "Moon to Mars Innovation" に採択された共同研究で、月・火星探査に向けた太陽放射線事前予測技術の開発を推進している。太陽高エネルギー粒子 (SEP) は、太陽フレアやコロナ質量放出といった太陽の突発現象に伴い発生し、宇宙空間を伝搬する宇宙放射線の一種であり、地球周辺だけでなく月面なども含めた宇宙空間において人体や宇宙システムへ影響を及ぼすことが知られており、月面での活動を想定した場合には重要な予測対象である。

我々は、富士通が開発した説明可能な AI Wide Learning を用いた月での SEP イベント予測モデルを構築した。予測モデルでは、予測時点から一定時間以内に SEP イベントが発生するかどうかを二値分類問題として予測する。Wide Learning は、少量のデータからでも高精度な予測を行うことができることに加えて、予測したい事象に特徴的なカテゴリカル変数や数値変数の範囲を組み合わせとして網羅的に発見することが特徴である。これにより、SEP イベントが発生すると予測する根拠を説明することが可能となる。

今回、月での SEP イベント予測モデルを構築するにあたり、月周回衛星 LRO (Lunar Reconnaissance Orbiter) に搭載された観測機器 CRaTER (Cosmic Ray Telescope for the Effects of Radiation) による観測データを活用する。LRO は月面高度 50km の極軌道を周回しており、CRaTER では SEP などによる宇宙放射線を計測している。我々はまず、予測対象の SEP イベント発生時のフレアを明確にするため、2010 年 6 月から 2025 年 5 月までの LRO/CRaTER 観測データによるイベント検出および太陽フレア同定を行った。さらに、検出された SEP イベントに紐づけられた 88 件の太陽フレアを正例、その他のフレアを負例として Wide Learning により学習を行い、SEP 予測モデルを構築した。本講演では、SEP 予測モデルに含まれる SEP イベントの発生予測根拠に基づく、SEP イベント予測に対する重要な因子の分析について報告する。

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Magnetic anomalies and landing site evaluation for STEP1 on Mars

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Magnetic field observations of Mars have revealed the presence of strong magnetic anomalies arising from crustal remanent magnetization, estimated to be up to ten times stronger than that of Earth's crust. A detailed understanding of these magnetic anomalies offers valuable insights into the history of Mars' magnetic field, interior dynamics, and surface environment. Martian magnetic anomalies have been investigated using magnetometers onboard spacecraft such as the Mars Global Surveyor and MAVEN (Mars Atmosphere and Volatile Evolution), as well as by landers and rovers like the InSight lander and the Zhurong rover. While spacecraft data provide a global view of the distribution of magnetic anomalies, the observation altitudes are relatively high compared to the depth of the magnetic sources and the spatial scales of the geological features. Notably, surface magnetic fields measured by the InSight lander and the Zhurong rover differ significantly from values predicted by orbital data: the predicted/observed field values are 700 nT/2013 nT (Johnson et al. 2020) and 81 nT/5.2 – 39.8 nT (Du et al. 2023) for InSight and Zhurong sites, respectively. This discrepancy highlights the need for direct, surface-based magnetic observations to achieve a more accurate and detailed understanding of Martian magnetic anomalies. The STEP1 concept, developed by the Japan Aerospace Exploration Agency, aims to deploy landers on the Martian surface equipped with fluxgate magnetometers. Based on current knowledge of Martian geology and magnetism, we are evaluating potential landing sites for the STEP1 lander, with a focus on regions favorable for magnetic anomaly investigations. Accurate interpretation of magnetic anomaly data requires an understanding of the events and timing during which the crustal rocks acquired their remanent magnetization. In this study, we focus on magnetic anomalies associated with impact craters. During crater formation, shock waves propagate through crustal rocks, potentially inducing remanent magnetization. Furthermore, because the ages of craters can be estimated, they can serve as chronological markers for magnetization events. We are currently identifying potential landing sites by referencing the geological map of Mars published by Tanaka et al. (2014) and crater age data compiled by Robbins and Hynes (2012). In this presentation, we will share the current status of our evaluation of candidate landing sites for the STEP1 mission in the context of magnetic anomaly exploration.

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Study of Ion Escape from Mars through Polar Plumes based on Global Multi-Fluid MHD Simulations

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The atmospheric escape to space is considered to be a major cause of ancient climate change on Mars. One of the ion escape pathways, the polar plume, is a phenomenon in which ions accelerated by the solar wind convection electric field escape from Mars, and its importance has been pointed out in previous studies [e.g., Dong et al., 2017; Sakakura et al., 2022]. Observations by the MAVEN spacecraft suggest that, in addition to O^+ , which has been considered the primary escape species, molecular ions such as O_2^+ and CO_2^+ are also escaping through the polar plumes. In some cases, although CO_2^+ is a minor component in the high-altitude ionosphere, CO_2^+ flux is higher than those of O^+ and O_2^+ in some localized regions [Sakakura et al., 2022]. One of difficulties to simulate the polar plumes is its kinetic nature, since the pick-up ions with a ring distribution function can contribute to the polar plumes. The global MHD simulations have been used as a powerful tool to simulate the ion escape from Mars [e.g., Ma et al., 2014; Sakata et al., 2024]. It is known that the multi-fluid MHD simulations result in asymmetric ion escape between +Z (+E) and -Z (-E) hemispheres in the MSE coordinates [e.g., Sakata et al., 2024], which has the same tendency as the polar plumes. However, the polar plume description capability of the multi-fluid MHD code is far from understood. If this capability can be understood, it will become easier to understand planetary atmospheric escape in a wider parameter space, including exoplanets. The objective of this study is to determine how well plume events can be described by the global multi-fluid MHD simulations.

In this study, we applied the global multi-fluid MHD model, MAESTRO, to the CO_2^+ -rich polar plume event observed by MAVEN on August 27 and 28, 2015, which was reported in details by Sakakura et al. [2022]. MAESTRO takes into account the production and loss processes due to chemical reactions, and can reproduce interaction between the solar wind and Martian atmosphere/crustal magnetic fields, including plasma boundaries, ionospheric profiles, and ion escape. MAESTRO separately solves ion and electron pressures, and photoelectron heating is also considered with a heating effect of 5 eV per photoelectron. In the simulation settings of this study, the solar wind conditions used in Sakakura et al. [2022] for the CO_2^+ -rich polar plume event were used as inputs to MAESTRO: the solar wind density, velocity, and interplanetary magnetic field (IMF) were set to 10 cm^{-3} , 350 km/s, and $5.0 \times (\cos 55^\circ, \sin 55^\circ, 0)$, respectively. We conducted multi-species (MS) and multi-fluid (MF) MHD simulations with MAESTRO for comparison. The MS results were similar to those shown in Sakakura et al. 2022, while MF results show clear asymmetry between +E and -E hemispheres as expected. Comparison between MS and MF results show that characteristic structures such as current sheet and magnetic pile-up boundaries tend to be more smoothed in MF than in MS. The dayside boundary of the molecular ion polar plumes region in MF, the smallest SZA (solar zenith angle) in the density and flux enhancements of CO_2^+ and O_2^+ , was similar to the observation by MAVEN, while the nightside structure was different with more continuous enhancements of the molecular ion densities in the simulations than the observation. We also report on the comparison of the MF results with the plume distributions obtained from statistical trajectory tracings of molecular ions in the electromagnetic fields obtained from the MHD simulations.

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火星周回機搭載を見据えたテラヘルツ分光装置の惑星保護カテゴリ IV に対応した周波数分離フィルターの開発

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Planetary Protection Category IV-Compliant Frequency-Separation Filter for a THz Heterodyne Spectrometer for Mars Orbiter Missions

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The MACO Working Group is developing an orbiter-based investigation of Martian space weather, climate, and the water cycle to assess the persistence of potentially habitable conditions. A key objective is to measure water-vapor structure in the atmospheric boundary layer and relate it to exchanges with surface/subsurface reservoirs and to vertical coupling processes. As a candidate payload, we are studying a Terahertz Heterodyne Spectroscopy Sensor (THSS) operating in three bands (460, 560, and 890 GHz). Routing these bands within the receiver requires frequency-separating filters. Polymer-membrane filters deform under the high-temperature dry-heat sterilization required for Planetary Protection Category IV, so we are exploring femtosecond-laser patterning of metal films as a robust alternative. Electromagnetic simulations (Altair Feko) predict >25 dB rejection at 460 GHz while maintaining <0.3 dB insertion loss at 890 GHz. Ongoing work focuses on filter planarization, uniform gold deposition over laser-affected regions, and construction of a spectral test bench. We will report the concept, fabrication trials, and current performance.

