R009-01
B 会場 ：11/6　AM1 （9:00-10:30）
09:00〜09:15

#村上　豪 [1)],Benkhoff Johannes[2)]
([1]JAXA/ISAS,([2]ESA

Updated status of BepiColombo and initial reports on Mercury flyby observations

#Go Murakami[1)], Johannes Benkhoff[2)]
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The ESA-JAXA joint mission BepiColombo is now on the track to Mercury. After the successful launch of the two spacecraft for BepiColombo, Mio (Mercury Magnetospheric Orbiter: MMO) and Mercury Planetary Orbiter (MPO), commissioning operations of the spacecraft and their science payloads were completed. BepiColombo will arrive at Mercury in the end of 2025, and it has 7-years cruise with the heliocentric distance range of 0.3-1.2 AU. The long cruise phase also includes 9 planetary flybys: once at the Earth, twice at Venus, and 6 times at Mercury. The first and second Mercury flybys were completed on 1 October 2021 and 23 June 2022, respectively. In both flybys the closest approach altitudes were ˜200km at the southern hemisphere. We performed science observations with almost all the instruments onboard Mio for about +-24 h from the closest approach. Especially the MPPE instrument successfully observed low energy ions and electrons simultaneously in the Mercury's magnetosphere first time ever. Here we present the updated status of BepiColombo mission, initial results of the science observations during the Mercury flybys, and the upcoming observation plans.

R009-02
B 会場 ：11/6　AM1 （9:00-10:30）
09:15〜09:30

#相澤　紗絵 [1)], 原田　裕己 [2)],Andre Nicolas[3)], 齋藤　義文 [4)],Sauvaud Jean-Andre[3)],Fedorov Andrei[3)], 横田　勝一郎 [5)], 三宅　亙 [6)],Barthe Alain[3)],Penou Emmanuel[3)],Rojo Mathias[3)], 村上　豪 [7)]
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Low-energy plasmas observed by MEA and MIA onboard Mio/BepiColombo during its second Mercury flyby

#Sae Aizawa[1)], Yuki Harada[2)], Nicolas Andre[3)], Yoshifumi Saito[4)], Jean-Andre Sauvaud[3)], Andrei Fedorov[3)], Shoichiro Yokota[5)], Wataru Miyake[6)], Alain Barthe[3)], Emmanuel Penou[3)], Mathias Rojo[3)], Go Murakami[7)]
([1]ISAS/UniPi,[2]Kyoto Univ.,[3]IRAP, Toulouse, France,[4]ISAS,[5]Osaka Univ.,[6]Tokai Univ.,[7]ISAS/JAXA

BepiColombo was launched in October 2018 and is currently en route to Mercury. Although its orbit insertion is planned for December 2025, BepiColombo will acquire new measurements during planetary flybys. During the cruise and planetary flyby phase, the two spacecraft are docked together with Mio being protected behind the MOSIF sun shield. Thus, only partial observations of plasma distribution functions can be obtained by the Mercury Plasma Particle Experiment (MPPE) onboard Mio. However, the Mercury Electron Analyzer (MEA) and the Mercury Ion Analyzer (MIA) of MPPE will provide us with new and unique measurements of low-energy plasma. Combining two instruments, we will present the observations obtained by MEA and MIA onboard Mio/BepiColombo during its second Mercury flyby that happened on the 23rd of June, 2022. In particular, we will focus on the properties of the low-energy plasma populations and inverted-V structures observed during its crossing of Mercury's magnetosphere.

R009-03
B 会場 ：11/6　AM1 （9:00-10:30）
09:30〜09:45

無水鉱物への水素イオン照射実験による水星表層における太陽風起源 H_2O 生成過程の解明

#北野　智大 [1)], 木村　智樹 [1)], 大槻　美沙子 [1)], 星野　亮 [1)], 仲内　悠祐 [2)]
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Water molecule creation by the solar wind on Mercury's surface modeled by the hydrogen irradiation to the anhydrous mineral

#Tomohiro Kitano[1)], Tomoki Kimura[1)], Misako Otsuki[1)], Ryo Hoshino[1)], Yusuke Nakauchi[2)]
([1]Tokyo Univ. of Science,[2]JAXA

At Mercury and Moon, water molecules are created from surface minerals through the thermal and non-thermal chemical processes driven by the solar photon and solar wind irradiations. Recent studies suggest that the water ice in the polar regions at Mercury based on the neutron spectroscopies onboard spacecraft (Lawrence et al., 2013) and at Moon based on the infrared spectroscopies onboard spacecraft (Li et al., 2018). Although the source of polar ice is still unknown, the recent numerical simulations of water transport on Mercury(Jones et al., 2020) suggested the water creation process by the solar wind hydrogen irradiation to the surface material as a potential source of polar ice. However, the water creation process on the surface by the solar wind hydrogen irradiation has not yet been directly demonstrated by neither the observations nor experiment. This study demonstrates the water creation from Mercury's surface material by the solar wind based on the hydrogen ion and electron irradiation experiments to an anhydrous silicate mineral, Enstatite, which is a candidate for Mercury's surface material. The hydrogen ion and electron were irradiated with a flux of 1e+14-1e+15/cm2/s for about 1e+4s, corresponding to a fluence of 1e+18-1e+19/cm2. Temporally stable water vapor release was confirmed only during the hydrogen ion irradiation. Reflectance spectrum of the irradiated sample suggests that water vapor was more efficiently released from the sample when electrons were irradiated after hydrogens. Yield of water molecules by the hydrogen ion irradiation after removing the water originally adsorbed on the sample is estimated to be 0.14-0.16/incident ion. If we assume that the water molecules are uniformly released from Mercury's day-side hemisphere, the estimated yield of 0.14-0.16/incident ion corresponds to a water creation rate of 5.2-5.6e+6 kg/year. With the rate of the ice accumulation to the surface water creation from the surface estimated by the water transfer simulation in the Jones et al. (2020), the total amount of ice accumulated on Mercury surface through 3 billion years is estimated to be 1.6-1.7e+14kg from our experiment. This is a significant amount compared to the estimation of 1e+14-1e+15 kg by the radar observations in the previous studies (Eke et al., 2017; Deutsch et al., 2018; Susorney et al., 2019), which suggests that the water creation by the solar wind irradiation is an essential source process of the polar ice on Mercury surface.

水星や月において、表層の鉱物は太陽光や太陽風の照射による熱的、非熱的な化学過程を経て、水分子を生成する。探査機搭載の中性子分光計や赤外分光器の観測に基づいた近年の研究によって、水星や月の極域での水氷の存在が示唆されている (Lawrence et al., 2013; Li et al., 2018)。その起源は未解明であるが、水星表面では太陽風水素イオン照射による表層鉱物における水生成が有力な候補であることが、近年の水輸送の数値シミュレーションから示唆された (Jones et al.,2020)。しかし、太陽風プラズマの組成（電子、陽子）やエネルギー（keV 帯）の条件を満たしたプラズマ照射による、表層鉱物の水生成過程は観測的・実験的には未実証である。本研究は水星表層組成に類似した無水ケイ酸塩鉱物である Enstatite 試料への水素イオン、電子照射実験に基づき、太陽風による水星表層の水生成の実証を試みた。水素イオンや電子を、1e+14 − 1e+15/cm2/s の flux、1e+18 − 1e+19/cm2 の fluence で照射したところ、水素照射時のみ長時間 (約 1e+4s) 安定してサンプルからの水分子の放出が確認された。また、サンプルの反射スペクトル分析から電子を水素の後に照射すると、より効率よくサンプルから水分子が放出されることが確認された。サンプルに元々付着していた水の影響が無い時間帯において、水素イオン照射に対する水分子の yield を見積もった結果、0.14-0.16/incident ion と推定された。昼側の水星半球から水分子が 0.14-0.16/incident ion で一様に放出されると仮定すると、5.2-5.6e+6kg/year の水生成率に相当する。Jones et al. (2020) の水輸送シミュレーションにおける水の生成に対する氷の堆積効率と、本実験で得られた水生成率に基づき、水星表層に堆積する氷の総量を見積もると、30 億年で 1.6 − 1.7e+14 kg になることが示唆された。これは先行研究のレーダー観測に基づく推定総量 1e+14-1e+15kg(Eke et al., 2017; Deutsch et al., 2018; Susorney et al., 2019) と比較して、有意な量である。この結果から、太陽風照射による水生成が極域氷の供給過程として有力であることが示唆される。

R009-04
B 会場 ：11/6　AM1 （9:00-10:30）
09:45〜10:00

#笠羽　康正 [1)], 小嶋　浩嗣 [2)], 栗田　怜 [2)], 八木谷　聡 [3)], 尾崎　光紀 [3)], 笠原　禎也 [3)], 松田　昇也 [3)], 土屋　史紀 [1)], 三澤　浩昭 [1)], 熊本　篤志 [1)], 木村　智樹 [4)], 北　元 [5)], 北原　理弘 [1)], 堺　正太朗 [1)], 安田　陸人 [1)], 三好　由純 [6)],BepiColombo　PWI team[1)],JUICE　RPWI team[1)]
[(1] 東北大・理,[(2] 京大・生存圏,[(3] 金沢大,[(4] 東京理大,[(5] 東北工大,[(6] 名大 ISEE

Mercury Flybys of BepiColombo/Mio PWI and Prelaunch of JUICE RPWI: Collaborations with Europe

#Yasumasa Kasaba[1)], Hirotsugu Kojima[2)], Satoshi Kurita[2)], Satoshi Yagitani[3)], Mitsunori Ozaki[3)], Yoshiya Kasahara[3)], Shoya Matsuda[3)], Fuminori Tsuchiya[1)], Hiroaki Misawa[1)], Atsushi Kumamoto[1)], Tomoki Kimura[4)], Hajime Kita[5)], Masahiro Kitahara[1)], Shotaro Sakai[1)], Rikuto Yasuda[1)], Yoshizumi Miyoshi[6)], PWI Team BepiColombo Mio[1)], RPWI Team JUICE[1)]
[(1]Tohoku Univ.,[(2]RISH, Kyoto Univ.,[(3]Kanazawa Univ.,[(4]Tokyo Sci. Univ.,[(5]Tohoku Inst. Tech.,[(6]ISEE, Nagoya Univ.

In electromagnetic waves and electron sensing, we are now running two major collaborations with Europe. The first is Plasma Wave Investigation (PWI) aboard the Mio spacecraft in BepiColombo, ESA-JAXA joint mission to Mercury, which was launched in 2018 and will observe Mercury on the orbit from the end of 2025. The second is Radio and Plasma Wave Investigations (RPWI) aboard ESA JUpiter ICy moons Explorer (JUICE) mission to Jupiter, which will be launched in 2024 (next year) and will observe Jovian system on the orbit from 2032. In both Japan and Europe, main players are overlapped and collaborating strongly in both missions and beyond.

In this presentation, we show (1) the latest status of BepiColombo/Mio PWI, focusing to recent two Mercury flybys, and (2) the prelaunch status of JUICE RPWI, focusing to the feasibility studies and the calibration plans. Other collaborations may also be introduced if those proposals will go on the track.

The PWI aboard the BepiColombo Mio will enable the first observations of electric fields, plasma waves, and radio waves in and around the Hermean magnetosphere and exosphere. After full deployment of all sensors following insertion into Mercury orbit at the end of 2025, the PWI will start its real measurements in the electric field from DC to 10 MHz along the spin plane and in the magnetic field from 0.3 Hz to 20 kHz in three-axis and from 2.5 kHz to 640 kHz in one-axis, with similar performance of Arase PWE which is now investigating Geospace.

During the cruising phase, unfortunately, long wire antennas (15-m x 4) for electric fields and the solid boom (4.5-m) for magnetic fields are not yet deployed. In this restricted configuration, we observed Hermean electromagnetic waves during the 1st fly-by in October 2021 and the 2nd fly-by in June 2022. In both flybys, we saw (1) the magnetic turbulences in several kHz in the dawn side magnetosphere after the closest approach, and (2) electric turbulences around the electron plasma density. For next flyby planned in June 2023, we are investigating our capability and try to detect better data including the waveforms.

The RPWI abord JUICE will provide an elaborate suite for electromagnetic fields and plasma environment around Jupiter and icy moons, with 4 Langmuir probes (LP-PWI; 3-axis E-field -1.6 MHz, and cold plasmas), a search coil magnetometer (SCM; 3-axis B-field -20 kHz), and a tri-dipole antenna system (RWI; 3-axis E-field 0.08-45 MHz, 2.5-m tip-to-tip length). RPWI Japan team mainly contributes to the high frequency part of this system, i.e., Preamp of RWI and its High Frequency Receiver (HF).

We will show the performance and operation concepts with their feasibilities, including the test and emulation results on the ground, planned activities in commissioning and cruise phases, and the full observations around Jupiter and icy moon system. It has been confirmed that this system has high sensitivity reaching close to the galactic background enough for the detection of 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.

The most key parts is the sensing of the ionospheres, surface, and subsurface of icy moons during the flybys and on the orbit around Ganymede. Our 'High frequency part of RPWI' can do unique remote observations of the ionospheres below the spacecraft orbit by the radio occultation and reflection of Jovian radio signals, It has a capability to detect the ionospheric density not only in usual status but also episodic plume ejections triggered by expected crustal activities. The sensing of surface and subsurfaces are more challenging topics, based on the passive subsurface radar (PSSR) concept which sounds the icy crusts of Galilean satellites by the reflections of penetrated Jovian radio emissions (HOM/DAM).