MACO WG は、火星のハビタブル環境の持続性解明に向けて、周回・探査技術の実証を通じた火星の宇宙天気・気候・水環境の包括的探査を目指している。特に周回機による観測では、大気境界層における水蒸気分布の観測を通じて、地表・地下の水リザーバーと大気の相互作用や、宇宙気候・水環境に関わる大気上下結合のメカニズム解明を視野にしている。その観測パッケージの重要な候補の一つとして、テラヘルツ分光装置 (Terahertz Heterodyne Spectroscopy Sensor: THSS) が検討されている。THSS は、複数の周波数帯 (Band1: 460 GHz 帯, Band2: 890 GHz 帯, Band3: 560 帯) を用いて上記の観測を行う。この複数バンドを受信機内へ導くための周波数分離フィルターが必要となる。従来のポリマーの膜を利用したフィルターは、火星の惑星保護カテゴリ IV で求められる乾熱滅菌の高温環境下では変形してしまう。そこで本研究では、フェムト秒レーザーにより金属膜にパターンニングする手法を試している。設計は電磁波解析ツール Altair Feko を用いて、シミュレーション上ではあるが 460 GHz 帯で高反射 (<-25dB)、890GHz で低損失 (<0.3dB) の透過特性が得られている。今後の課題はこの金属フィルターの平坦化の手法の確立や、レーザーによる熱ダメージ部の金メッキの均一性の実現と、フィルターの性能評価系の構築である。本講演ではこれらの取り組み・開発の進捗について報告する。

北半球の夏の火星 H₂O₂ に関する IRTF/TEXES による新たな観測：初期解析結果

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New IRTF/TEXES Measurements of Martian H₂O₂ During Northern Summer: Preliminary Results

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Mars' atmosphere is composed of approximately 96% CO₂. Despite decades of space research, the stability of this atmosphere remains poorly understood. Ultraviolet light splits CO₂ into CO and O. However, the reverse reaction that recombines CO and O into CO₂ is very slow due to being spin-forbidden. This suggests that CO₂ should be unstable, and the composition of the Martian atmosphere should have large components of CO and O₂ (greater than 10%). However, the observed fractions of CO and O₂ are only around 0.1%. This discrepancy is commonly referred to as the “stability problem”. Theoretical studies propose that photolysis products of atmospheric water, known as “odd hydrogen” or “HOx species” (H, OH, HO₂), could participate in a catalytic cycle that regenerates CO₂ from CO. Two main pathways have been suggested: one involving HO₂ [1], and another involving H₂O₂ [2]. In both cases, OH reacts with CO, regenerating CO₂ and H, which helps stabilize the overall CO₂ composition. However, this hypothesis remains unconfirmed since the key reactive species, OH and HO₂, have never been directly observed on Mars. Additionally, theoretical models have been unable to replicate the observed long-term equilibrium mixing ratios of CO and O₂ in the Martian atmosphere. The volume mixing ratios (VMRs) of catalytic HOx species are predicted to be extremely low, around 10 ppt for OH and 1 ppb for HO₂, which places them beyond the detection capabilities of previous telescopes and space-borne instruments. Hydrogen peroxide (H₂O₂) is the only HOx-related species that has been observed, as its VMR ranges from 0 to 40 ppb. Although H₂O₂ does not directly participate in HOx catalytic cycles, it acts as a relatively stable reservoir species, being formed through the self-reaction of HO₂ and later photolyzed back into OH. As such, H₂O₂ provides an indirect but valuable constraint on HOx abundances. H₂O₂ has distinct spectral signatures in the mid-infrared and submillimeter ranges. Unfortunately, no past, current, or planned space missions have specifically targeted H₂O₂ on Mars, making its detection critically reliant on ground-based observations. H₂O₂ was first detected at a submillimeter frequency (362 GHz) using the James Clerk Maxwell Telescope (JCMT) during the southern summer on Mars [3], where a very weak H₂O₂ absorption line (~0.2%) was observed over the Martian disk, with a retrieved VMR of 18 ± 4 ppb. A subsequent attempt to detect H₂O₂ in the submillimeter range during the northern summer using the space-borne Herschel telescope was unsuccessful, yielding an upper limit of 2 ppb [4].

Measurements were conducted using the Texas Echelon Cross Echelle Spectrograph (TEXES) mounted on the NASA Infrared Telescope Facility (IRTF) [5 – 9], spanning several Martian Years. Thanks to its high spectral resolution, TEXES was able to capture the weak signatures of H₂O₂, providing a reference dataset for H₂O₂ VMRs. The TEXES data suggests significant seasonal and interannual variation, patterns that are not yet explained by current Mars climate models [e.g., 10 – 11].

In this study, we performed new observations of H₂O₂ on Mars using TEXES at the IRTF on June 12 and 13, 2025, during the northern summer season.

To measure Martian H₂O₂ absorption, we used TEXES configured to cover 1237 – 1243 cm⁻¹, enabling detection of two isolated H₂O₂ lines near 1241 cm⁻¹.

Our objective is to analyze the TEXES spectra through detailed comparison with radiative transfer calculations. Previous analyses were based primarily on equivalent widths of H₂O₂ and CO₂. The northern summer is of particular interest because past observations exist from the same season in earlier Mars years, allowing direct comparison. In addition, heterogeneous chemical reactions are expected to play an important role during this period [10]. Although, the weather conditions on June 12 were poor, successful observations were obtained on June 13. In this presentation, we will present preliminary results from our data analysis.

火星の大気は約 96% が CO₂ で構成されている。数十年にわたる研究にもかかわらず、この大気の安定性は未だ十分に解明されていない。紫外線は CO₂ を CO と O に分解する。しかし、CO と O を再結合させて CO₂ にする逆反応は、スピン禁制のため非常に遅いことが知られている。これは、CO₂ が不安定であり、火星の大気には CO と O₂ が 10% 以上含まれているはずであることを示唆している。しかし実際には、観測されている CO と O₂ の割合はわずか 0.1% 程度である。この矛盾は一般に「安定性問題」と呼ばれている。理論的研究では、大気中の水の光分解生成物である「HOx 種」(H, OH, HO₂) が、CO から CO₂ を再生する触媒サイクルに関与している可能性が提唱されている。2 つの主な経

路が提案されており、1 つは HO₂ [1]、もう 1 つは H₂O₂ [2] が関与している。どちらの場合も、OH は CO と反応して CO₂ と H を再生し、全体的な CO₂ 組成の安定化に貢献する。しかし、主要な反応性物質である OH と HO₂ は火星で直接観測されたことがないため、この仮説は未だ検証されていない。さらに、理論モデルは火星大気中の CO と O₂ の観測された長期平衡混合比を再現できていない。

触媒 HO_x の体積混合比 (VMR) は、OH で約 10 ppt、HO₂ で約 1ppb と極めて低いと予測されており、従来の望遠鏡や宇宙搭載機器の検出能力を超えている。過酸化水素 (H₂O₂) は、VMR が 0~40 ppb の範囲にあるため、観測されている唯一の HO_x 関連物質である。H₂O₂ は HO_x の触媒サイクルに直接関与することはないが、HO₂ の自己反応によって生成され、後に光分解されて OH に戻るため、比較的安定した貯蔵種として働く。そのため、H₂O₂ は HO_x の存在量に関する間接的ではあるが貴重な制約条件を提供する。H₂O₂ は、中赤外線およびサブミリ波領域で明確なスペクトル特性を示す。残念ながら、過去、現在、そして計画中の宇宙探査において、火星上の H₂O₂ を特にターゲットとしたものはなく、その検出は地上観測に大きく依存している。

H₂O₂ は、火星の南半球の夏にジェームズ・クラーク・マクスウェル望遠鏡 (JCMT) を用いてサブミリ波周波数 (362GHz) で初めて検出された [3]。このとき、火星の円盤上に非常に弱い H₂O₂ 吸収線 (約 0.2%) が観測され、取得された VMR は 18 ± 4ppb であった。その後、北半球の夏季に宇宙搭載のハーシェル望遠鏡を用いてサブミリ波帯の H₂O₂ を検出する試みが行われたが、上限値は 2ppb にとどまり、成功しなかった [4]。測定は、テキサス・エシロン・クロス・エシエル分光器 (TEXES) IRTF [5 – 9] を用いて、数火星年にわたって実施された。TEXES は高いスペクトル分解能を有していたため、H₂O₂ の微弱な特徴を捉えることができ、H₂O₂ VMR の参照データセットを提供している。TEXES データは、現在の火星気候モデルではまだ説明できない、顕著な季節変動および年々変動を示唆している [10 – 11]。

本研究では、2025 年 6 月 12 日と 13 日の北半球の夏季に、IRTf/TEXES 装置を用いて火星における H₂O₂ の新たな観測を実施した。本研究の目的は、放射伝達計算との詳細な比較を通して、TEXES スペクトルを解析することである。これまでの解析は、主に H₂O₂ と CO₂ の等価幅に基づいていた。北半球の夏は、火星の初期の同時期の観測データが存在するため、直接比較することができる。さらに、この時期には異種化学反応が重要な役割を果たしていると予想されている [10]。6 月 12 日の天候は悪かったものの、6 月 13 日に観測に成功した。火星の H₂O₂ 吸収を測定するために、1237 ~ 1243 cm⁻¹ をカバーするように構成された TEXES を使用し、1241 cm⁻¹ 付近に 2 つの孤立した H₂O₂ 線を検出した。本発表では、データ解析の初歩的な結果を紹介する。

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Mars Express/OMEGA を用いた、火星表面圧力の MY27-29 年における全球解析

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Global Analysis of Martian Surface Pressure in MY27-29 using Mars Express/OMEGA

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Understanding the dynamics of the Martian atmosphere requires continuous observations of surface pressure. Previous observations obtained by landers such as Viking, InSight, and Perseverance have significantly contributed to characterizing seasonal and diurnal variations at specific locations (e.g., Sánchez-Lavega et al., 2022; Banfield et al., 2020; Zurek et al., 1992). However, these datasets are inherently limited to point observations, making them insufficient for capturing the spatial extent and propagation of planetary-scale phenomena such as dust storms and thermal tides. To address this limitation, global and spatially distributed pressure data are essential.