R009-05
B 会場 ：11/6　AM1 （9:00-10:30）
10:00〜10:15

Comet Interceptor に搭載するイオン分析器の検出器の開発

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([1] 東京大学,[2] 大阪大学,[3] 宇宙科学研究所,[4] 名古屋大学

Development of detector for ion analyzer to be installed in Comet Interceptor

#Ryo Tao[1)], Emiko Yoshida[1)], Satoshi Kasahara[1)], Shoichiro Yokota[2)], Yoshifumi Saito[3)], Kazushi Asamura[3)], Masafumi Hirahara[4)]
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Comet explorations have been conducted in the past, but there has been no direct exploration of any long-period comet. Long-period comets are thought to have originated in Oort's cloud and are likely to retain primordial features from the early stages of solar system formation. Understanding these are expected to provide important clues to the origin of the solar system. The Comet Interceptor Mission, jointly planned by ESA and JAXA, is a mission to directly explore long-period comets or interstellar objects. The Comet Interceptor is scheduled to be launched in 2029 with the scientific goals of characterizing the surface composition, shape, composition of comets, and composition of coma. A breadboard model of the ion analyzer, one of the observation instruments to be installed in the Comet Interceptor, was tested for its performance. The ion analyzer consists of an electrostatic energy analyzer in the front and an ion mass analyzer in the back. Ions and electrons that pass through the analyzer are finally multiplied by the microchannel plates at the bottom and detected at the anode. Since the signal generated during detection is subject to noise, it is important that the signal pulse heights should be high relative to the noises. In this study, two types of substrates were prepared: (1) a substrate with a ground pattern on the backside of the anode, mainly to shield external noises, and (2) a substrate without a ground pattern in the center corresponding to the detection location on the backside of the anode, mainly to prevent attenuation of the signal pulse heights, and were compared through ion measurements in a laboratory vacuum chamber. As a result, it was found that both substrates were able to detect the signals as required, and that the signal pulse heights tended to be higher for the substrate (2), while there was not much change in the noise level. Specifically, the sensitivity to detect the signal pulse heights greater than 10 mV was increased by up to 30% for (2). For this reason, we decided to adopt (2) as the nominal substrate for the Comet Interceptor mission.

過去に彗星探査は行われてきたが、彗星の中でも長周期彗星を直接探査した例はない。長周期彗星の起源はオールトの雲にあると考えられており、太陽系形成初期の始原的な特徴を留めている可能性が高い。これを理解することは、太陽系の起源を知る上で重要な手がかりとなることが期待される。ESA と JAXA が共同で計画している Comet Interceptor Mission は、長周期彗星 (Long-period comet) あるいは恒星間天体 (Interstellar object) を直接探査するミッションである。彗星探査機 Comet Interceptor は、彗星の表面組成、形状、構成、コマの組成などの特性評価することを科学目標に掲げ、2029 年に飛翔体を打ち上げ予定である。この Comet Interceptor に搭載する観測機器の一つであるイオン分析器のブレッド・ボード・モデルについて、その性能試験を行った。イオン分析器は前部が静電エネルギー分析器、後部がイオン質量分析器からなり、分析器内部を通過したイオンや電子が最終的に底部のマイクロチャンネルプレートで増倍され、アノードにて検出される仕組みである。検出時に発生する信号にはノイズが乗るため、信号の波高がノイズに対して高いことが重要である。そこで本研究では、(1) 外来ノイズをシールドすることに主眼を置きアノード裏面にグラウンドパターンを配置した基板と、(2) 信号波高を減衰させないことに主眼を置いてアノード裏面の検出位置に対応する中央部にはグラウンドパターンを配置しない基板の 2 種類を用意し、実験室の真空槽でイオン計測による比較を行った。その結果、両者とも必要な信号を検出できていること、(2) の基板の方が信号の波高が高くなる傾向があり、一方でノイズレベルにはそれほどの変化は無いことなどがわかった。具体的には 10mV 以上の波高を検出する感度が、(2) の方が最大 30% 上昇した。このため、Comet Interceptor ミッションでは (2) をノミナル基板として採用することとした。

R009-06
B 会場 ：11/6　AM1 （9:00-10:30）
10:15〜10:30

彗星のコマ中のライマンα線の放射輝度分布に対する原子間衝突および多重散乱の寄与

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Contribution of interatomic collisions and multiple scattering to the distribution of Lyman alpha emission in comets' comae

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Comets are important in understanding the material balance of current and past planets.

Water production rate from comets' nuclei has been evaluated using a variety of instruments including Hisaki, a Japanese satellite. In case of observations using ultraviolet light, water production rate is generally evaluated through the comparison of the observations of the distribution of Lyman-α emission and kinetic model of hydrogen atoms generated by the photo-dissociation of water molecules in comae. However, dynamics of hydrogen atoms in comae near nuclei has not been understood well especially for long period comets with large water production rate.

In this study, we obtained the spatial distribution of Lyman-α emission through the analysis of spectroscopic data of long period comets such as C/2013 US_{10} (Catalina) observed by Hisaki. Model of Lyman-α emission distribution considering interatomic collisions and photons' multiple scattering was also constructed. Comparing them revealed following three results.

(1) Without considering interatomic collisions and multiple scattering, model and observations are inconsistent below the altitude of about 10^4 – 10^5 km.

(2) In case of water production rate similar to that of Comet Catalina (~10^{29} /s), interatomic collisions have little impact on the density distribution of hydrogen at higher altitude.

(3) In case of water production rate similar to that of Comet Catalina (~10^{29} /s), multiple scattering suppresses radiance of Lyman-α emission below the altitude of about 10^4 km.

Based on these results, in the evaluation of water production rate from observations of Lyman-α emission, multiple scattering is necessary to be considered for comets with larger water production rate such as Comet Catalina. Besides, multiple scattering possibly enhances apparent D/H ratio around nuclei since deuterium's Lyman-α is optically thin even if hydrogen's Lyman-α is optically thick.

In this talk, we discuss the contribution of interatomic collisions and multiple scattering in comets' comae through the comparison of observations by Hisaki satellite and model calculation on the distribution of Lyman-α emission in comae.

彗星は現在および過去の惑星の物質収支を理解する上で重要な存在である。

これまでに、日本のひさき衛星を含む様々な観測機器によって、彗星の核からの水放出率が求められてきた。紫外線による観測の場合、水の光解離によって生成された水素の放出するライマンα線の放射輝度分布を観測し、水素原子の運動モデルを介して水分子の核からの放出率を推定するのが一般的である。しかし、水放出率が大きい長周期彗星については核付近の観測データに乏しく、彗星大気中での水素の運動の理解が進んでいない。

本研究では、まずひさき衛星による C/2013 US_{10} (Catalina) などの長周期彗星の分光観測データの解析を行い、コマ中のライマンα線の放射輝度分布を得た。続いて、原子同士の衝突および光子の多重散乱を考慮したコマ中のライマンα線の放射輝度の空間分布のモデルを構築した。これらの比較により、以下の 3 つの結果が得られた。

(1) 原子間衝突および多重散乱を考慮していない場合、高度 10^4 – 10^5 km 以下ではモデルの計算結果が観測結果と大きく乖離する

(2) Catalina 彗星程度の水放出率（10^{29} /s 程度）の場合、原子間衝突が高高度の水素の密度分布に与える影響は小さい

(3) Catalina 彗星程度の水放出率（10^{29} /s 程度）の場合、多重散乱により 10^4 km 以下のライマンα線の放射輝度が抑制される

これらを踏まえると、紫外線によるライマンα線の観測から水放出率を推定する際、Catalina 彗星のように水放出率の比較的大きい彗星については、多重散乱の考慮が必要である。また、水素原子のライマンα線が光学的に厚い場合でも重水素のライマンα線は光学的に薄いため、多重散乱によって核付近では D/H 比が見かけ上増加することが分かる。

本発表では、彗星コマ中のライマンα線の放射輝度分布に関するひさき衛星の観測結果とモデル計算の比較から、彗星コマ中での原子間衝突および多重散乱効果の寄与について議論する。

R009-07
B 会場 ：11/6　AM2 （10:45-12:30）
10:45〜11:00

月面からの光電子とオージェ電子放出モデルの開発

#加藤　正久 [1)], 原田　裕己 [1)],Xu　Shaosui[2)],Poppe　Andrew[2)],Halekas　Jasper S.[3)], 三宅　洋平 [4)], 臼井　英之 [5)], 西野　真木 [6)], 松本　徹 [7)]
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Development of an emission model of photoelectrons and Auger electrons from the lunar surface

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Since the Moon does not possess its intrinsic and global magnetic field and dense atmosphere, charged particles directly interact with the lunar surface. On the dayside of the Moon, photoelectrons and Auger electrons are emitted from the surface by solar irradiation. The emitted electrons travel along the magnetic field line. Therefore, the photoelectrons and the Auger electrons are both thought to be observed above the lunar surface and were indeed reported from ARTEMIS observations by Xu et al. (2021).

The Auger electrons have intrinsic energies characteristic of the emitting element, suggesting that detailed measurements of their energy distributions could provide valuable information on the composition and electrostatic potential of the lunar surface. However, we cannot investigate their energy distributions in detail from present observations because the energy resolutions of Electrostatic Analyzer (ESA) onboard ARTEMIS are not sufficiently high to capture the spectral shapes and energy shifts of the Auger electrons. To properly interpret the limited observations, we develop a simple model of lunar photoelectrons and Auger electrons energy spectra based on the flux of solar irradiation, the chemical composition of the lunar surface, and photoionization cross sections of the elements derived from theoretical formula. We report a present state of model development and comparison between our model and ARTEMIS observations near the sunlit lunar surface.

月は固有の全球的磁場と、濃い大気を持たない天体であるため、荷電粒子が月面と直接相互作用をする。月面の昼側では、太陽放射によって表面から光電子とオージェ電子が放出されている。これらの放出された電子は磁力線に沿って運動を行う。このため、放出された光電子とオージェ電子は月面上空で観測されると考えられ、実際に ARTEMIS 探査機による観測が Xu et al. (2021) によって報告されている。

オージェ電子は放出源となる原子に応じた特徴的なエネルギーを持つため、これらのエネルギー分布の詳細な観測が行えれば、表面組成や月面電位についての貴重な情報を与える可能性がある。しかしながら、現在の観測ではエネルギー分布について詳細に調べることは困難である。これは、ARTEMIS 探査機に搭載されている静電分析器 (ESA) のエネルギー分解能がスペクトル形状とオージェ電子のエネルギー変化を捉えるのには不十分であるためである。この限られた観測を適切に解釈するために、我々は月の光電子とオージェ電子のエネルギースペクトルについての簡単なモデルを開発した。このモデルは太陽放射フラックスと月面の化学組成、そして理論的な式から得られる各原子の光電離断面積のデータに基づくものである。今回、我々はこのモデル開発の現状と、我々のモデルと月面昼側付近での ARTEMIS 観測との比較について報告する。

R009-08
B 会場 ：11/6　AM2 （10:45-12:30）
11:00〜11:15

月面の凹凸に起因する非従来型帯電現象に関するプラズマ粒子シミュレーション

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Plasma Particle Simulations on the Unconventional Surface Charging Associated with Lunar Surface Irregularities

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On the surface of a solid celestial body with a thin atmosphere, such as the Moon, space plasma such as solar wind and sunlight fall directly on the surface, creating an electrostatic environment near the surface along with the accumulation of electric charge on the celestial body surface due to colliding plasma and the generation of photoelectrons by the photoelectric effect. Orbital observations by lunar explorers have suggested that the lunar diurnal surface is positively charged. In general, space plasma has the ability to negatively charge solid surfaces, and it has been believed that electron emission processes such as the photoelectric effect are essential to maintain the lunar surface at a positive floating potential. On the other hand, the lunar surface has various spatial-scale irregularities ranging from topographic features such as craters, vertical holes, and boulders to rock and regolith layers. Several simulation results have shown that these irregularities limit free plasma motion in space and create a specific electrostatic environment depending on the surface topography. Similar to these topographic-scale surface features, microcavities formed by rocks and regolith particles at smaller scales are also interesting targets in terms of mass transport by electrostatic energy. At such spatial scales, the inadequate ability of Debye shielding generates a stronger electrostatic field, which is considered to be one of the key factors in the mobilization and suspension of charged regolith particles.

In this study, a simulation was conducted assuming a situation in which solar wind plasma pours down from the sky onto the lunar surface, which has a cavity of equal or smaller size than the Debye length, and the effects of the stenosis and expansion of the cavity interior on the electrostatic environment, including variations in the electric potential distribution and charged particle flux distribution, were analyzed. As a result, it was found that the solar wind plasma flow forms a positive potential in a simple rectangular cavity and can positively charge the cavity up to several hundred volts, which is equivalent to the kinetic energy of ion particles, as the width-depth ratio of the cavity increases. The present study was conducted to quantitatively evaluate the effect of a more detailed cavity geometry that takes into account the curvature of the cavity interior on the charging process.

In this presentation, we will mainly report on the changes in the electrostatic environment due to the cavity interior geometry and the formation of a current path for the relaxation of the cavity interior potential by photoelectrons generated by the photoelectric effect, which were obtained from the above simulation results. After that, we will report on the future prospects of this study, including the applicability of the results of this study to a small spatial scale model of the Moon and the numerical method that we are currently working on in order to perform simulation analysis for the small model.

月を始めとする大気が希薄な固体天体表面では、太陽風などの宇宙プラズマや太陽光が直接降り注ぎ、衝突プラズマによる天体表面への電荷の蓄積や光電効果による光電子の発生とともに表面近傍での静電気環境を形成する。月探査機による軌道上観測では月昼側表面は正に帯電していることが示唆されてきた。一般に宇宙プラズマは固体表面を負に帯電させる能力を持っており、月面を正の浮遊電位に保つためには光電効果などの電子放出過程が不可欠であると考えられてきた。一方、月面はクレーターや縦孔、ボルダーなどの地形から岩石・レゴリス層にいたるまで様々な空間スケールの凹凸を持つ。こうした凹凸は宇宙空間中の自由なプラズマ運動を制限し、表面形状により特有の静電気環境を作り出すことがいくつかのシミュレーション結果によって明らかにされている。こうした地形スケールの表面形状と同様に、より小さいスケールの岩石やレゴリス粒子により形成される微小空洞も静電エネルギーによる物質輸送の観点において興味深い対象である。このような空間スケールでは、デバイ遮蔽の能力が不十分なためより強い静電場が発生し、これが荷電したレゴリス粒子の動員と浮遊の重要な要因の一つであると考えられている。

本研究では、デバイ長と同等かそれより小さい空洞を有する月面に対し、上空から太陽風プラズマが降り注ぐ状況を想定しシミュレーションを実施し、空洞内部の窄み・広がりが電位や荷電粒子フラックス分布の変動などを含む静電気環境へもたらす影響についての解析を行った。その結果、太陽風プラズマ流は単純な直方体空洞内に正電位を形成し、空洞の幅深さ比の増大に伴いイオン粒子の運動エネルギーと同程度の数 100V まで正に帯電させ得ることが判明した。また、空洞内部の窄み・広がりを考慮したより詳細な空洞形状が持つ帯電過程への影響を定量的に評価することを目的とし解析を行った。

本発表では、主に上述のシミュレーション結果から得られた空洞内部形状による静電気環境の変化及び光電効果により発生する光電子による空洞内部電位の緩和電流路の形成について報告する。その後、本研究結果の月面の微小な空間スケールモデルへの適用可能性と微小モデルを対象とするシミュレーション解析を実行するため現在取り組んでいる数値計算手法を含む、本研究の今後の展望について報告する。

R009-09
B 会場 ：11/6　AM2 （10:45-12:30）
11:15〜11:30

硫酸塩へのプラズマ照射実験によるエウロパ表層物質の内部海起源説の検証

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Verification of the endogenic hypothesis for Europa's surface materials by the oxygen ion and electron irradiation experiment

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Jupiter's icy moon Europa likely has the interior water ocean beneath the icy shell. The chemical composition of the interior ocean is the most important problem to be solved for assessing the interior ocean's habitability. Sulfur is one of the possible major constituent elements of Europa's surface materials. Two hypotheses have been proposed for the source of sulfur: the sulfates plumed from the interior ocean [Kargel et al., 2000], or the sulfur ion originating from the volcanic gasses plumed from the moon Io [Alvarellos et al., 2008]. The surface materials are suggested to be chemically altered continuously by irradiation of high-energy plasma from Jupiter's magnetosphere, which drives the radiolytic cycles between several sulfur compounds [Carlson et al., 2002]. Because such cycles prohibit understanding the source of surface sulfur, neither the endogenic nor exogenic hypotheses have been demonstrated yet. This study verifies the endogenic hypothesis for Europa's surface sulfur by modeling the radiolytic sulfur cycles based on the laboratory experiment. Oxygen ions and electrons were irradiated to the magnesium sulfate ($MgSO_4$) sample, which is a possible candidate for the constituents of the surface and interior ocean of Europa. We confirmed that some sulfur compounds such as octasulfur (S_8), sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) were newly synthesized from $MgSO_4$. This result successfully demonstrates the radiolytic sulfur cycle on Europa's surface. Numerical simulation for time variation of surface chemical composition was made with the production rates of each sulfur compound estimated by our experiments. The depletion time of $MgSO_4$ was found to be 3.3e+05 years for the oxygen irradiation and 3.3e+03 years for the electron irradiation. Assuming the simultaneous irradiation of oxygen ions and electrons to model the actual Europa's surface environment, the total depletion time of $MgSO_4$ is estimated to be 8.8e+02 years, and the total amount of S_8, SO_2, and H_2S produced in the depletion time to be 17.0%, 42.7% and 40.3% respectively of the original $MgSO_4$. The lifetime of ˜1.0e+03 years is sufficiently shorter than Europa's average surface age of ˜1e+07 years estimated by the creator chronology. Therefore, the endogenic sulfate is suggested to be depleted by the plasma irradiation before it is turned over by the geological processes. In the previous studies, the infrared observations suggested the sulfate and sulfuric acid hydrate in the geological units that likely have active plumes [Carlson et al., 2009]. If the sulfate is present in the units, it suggests that the seawater from the interior ocean containing the endogenic sulfate was supplied to Europa's surface within the last 1e+03 years, and the supplied sulfate has survived without depletion while been involved in the radiolytic sulfur cycles. We are going to conduct the irradiation experiment for sulfur allotrope and H_2O icy samples to verify the endogenic and exogenic hypotheses.

木星の氷衛星エウロパは氷地殻の下に内部海を持つとされる。内部海の化学組成の理解はハビタビリティ解明の上で最重要の課題である。エウロパ表層物質の主要元素の一つである硫黄は、内部海起源の硫酸塩として供給される説 [Kargel et al., 2000] と、イオの火山ガス起源の硫黄イオンとして木星磁気圏から供給される説 [Alvarellos et al., 2008] の 2 つの仮説が提案されている。木星磁気圏からの高エネルギープラズマの照射により表層物質は化学組成の変化を繰り返し、硫黄を含んだ特定の物質間を循環するサイクルを形成すると示唆されている [Carlson et al., 2002]。この繰り返される化学変化により起源の解明は阻まれており、内部海起源説と外部起源説はいずれも未検証である。そこで本研究ではエウロパ表層や内部海の構成物質の候補の 1 つである硫酸マグネシウム ($MgSO_4$) への酸素イオンと電子の照射により表層での化学サイクルを実験室で再現し、内部海起源説の検証に取り組んだ。実験の結果、$MgSO_4$ から新たに S_8 等の硫黄同素体、二酸化硫黄 (SO_2)、硫化水素 (H_2S) が生成されることが判明し、初めてエウロパ表層の硫黄化学サイクルを実験的に再現することができた。実験で得られた各物質の生成率から $MgSO_4$ が枯渇するまでの時間を数値シミュレーションしたところ、酸素イオン照射では 3.3e+5 年、電子照射では 3.3e+3 年と見積もられた。実際のエウロパ環境を想定し、電子と酸素イオンの同時照射による $MgSO_4$ の枯渇年数をシミュレーションした結果 8.8e+2 年と見積もられ、また枯渇までに生成された S_8, SO_2, H_2S の総量は硫黄原子の個数比でもとの $MgSO_4$ の 17.0%, 42.7%, 40.3% であった。この 1e+3 年というライフタイムはクレーター年代学等で示唆されているエウロパの平均表層年代 1e+7 年よりも十分短く、内部海起源の硫酸塩は表層の地質学的プロセスで更新されるより先にプラズマ照射によって枯渇すると考えられる。先行研究では探査機赤外観測によって、水噴出が活発と思われる一部の地形に硫酸塩や硫酸の水和物の存在が示唆されている [Carlson et al., 2009]。仮にこの地形に硫酸塩が存在しているとすると、この地形では˜1e+3 年以内に海水噴出等により硫酸塩が内部海から表層へ供給され、化学サイクルを経験しつつも枯渇せずに生存していることを示唆している。今後は硫黄同素体を母物質とする照射実験や化学組成のシミュレーションによってさらに内部起源説を検証する。また氷表層へ降り込んだ

イオ起源の硫黄を想定した照射実験による外部起源説を検証することでエウロパ上の硫黄の起源解明に取り組む。

R009-10
B 会場 ：11/6　AM2 （10:45-12:30）
11:30〜11:45

望遠鏡観測と室内実験による木星衛星エウロパ表面 NaCl の起源の検討

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Examination of the origin of NaCl on the surface of Jupiter's moon Europa by telescope observation and laboratory experiments

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The Hubble Space Telescope (HST) observed a geyser due to a mantle plume on Jupiter's moon Europa [Roth et al., 2014]. Hypothetically, geysers contain material from the inner sea that is suggested to exist under Europa's ice shell,If the materials ejected by geysers are deposited on the ground surface, it is possible to estimate the composition of the internal sea materials from the survey of the surface material composition. So far, HST observations have shown absorption of light with a wavelength of 460 nm due to lattice defects (color centers) that occur on the Europa surface when NaCl receives radiation. The presence of NaCl at the ground surface was suggested [Trumbo et al., 2019]. However, absorption near 720 nm, which is the absorption wavelength of other color centers, has not been confirmed. In addition, observations by HST are limited to four times in four months, and long-term time variations of uptake on an annual basis that indicate new NaCl deposition have not been investigated. Therefore, the sedimentary age for examining the origin of NaCl is unknown. In this study, using the spectral imager MSI mounted on the Pirka telescope with a primary mirror diameter of 1.6 m owned by Hokkaido University, continuous broadband (up to 400-1,100 nm) observations were carried out on an annual basis and the reflection of Europa was observed. By investigating the temporal variation of the spectrum, we will clarify the age of NaCl deposition on Europa's surface. The method uses the results of electron beam irradiation experiments on NaCl in an environment that reproduces the surface of Europa [Poston et al., 2017], and uses the observed time variations in absorption at 460 nm and 720 nm to determine how long it has been since NaCl was irradiated with electron beams.

In this study, observation of Europa started in August 2020, and the band width between 400-550 nm and 650-800 nm is 3.90-10.2 nm, and 650-800 nm is 4.17-7.62 nm. , a total of 18 images were taken at intervals of 10 nm between the center wavelengths. Absorbance was confirmed at 430 nm and 520 nm when the absorption dip was evaluated. Also, no absorption was confirmed near 720 nm.

To interpret this result, a high-energy electron beam irradiation experiment was conducted at Hokkaido University LINAC on February 14, 2022, about 1000 times higher than the previous research. As a result, absorption was confirmed at 460 nm, but the attenuation of absorption that occurs after irradiation, which has been confirmed in previous studies, was not confirmed.

These results suggest that the results observed this time are not the absorption of the NaCl color center, but the Sun's Fraunhofer lines, and further analysis is required.

ハッブル宇宙望遠鏡 (HST) により、木星衛星エウロパにはマントルプルームによる間欠泉が観測された [Roth et al., 2014]。仮に、エウロパ氷殻下に存在が示唆される内部海の物質が間欠泉に含まれ、間欠泉により噴出した物質が地表面に堆積しているとすると、地表面物質組成の調査から、内部海物質組成の推定が可能である。これまで、HST の観測によって、エウロパ表面には NaCl が放射線を受けることによって生じる格子欠陥 (カラーセンター) による波長 460 nm の光の吸収が観測されたことから、地表面における NaCl の存在が示唆された [Trumbo et al., 2019]。しかし、その他のカラーセンターの吸収波長である 720 nm 付近の吸収は確認されていない。また HST による観測は 4 か月間に 4 回と限られており、新たな NaCl の堆積を示すような、年単位の長期的な吸収の時間変動は調べられていない。そのため、NaCl の起源を検討するための堆積年代が不明である。本研究では、北海道大学が所有する主鏡口径 1.6 m のピリカ望遠鏡に搭載されているスペクトル撮像装置 MSI を用い、広帯域（最大で 400 − 1,100 nm）における年単位の継続観測を行い、エウロパの反射スペクトルの時間変動を調査することで、エウロパ表面の NaCl が堆積した年代を明らかにする。方法はエウロパ表面を再現した環境での NaCl への電子線照射実験 [Poston et al., 2017] の結果を用いて、観測した 460 nm と 720 nm の吸収の時間変動から NaCl が電子線に照射され始めてどのくらいの期間が経過しているかを求める。

本研究では 2020 年 8 月からエウロパの観測を開始し、400 − 550 nm および 650 − 800 nm の間を、バンド幅が 400 − 550 nm は 3.90 − 10.2 nm、650 − 800 nm は 4.17 − 7.62 nm、中心波長の間隔 10 nm で計 18 回撮像を行った。吸収の凹みを評価したところ、430 nm と 520 nm に吸収が確認された。また、720 nm 付近に吸収は確認されなかった。

この結果の解釈のため、2022 年 2 月 14 日に北海道大学 LINAC にて、先行研究の約 1000 倍の高エネルギー電子線照

射実験を行った。結果として、460 nm に吸収が確認されたが、先行研究では確認されている照射後に起こる吸収の減衰は確認されなかった。

　これらの結果から、今回観測された結果は NaCl のカラーセンターの吸収ではなく、太陽のフラウンホーファー線ということが考えられ、さらなる解析が必要である。

R009-11
B 会場 ：11/6　AM2 （10:45-12:30）
11:45〜12:00

塩化ナトリウムへのプラズマ照射実験と物理化学モデリングによるエウロパの希薄大気生成と表層組成の解明

#星野　亮 [1)], 木村　智樹 [1)], 大槻　美沙子 [1)], 北野　智大 [1)], 仲内　悠祐 [4)], 土屋　史紀 [2)], 木村　淳 [3)]
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Europa's surface composition uncovered by the plasma irradiation experiment for NaCl samples

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Jupiter's icy moon Europa potentially has the interior water ocean with the habitable environment for life. Elemental and molecular compositions of Europa's surface materials tell us that of the interior ocean because the materials may be transported between the ocean and surface. Europa's surface materials are continuously irradiated with Jovian plasmas, UV, and micrometeorites from the space. The irradiated energy drives the space weathering process. In particular, Jovian plasmas are dominant energy sources of the space weathering at Europa. Europa's materials are sputtered from the surface by the plasma irradiation and create the tenuous atmosphere. The residual unsputtered surface material may change in the elemental and molecular compositions by the irradiation. However, since this process comprises complex physics and chemistries that are hard to theoretically estimate, it has been a big unsolved problem to quantitatively associate the tenuous atmosphere with the surface compositions accompanying the space weathering.