In this study, we attempt to retrieve Martian surface pressure variations using orbiter data. Specifically, we employed data from the OMEGA near-infrared imaging spectrometer onboard the Mars Express. Previous studies retrieving surface pressure from remote sensing data were limited to the early Martian Year (MY) 27 (Forget et al., 2007; Spiga et al., 2007). The objective of this work is to develop a new retrieval tool capable of retrieving surface pressure rapidly and accurately, apply it to OMEGA observations since MY27, and thereby advance our understanding of the mechanisms of planetary-scale atmospheric phenomena such as thermal tides and gravity waves.

Our method combines a lookup table approach with equivalent width analysis of $2\ \mu\text{m}$ CO₂ absorption bands to balance computational efficiency with accuracy. In addition, instead of relying solely on models, we estimated dust opacity directly from the $2.77\ \mu\text{m}$ CO₂ absorption within the OMEGA observations (Kazama et al., under review), which was then incorporated into the retrieval process. Based on comparisons of repeated observations of the same region under similar conditions within three days, the relative error of our method is estimated to be $\pm 2.5\%$. This level of accuracy is sufficient for analyzing meteorological phenomena such as thermal tides, whose typical amplitude is on the order of $\sim 5\%$ (Banfield et al., 2020).

We applied this method to ~ 4000 orbits of OMEGA data with high-quality spectra (ORB0006 – 5320; late MY26 to mid-MY29) and derived the global seasonal variability of surface pressure. The retrieved pressures consistently showed global increases during northern spring and autumn and decreases during summer and winter. This behavior reflects seasonal condensation and sublimation of atmospheric CO₂ at the polar caps and is consistent with observations from multiple landers (e.g., Tillman et al., 1993).

Ongoing efforts focus on two directions: (1) the observational verification of the spatial structures of thermal tides, and (2) development of an automated detection algorithm for signatures of atmospheric gravity waves. The former will enable the first observational confirmation of spatial dependencies of thermal tides that have been predicted by GCM but remain insufficiently validated (Guzewich et al., 2015). The latter builds upon the fact that previously reported gravity wave signatures (Spiga et al., 2007) are reproducible in our pressure retrievals, suggesting that quantitative detection and statistical characterization are feasible.

In this presentation, we will discuss the details of the developed methodology and its limitations, present results on global seasonal variability, and report current progress and perspectives on the analysis of thermal tides and atmospheric gravity waves.

火星大気の力学を理解するためには、地表面圧力の観測が不可欠である。これまで Viking や InSight, Perseverance といった着陸探査機による観測は、特定の地点における季節変動や日周変動の解明に貢献してきたが、得られるのはあくまで「点」のデータに限られ、惑星規模の大気現象を把握するには不十分であった (e.g., Sánchez-Lavega et al., 2022; Banfield et al., 2020; Zurek et al., 1992)。特に、砂嵐や熱潮汐のような全球的な大気現象の空間的な広がりや伝播を理解するためには、面的かつ広域にわたる圧力データが求められる。

本研究は、この課題を克服するために、周回探査機が持つ面の観測データを活用して、火星表面圧力変動の解析を試みる。具体的には、火星周回探査機 Mars Express (MEx) に搭載された近赤外分光撮像装置 OMEGA のデータを利用した。これまでリモートセンシングから表面圧力を導出した研究は、MY27 初期を対象とする例に限られており、その適用範囲は極めて限られていた (Forget et al., 2007; Spiga et al., 2007)。本研究の目的は、高速かつ高精度に表面圧力を導出する新しいツールを開発し、それを OMEGA の MY27 以降の観測に適用して、熱潮汐波や大気重力波といった惑星規模の大気現象のメカニズムを解明することである。

地表面圧力の導出には、高速・高精度を両立させるため、ルックアップテーブルと $2\ \mu\text{m}$ の CO₂ 吸収帯の等価幅を組

み合わせた手法を用いた。また、従来はモデルに依存していたダストの影響を、OMEGA 観測内の $2.77\ \mu\text{m}$ の CO_2 吸収帯から推定 (Kazama et al., under review) し、導出プロセスに組み込むことで、より高精度な圧力導出を可能にした。短期間 (3 日以内) で取得された同一地域・同一条件の観測データの比較により、本手法の相対誤差は $\pm 2.5\%$ と推定された。この精度は、熱潮汐波の振幅 (約 5%) といった火星の気象現象の解析する上で十分である (Banfield et al., 2020)。

本手法をスペクトルが良好な OMEGA 観測期間 (ORB0006 – 5320 ; MY26 後半~MY29 中期) の約 4000 軌道に適用し、表面圧力の全球季節変動を導出した。導出された地表面圧力が、各火星年で北半球の春・秋頃に圧力が上昇し、夏・冬頃に減少することが全球にわたって確認された。これは、季節に応じた CO_2 大気極冠への凝結・昇華を反映しており、複数の着陸機による観測事実とも整合的である (Tillman et al., 1993)。

さらに現在、(1) 熱潮汐の空間構造の観測的検証、(2) 大気重力波の痕跡の自動検出アルゴリズムの開発を進めている。前者では、これまで GCM で予測されながら観測的に十分検証されてこなかった熱潮汐の空間依存性を明らかにすることが可能となる (Guzewich et al., 2015)。後者では、本研究で得られた圧力データに Spiga et al., 2007 で報告された痕跡が再現可能であることから、これを数値化することで自動検出アルゴリズムを開発できる可能性がある。

本講演では、本研究の手法の詳細とその課題について議論し、季節変動の解析結果、および熱潮汐と大気重力波の解析進捗と今後の展望について報告する。

MGS 電波掩蔽観測と MCS 気温気候値を用いた火星南半球極夜の CO₂ 過飽和に関する研究

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CO₂ supersaturation in the Martian southern polar night using MGS radio occultation rederived with MCS temperature climatology

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In the Martian polar night, the major atmospheric component, carbon dioxide (CO₂), condenses to form a polar cap on the surface, thereby depleting the atmosphere. Radio occultation (RO) observations, which provide high-vertical-resolution and precise temperature profiles, are suitable for studying CO₂ supersaturation in the polar night. However, changes in atmospheric composition associated with CO₂ condensation introduce systematic errors. In addition, RO analysis requires an assumed temperature at the uppermost altitude, and previous studies fixed this value, thus introducing additional systematic errors in temperature retrievals.

In this study, we rederived temperature profiles from Mars Global Surveyor (MGS) RO data by accounting for CO₂ depletion during the polar night and improving the temperature assumption at the uppermost altitude. The evaluation of CO₂ depletion in the polar night was based on argon measurements obtained by the Gamma Ray Spectrometer (GRS) onboard Mars Odyssey [Noguchi et al., 2014]. The upper boundary temperature assumption was refined by constructing new climatological values based on temperature measurements from the Mars Climate Sounder (MCS) onboard Mars Reconnaissance Orbiter (MRO).

Analysis of CO₂ supersaturation events in the southern polar night using the rederived temperatures revealed that CO₂ supersaturation occurred much more frequently than indicated by the original dataset, suggesting that previous studies underestimated its occurrence. CO₂ supersaturation frequently occurred south of 65° S and extended up to altitudes of about 15 km around the winter solstice. After the solstice, the vertical extent rapidly decreased, but supersaturation near the surface persisted at high latitudes. Furthermore, a cold near-surface layer remained, accompanied by a strong temperature inversion was present even after the equinox.

火星の極夜域では、大気主成分である二酸化炭素（CO₂）が凝結して地表面に極冠を形成することで、大気から失われる。高い鉛直分解能で精度の高い気温高度分布を取得可能な電波掩蔽観測は、極夜域における CO₂ 過飽和の研究に適しているが、CO₂ 凝結に伴う大気組成の変化が系統的な誤差をもたらす。さらに、電波掩蔽観測では上端高度での気温を仮定して導出する必要があり、従来の解析ではこの値を固定していたため、この点も気温導出に系統的な誤差をもたらしていた。

本研究では、極夜における CO₂ 減少の考慮と上端高度での気温仮定の改善を行い、Mars Global Surveyor (MGS) RO による気温の高度分布を再導出した。極夜における CO₂ 減少の評価には、Mars Odyssey 探査機搭載のガンマ線分光計 (GRS) によるアルゴンの測定結果を利用した [Noguchi et al., 2014]。上端高度での気温仮定の改善は、Mars Reconnaissance Orbiter (MRO) 探査機搭載の熱赤外放射計 (MCS) による気温を用いた気候値を新たに作成することで実現した。

再導出した気温を用いて南半球における極夜域の CO₂ 過飽和イベントを解析したところ、従来のデータセットで示されていたよりもはるかに高頻度で CO₂ 過飽和が発生しており、過去の研究では CO₂ 過飽和が過小評価されていた可能性が明らかとなった。また、CO₂ 過飽和は南緯 65 度以南で多く発生し、冬至の頃には過飽和域が高度 15 km 付近まで達していた。冬至後にはその厚みが急速に縮小するが、高緯度では地表面付近で持続していた。さらに、春分以降も地表付近には低温層が残存し、強い逆転層を形成していた。

電気力学天秤とラマン分光を用いた液滴内ホルムアルデヒド反応の測定

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Formaldehyde reaction measurement in a droplet with an electrodynamic balance and Raman spectroscopy

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The RNA world hypothesis is one of the leading theories regarding the origin of life. It postulates that in the early stages of life's emergence, RNA functioned as both the carrier of genetic information and a catalyst, forming the foundation of biological systems. A crucial aspect of this hypothesis is understanding how its constituent materials, such as the ribose that forms RNA, were naturally synthesized.