Here we present the laboratory experiment that quantitatively associates the tenuous atmospheric sputtering with the surface composition at Europa for the first time. We also measured the number of the sputtered Na and Cl particles by the mass spectrometer during the irradiation experiment. We irradiated energetic H2+,O2+ ions and electrons at 10 keV with a fluence of 5e+18 /cm^2 to NaCl samples to model the sputtering by Jupiter's plasma irradiation to Europa's surface materials. We found that the electron more efficiently sputters Europa's surface than the ions under Europa's environment. For example, the total Na production rate by the hydrogen and oxygen ion irradiations is estimated to be 1.1e+6 /cm^2/s, while that by the electron irradiation is to be 2.7e+5 /cm^2/s. We also found that the yield of Cl (8.7e-1 ejected particles/incident particle) is greater than that of Na (2.8e-2 ejected particles/incident particle). These results suggest that the surface NaCl is decomposed predominantly by the electron irradiation and forms the resultant tenuous atmosphere, while on Europa's surface Na is concentrated more effectively than Cl because of the small volatility of Na.

We estimated the column density of Europa's Na atmosphere by our 0-dimensional atmospheric model with constraints on the sputtering yield obtained by our irradiation experiment. The estimated column density is found to be comparable with that estimated by the ground-based telescope observation of Na atmosphere (Brown and Hill 1996), which corresponds to the total Na atmospheric mass of 770 kg.

Our Na atmospheric model assumed 100% NaCl on Europa's surface. The estimated column density is consistent with the ground-based observational one, which suggests a high concentration of NaCl on Europa's surface. The interior ocean brain is likely concentrated during the upwelling process or by the space weathering after geysering to the surface.

We are going to conduct the experiment of H_2^+, O_2^+, Ar^+ ions and electron irradiations to the icy sample that comprises NaCl and H_2O at about 100 K to model a more realistic surface environment at Europa. Our irradiated samples will be compared with the previous spacecraft and telescope observations to uncover the surface and interior ocean compositions.

木星の氷衛星であるエウロパは、内部海を持つことから生命の存在可能性が示唆されている天体の 1 つである。その内部海と表層の間では水や塩などの物質の輸送が行われている可能性があり、エウロパ表層の物質組成等の理解は内部海環境の理解につながる。エウロパでは、宇宙空間からのプラズマや紫外線などが表層物質に照射され、宇宙風化が起こる。木星氷衛星で宇宙風化の主要因とされるプラズマは表層でスパッタリングを引き起こし、それにより弾き出された粒子はエウロパの希薄大気を生成する一方、表層物質の組成は変化すると考えられる。しかし、その一連の生成過程は物理・化学的に複雑で、プラズマスパッタリングによる希薄大気生成と表層風化に伴う組成の変化について、定量的な関連付けは未だなされていない。

そこで、本研究では、エウロパ表層候補物質である NaCl に H_2^+,O_2^+ , 電子を同条件 (10 keV, 5e+18 個/cm^2) で照射し、初めてエウロパ環境におけるスパッタリングと表層物質の組成変化を再現した。また、照射中に NaCl からスパッタされた Na と Cl の粒子数を質量分析器で測定した。その結果、エウロパ環境下ではイオンに比べ、電子の方が効率的にスパッタリングを起こすことが明らかになった。例えば、水素イオンと酸素イオンの照射による Na 大気の生成率の合計が 2.7e+5 個/cm^2/s である一方、電子照射による生成率は 1.1e+6 個/cm^2/s であった。また、Cl 原子は Na 原子よりも効率的にスパッタリングされることがわかった。例えば、水素イオンと酸素イオンの照射による Na 大気の yield の合計は 2.8e-2 ejected particles/incident particle であり、同照射による Cl 大気の生成率は 8.7e-1 ejected particles/incident particle であった。上記より、エウロパ環境下では、NaCl が主に電子照射により解離し希薄大気を生成するが、Na よりも Cl が

効率よく揮発することで Na が表層に濃縮されることが示唆された。

実験で得た Na の yield を制約条件とした 0 次元大気モデリングに基づき、エウロパ Na 大気の柱密度を見積もった結果、Na 希薄大気の地上望遠鏡観測による柱密度の見積もり [Brown and Hill,1996] と同程度になった。この柱密度は 770 kg の大気総量に相当する。我々の Na 大気モデリングが表層の Na 濃度を 100% を前提として行っており、それが地上観測結果と整合していることから、実際のエウロパ表層で NaCl が高濃度で存在することを示唆する。NaCl を含む海水が、内部海から表層に湧昇する過程、もしくは表層へ噴出したあとの宇宙風化により濃縮されている可能性がある。

今後は、エウロパ表層温度下 (約 100 K) で、NaCl と水の氷を混ぜた、より実環境に近いサンプルに対して H_2^+,O_2^+, Ar^+ , 電子照射を行い、Na 大気密度および表層 NaCl 濃度を推定する。また、照射後サンプルのスペクトルと探査機や望遠鏡で観測した表層スペクトルとの比較により、表層と内部海物質の組成を推定する。

R009-12
B 会場 ：11/6　AM2 （10:45-12:30）
12:00〜12:15

#安田　陸人 [1)], 木村　智樹 [2)], 三澤　浩昭 [1)], 土屋　史紀 [3)], 佐藤　晋之祐 [4)], 堺　正太朗 [5)], 熊本　篤志 [3)], 笠羽　康正 [6)],Cecconi　Baptiste[7)],Louis　Corentin[8)],Zarka　P.[9)]
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Numerical radar simulation for the explorations of the ionospheres of Jupiter's icy moons

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Jupiter's icy moons such as Europa and Ganymede may harbor subsurface liquid water oceans. While only Earth has the ocean on the surface in the current solar system, multiple icy bodies like the icy moons of giant planets have oceans in their subsurface under the icy crust. So, the icy bodies are potentially more universal habitable environment than the Earth-type bodies. The icy bodies' ionospheres include essential information for understanding the habitable environments because the ionospheres are formed as a result of the crusts' weathering and putative water plumes from the subsurface oceans. Especially, the ionospheric structures and time variability reflect the activity of the crusts and oceans. However, the structures are still unclear because the ionospheric radio occultation and other effective explorations have difficulties of limited observing opportunities. So, we have been trying to uncover the structures by radar exploration, which will be connected to the explorations with the Radio & Plasma Wave Investigation (RPWI) and the Radar for Icy Moon Exploration (RIME) onboard the Jupiter ICy moons Explorer (JUICE). For future investigations of radio wave sounding with RPWI and RIME ranging in tens KHz to tens MHz, we have developed a numerical simulation code that models the propagation of electromagnetic (EM) waves and emulated occultation of the Jovian radio waves by the icy moon's ionosphere during the flybys of the Galileo spacecraft to Jupiter's icy moons. Here, we show the vertical ionospheric profiles using our numerical simulation code. We found that the maximum electron density is estimated at ˜50 /cc in lower latitudes of Ganymede's trailing hemisphere and ˜150 /cc in higher latitudes of the leading hemisphere. We argue that these results reflect surface weathering due to magnetospheric particle bombardment. In this presentation, we will also indicate the ionospheric profiles of Europa and Callisto and discuss the generation processes of the profiles. As the next step, we plan to simulate the reflection and transmission of the EM waves in the icy crust and underlying ocean. By combining this new simulation with our current one for the ionospheres, the icy moon's ionospheric and subsurface structures are expected to be elucidated. These simulations would also give constraints on the pressure and temperature of the subsurface, which finally lead to deep understandings of the icy moon's habitability.

R009-13
B 会場 ：11/6　AM2 （10:45-12:30）
12:15〜12:30

#Imai Masafumi[1)],Kurth William[2)],Kolmasova Ivana[3)],Santolik Ondrej[3)],Wong Michael[4,5)],Brown Shannon[6)],Hospodarsky George[2)],Bolton Scott[7)],Levin Steven[6)]
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Global distribution of Jovian ionospheric holes associated with Jupiter lightning

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The polar perijove passes of Juno provide a unique opportunity to monitor Jovian lightning. One of the lightning-induced electromagnetic waves is a group of dispersed millisecond pulses called Jupiter dispersed pulses (JDPs), observed at frequencies below 150 kHz. During the course of Juno perijoves through 33 orbits, we collected over four thousand snapshots including one or more JDPs recorded by the radio and plasma wave (Waves) instrument. Assuming that JDPs propagate in the free left-hand ordinary (L-O) mode, we proposed an O mode propagation model in which low-density plasma irregularities are located between Juno and lightning strokes. These irregularities directly connect to ionospheric holes with densities below 250 cm^{-3}. Hence, observing JDPs gives a useful tool to identify low density holes in the Jovian ionosphere. Also, we compare the JDP locations with the cloud features captured by the Hubble Space Telescope. In this presentation, we show the global distribution of ionospheric holes estimated from JDPs.

R009-14
B 会場 ：11/7　AM1 （9:00-10:30）
09:00〜09:15

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の検討状況

#土屋　史紀 [1)], 村上　豪 [2)], 山崎　敦 [2)], 木村　智樹 [3)], 吉岡　和夫 [4)], 鍵谷　将人 [1)], 古賀　亮一 [5)], 木村　淳 [6)], 成田　憲保 [7)], 亀田　真吾 [8)], 生駒　大洋 [9)], 大内　正己 [7,9)], 田中　雅臣 [1)], 益永　圭 [2)], 堺　正太朗 [1)], 垰　千尋 [10)], 桑原　正輝 [9)], 鳥海　森 [2)]
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LAPYUTA(Life-environmentology, Astronomy, and PlanetarY Ultraviolet Telescope Assembly) mission

#Fuminori Tsuchiya[1)], Go Murakami[2)], Atsushi Yamazaki[2)], Tomoki Kimura[3)], Kazuo Yoshioka[4)], Masato Kagitani[1)], Koga Ryoichi[5)], Jun Kimura[6)], Norio Narita[7)], Shingo Kameda[8)], Masahiro Ikoma[9)], Masami Ouchi[7,9)], Masaomi Tanaka[1)], Kei Masunaga[2)], Shotaro Sakai[1)], Chihiro Tao[10)], Masaki Kuwabara[9)], Shin Toriumi[2)]
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Ultraviolet observation technique is one of the most powerful tools to cover wide science fields, from planetary science to astronomy. Here we propose a UV space telescope, LAPYUTA (Life-environmentology, Astronomy, and PlanetarY Ultraviolet Telescope Assembly), as a Japanese-leading mission, by using heritages of UV instruments for planetary science (e.g., Hisaki) and space telescope techniques for astronomy. We will accomplish the following four goals: (1) dynamics of our solar system planets and moons as the most quantifiable archetypes of extraterrestrial habitable environments in the universe, (2) transit spectroscopy of exoplanetary atmosphere, especially hydrogen and oxygen exospheres, to observe ongoing atmospheric escaping predicted to occur on Earth-like exoplanets in the habitable zone of low temperature star system, (3) the unique UV map of the gaseous large-scale structures (LSSs) to test the structure formation scenario of the Λ cold dark matter (CDM) model and to unveil galaxy growth and feedback processes in the LSSs, and (4) the time-domain survey for transient sky in the UV wavelength to witness the first moments of high-energy events such as compact-object mergers and supernovae with a great synergy of the growing facilities of multi-messenger astronomy including gravitational-wave observatories.

宇宙における生命生存可能環境の探査は宇宙科学の根源的な課題の１つである。太陽系内の惑星・衛星は異なる形成・進化の過程を経た結果、多様な内部構造、表層・大気環境を持つに至っており、生命生存可能環境の多様性を探査する格好の対象である。低温環境の木星・土星系では、衛星の地下海が安定的な水の存在形態となっている可能性があり、生命生存環境を持ち得る天体として注目されている。液体の水が表層に安定に存在する天体は地球のみであるが、火星・金星にも過去に大量の水を保有した証拠が見つかっている。失われた水の行方や惑星が水を保有する条件を明らかにすることは、地球型惑星の生命生存可能環境の形成を理解する鍵となる。複数の飛翔体による探査が進行中の地球・火星、2030 年代に国際大型探査が予定されている木星系に加え、金星にも新たな探査計画の機運があり、今後 20-30 年は太陽系を舞台にした生命生存可能環境の理解が飛躍的に進むことが期待される。生命生存可能環境の探査に向けた現在の課題として、以下が挙げられる。(1) 氷衛星の地下海：土星の衛星はエンセラダスの地下海の存在は表層から噴き出す水プリュームの発見によりもたらされた。木星の氷衛星においても水プリュームの存在が証明され、その物理的特徴が明らかになれば、地下海の探査手段が得られる。(2) 氷衛星への化学エネルギー供給過程：低温環境の氷衛星では、太陽放射に加え磁気圏プラズマが生命生存可能環境を維持する化学エネルギー源を担う可能性が指摘されており、磁気圏の高温プラズマと衛星の相互作用過程の理解の重要性が高まっている。(3) 地球型惑星の大気散逸：火星・金星から失われた水の消失先の有力な候補が宇宙空間への散逸である。過去の太陽活動に遡って水や温暖化ガスの散逸を明らかにするためには、太陽放射や太陽風の変動に対する大気の広がりや大気散逸総量の応答を把握する必要がある。(4) 系外惑星大気の特徴づけ：地球型惑星の超高層大気の広がりは大気の組成に関係している。太陽系の惑星大気の知見を系外惑星に拡張すると、系外惑星大気の広がりは大気の組成やひいては表層環境を特徴づけるマーカーとして利用できる可能性がある。これらの課題を解決する手段として、LAPYUTA（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）ワーキンググループでは 2030 年代初頭の打ち上げを目指す高解像度・高感度の紫外線望遠鏡計画を提案しようとしている。紫外線波長域には、大気を構成する主要元素である水素、酸素、炭素、及び窒素の輝線があり、惑星・衛星の大気とその周りに分布する希薄なガスを高コントラストで観測することができる。空間構造を俯瞰的に観測しその長期連続観測を行うことによって、飛翔体によるその場観測では不可能な空間構造と時間変動の分離が可能となる。2030 年代の太陽系の惑星探査計画と同時期の観測を実現できれば、科学成果を相乗効果で挙げることも可能になる。LAPYUTA 計画では、太陽系惑星科学に対する科学課題に加え、銀河形成論や時間領域天文学に関する未開拓の研究課題も、サーベイ観測と機動的な観測を通して取り組む計画である。紫外線宇宙望遠鏡に求められる設計目標は以下のように設定している。光学系有効面積 350cm2、空間分解能 0.1 秒角、観測波長範囲 110nm〜190nm、波長分解能 0.02nm 以下、分光及び撮像視野 180arcsec 以上。紫外線は地球大気を透過しないため、宇宙機からの観測が必須となる。口径 60cm 以上の紫外線宇宙望

遠鏡に分光観測装置とイメージャを搭載した宇宙望遠鏡を公募型小型計画の規模で実現を目指している。地球外圏大気の酸素、水素原子発光の影響を低減しつつ放射線の影響を極力回避するため、遠地点高度 7,500km を想定している。講演では現在進めている科学目標の定量評価並びに設計目標の実現性検討を中心に計画の進捗状況について発表する。

R009-15
B 会場 ：11/7　AM1 （9:00-10:30）
09:15〜09:30

#鎌田　有紘 [1)], 黒田　剛史 [1)], 小玉　貴則 [2)], 笠羽　康正 [1)], 寺田　直樹 [1)]
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Global simulation of valley network formation by rivers and ice sheets in early Mars for various surface pressure and H2 amount

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Valley networks are dendritic feature on Mars and they are considered as evidence of prolonged water existence during the late Noachian and the early Hesperian (3.85-3.6 Ga). Early Mars at that time is thought to have had a CO_2 atmosphere of 1-2 bar in surface pressure from the constraint of the past geological studies, and a strong infrared absorption such as a collision-induced absorption of CO_2 and H_2 should be needed to warm enough to make fluvial activities. We have explained the formations of valley networks by coupling simulations between global climate model (PMGCM), global river model (CRIS), and global ice sheet model (ALICE), and suggested the possibilities of two opposite scenarios. One is that valley network was formed by rainfall-fed rivers (warm early Mars, Kamada et al., 2021), and the other is that valley network was formed by subglacial meltwater-fed rivers from ice sheets (cool early Mars, Kamada et al., 2022).

In this study, to explore the best climate scenario of early Mars, we performed a series of climate simulation of early Mars for a long timescale of over 10^5 Mars years, as an extension of our previous studies. We assumed a CO_2/H_2O/H_2 atmosphere with surface pressures of between 1 and 2 bar, H_2 mixing ratios of between 0% and 6%, obliquity of 40 degree, and geothermal heat flux of 55 mW m^{-2}. We defined an ancient northern ocean and lakes in our model with the amount of 500 m global equivalent layer (GEL) at the initial state, and implemented a pre-True Polar Wander topography to investigate the global water cycle of early Mars before late Tharsis formation. We iterated the runs of ALICE and coupled PMGCM-CRIS several times over the course of 10^5 Mars years to explore the long-term evolution states for each condition of surface pressure and H_2 mixing ratio.

We found that climate on early Mars should be divided mainly into 3 types. First, with high surface pressure and H_2 mixing ratio, climate on early Mars was "warm and semi-arid", characterized by global mean temperature of above 273 K and prolonged rainfall-fed river systems carving valleys on southern highlands where the most of valley networks are observed. These valleys were formed within a relatively short geological timescale (~10^4 Mars years), which agrees with previous geological studies of valley network formation timescale (10^4-10^6 Mars years). Second, with middle surface pressure and H_2 mixing ratio, climate on early Mars was "cool and wet", characterized by global mean temperature slightly below 273 K and widespread temperate-based ice sheets. Subglacial meltwater-fed river systems carved valleys on southern highlands with a relatively longer geological timescale (~10^5 Mars years) than "warm and semi-arid" case. Third, with low surface pressure and H_2 mixing ratio, climate on early Mars was "cold and icy", characterized by global mean temperature much below 273 K and widespread cold-based ice sheets, preventing ice sheet from melting. In both cases of "warm and semi-arid" and "cool and wet" scenarios, our river model CRIS produced widespread valleys which are consistent with more than half of the observed ones, indicating that many of river systems in the southern highlands are likely to have been formed by either rainfall or subglacial meltwater. However, in case of "cold and icy" scenario, there was almost no apparent surface liquid water activity, which is contradictory to observations. Even though with the scenario, there is a possibility that several valleys were produced by short-lived climatic warming, possibly through an increase of atmospheric greenhouse gas by volcanism and meteorite events.

R009-16
B 会場 ：11/7　AM1 （9:00-10:30）
09:30〜09:45

Mars Express/OMEGA と MMX/MIRS への応用を目指した CO2 2 μ m 吸収帯による火星表面圧力導出のための放射伝達ツール開発

#風間　暁 [1)], 笠羽　康正 [2)], 青木　翔平 [3)], 中川　広務 [4)], 佐藤　隆雄 [5)], 佐藤　晋之祐 [6)], 吉田　奈央 [7)]
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Development of a radiative transfer tool for surface pressure retrievals on Mars for Mars Express/OMEGA and MMX/MIRS

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To understand atmospheric variability on Mars, the distribution of surface pressure is important. Since Mars has a large orbital eccentricity, solar radiation fluctuates by more than 30% per year. As a result, large global and mesoscale variations are caused by the condensation and sublimation of CO2 and H2O and the local and seasonal variations of dust. On Earth, the distribution of surface pressure can be obtained by many observation points on the ground. However Mars only has a few numbers of landers at specific locations, so the horizontal distribution of the surface pressure has been poorly understood. global surface pressure distribution of Mars can only be delivered from the orbiter data.

Forget et al. (2007) and Spiga et al. (2007) are the only examples of the successful derivation of mesoscale surface pressure distribution. In this trial, the surface pressure was retrieved from the near-infrared CO2 absorptions at 2 um taken by OMEGA onboard Mars Express (MEx) during its initial observation (2004-2005). The CO2 mixing ratio in the lower Martian atmosphere (well known as 0.9532 in early summer obtained by the Viking Lander mass spectrometer) can be assumed as uniform in altitude, and we can assume that the surface pressure is in proportion to the CO2 column density when the atmosphere is hydrostatic.

In this previous case, only ideal data (e.g., no aerosol scattering, etc.) were used, and only about 0.7% of the total data (29 out of about 4,000 nadir observations) were utilized. From those limited data sets, the pressure distribution over 95 x 150 km (2.5 deg in longitude, 4 deg in latitude) could be derived and succeeded to show the pressure gradients and atmospheric waves.

The near-infrared spectrometer MIRS onboard the Martian Moons eXploration (MMX) mission, which is scheduled for launch in 2024, will be able to observe a wide area in the mid-to low-latitudes in one-hour intervals by using the scanner mirror of the instrument and the maneuver operation of the spacecraft. Continuous observations of the mid-and low-latitude Martian atmosphere are planned from its orbit around Phobos. We have tried to make use of this capability to retrieve a wide-area surface pressure distribution.

We first retrieve the mesoscale surface pressure from the entire period of MEx/OMEGA observations (2004-2010) in its SWIR (near-infrared) channel 1.8-2.2 um (25 points, wavelength resolution ˜20 nm). Following the method adopted in Forget et al. (2007) and Spiga et al. (2007), the CO2 column density is used for the estimation of the surface pressure with surface altitude correction. Eight physical parameters (atmospheric pressure, temperature, surface albedo, dust opacity, water ice, solar zenith angle, solar viewing angle, and phase azimuth angle) can affect the observed spectra. Therefore, at first, we prepared ˜3,640,000 cases of calculated spectra based on the HITRAN2020 database, calculated with the radiative transfer code ARS (Ignatiev et al, 2005). Using this spectral table, surface pressure could be quickly retrieved by matching the calculated spectra and the observed one, by the maximum likelihood estimation method. In this presentation, we will report the status of and results from our surface pressure derivation system adopted for MEx/OMEGA. In addition, we will also discuss the potential issues requested for the global pressure derivation system to be adopted by MMX/MIRS. We will work to fully make the most of the wide-field spectroscopic imaging capability of MMX (19.8x40 deg field of view, about 80 times larger than OMEGA/MEx). For this application, the treatment of real atmospheric conditions with aerosol scattering is a challenging point.

火星の大気変動の把握には、表面気圧の分布を知ることが重要である。火星は軌道離心率が大きく、太陽輻射量は年間で 30% 以上変動する。これに伴う CO2 と H2O の凝結・昇華や浮遊ダスト量の地域・季節変動により、大気はグローバル・メソスケールで大きく変動する。地球での表面気圧分布は、地表にある多数の観測点から直接求めることができるが、火星では特定箇所の着陸機群しか観測点が無い。このため、周回観測機のデータを用いた表面気圧分布の導出が必要である。

Forget et al. (2007) および Spiga et al. (2007) は、探査機データからメソスケール地表面気圧分布の導出に成功した唯一の例である。この例では、Mars Express (MEx) 探査機搭載 OMEGA の初期観測（2004-2005）で得られた近赤外域の CO2 吸収量から表面気圧を導出した。火星大気の CO2 混合比（Viking Lander 質量分析計による 0.9532 (初夏の値) がよ

く知られる）は下層で、ほぼ高度方向に一様であり、静水圧平衡仮定の元では表面気圧は CO2 気柱量に比例するとみなせる。この先行事例では、エアロゾルの散乱がない等の理想的なデータのみを対象とし、気圧の導出は全データの 0.7 % 程度 (約 4000 回の nadir 観測中 29 回) に留まる。しかし、95 × 150 k m（経度幅 2.5°、緯度幅 4°）の表面気圧分布を求めることに成功し、平衡状態から逸脱した圧力勾配や大気波動などが観測可能であることを示した。

2024 年の打ち上げを目指す火星衛星サンプルリターン計画 (MMX : Martian Moons eXploration) 搭載近赤外分光器 MIRS では、装置のスキャナーミラーと探査機のマヌーバー運用により 1 時間単位で中低緯度の広域が観測可能であり、フォボス近傍の周回軌道上から火星中低緯度大気の広域連続観測が計画されている。我々はこれを活かした広域気圧分布導出を目指している。この目標に向け、まずは MEx/OMEGA 近赤外線観測データが存在する全期間（2004-2010）を用いてメソスケール表面気圧の導出を試みる。Forget・Spiga の手法に則り、CO2 の吸収量から Column density を導出し、高度補正等を考慮して地表面気圧を推定する。この手法を OMEGA SWIR(近赤外) チャネルで取得される 1.8-2.2 μ m（25 点、波長分解能 〜20 nm）の 2 μ m CO2 吸収帯データに適用し、表面気圧を導出する。まず観測スペクトルに影響しうる物理パラメータ群（気圧、温度、表面アルベド、ダスト光学的厚さ、水氷気柱量、太陽天頂角、太陽視野角、位相方位角）において、HITRAN2020 データベースに基づき、Ignatiev et al. (2005) で開発された放射伝達コードを用いて計算を行い、擬似スペクトルを約 364 万ケース用意した。現在、擬似スペクトルから吸収量を算出し、観測スペクトルに最も近いものを最尤推定法より選択することで、表面気圧値の決定を検討中である。

本講演では MEx/OMEGA からの表面気圧導出状況を報告する。さらに、MMX で実現を目指すグローバル気圧導出の実現に要する課題についても述べる。エアロゾル散乱がある大気条件でこのリトリーバルツールをどのように適用していくかが今後の課題である。MMX の広視野分光撮像の能力 (視野 19.8° × 40°、OMEGA/MEx の約 80 倍) を十全に発揮することを目指して取り組んでいく。

R009-17
B 会場 ：11/7　AM1 （9:00-10:30）
09:45〜10:00

火星ディフューズオーロラの変動機構の研究

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Study of variation mechanisms of the Martian diffuse aurora

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The diffuse aurora at Mars (e.g., Schneider et al. 2015) is considered to be caused by solar energetic particles (SEPs) penetrating into the Martian atmosphere along the interplanetary magnetic field lines draped around the planet. The diffuse aurora emission consists of significant $CO_2{}^+$ ultraviolet doublet emission and having peak below 100 km altitude. Schneider et al. (2018) showed that the time variation of the auroral emission does not always correlate with the variation of the SEP electron flux. The emission correlates also with SEP protons in some events. The cause of the time variations of the auroral emission is far from understood. The horizontal induced magnetic field is developed when interplanetary magnetic field is draped around the Mars, and the structure of the magnetic field will change the flux of the penetrating SEPs. Therefore, one of the candidate mechanisms to cause the auroral variations is the change in the magnetic field orientation around Mars by affecting the vertical auroral emission profile. The purpose of this study is to investigate effects of magnetic field on the vertical emission profile of Martian diffuse aurora based on a Monte Carlo simulation and MAVEN observations.