Formaldehyde (HCHO) is a molecule of key interest in this context. HCHO is the starting material for the formose reaction, which synthesizes sugars and could be the starting point for ribose generation. On early Earth and early Mars, it is estimated that HCHO was produced by photochemical reactions in the atmosphere, incorporated into droplets, and delivered to the oceans (Pinto et al., 1980; Koyama et al., 2024). However, HCHO is diluted by dissolving into the oceans, which would have imposed a kinetic constraint on the formose reaction. Specifically, the initial step of the formose reaction, the dimerization of two HCHO molecules to form glycolaldehyde, has a high energy barrier, resulting in an extremely slow reaction rate that acts as the rate-limiting factor for the entire process (Breslow, 1959).

To address these challenges, we have focused on atmospheric droplets as a potential reaction field. As the relative humidity of the surrounding atmosphere decreases, water evaporates from the droplets, thereby concentrating the HCHO. This highly concentrated environment could provide the opportunity to overcome the reaction barrier for glycolaldehyde formation. To test this hypothesis, we need to determine the production rate of glycolaldehyde resulting from the concentration of HCHO in droplets. We have developed a combined system that integrates an electrodynamic balance (EDB) with a Raman spectrometer. The EDB uses alternating and direct current electric fields to stably levitate a single charged droplet in mid-air. Meanwhile, Raman spectroscopy is a technique that identifies the internal chemical composition of the levitated droplet non-destructively and in real-time by irradiating it with a laser and measuring the inelastically scattered light derived from molecular vibrations. In this presentation, we report preliminary results of measurements of chemical reactions when HCHO in droplets is concentrated using these devices.

Reference:

Breslow, R. On the mechanism of the formose reaction. *Tetrahedron Lett.* 1, 22 – 26 (1959).

Koyama, S. et al. Atmospheric formaldehyde production on early Mars leading to a potential formation of bio-important molecules. *Sci. Rep.* 14, 2397 (2024).

Pinto, J. P., Gladstone, G. R. & Yung, Y. L. Photochemical production of formaldehyde in Earth's primitive atmosphere. *Science* 210, 183 – 185 (1980).

生命の起源を考える上で有力な仮説のひとつに RNA ワールド仮説がある。これは、生命が誕生する初期の段階において、RNA が遺伝子情報を担うと同時に触媒としても働き、生命システムの基盤をつくったとする考え方である。この仮説において重要なのは、RNA の骨格を構成する糖（リボース）などの材料物質が、どのように自然界で合成されたのかを理解することである。ここで注目される分子がホルムアルデヒド（HCHO）である。HCHO は糖を合成するホルモース反応の出発物質であり、リボース生成の出発点となり得る。初期地球や初期火星において、HCHO は大気中の光化学反応で生成され、液滴に取り込まれて海に供給されたと推定されている (Pinto et al., 1980, Koyama et al., 2024)。しかし、HCHO は海に溶け込むことで希釈され、ホルモース反応が進むには速度論的な制約があったと考えられる。特に、反応の初期段階で HCHO が 2 分子結合してグリコールアルデヒドを生成する過程は、高いエネルギー障壁を伴うため反応速度が極めて遅く、反応全体の律速要因となっている (Breslow 1959)。

そこで我々は、これらの課題を解決する反応場として、大気中の液滴に注目した。液滴中の水は、周囲の大気中の相対湿度の低下に伴い蒸発して、HCHO を濃集する。この高濃度環境がグリコールアルデヒドを生成する反応障壁を乗り越える契機となる可能性がある。この仮説を検証するためには、液滴における HCHO の濃集によるグリコールアルデヒドの生成速度を求める必要がある。この目的を達成するため、我々は電気力学天秤（electrodynamic balance: EDB）とラマン分光装置を組み合わせた複合システムを開発した。EDB は、交流および直流電場を用いて単一の荷電液滴を空中に安定して捕捉できる装置である。一方、ラマン分光法は、浮遊する液滴にレーザー光を照射し、分子振動に由来する非弾性散乱光を計測することで、内部の化学組成を非破壊かつリアルタイムで特定する手法である。本発表では、これらの装置を用いて液滴に溶けた HCHO を濃集した際の化学反応を測定した初期結果について報告する。

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The Observational Feasibility of Escape of Water Vapor Atmosphere from Terrestrial Exoplanets by Ultraviolet Transit Spectroscopy

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In current terrestrial exoplanet explorations, the primary targets are planets orbiting low-mass stars. Although atmospheric observations are underway to estimate the habitability of such planets, our understanding of the atmospheres remains limited due to their small radius. On the other hand, low-mass stars emit strong XUV (X-ray and extreme ultraviolet) radiation over gigayear timescales. Therefore, atmospheric escape is expected to occur due to the strong heating of the upper atmosphere by XUV radiation, even near the habitable zone where the intensity of visible and infrared radiation is comparable to that of present-day Earth. If terrestrial planets with oceans receive stellar radiation beyond the radiation limit, a water vapor atmosphere would form because of the runaway greenhouse effect. In the upper atmosphere of such planets, the photodissociation of water vapor produces hydrogen and oxygen atoms, which eventually escape. As a result, it would form an optically thick atmosphere covering the stellar disk. This causes apparent dimming during planetary transits in the hydrogen Ly- α line (121.6 nm) and OI emission lines (130.2, 130.5, 130.6 nm) due to scattering by atmospheric hydrogen and oxygen atoms. The transit depth reflects the atomic number density of the exosphere, thus allowing us to estimate the atmospheric escape rate in high XUV conditions, which is not observable in the current Solar system. The atmospheric escape rate under such XUV conditions is an important parameter for understanding the atmospheric evolution of terrestrial planets in the early solar system. Hence, observations of the upper atmosphere are expected to advance our understanding of atmospheric evolution on terrestrial planets.

Future missions with ultraviolet detectors, such as LAPYUTA (JAXA) and HWO (NASA), are expected to detect atmospheres of terrestrial exoplanets by ultraviolet transit spectroscopy. Therefore, numerical models that can capture the strong radiation pressure and photoionization, such as in environments around low-mass stars, are necessary to examine and interpret observations.

In this study, we examined the feasibility of observing the upper atmosphere in a terrestrial planet with a water vapor atmosphere using a three-dimensional particle model. This model accounts for stellar and planetary gravity, radiation pressure of atomic emission lines, and photoionization. The simulation results showed that large exospheric clouds composed of hydrogen atoms form a comet-like tail structure, observed in some hydrogen-dominant gas exoplanets, due to the high radial velocity caused by a strong hydrogen Lyman- α radiation pressure and the rapid orbital motion of planets orbiting at short intervals of several days. We also confirmed that the absorption in the blue wing and the transit duration last over several hours, which sustains for a while in the post-transit phase due to the elongated tail structure. In contrast, oxygen clouds have a compact and spherical spatial distribution because of a higher photoionization rate and the negligible effect of radiation pressure compared to hydrogen. For this reason, the transit duration is shorter than for hydrogen atoms, and the transit depth is symmetric in time with respect to the transit center. In this presentation, we will demonstrate how XUV radiation intensity, atmospheric temperature, and the strength of radiation pressure from atomic emission lines influence the structure of the atmosphere and the transit features of the hydrogen Lyman- α and O I lines. We will also discuss the feasibility of exospheric atmospheres in terrestrial exoplanets with future UV observatories.

ひさき衛星と Venus Express 同時観測の比較による金星外気圏水素の太陽風応答の解析

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Response of the Venusian hydrogen exosphere to the solar wind coordinated observations by Hisaki and Venus Express

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Observations of Ly- α emission from the hydrogen exosphere of Venus are crucial for understanding atmospheric escape mechanisms. Spacecraft observations have found that the hydrogen exosphere of Venus consists of thermal and non-thermal components. These components play an important role in thermal and non-thermal hydrogen escape, but their spatial and time variations remain unclear. Especially, response of the hot hydrogen distribution to the solar wind variations is poorly understood due to observational and analytical limitations, under which the exospheric physical quantities and their temporal variations have not been investigated separately for the thermal and non-thermal components. Disk-averaged Lyman- α observations made by Hisaki satellite in March – April 2014 revealed an $\sim 18\%$ increase in the hydrogen column density over 2 – 3 days following the arrival of high-speed solar wind streams. This increase has been interpreted as a possible enhancement of the non-thermal component caused by charge exchange reactions between ionospheric ions and thermal hydrogen in the exosphere. However, due to the low spatial resolution of Hisaki measurements, it was unclear how the spatial distribution of the atomic hydrogen density changed during this time period.