We have developed a Monte Carlo model that calculates the vertical emission profile of $CO_2{}^+$ UVD, which is a typical emission line of the diffuse aurora. Our model used similar methods to the model by Bhardwaj & Jain (2009), which calculates the energy degradation of electrons below 1000 eV through collisions between CO_2 and electrons. The energy range of our models is expanded up to hundreds of keV by including the cross sections for collisional reactions between electrons and neutral atmosphere used in the model by Gerard et al. (2017), which reproduces vertical emission profiles of Martian diffuse aurora. A difference of our model from the previous models is to trace the trajectory of each electron in the given magnetic field structure including its cyclotron motion to investigate the effect of the draped magnetic field. We use MAVEN observational data, such as electron flux and magnetic fields, during the diffuse auroral event as inputs to our model. The results showed that the peak altitude of the emission intensity decreases with increasing dip angle of the magnetic field from the horizontal direction. Effects of the magnetic field strength are smaller than those of the dip angle. The result suggests that the magnetic field orientation in the vicinity of the planet is one of the important factors to cause variations of the vertical emission profile of the Martian diffuse aurora.

R009-18
B 会場 ：11/7　AM1 （9:00-10:30）
10:00〜10:15

#益永　圭 [1)], 寺田　直樹 [2)], 堺　正太朗 [3)], 横田　勝一郎 [4)], 原田　裕己 [5)], 原　拓也 [6)], 臼井　寛裕 [1)]
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Variations of hot oxygen corona of Mars during a comet approach

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Ion pickup by the solar wind is a ubiquitous feature in space plasma. Because pickup ions are originally generated by ionization of the exospheric neutral atmosphere, their measurements contain information on the exospheric number densities. Here we establish a method to retrieve exospheric number densities, by analyzing ion velocity distribution functions of pickup ions measured by the SupraThermal And Thermal Ion Composition (STATIC) instrument on Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft. We successfully reproduced exospheric oxygen density distributions from ˜500 to 10,000 km altitudes of Mars.

Using the retrieval method of exospheric number density, we examined variations of hot oxygen corona during a period when the comet Siding Spring approached Mars in October in 2014. We examined variations of O number density profiles every MAVEN orbit and found that number density of hot oxygen corona above 2000 km increased by a factor of a few after the comet approach. However, a Coronal Mass Ejection (CME) hit Mars ˜2 days before the comet approach, and a regional dust storm started to expand ˜2 days after that, and these events could have also affected the upper atmosphere of Mars. Thus, it was not straightforward to identify the cause of the change in hot oxygen corona and careful data analysis was necessary to understand effects of the comet approach.

In this presentation, we will show variations of the retrieved O number density profile before and after the CME, comet approach, and dust storm events, and discuss their time scales to discuss possibilities of direct cometary water transportation, sputtering by cometary pickup ions, and the Martian atmospheric heating effects by cometary atmosphere. We also discuss the CME and dust storm effects on the hot oxygen corona based on their onset timings and variation time scales.

R009-19
B 会場 ：11/7　AM1 （9:00-10:30）
10:15〜10:30

#吉田　奈央 [1)], 青木　翔平 [2)],Daerden　Frank[3)],Erwin　Justin[3)], 中川　広務 [4)],Vandaele　Ann Carine[3)],Thomas　Ian[3)],Trompet　Loic[3)], 村田　功 [5)], 寺田　直樹 [6)],Neary　Lori[3)],Lopez-Valverde　Miguel Angel[7)],Modak　Ashimananda[7)],Geronimo　Villanueva[8)],Giuliano　Liuzzi[8)], 笠羽　康正 [9)],Patel　Manish[10)],Ristic　Bojan[3)],Bellucci　Giancarlo[11)],Lopez Moreno　Jose Juan[7)]
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CO distributions and climatology in the Martian mesosphere and lower thermosphere retrieved from TGO NOMAD solar occultation

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Carbon monoxide (CO) is one of the tracers which can see the dynamics in the Martian atmosphere because the lifetime of CO is longer than the timescale of dynamics. CO is produced by the photodissociation of CO_2 and recycled to CO_2 by the catalytic cycle by odd hydrogen [e.g., McErloy & Donahue, 1972]. CO volume mixing ratio (VMR) is well mixed in the lower atmosphere, but it increases with altitude above ~60 km. The further enhancement of CO VMR is simulated in the polar regions due to the meridional circulation from the thermosphere using the 3D GCM models [Daerden et al., 2019; Holmes et al., 2019]. The vertical distribution of CO VMR has been observed for the first time by the ExoMars Trace Gas Orbiter (TGO) mission [Olsen et al., 2021; Modak et al., submitted; Yoshida et al., 2022]. Olsen et al. (2021) focused on the distribution in MY34 L_s = 160 – 240, which includes the onset of the global dust storm event. Modak et al. (submitted) investigated the CO VMR in MY34. Yoshida et al. (2022) discussed the CO/CO_2 ratio with a subset of the data taken in MY35, and the altitude range was limited above 70 km due to the retrieval method. The retrieved CO VMR in Olsen et al. (2021) and Modak et al. (submitted) are qualitatively similar to the GCM model (Forget et al., 1999; Lefevre et al., 2004). However, they mentioned the quantitative disagreement with simulations. In this study, we report the CO distribution from MY34 L_s = 160 to MY35 L_s = 100 retrieved from the solar occultation (SO) channel of Nadir and Occultation for MArs Discovery (NOMAD) instrument aboard TGO [Vandaele et al., 2018]. We aim to show the CO climatology and the interannual variation and interpret its distribution using the GEM-Mars model [Daerden et al., 2019; 2022].

NOMAD is a spectrometer measuring between 0.2 and 4.3 μ m aboard the ExoMars TGO [Vandaele et al., 2018]. Solar Occultation channel (SO) of NOMAD measures infrared between 2.3 and 4.3 μ m (between 2320 and 4350 cm^{-1}) with a high spectral resolution, R ~17000, thanks to the combination of an Acousto Optical Tunable Filter (AOTF) and an echelle grating [Neefs et al., 2015; Thomas et al., 2016; Vandaele et al., 2018]. The AOTF instantaneously selects diffraction orders (~20 – 25 cm^{-1}), which enables us to measure 5 to 6 orders simultaneously during the same orbit. The spectral features of CO 2-0 bands (3970.72 – 4360.10 cm^{-1}) are recorded in order 186 – 192. The strongest line in the CO 2-0 bands, 4291.5 cm^{-1}, is included in order 190. The line intensities of the CO 2-0 bands in orders 186 and 192 are weaker by one order than that in order 190. Here, we analyze the transmittance spectrum observed in orders 190 and 186 because these are more frequently observed. The retrieval of CO is performed with the radiative transfer code, named ASIMUT [Vandaele et al., 2006], and the optimal estimation method (OEM) [Rodgers, 2006]. The atmospheric temperature and pressure profiles are inputted from the GEM-Mars simulation [Daerden et al., 2019; Neary & Daerden, 2018], whose model takes into account the effects of the dust storm events in MY34 [Neary et al., 2020]. The fitting is conducted for continuum and CO absorption features. The continuum is assumed to be the 4th polynomial function. The retrieval is calculated for each spectrum at each tangential altitude independently [e.g., Aoki et al., 2019].

The CO VMR is retrieved from the near-surface to 120 km altitude. We have validated the results in the altitude range between ~50 and 110 km. The increase of CO VMR typically above 60 km is obtained as same as Olsen et al. (2021) and Modak et al. (2022). Our observation showed that the CO VMR is generally higher in the morning terminator than in the evening terminator. However, such a local time variation disappears in L_s = 120-126 and L_s = 277-283 in MY35, and L_s = 59-65 in MY36. The latitudinal-altitudinal distribution is symmetric near the equinox, but it is asymmetric near the solstice, which is the same result predicted by the GEM-Mars simulation presented in Daerden et al. (2019). A decrease in CO VMR in the upper atmosphere during the global dust storm event is measured, whose phenomena are observed by ACS as

described in Olsen et al. (2021). We find that the interannual variation of CO distribution showed that the decrease in CO VMR during the global dust storm is restricted in the middle-latitude to the polar region. In the lower latitude, the CO VMR in MY34 is the same and/or large compared to that in MY35. At the presentation, we will show those variabilities in more detail and interpret the CO climatology using the GEM-Mars model [Daerden et al., 2019; 2022].

R009-20
B 会場 ：11/7　AM2 （10:45-12:30）
10:45〜11:00

大気波動と太陽風が火星熱圏電離圏擾乱に与える影響の同定

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Identifying atmospheric waves and solar wind impacts in the Martian atmosphere and ionosphere

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Atmospheric gravity waves (GW) are ubiquitous features of planetary atmospheres. They act as “conduits” to transport energy and momentum between different regions, and they affect a variety of atmospheric processes from mixing of minor species to momentum balance, thermal balance, and dynamic circulation. These waves achieve far larger amplitudes in the Martian thermosphere than are typically observed at Earth. Thus, at Mars such waves may play an even more important role than they do at Earth. Without a strong magnetic field, observations of ions at Mars also commonly reveal features of GW that frequently track those in the neutral atmosphere. However, the solar wind (SW) is also capable of producing fluctuations or irregularities in the ions that may have wavelengths similar to GW and can confuse such an analysis unless data from both ions and neutrals are used simultaneously.

Here we identify characteristics of both atmospheric waves and SW induced fluctuations seen in MAVEN observations of the Martian thermosphere and ionosphere. We applied the Neutral Gas and Ion Mass Spectrometer (NGIMS) aboard MAVEN measures both neutral and ion densities during the period from 2015 to 2020 for five years. The wavelike fluctuations of neutrals, CO_2, N_2, O, and ions, O_2^+, CO_2^+, O^+, are identified by the polynomial fit to the individual profile altitudes from 160 and 240 km. The two-fluid model has been used to identify properties of GW and acoustic waves (AW). For each set of NGIMS observations orbit by orbit to both the neutrals and ions, we search through the range of possible GW/AW frequencies, wavelengths and see if they can fit the observed density fluctuation amplitudes and phases.

Based on the analysis of 68 characteristic cases, we demonstrate that atmospheric waves do not explain the fluctuations attributed to impacts of the SW. In at least some cases, this transition is consistent with the increasing gyro/collision frequency ratio along the height. We then present the occurrence rates of these SW impacts, their relationship to the solar wind itself, and spatial distribution across the planet. In a wide survey, we see currently unexplained behavior both at night, and especially near dusk over the stronger crustal magnetic field features. Although the basic process might be understood by analogy in the Earth with a stronger intrinsic magnetic field, we would like to deepen our consideration from a comparative planetary perspective.