To investigate the altitude variations of hydrogen from the thermosphere to the exosphere in more detail, we analyzed limb observations obtained over ten years by the Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Venus (SPICAV) ultraviolet spectrometer onboard Venus Express. In this presentation, we focus on SPICAV observations obtained simultaneously with the Hisaki measurements and examine how the global increase in hydrogen observed by Hisaki is manifested locally and how its vertical distribution varied. The observations were made on March 16 and March 26, 2014, and the tangent point local times were 19 and 20 hours, respectively. In order to derive temperature and density from these observations, we applied forward modeling using a three-dimensional exospheric hydrogen model (Chaufray et al., 2015) combined with Monte Carlo radiative transfer calculations to separate the contributions of thermal and non-thermal components.

A comparison of the common altitude range of 500 – 2000 km between the two days shows that the Ly- α brightness on March 16 was up to twice as high as that on March 26. This difference exceeded the expected variability due to local time and solar irradiance and exhibited an opposite trend to the Hisaki results, which indicated that the integrated brightness over the dayside was higher on March 26 than on March 16.

To further investigate the observed variability by separating the hot and cold components, we first fixed the exobase temperature and varied only the density distribution in the forward modeling. In this presentation, we discuss the observational results together with the forward-modeling analyses.

金星における水素原子 Ly- α 輝線の観測は、大気散逸メカニズムの解明において重要である。金星外気圏の水素は熱的成分と非熱的成分から構成され、両者が散逸過程に寄与していることが知られている。しかし、それぞれの時空間変動は十分には理解されておらず、特に太陽風到来時における高温成分の分布変化については知見が限られている。

ひさき衛星による 2014 年 3 月～4 月の全球平均観測では、高速太陽風到来後に Ly- α 大気光から導出した水素原子柱密度が 2 – 3 日かけて約 18 % 増加する現象がみられた。この増加は、高速太陽風到来に伴い、電離圏イオンと外気圏熱的水素との電荷交換反応によって非熱的成分が増加した可能性が示唆される。しかしひさきは空間分解能が低く、この期間の水素原子の密度の空間分布の変化は明らかになっていない。

本研究では、熱圏から外気圏にかけての水素原子の高度分布変動を詳細に調査するため、10 年間に渡る Venus Express 搭載紫外線分光器 Spectroscopy for the investigation of the characteristics of the atmosphere of Venus (SPICAV) のリム観測データを解析しようとしている。本発表では、ひさき衛星観測と同時期に取得された SPICAV 観測データを解析し、ひさきがとらえた全球平均の水素原子の増加が局所的にはどのように変化したか、高度分布がどのように変化したかを検証した。

解析対象は 2014 年 3 月 16 日および 26 日の観測で、視線上のタンジェントポイントの地方時は 19 時、20 時であった。Ly- α 波長の光は光学的に厚いため、観測値から直接的に温度や密度を導出することは困難である。そこで得られた Ly- α 光の高度プロファイルに対し、Chaufray et al. (2015) に基づく三次元外気圏水素モデルとモンテカルロ放射輸送計算を用いたフォワードモデル解析を行い、熱的成分と非熱的成分の寄与を分離した。

両日の観測高度が共通する 500～2000 km の範囲で比較した結果、3 月 16 日の Ly- α 光強度は 3 月 26 日より最大

で約 2 倍高いことが明らかとなった。この差は、観測地方時や太陽放射照度の違いから予測される変動を上回るものであった。この傾向は、主に昼側全体の積分強度が、3 月 26 日の方が 3 月 16 日より明るいとしたひさき観測結果とは逆の傾向を示した。

さらに観測された大気光の変動を高温成分と低温成分に分離して調べるため、まず外気圏底の温度を固定し、密度分布のみを変化させてフォワードモデル計算を行った。本発表では観測及びフォワードモデル計算結果について議論する。

R009-P18

ポスター 3 : 11/26 PM2/PM3 (14:50-18:25)

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Formation of V0 Layer in Venus' Nightside Ionosphere Induced by SEP Events

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The V0 layer of the Venusian ionosphere is a sporadic electron-density peak detectable on both the dayside and nightside by radio occultation experiments. Based on the Venus Express Radio Science Experiment (VEx/VeRa) and the Radio Science Experiment onboard Akatsuki measurements, we find the dayside V0 peak typically near ~110 km while the nightside peak lies near ~120 km, yet the formation mechanisms of both remain unclear and nightside studies are scarce (Tripathi et al., 2024). Here, we investigate the relationship between V0 occurrence and solar activity, with emphasis on solar energetic particle events (SEPs). We quantify solar activity using fluctuations in VEx/MAG data and evaluate the association between the nightside V0 occurrences ($\text{SZA} > 110^\circ$) and magnetic-field fluctuations at 3-day and 5-day periods: a chi-square test for the 3-day period yields $p = 0.0004$, indicating a highly significant correlation, whereas the 5-day period yields $p \approx 0.05$ and is less significant. We further analyze the interval 2 – 21 March 2011, when STEREO-A was closely connected to Venus along Parker spiral, using its electron and proton fluxes to represent SEP inputs to the Particles TRansport In Planetary atmosphere (PTRIP) model (Nakamura et al., 2022) to simulate the atmospheric ionization rates, which were then fed into the Photochemical and RadiatiOn Transport Model for Extensive Use (PROTEUS) model to simulate the V0 peak altitude and electron density (Nakamura et al., 2023). The modeled peak heights and densities agree with VEx/VeRa measurements, supporting the proposition that SEPs may be a contributing mechanism for the nightside V0 formation and providing a basis for deeper investigation of Venusian ionospheric dynamics and chemistry.

R009-P19

ポスター 3 : 11/26 PM2/PM3 (14:50-18:25)

金星雲における硫酸液滴の共凝結における分岐と力学的安定性に関する研究

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Bifurcation and stability of the co-condensation dynamics of H₂SO₄-H₂O droplets in Venusian clouds

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The clouds covering Venus globally, that are primarily composed of H₂SO₄-H₂O droplets, strongly influence the thermal structure and dynamics of the atmosphere. However, the mechanism governing their growth and long-term maintenance remains poorly understood. In this study, the bifurcation structure of the droplets' growth dynamics through the co-condensation of H₂O and H₂SO₄ is investigated by constructing a box model under the assumption of a monodisperse droplet population. Our analysis reveals that the phase portrait depends on the saturation ratios of the H₂O and H₂SO₄ gases and that the mass of H₂O in the droplet varies much more rapidly than that of H₂SO₄ under conditions near the Venusian cloud base. The condition for the stable existence of Venusian cloud droplets is also investigated in terms of the saddle-node bifurcation. Based on these findings, we simulate the droplets' growth under the thermodynamic conditions near the Venusian cloud base and find that the small cloud droplets, such as Mode 1, may rapidly grow into larger ones, such as Modes 2 or 3, depending on the droplet number density.

R009-P20

ポスター 3 : 11/26 PM2/PM3 (14:50-18:25)

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Variations in the distribution of the unknown UV absorber associated with planetary-scale waves at the Venus cloud top

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The fast-rotating atmosphere of Venus, known as super-rotation, reaches velocities up to $\sim 100 \text{ m s}^{-1}$ at the cloud-top altitude ($\sim 70 \text{ km}$). Planetary-scale waves, including the ~ 5 -day Rossby wave and the ~ 4 -day Kelvin wave with zonal wavenumber 1, are observed as periodic variations in winds and temperatures. Recent general circulation model (GCM) studies [Takagi et al., 2022; 2023] demonstrated that these waves undergo alternating phases of growth and decay, which are closely linked to quasi-periodic variations of the mean zonal winds. Because planetary waves play an essential role in transporting angular momentum and heat, understanding their dynamics is key to revealing the mechanisms that maintain super-rotation and the general circulation on Venus.

Observations by Venus Express and Akatsuki revealed quasi-periodic variations of more than 20 m s^{-1} in the super-rotation, along with multi-year to decadal changes of up to 40% in cloud albedo at 365 nm [Lee et al., 2019]. These albedo variations are estimated to modulate the solar heating rate in the upper atmosphere by a factor of ~ 2 ($27 - 50 \text{ K day}^{-1}$). In addition, Akatsuki/UVI observations identified a prominent 5-day Rossby wave associated with equatorially symmetric, planetary-scale vortices [Imai et al., 2019], and showed that the growth and decay of these waves on a timescale of 2 – 3 months coincide with large ($\sim 10\%$) changes in the spatial contrast of the ultraviolet albedo.

In this study, we focus on the periods in 2017 and 2018, during which signatures of planetary waves were prominent in Akatsuki observations. We investigate how the distribution of the unidentified ultraviolet absorber at the cloud top evolved in association with the growth and decay of planetary waves. By comparing these temporal changes in detail, we aim to improve our understanding of the vertical structure of planetary waves and the three-dimensional distribution of the ultraviolet absorber in the Venus atmosphere.