大気重力波は、惑星大気中に普遍的に存在しており、エネルギーや運動量を異なる高度領域間で輸送する”導管”として働く。微量成分の混合、運動量・熱バランス、大気の循環まで様々な大気プロセスに影響を及ぼす。これら大気波動擾乱は火星熱圏では地球で一般的に観測されるよりも遥かに大きな振幅が観測されている。従って、火星では地球よりもさらに重要な役割を担っている可能性がある。強い磁場が存在しない火星では、電離大気中にも中性大気とよく似た特徴を示すことが多い。一方で、磁場がないことにより、宇宙からの太陽風や高エネルギー粒子が直接大気に降り注ぐことによって電離大気の揺らぎや不規則構造を生成しうる。そのため、火星電離圏では下層からと宇宙からの両方からの影響が複雑に絡み合って変動が励起されており、その相対的な重要性や切り分けが変動理解のためには重要である。

本研究では、米火星探査衛星 MAVEN による火星熱圏電離圏観測データを用いて下層からの大気波動と宇宙からの太陽風による揺らぎ両方の特徴を明らかにする。MAVEN に搭載された中性・イオン質量分析器 NGIMS を用いて 2015 年から 2020 年の 5 年間に観測された中性 CO_2,N_2,O と、イオン O_2^+,CO_2^+,O^+ の密度擾乱成分を解析する。それぞれの擾乱成分は、高度 160〜240 km の個々の軌道で得られた高度分布に対して多項式フィットにより抽出する。観測で得られた擾乱成分に対して、二流体数値モデルを比較することで、大気重力波・音波の特性を同定する。観測された密度変動の振幅と位相を説明可能な大気波動の特性が現実的な範囲で再現できるかを評価する。

特徴的な 68 例のデータを解析した結果から、太陽風に起因する擾乱成分は多流体モデルを用いた大気波動では説明がつかないことを実証することができた。その際、中性・イオンとの衝突周波数が磁場によるジャイロ周波数よりも卓越する場合、衝突による強い中性イオンカップリングにより、電離大気中にみられる擾乱は中性大気と類似した大気波動で説明することができ、一方でジャイロ周波数が卓越する場合は、電離大気特有の擾乱がみられることが、少なくともいくつかのケースで確認することができた。次により多くのデータを用いて、太陽風条件との関係、空間分布や SZA 依存性など統計的な特徴を明らかにした。その結果、夜間、特に強い地殻磁場構造や夕暮れ時に、大気波動では説明のつかない振る舞いがみられることがわかった。より強い固有磁場を持つ地球におけるアナロジで基本的なプロセスは理解できると考えているが、比較惑星学的に考察を深めていきたい。

R009-21
B 会場 ：11/7　AM2 （10:45-12:30）
11:00〜11:15

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Simultaneous observations of ionospheric irregularities at Mars by Mars Express MARSIS topside sounder and MAVEN

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Since Mars has no intrinsic magnetic field, the solar wind directly interacts with the Martian ionosphere, leading to ionospheric disturbances driven by the solar wind. Meanwhile, observations in the dayside ionosphere by Mars Atmosphere and Volatile EvolutioN (MAVEN) indicate that there is a strong correlation between ion and neutral density profiles structure, suggesting an ion-neutral coupling in the upper atmosphere (Mayyasi et al., 2019). Gurnett et al. (2008) reported that diffuse echoes sometimes appear on the ionogram obtained by the Mars advanced radar for subsurface and ionospheric sounding (MARSIS) on Mars Express. These echoes are presumed to be caused by irregularities in the ionosphere. However, no studies have yet compared echoes from remote observations with in-situ electron density perturbations, and the detailed properties of ionospheric irregularities that cause diffuse echoes are still unknown. Here, we surveyed conjunction events in which Mars Express and MAVEN observed the ionosphere quasi-simultaneously. We then, for each event, determined whether the in-situ electron density perturbations were driven by solar wind forcing or neutral atmospheric waves by examining the ratio of gyro frequency to collision frequency and the correlation between neutral density fluctuations and ion density fluctuations. The case analysis revealed that the spatial scale of the in-situ electron density perturbations is approximately 120 -400 km. In some cases, high solar wind dynamic pressure appeared to be the driving source of electron density perturbations that are specific only to ionized atmospheres. Additionally, the statistical analysis results show that the in-situ electron density perturbations create diffuse echoes on the ionogram. In this presentation, we discuss the frequency and wavelength characteristics of the in-situ electron density perturbations that cause diffuse echoes based on the observations, and what parameters they depend on.

R009-22
B 会場 ：11/7　AM2 （10:45-12:30）
11:15〜11:30

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Multifluid MHD simulation of the effects of a dipole field on ion escape at ancient Mars

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Escape of the ionized atmosphere, ion escape, played an important role in atmospheric loss and climate change at ancient Mars due to intense solar X-ray and EUV (XUV) radiation and solar wind from the young Sun. The distribution of the crustal magnetic field on the surface indicates that ancient Mars once had an intrinsic magnetic field. In addition to the solar XUV and solar wind conditions, the presence of an intrinsic magnetic field affects ion escape. Our previous studies (Sakata et al., 2020; Sakata et al., 2022) investigated the effects of the dipole field on ion escape processes and rates under the ancient solar XUV and solar wind conditions based on global multispecies magnetohydrodynamics (MHD) simulations. They revealed that the ion escape rates depend on the ratio of the dipole field's magnetic pressure at the equatorial surface to the solar wind dynamic pressure. The effects are more pronounced on the escape of molecular ions (O_2^+, and CO_2^+) by ionospheric outflow. However, the multispecies MHD model neglects kinetic effects and different dynamics among ion species. The outflow from the ionosphere often occurs in a region where the solar wind H^+ inflow and the planetary ion outflow coexist. The multispecies MHD simulations may therefore underestimate the ionospheric outflow.

We developed a new 3D global multifluid MHD model with the cubed sphere grid. It solves the continuity, momentum, and energy equations for five ion species (solar wind H^+, planetary H^+, O^+, O_2^+, and CO_2^+), the induction equation for the magnetic field, and the electron pressure equation. It considers the ionization processes, chemical reactions, and collisions which are important in the ionosphere. In this study, we assumed the ancient solar XUV and solar wind conditions used in Sakata et al. (2022). The solar wind density and velocity were 700 cm^{-3} and 1400 km s^{-1}, respectively. The interplanetary magnetic field was 20 nT in the away-sector of the Parker spiral. The solar XUV radiation was 50 times higher than the current value. The two simulation cases were conducted: the case with no dipole field and the case with a weak dipole field with the strength of 100 nT at the equatorial surface. We also conducted the multispecies MHD simulations on the same grid system for comparison.

The multifluid MHD simulation results show that the asymmetric flux distribution of heavy ions (O^+, O_2^+, and CO_2^+) due to the convectional electric field of the solar wind, which is not seen in the multispecies MHD simulations. We will focus on the difference in the escape processes and rates and its implication for the effects of an intrinsic magnetic field on ion escape.

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R009-23
B 会場 ：11/7　AM2 （10:45-12:30）
11:30〜11:45

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Birthplace of energetic ions around the Phobos' orbit at midnight: Implications for future MSA observations onboard MMX

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Mars has experienced drastic climate changes over the past 4.6 Gyr due to a significant atmospheric escape. How much carbon dioxide (CO2), which is a major component of the Martian atmosphere, has escaped into space is important for understanding the climate change on Mars. The isotope ratio is particularly one of the key parameters in revealing the Martian atmospheric evolution. Jakosky et al. (2017) suggested that more than 1 bar of oxygen (O) was lost to space from measurements of argon isotope ratios based on observations by the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft, assuming that the all lost O primarily originated from CO2, but these estimations were not derived from direct observations of CO2. The evolution of O and carbon (C) isotope ratios between the surface and upper atmosphere is relevant to understanding the CO2 loss process, but there have been no observational constraints on these isotope ratios in the upper atmosphere. Note that Curiosity identified the isotope ratios of 16O/18O ˜476 and 12C/13C ˜85 near the surface (e.g., Mahaffy et al., 2013), and the Atmospheric Chemistry Suite onboard Trace Gas Orbiter (TGO) found the isotope ratio of 16O/18O ˜420 in the middle atmosphere below 60 km altitude (Alday et al., 2019). Japanese future sample return mission "Martian Moons eXploration (MMX)" is a candidate for this observation.

One of the MMX mission is to determine the total amount of atmospheric escape that Mars has experienced in its history, based on the isotope ratios of the ions observed around Phobos. This study aims to classify the characteristics of ions around Phobos with a focus on their energies and velocities. We particularly investigate the birthplace of ions around the Phobos orbit on the midnight side, where the electromagnetic field environment is more complex, by means of test particle simulations. Simulations are performed with four cases of interplanetary magnetic field (IMF) clock angles. The difference in IMF clock angle has little effect on the birthplace of ions detected around the Phobos orbit on the midnight side. Ions with energies of a few keV are supplied from the magnetosheath, while those with energies greater than ˜10 keV are supplied by the solar wind. The ions coming from the magnetosheath have three sources that are (1) in the flank region of the induced magnetosphere, (2) around the terminator, and (3) on the dayside, which are determined by the electric field and potential in the magnetosheath. The dependence of ion birthplaces on IMF intensity is also studied, suggesting that a larger IMF produces higher energy ions in the magnetosheath and solar wind, resulting in closer ion birthplaces. This study would be useful for retrieval of the exospheric atmosphere from future MMX observations on the nightside under the complicated electromagnetic environment.

R009-24
B 会場 ：11/7　AM2 （10:45-12:30）
11:45〜12:00

MAVEN および MEX による太陽風が駆動する ULF 波動の火星電離圏への伝搬の準同時多地点観測

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MAVEN and MEX Quasi-Simultaneous Multipoint Observations of Propagation of Solar Wind-Driven ULF Waves into the Martian Ionosphere

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Electromagnetic waves generated upstream of bow shocks of unmagnetized planets such as Mars are important since the waves could have a significant impact on the planetary plasma by propagating through the magnetosheath into the ionosphere (Fowler et al., 2018, 21).

At Mars, it has been reported that so-called “Proton Cyclotron Waves” (PCW) are driven by cyclotron resonant interaction with newborn pickup protons in the upstream solar wind region (Russell et al., 1990,92; Barabash et al., 1991; Brain et al., 2002; Romeo et al., 2020). The waves are then advected downstream to the magnetic pileup boundary and drive compressional magnetosonic ultralow frequency (ULF) waves within the ionosphere at a similar frequency (Collinson et al., 2018; Fowler et al., 2018, 21). These compressional magnetosonic waves inject energy into the ionosphere and heat planetary ions via wave-particle interactions, possibly leading to ion escape to space (Fowler et al., 2018, 21). This series of processes have been actively studied as one of the mechanisms of ion escape from Mars, because the ion escape may play an important role in the long-term climate evolution of unmagnetized bodies.

However, previous studies of the solar wind-driven ULF waves at Mars have been based almost exclusively on single-spacecraft observations. Because of the orbital constraints of single spacecraft, it has been challenging to characterize the likelihood of the upstream waves propagating into the ionosphere.

In this study, we investigated the ULF wave propagation rate from upstream of the bow shock into the ionosphere of Mars with quasi-simultaneous multipoint observations of local magnetic fields. We identified 120 events in which Mars Atmosphere and Volatile EvolutioN (MAVEN) observed the PCWs with its magnetometers in the upstream region, while Mars Express (MEX) observed compressional fluctuations at a similar frequency in the ionosphere by measuring the local magnetic field magnitude from electron cyclotron echoes recorded by MARSIS (we utilized the method established by Akalin et al., 2010). We define these events as ”wave propagation events” and investigate the dependence of the wave propagation rate on various parameters such as MEX’s location and upstream drivers.

The results suggest that wave propagation into the ionosphere could be not an uncommon phenomenon on the dayside of Mars and the propagation rate was found to be highly dependent on SZA and the upstream solar wind dynamic pressure. It was also found that the rate depends on altitude and crustal magnetic field magnitude, although not as much as the former two.

R009-25
B 会場 ：11/7　AM2 （10:45-12:30）
12:00〜12:15

#西岡　知輝 [1)], 関　華奈子 [1)], 坂田　遼弥 [1)], 山本　和弘 [1)], 堺　正太朗 [2)], 寺田　直樹 [2)], 品川　裕之 [3)], 中山　陽史 [4)]
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Effects of planetary intrinsic magnetic fields on the atmospheric ion escape from exoplanet TOI-700 d

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The atmospheric escape from a planet can be greatly affected by existence of a planetary intrinsic magnetic field. For example, a strong dipole intrinsic magnetic field of ancient Mars may have reduced the atmospheric ion escape rate (Sakata et al., JGR, 2020, 2022). There have been many studies which focus on atmospheric escape from planets in our solar system. However, space environments around exoplanets can be very different from those around Earth because of differences in the stellar X-ray and EUV (XUV) radiation, stellar wind, and strength of the planetary intrinsic magnetic field. In this study, we investigated how the space environment affects the atmospheric escape from a terrestrial exoplanet in the habitable zone of a M dwarf star with a focus on the effects of the intrinsic magnetic field.

We focused here on exoplanet TOI 700 d, which is the first Earth-sized planet in the habitable zone (HZ) discovered by the Transiting Exoplanet Survey Satellite (TESS) (Gilbert et al., AJ, 2020; Rodriguez et al., AJ, 2020). The host star is a M dwarf star, which has lower surface temperature, thus closer HZ to the host star, and stronger XUV radiation in HZ than the solar system around a G-type star. Another important difference is that direction of the interplanetary magnetic field (IMF) around the planet may be dominated by the radial component because of the proximity to the host star and planet. The IMF orientation can change the atmospheric escape rate from the exoplanet. In this study, we simulated the atmospheric ion escape from TOI-700 d.