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Cloud top circulation of Venus obtained from denoised thermal infrared images

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This study derives and analyzes the wind field at the Venusian cloud top using the thermal infrared images from the Long-wave Infrared Camera (LIR) onboard Japan's Akatsuki orbiter. LIR detects thermal emission in a waveband 8-12 μ m from the cloud deck of Venus on dayside and nightside with equal quality[1]. The data used spans from December 2015 to March 2024, providing substantial observations to ensure the reliability of our results.

However, the noise in the infrared images prevents further investigation of the fine-scale cloud features. To improve data quality, we first applied the Block-Matching and 3D Filtering (BM3D) algorithm to denoise the LIR images. This method suppresses noise based on the inherent non-local self-similarity within an image. The algorithm operates in two stages: grouping structurally similar 2D image patches into 3D arrays, and then collaboratively filtering these arrays in a transform domain to effectively reduce noise. This denoising process significantly enhanced fine-scale cloud structures, which is essential for the subsequent retrieval of wind fields.

With denoised LIR images, we implemented an automated cloud tracking method to estimate cloud motion vectors[2]. This approach identifies and tracks patchy cloud features between consecutive images to derive the wind velocity. We examined the cloud motion vectors with strict screening criteria to ensure the reliability of the wind field. Wind estimation errors were statistically evaluated by dividing images into odd- and even-numbered subsets, deriving wind fields independently from each, and comparing the results.

Comparing with previous studies based on the ultraviolet or near infrared imagery, this work retrieves a long-term dataset of the Venusian wind field on both dayside and nightside, offering a more complete view of the global circulation. Besides, our processing method does not rely on averaging, thereby preserving a higher temporal resolution that allows for the identification of transient features or those not moving at the speed of the background superrotation. Using this dataset, we observed and compared the wind field structures and the circulation. We further evaluated the momentum transport on the dayside and nightside, promoting our understanding of the dynamics in the Venusian atmosphere.

[1] Taguchi, M., Fukuhara, T., Imamura, T., Nakamura, M., Iwagami, N., Ueno, M., Suzuki, M., Hashimoto, G. L., and Mitsuyama, K. (2007). Longwave Infrared Camera onboard the Venus Climate Orbiter. *Advances in Space Research*, 40(6), 861-868.

[2] Ikegawa, S., & Horinouchi, T. (2016). Improved automatic estimation of winds at the cloud top of Venus using superposition of cross-correlation surfaces. *Icarus*, 271, 98-119. <https://doi.org/10.1016/j.icarus.2016.01.018>

Juno/Waves データを用いた木星狭帯域キロメートル放射 (nKOM) の出現特性解析

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Occurrence characteristics of Jovian narrowband kilometric radiation (nKOM) using Juno/Waves data

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In Jupiter's inner magnetosphere, narrowband kilometric radiation (nKOM) appears around ~100 kHz which is thought to originate in the Io plasma torus. nKOM was first detected by Voyager 1 (Kaiser & Desch, 1980) in 1979, however observing areas of past planetary explorers (such as Voyager and Galileo) were limited near the Jovian magnetic equator, preventing a comprehensive view of its occurrence properties. With Juno's polar orbit since 2016, its Waves instrument has enabled observations across the full magnetic-latitude range, revealing a distinctive nKOM source distribution: occurrence rates are low near the magnetic equator and peak at mid-latitudes (Louis et al., 2021). This distribution is closely linked to generation and beaming/propagation characteristics. Using this source distribution, Boudouma et al. (2024) built a 3-D model suggesting that nKOM is radiated by waves excited near the local plasma frequency and beamed anti-parallel to ambient density gradients. They also proposed existence of two nKOM types depending on observation latitudes; i.e., low-frequency ordinary-mode (O) at high latitudes and high-frequency extraordinary-mode (X) at low latitudes. These pictures are statistically obtained by an accumulation of about 20 Jupiter orbits in 2016 – 2019, however its long-term stability and temporal variability of nKOM occurrence remains insufficiently constrained.

The aim of this study is to determine nKOM occurrence tendencies and intensity variability over longer Juno orbital periods (6 July 2016 – 27 April 2023; ~50 perijoves) and thereby explore temporal variability of the inner magnetospheric environment. We use absolute-flux dynamic spectra from Juno/Waves calibrated by the Paris Observatory team (see Louis et al., 2021). To process seven years of observation data efficiently, we first generated daily dynamic spectra and picked up nKOM visually, then applied an automated intensity thresholding routine for observed phenomena to extract significant nKOM events. For each event we recorded start/end times and radiated intensity and compiled them, together with the spacecraft's magnetic latitude, into a catalog comprising thousands of nKOM events. In the visual step, narrowband emission within ~60 – 160 kHz was the primary criterion, while the ~10-hour (comparable to the Jovian rotation period) recurrence served only as an auxiliary indicator; events without clear periodicity were still classified as nKOM when their spectral characteristics matched.

As an initial check, intensity maps on the magnetic latitude – frequency plane reproduce the key occurrence features reported by Louis et al. (2021) — a near-equatorial depletion and a mid-latitude peak — supporting the validity of our nKOM detection approach.

Using the produced database, we are now investigating nKOM occurrence characteristics on the Juno orbital period (~53 days) and/or annual timescales. Variations in Io's volcanic activity modulate plasma supply, and plasma injection events and solar wind pressure variations also affect environment of the Jovian inner magnetosphere. nKOM occurrence would respond to these magnetospheric phenomena. The long-term nKOM event catalog assembled in this study will allow us to examine these influences quantitatively.

In the presentation, we will describe the construction of the long-term nKOM event catalog, derived variability in occurrence properties, and also discuss relations between nKOM occurrence variability and internal/external drivers of the Jovian magnetosphere.

木星の内部磁気圏には、100 kHz 付近に出現する狭帯域キロメートル波 (nKOM) と呼ばれる電波放射が存在し、その起源は衛星イオの公転軌道付近に形成されているプラズマトーラスの外縁から放射されると考えられている。nKOM は 1979 年に Voyager 1 号によって初観測されたが (Kaiser & Desch, 1980)、過去の惑星探査機 (Voyager や Galileo など) は観測者の磁気緯度が木星赤道近傍に限られ、この放射の出現特性の全体像を十分に捉えることができなかった。2016 年に木星の極軌道へ投入された Juno 探査機搭載のプラズマ波動計測器 Waves によって初めて全磁気緯度域からの観測が可能となり、nKOM の出現頻度が磁気赤道付近で低く中緯度で極大になるという特異な緯度分布が明らかにされた (Louis et al., 2021)。このような緯度分布特性は、電波の発生機構や電波の放射・伝搬特性と密接に関連している。Boudouma et al. (2024) はこの緯度分布特性を用いて、緯度分布を再現する 3 次元モデルを構築し、nKOM は局所プラズマ周波数で励起された波動が周囲の密度勾配に反平行に放射される可能性を示した。また、観測緯度に応じて 2 種類の nKOM が存在すること、即ち、高緯度では低周波・通常モード (O モード)、低緯度では高周波・異常モード (X モード) が存在し得ることを提唱している。この緯度分布特性は Juno の初期木星周回期である 2016~2019 年の約 20 周回で得られた統計的な描像であるが、nKOM の出現特性の長期的な安定性や変動性は十分には調べられていない。

本研究の目的は、Juno 探査機で得られた、より長期の観測期間 (2016 年 7 月 6 日~2023 年 4 月 27 日、約 50 周回) の

データを用いて nKOM の出現傾向および強度変動を求め、それにより木星内部磁気圏環境の時間変動の特徴を探究することである。この解析には較正処理された Juno/Waves スペクトルデータを用いた。約 7 年分の膨大な観測データを効率よく処理するため、目視識別と自動閾値処理を組み合わせ、nKOM イベントを検出した。各イベントの開始・終了時刻と放射強度、周波数を観測時の磁気緯度情報とともに蓄積し、数千件規模の nKOM イベントカタログを構築した。目視識別では、 $\sim 60 - 160$ kHz 帯で観測される狭帯域放射を nKOM の主要判定基準とした。また、約 10 時間周期（木星の自転周期にほぼ相当）で繰り返し出現する特徴を参考情報として用い、周期性が不明瞭でもスペクトル特性が合致する事例は nKOM として採用した。

初期結果として、磁気赤道近傍の低出現域と中緯度付近の高出現率域という Louis et al. (2021) と同様の特徴が再現され、本検出手法の有効性が確認できた。

現在、作成したデータベースを用いて Juno の木星周回周期単位（約 53 日）での nKOM 出現特性を求めつつある。nKOM 出現の緯度依存性には、イオの火山活動変化に伴う内部磁気圏へのプラズマ供給・注入変動の影響が現れることが想定される。また、その出現頻度には、木星磁気圏のプラズマインジェクションや太陽風動圧変動が関わるものが想定される。本研究で構築した長期モニタリングデータによりそれらが検証されることが期待される。

講演では、本研究で行っている nKOM の長期イベントカタログの構築と得られた nKOM 出現特性変動の紹介、および、nKOM 変動と木星磁気圏変動の磁気圏内・外変動因との関係について議論を行う予定である。

R009-P23

ポスター 3 : 11/26 PM2/PM3 (14:50-18:25)

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New Compact Low-Frequency Radio Observatory LWA-Niyodo

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The low-frequency radio observatories at frequencies below 100 MHz are widely distributed around the world, and some of them operate the daily observations of natural radio emissions from the Sun and Jupiter. Monitoring the low-frequency radio emissions requires three equally separated observatories around the world. While most of the low-frequency radio observatories are located in Europe and the US, there are fewer of the observatories in Japan. We built a new compact low-frequency radio observatory located in Niyodogawa-cho, Kochi, Japan. The observatory called LWA-Niyodo consists of eight bow-tie antennas (originally designed for the Long Wavelength Array station One in New Mexico, US), in which each antenna receives two perpendicular linearly polarized radio waves. Currently, these signals are combined into two channels using two 8-to-1 analog combiners. With two independent receivers of the Software Defined Radios (SDRs) and Raspberry Pi systems, we have operated the daily observations since March 2024. This receiver is based on Jupiter's radio receiver onboard the KOSEN-1 CubeSat. In this presentation, we report the detailed specifications of the LWA-Niyodo and highlight some early observations.

惑星雷の発生機構に関する一考察 — 起き上がりこぼし理論・近接双極子電子リレー理論・双極子直列電池理論・結合静電容量減少理論に基づく比較 —

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Planetary Lightning -Based on the Roly-Poly, the Dipole Proximity Electron Relay, the Dipole Series Battery, Capacitance-Decrease-

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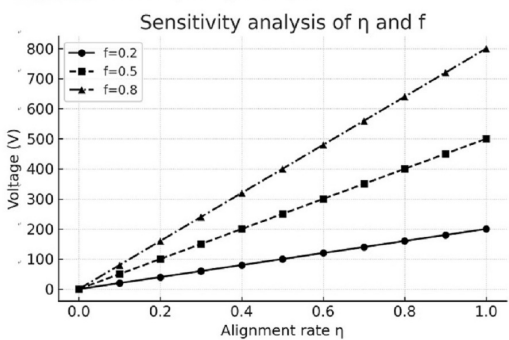
Lightning has been observed not only on Earth but also on Jupiter, Saturn, Uranus, Neptune, and possibly Venus. The conventional collisional charging theory, which assumes charge separation through collisions of ice particles or droplets, cannot fully explain volcanic lightning, planetary lightning, or blue-sky discharges. This study integrates four mechanisms: (1) the Acceleration-Rectified Dipole Alignment (ARDA), (2) the Dipole Proximity Electron Relay theory, (3) the Dipole Series Battery theory, and (4) the Capacitance-Decrease Mechanism. The ARDA explains how molecular alignment is rectified by asymmetry between mass and charge centers under external acceleration. the Dipole Proximity Electron Relay theory explains how electrons propagate domino-like between adjacent dipoles, forming discharge pathways. The Dipole Series Battery describes how aligned dipoles add their moments to form a potential difference ($\Delta V = \alpha \times E \times d$). Additionally, The Capacitance-Decrease Mechanism shows how growth of ice particles reduces capacitance, leading to voltage amplification. Comparative analysis indicates that on Earth, aligned water vapor initiates charge layers in thunderclouds, while ice growth and capacitance decrease trigger discharges. On Jupiter and Saturn, extensive alignment occurs within deep water – ammonia clouds, where alignment distances of tens to hundreds of kilometers allow much stronger potential differences than terrestrial lightning. On Venus, however, the CO₂-rich atmosphere and sulfuric acid clouds provide few dipolar molecules or ice particles, so lightning is limited to localized regions. Sensitivity analysis with alignment rate η and dipole fraction f shows that higher values sharply increase $V - I$ characteristics and reduce the required number of ice particles N . Thus, in ice-rich environments such as Jupiter, capacitance decrease strongly accelerates reaching the discharge threshold, whereas in ice-poor Venus, this trigger is absent. The integrated model is consistent with observations from the Juno and Cassini missions and offers a unified framework for planetary lightning. Future work will involve parameter identification from spacecraft data and simultaneous measurement of alignment, dipole fraction, and particle number.

雷は地球のみならず、木星・土星・天王星・海王星などのガス惑星や金星の大気中でも観測されている。従来の衝突帯電説は氷粒や水滴の衝突を前提とするが、火山雷や惑星雷、青天の霹靂などを十分に説明できない。本研究では、①起き上がりこぼし理論（ARDA）、②近接双極子電子リレー理論、③双極子直列電池理論、④結合静電容量減少理論の四理論を統合し、惑星大気における雷発生モデルを検討する。起き上がりこぼし理論は分子の重心と電荷中心の非対称性により、外力下で整列が整流される機構を示す。近接双極子電子リレー理論は、隣接分子間で電子がドミノ的に伝搬し、放電経路を形成する機構を説明する。双極子直列電池理論は整列分子のモーメント加算により空間電位差 $\Delta V = \alpha \times E \times d$ を生じ、結合静電容量減少理論は氷粒や液滴の成長で容量が低下し電位差が増幅される。比較の結果、地球では積乱雲下層で水蒸気整列が起点となり、氷粒帯電と容量減少が加わって放電に至る。木星や土星では深い水雲やアンモニア雲で広範な整列が生じ、整列距離が数十～百 km に達し、地球雷を超える電位差形成が可能となる。一方、金星は二酸化炭素主体で雲頂は硫酸液滴に覆われ、水分子や氷粒が乏しく、雷は局所的に限定される。また、整列率 η と双極子成分比 f を変化させた感度分析により、 η や f が高いほど $V - I$ 特性が急増し、必要氷粒数 N は減少することが示された。木星のように氷粒供給が豊富な環境では容量減少効果が強く作用し、短時間で放電閾値に達する。金星のように氷粒形成が困難な場合、このトリガーが働かず雷活動は限定的である。本モデルは Juno 探査機やカッシーニ探査機の観測結果と整合し、従来説では説明困難な惑星雷の統一的理解を可能にする。今後は探査機データに基づくパラメータ同定と、整列率・双極子比・氷粒数の同時計測が重要である。

Figure 1. Planetary atmospheric comparison

Planet	Main components	Pressure (bar)	Temperature (K)	Main dipole molecules	Acceleration sources
Earth	N ₂ , O ₂ , H ₂ O	1	288	H ₂ O	Convection, storms
Venus	CO ₂ , H ₂ SO ₄	90	730	H ₂ SO ₄ (weak)	Thermal convection
Jupiter	H ₂ , He, H ₂ O, NH ₃	1-10	110-160	H ₂ O, NH ₃	Strong convection, planetary waves
Saturn	H ₂ , He, NH ₃ , H ₂ O	1-10	90-140	H ₂ O, NH ₃	Strong convection
Uranus	H ₂ , He, CH ₄ , NH ₃	1-10	60-80	NH ₃ , CH ₄	Convection, rotation
Neptune	H ₂ , He, CH ₄	1-10	60-80	CH ₄ (weak)	Convection, rotation

Figure 2. Sensitivity analysis of η and f



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Radio instrument of Radio and Plasma Wave Instruments (RPWI) aboard ESA JUICE: from Launch, via Lunar-Earth, toward Venus

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This paper provides initial status of Radio & Plasma Wave Investigation (RPWI) aboard Jupiter ICy moons Explorer (JUICE), from the view for its high frequency radio observation capability in 80k – 45MHz.

The high frequency part of this system, i.e., Preamp of RWI and its High Frequency Receiver (HF), is procured by the RPWI team in Austria, France, Japan, Poland, and Sweden. This part enables the characterization of Jovian radio emissions (including gonio-polarimetry), passive radio sounding of the ionospheric densities of icy moons, and passive sub-surface radar measurements. It has an enough capability to detect Jovian radio emissions from magnetosphere (aurora etc.), atmosphere (lightning), and icy moons. Direction and polarization capabilities are first enabled in the Jovian system, to identify their source locations and characteristics.

After the launch on April 14, 2023, the RPWI did the deployment of our antennas. Although it had to wait due to a problem happened with the RIME antenna, all deployments were successfully completed in May 2023. However, immediately after that, we started the life struggling with the spacecraft noise. As a result, new onboard software with the noise reduction function was uploaded in January 2024.

The spacecraft succeeded to do the Lunar-Earth Gravity Assist (LEGA) operation in August 2024. It was the unique opportunity to observe "an airless body" before real icy moons flybys in 2030s. Associated with this observation chance, we executed (1) AKR occultation test for sensing the moons' thin ionospheres, (2) AKR reflection test for sensing the moons' surface and subsurface, (3) AKR polarization measurement test for separating and investigating Jovian northern & southern radio sources, (4) flux calibration test with Solar radio burst comparing the Wind, Parker Solar Probe, Solar Orbiter etc.

Recently, JUICE was passed Venus in August 2025. Next flybys are Earth I (September 2026) and Earth II (January 2029). Arrival to Jupiter will be in July 2031.

This paper reviews those activities in 2023-2025. We also summarize the plans with the proved performances for Jupiter and icy moons in 2030s.

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A test particle simulation for re-evaluation the energy input into the Saturn's atmosphere by keV electrons

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Saturn's inner magnetosphere is dominated by water group neutrals originating from Enceladus, which are a major cause of plasma loss. Our previous studies focused on electron loss mechanisms through elastic collisions with these water molecules, estimating the loss rate and energy input into the atmosphere for electrons with energies ranging from 500 eV to 50 keV. However, the peak energy of this electron energy input remained elusive. These results demonstrated the necessity of constructing a model for the elastic scattering cross sections that depend on electron energy. We re-calculate the keV electrons using a test particle simulation [Tadokoro and Katoh, 2014]. We will show these results.

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UV space telescope LAPYUTA: overview of the mission instruments and development updates

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The Life-environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly (LAPYUTA) mission aims to carry out spectroscopy with a large effective area ($>300\text{ cm}^2$) and a high spatial resolution (0.1 arc-sec) and imaging in far ultraviolet spectral range (110-190 nm) from a space telescope. The main part of the science payload is a Cassegrain-type telescope with a 60 cm-diameter primary mirror. As a current design, three main UV instruments are installed on the focal plane of the telescope: a mid-dispersion spectrograph, a high-dispersion spectrograph, and a slit imager. The mid-dispersion spectrograph contains a movable slit with different slit width, a holographic toroidal grating with 2110 lines/mm, and an MCP detector coupled with CMOS imaging sensors. Spectral resolution of 0.02 nm and field-of-view of 100 arc-sec will be achieved. The high-dispersion spectrograph consists of a slit, a toroidal mirror, an echelle grating, a cross disperser, and a detector. Highest spectral resolution of 3 pm will be achieved at the target wavelength (130.5 nm). The UV slit imager consists of imaging optics, several bandpass filters with a rotation wheel, and a same type of UV detector as the one installed in the spectrometer. In order to achieve a high spatial resolution of 0.1 arc-sec, we will install a target monitoring camera at 0th order position inside the spectrometer and slit imager for both attitude control and image accumulation process. We also plan to install a fine guidance sensor to monitor guidance stars. In addition, new key technologies such as funnel-type MCPs and CMOS-coupled readout system and highly reflective UV coatings will be applied to satisfy requirements of LAPYUTA. We have demonstrated performance of prototype models and samples of such key components. These key technologies can be applied to the future international flagship missions such as Habitable Worlds Observatory. Here we present the LAPYUTA concept design, the overview of the mission instruments, and the updated status of key technology developments.

LAPYUTA 搭載に向けた大型高感度紫外線検出器の開発

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Development of a large, high-sensitivity ultraviolet detector for installation on LAPYUTA

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Ultraviolet observation is a powerful tool of remotely monitoring planetary upper atmospheres, exospheres, and plasma environments. The Spectroscopic Planet Observatory Satellite “Hisaki” (SPRINT-A) is the world’s first space telescope mission dedicated to planetary observation and it has successfully captured the spatial and temporal variations in Jupiter’s Io plasma torus and the upper atmospheres of Mars and Venus. However, due to limitations in sensitivity and spatial resolution, it has been difficult to observe the spatial structure of the atmospheres of Mars and Venus, small bodies such as moons of Jupiter, and exoplanet atmospheres.

As a next-generation mission, the Life-environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly (LAPYUTA) aims to explore habitable environments and investigate the origin of matter and space in the universe, which were not achieved by Hisaki. Ultraviolet mission instruments consist of a Cassegrain telescope with a 60 cm primary mirror ($F = 2.5$), two ultraviolet spectrographs (a medium-resolution spectrograph MRS and a high-resolution spectrograph HRS), and an ultraviolet slit imager UVSI. To achieve LAPYUTA’s scientific objectives, the MRS must have an effective area of 350 cm^2 , a wavelength range of $110 - 190 \text{ nm}$, a wavelength resolution of 0.02 nm , and a spatial resolution of 0.1 arcseconds.

The detector is a particularly key component for the MRS instrument. To satisfy the required specifications, a large and high-sensitivity detector with an effective area of $120 \text{ mm} \times 30 \text{ mm}$ is needed while maintaining the conventional position resolution ($15 \text{ } \mu\text{m}$). The detector consists of microchannel plates (MCP) with a CsI photocathode, a fiber optics plate (FOP) with a phosphor screen, and a CMOS sensor readout. In order to increase quantum efficiency, funnel-type MCP has been developed in recent years. Since funnel-type MCP has a tapered shape for the channel input, the aperture ratio can be increased from approximately 60% in standard type to around 90%, achieving higher quantum efficiency. While funnel-type MCPs with diameters of 18 mm or $53 \text{ mm} \times 53 \text{ mm}$ have been developed, the large size of 120 mm required for MRS has not been achieved yet. This scaling up process raises concerns about mechanical issues such as reduced strength and bending, as well as performance issues like non-uniformity in quantum efficiency and gain within the effective area.

Therefore, this study aims to manufacture a prototype of a funnel-type MCP detector with the maximum size ($80 \text{ mm} \times 80 \text{ mm}$) that can be achieved using current equipment and to verify its functionality and evaluate its performance. The prototyped detector consists of funnel-type MCPs (3 stages) with a CsI photocathode and a FOP with a phosphor screen, assembled on a vacuum flange. After verifying the functionality of the prototype, we varied the high voltage applied to the MCP and measured the voltage dependence of the pulse height distribution. Additionally, monochromatic light was irradiated at different positions within the effective area to measure the in-plane uniformity of quantum efficiency and gain at each wavelength.

The large and high-sensitivity detector being developed in this study is not useful only for LAPYUTA. It is one of key technologies that can be applied to NASA’s flagship mission, Habitable Worlds Observatory (HWO), which is scheduled to be launched in the 2040s.

紫外線観測は、惑星上層大気や外圏大気、プラズマ環境などの遠隔監視を可能とする手段として有用である。世界初の惑星観測に特化した宇宙望遠鏡である惑星分光観測衛星「ひさき」では、木星イオプラズマトーラスや火星・金星上層大気の時空間変化を捉えることに成功した。しかし、感度と空間分解能の制約から火星・金星大気の空間構造を分解した観測や、木星衛星のような小天体の観測、および系外惑星大気の観測は困難であった。

次世代計画である惑星科学、生命圏科学、および天文学に向けた紫外線宇宙望遠鏡計画 Life-environmentology, Astronomy, and Planetary Ultraviolet Telescope Assembly (LAPYUTA) では、「ひさき」では実現できなかった、生命存在可能環境の探求と宇宙の構造および物質の起源の理解を科学目標としている。そのためには高感度化・高空間分解能化の技術開発が重要となる。

LAPYUTA は、口径 60 cm の主鏡 ($F = 2.5$) をもつカセグレン式望遠鏡と、2 台の紫外線分光器 (中分散分光器 MRS と高分散分光器 HRS)、及び紫外線スリットイメージャ UVSI で構成される。このうち MRS の要求仕様は、有効面積 350 cm^2 、波長範囲 $110 \sim 190 \text{ nm}$ 、波長分解能 0.02 nm 、空間分解能 0.1 秒角である。要求される仕様を満たすために

は、特にキーとなる開発課題が検出器である。従来の位置分解能（15 μ m）を保ちつつ 120 mm $\times$ 30 mm の大型かつ高感度の検出器が必要となる。検出器は CsI 光電面付マイクロチャンネルプレート（MCP）、蛍光面付ファイバーオプティクスプレート（FOP）、CMOS センサ読み出し部から構成される。検出器の高感度化の手段として、近年ファネル型 MCP の要素開発が進められてきた。ファネル型 MCP は、入力側がテーパ形状に改良されたもので、チャンネル入口の開口率を標準品の 60% 程度から 90 %ほどまで向上させ、より高効率で光電子を電子増倍部に取り込むことができる。これまで、 ϕ 18 mm や 53 mm $\times$ 53 mm のファネル型 MCP の開発例はあるが、MRS で要求される 120 mm までの大型化には至っていない。変形や湾曲などを引き起こす機械的強度の課題や、有効面内における量子効率・ゲインの非一様性など性能の課題が残る。

そこで本研究では、現行の製造装置で製作することのできる最大サイズである 80 mm $\times$ 80 mm のファネル型 MCP を試作し、機能の検証と性能の評価を行うことを目的とする。試作した検出器は CsI 光電面付のファネル型 MCP（3 段）と蛍光面付 FOP で構成され、真空フランジ上に組み上げられている。試作機の機能検証を行ったのちに、MCP への印加電圧を変化させ、波高分布の電圧依存性を測定した。また単色光を有効面内の異なる位置に入射し、各波長における量子効率及びゲインの面内一様性を測定した。

本研究で開発を進める大型高感度検出器は 2040 年代の実現を目指す NASA の紫外線可視近赤外線望遠鏡 Habitable Worlds Observatory（HWO）でも応用可能な技術であり、その波及効果は計り知れない。本試作機の評価結果を踏まえ、今後は LOPYUTA で要求される 120 mm $\times$ 30 mm の大型ファネル MCP の試作、評価に向けて検討・開発を進める。