To model the space environment around TOI-700 d, we used the REPPU-Planets multi-species MHD simulations (e.g., Terada et al., JGR, 2009; Sakata et al., JGR, 2022). Our model solved three-dimensional multispecies MHD equations including continuity equations for 11 ion species (O^+, $O_2{}^+$, $CO_2{}^+$, NO^+, CO^+, $N_2{}^+$, N^+, C^+, He^+, H^+, Ar^+) from the bottom of the ionosphere to the inter-planetary space where a constant stellar wind is assumed. The model includes photoionization, electron impact ionization, charge exchange, ion-neutral reactions, dissociative recombination, collisions (ion-electron, ion-neutral, electron-neutral). As stellar wind conditions, number density, velocity, and temperature were set to 450 cm^{-3}, 470 km s^{-1}, and 1.3 x 10^6 K, respectively, by referring to previous studies (Cohen et al., ApJ, 2020; Dong et al., ApJL, 2020). IMF was assumed to be a Parker spiral with an angle of 4^o or 45 ^{o} degrees and a magnitude of 12 nT. Also, the stellar XUV flux was set between 1 and 50 times of the current Earth value. We assumed a Venus-like atmospheric composition that depends on the stellar XUV flux as the input neutral atmosphere based on Kulikov et al. (SSR, 2007). Since there is no information on the intrinsic magnetic fields of TOI-700 d, we assumed a global dipole magnetic field and direction of the dipole moment is perpendicular to the ecliptic plane of the stellar system. To investigate the dependence on the strength of the intrinsic magnetic field, the equatorial surface strength of the dipole magnetic field was set between 0 nT to 1000 nT. In the 1000 nT case, it is strong enough to deflect the stellar wind and expected to reduce the atmospheric ion escape rate (Sakata et al., JGR, 2022). When the exoplanet does not possess the intrinsic magnetic field (0 nT case), the high XUV condition results in the large ion escape rate to remove the atmosphere within a few billion years. The existence of the strong magnetic field reduces the escape rate. In the presentation, effects of the global planetary magnetic field on the ion escape mechanisms will be also reported in detail.

R009-26
B 会場 ：11/7　AM2 （10:45-12:30）
12:15〜12:30

#関　華奈子 [1)], 中山　陽史 [2)], 坂田　遼弥 [1)], 今村　剛 [3)], 堺　正太朗 [4)], 寺田　直樹 [4)], 桂華　邦裕 [1)], フランス　ケビン [5)], ブレイン　デービッド [5)]
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Study of plasmasphere formation at terrestrial exoplanets around M-Dwarf stars and its detectability

#Kanako Seki[1)], Akifumi Nakayama[2)], Ryoya Sakata[1)], Takeshi Imamura[3)], Shotaro Sakai[4)], Naoki Terada[4)], Kunihiro Keika[1)], Kevin France[5)], David Brain[5)]
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Many terrestrial exoplanets or super-Earth have been found around low mass stars such as M dwarfs. A red dwarf (M type star) has comparatively narrow habitable zone, which is very close to the host star, and exoplanets are considered to be exposed to extreme levels of X-ray and ultraviolet (UV) radiation [e.g., France+, 2016]. Classic equilibrium tide theories predicts that K or M-type stars induce strong tidal effects on potentially habitable exoplanets, and tidal locking is possible for most planets in the habitable zones of K and M dwarf stars [e.g., Barnes, 2017]. When a planet has dipole magnetic field and rapid rotation, superposition of the stellar wind induced and corotation electric fields results in the tear-drop-shaped region of the closed drift, where planetary ionized atmosphere can fill the magnetic flux tubes along the field lines. The region is characterized with cold dense planetary plasma and called as the plasmasphere. In this study, a simple estimation method of the size of terrestrial exoplanetary plasmasphere is shown based on the knowledge of the solar system planets.

First, we considered the role of rapid rotation of the atmosphere (superrotation) in the formation of the plasmasphere of tidally-locked exoplanets. Many GCMs of exoplanets show that the circulations of typical tidally locked terrestrial exoplanets can become superrotation [e.g., Showman+, 2013]. However, the horizontal circulation in the thermosphere is far from understood [e.g., Machado+, 2017]. As for the planetary atmosphere, we assumed the Venus-like composition and thermospheric and ionospheric density altitude profiles of various species are estimated based on newly developed 1-D thermosphere model [Nakayama and Seki, in preparation]. As a representative stellar radiation input of M dwarf stars, we used XUV radiation of the Proxima Centauri (PC) [France+, 2016]. As a result, the model estimates ionospheric densities for CO2+, CO+, O2+, N2+, O+. N+, and C+ for imaginary exoplanets with the intrinsic dipole strength as strong as that of Earth and Venus-like atmospheric composition with two planetary mass cases, i.e., Venusian mass or 2 times of Earth mass.

The results indicate that the main ion species in the ionosphere and plasmasphere is C+, and it is different from current Venusian ionosphere whose main ion species is O+. The results of plasmasphere estimation show that Earth/Venus-like magnetized exoplanet can have a plasmasphere with a size of 4-6 times of the planetary radius. The size of the plasmasphere depends on the superrotation speed of the thermosphere, ionospheric conductance, stellar wind dynamic pressure, and IMF cone angle. Estimation of the transit depth of C+ line around 1334-1336 Angstrom indicates that the FUV absorption of plasmaspheric C+ ions can cause a few to several percent of the transit depth depending on the planetary size and plasmaspheric C+ density, which might be observable by space telescopes. Since the plasmasphere formation requires the existence of both the thick atmosphere and global intrinsic magnetic field, the observation of plasmasphere can provide possible evidence and clues of the exoplanetary atmosphere and intrinsic magnetic field.

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R009-27
B 会場 ：11/7　PM1 （13:45-15:30）
13:45〜14:00

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Two-band simultaneous observation for planetary lightning by using the photomultiplier tubes mounted on a ground-based telescope

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The activity and distribution of lightning can be used to understand the mechanism of atmospheric dynamics on the other planets. The moist convection is a source of generating lightning, which is important to transfer the energy in the atmosphere. The spacecraft has detected lightning on Jupiter through night-side optical imaging and radio wave observation. From the existence of cumulonimbus near the observed lightning region, moist convection is expected to be correlated with the jovian lightning distribution, like on Earth. Previous studies (Gierash et al., 2000; Ingersoll et al., 2000) suggested that the many small-scale eddies, receiving their energy from the moist convection, drive the zonal jet. We can obtain information about the convection by monitoring jovian lightning. About Venus, LAC onboard AKATSUKI recorded a possible optical signal from Venusian lightning on March 1, 2020 (Takahashi et al., 2020). If the lightning discharge originates the signal, the occurrence rate is equal to 2.7×10^{-12} $s^{-1}km^{-2}$ estimated by Hansell et al., 1995. If we can monitor global Venusian lightning activity and distribution, it could be helpful to understand the Venusian atmospheric dynamics.

We have developed the Planetary lightning Detector (PLD) to observe the optical Jovian and Venusian lightning flashes and be mounted on a 1.6-m Pirka ground-based telescope. The PLD is a high-speed photon-counting sensor using the photomultiplier tube to obtain the light curve of lightning optical flashes. PLD observes the background level simultaneously with a second photomultiplier tube with a broadband filter to ensure the light detected at the lightning emission line is well over the noise level and background variation. We use a beamsplitter to separate the incident light from the telescope into two photomultiplier tubes. The first photomultiplier tube observes the wavelength of Jovian or Venusian lightning. The PLD has narrowband filters of 777 nm (FWHM = 1nm) for Venusian lightning and 656 nm (FWHM = 1nm) for Jovian lightning (Borucki et al., 1996). The second photomultiplier tube observes the background variation with the broadband filter, 700 nm (FWHM = 10 nm). We have observed Venus and Jupiter since 2021. We analyze the data with wavelet denoising to remove the pulses caused by cosmic rays and shot noise. We compare the light curve obtained by the first PMT and the background variation observed by the second PMT. Suppose the first PMT recorded the waveform showing an increase in value, unlike the second PMT, and the pulses have a larger count value above the trigger level estimated by the background noise amplitude. In that case, the candidate pulses are considered to have been detected. Several possible pulses are found in the case of Venus. We can't rule out the possibility that all recorded light curves originate from noise. We discuss statistically and precisely to conclude the lightning detection.

R009-28
B 会場 ：11/7　PM1 （13:45-15:30）
14:00〜14:15

あかつき電波掩蔽による高鉛直分解能温度データから求めた大気重力波の緯度高度分布

#福岡　誠喜 [1)], 安藤　紘基 [2,3)]
([1] 東京大学,([2] 東京大学,([3] 京産大

Latitude-altitude distribution of gravity waves of Venus derived from temperature profiles obtained by Akatsuki radio occultation

#Seiki Fukuoka[1)], Hiroki Ando[2,3)]
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Atmospheric gravity waves are thought to have a significant impact on the maintenance of the Venusian atmosphere through the transport of energy and momentum. The elucidation of the generation, propagation and extinction of gravity waves is a key to understand their roles.

Vertical propagation of gravity waves has been detected as wavelike structures in temperature profiles obtained by radio occultations in ESA's Venus Express and JAXA's Akatsuki missions. Tellmann et al. (2012) obtained the amplitude of small-scale temperature fluctuations as functions of the latitude and the altitude. Their analysis limited the wavelengths to of 1 – 4 km because of the use of the geometric optics method; however, gravity waves with vertical wavelengths shorter than 1 km have been detected in Earth's atmosphere and are thought to play important roles in the development of the atmospheric structure. In addition, the geometric optics method cannot account for multipath effects that deteriorate the retrieval. On the other hand, a method called Full Spectrum Inversion (FSI) (Jensen et al. 2013), which is a type of radio holography, can decipher the multipath and achieve a vertical resolution as high as ˜0.1 km. FSI has been applied to a limited number of radio occultation data of Venusian atmosphere to obtain high-vertical resolution profiles (Imamura et al. 2018; Mori et al. 2021).

In this study, we analyze larger number of radio occultation data obtained by Akatsuki than the previous studies using FSI. The high vertical resolution temperature profiles allow estimation of gravity wave amplitudes for different wavelength ranges including those <1 km. The amplitude is evaluated for different altitudes and latitudes to identify the locations where the waves are generated and attenuated.

大気重力波は、エネルギーや運動量の輸送を通じて、金星大気の維持に大きな影響を与えると考えられています。その役割を理解するためには、重力波の発生・伝播・消滅を解明することが鍵となる。

重力波の鉛直伝播は、ESA の Venus Express や JAXA の Akatsuki ミッションの電波掩蔽観測で得られた温度分布に波状構造として検出されています。Tellmann ら (2012) は、小規模な温度変動の振幅を緯度と高度の関数として求めました。幾何光学法を用いた解析では、波長は 1-4km に限定されるが、地球大気中には 1km より短い波長の重力波が検出されており、大気構造の発達に重要な役割を果たすと考えられています。また、幾何光学法では、マルチパスの影響を考慮することができない。一方、電波ホログラフィーの一種である Full Spectrum Inversion (FSI) (Jensen et al. 2013) は、マルチパスを考慮し、〜0.1 km という高い垂直分解能を達成することができる。現在、FSI は金星大気の限られた数の電波掩蔽データに適用され高い垂直分解能のプロファイルが得られている（Imamura et al.2018; Mori et al.2021 ）。

本研究では、これまでの FSI を用いた研究よりも多くの Akatsuki が取得した電波掩蔽データを解析した。垂直分解能の高い温度プロファイルにより、1km 未満を含む異なる波長域の重力波振幅を推定することができる。また、高度や緯度を変えて振幅を評価し、波の発生場所や減衰場所を特定する。

R009-29
B 会場 ：11/7　PM1 （13:45-15:30）
14:15〜14:30

自転軸の傾きを入れた金星大気循環シミュレーション

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Simulation of Venus atmospheric circulation with a tilt of rotation axis

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The tilt of the rotation axis of Venus is very small (about 2.6 deg), so that its effect (seasonal variation) has not been studied well. Seasonal variations are unlikely near the surface because the radiative relaxation time can be as long as tens of thousands of Earth days. On the other hand, around altitudes of 60-70 km, the radiative relaxation time is from few tens to several Earth days, not much different from that of the Earth atmosphere, and the effect of the rotation-axis tilt is not necessarily negligible. Yamamoto and Takahashi (2007) numerically investigated the effect of the rotation-axis tilt on the Venusian atmospheric circulation and found that the influence to the strength of the superrotation by a tilt of 2.6 deg was negligible. Based on this result and also for simplicity of setup, the tilt of the rotation axis has been omitted in Venus atmospheric simulations performed by many groups in the world. In recent decades, the Venus Express and Akatsuki have provided estimates of the horizontal wind distribution at cloud-top altitudes (around 65 km). In addition, Venusian atmospheric simulations with high resolution have enabled us to express circulation structures in details. In other words, it is now possible to discuss the spatial structure of Venusian atmospheric circulation including superrotation.

In this study, we performed a Venusian atmospheric simulation including the tilt of the rotation axis. AFES-Venus (Sugimoto et al., 2014) was used for the numerical model. Although AFES-Venus is a dynamical model that uses simplified radiative processes and omits cloud microphysics and topography, the introduction of a low-stability layer and the use of high resolution lead us to represent observationally consistent structure such as the cold collar (Ando et al., 2016) and the planetary-scale streak structure (Kashimura et al., 2019). In this study, we performed a time-integration for 6 Venus years with a horizontal resolution of 1.4 deg x 1.4 deg (T85) and 120 layers (dz = 1 km) in vertical; the rotation-axis tilt is 2.6 deg and an idealized superrotational flow is used for the initial state. Other (resolution-independent) settings are the same as those in Kashimura et al. (2019).

The numerical results show significant seasonal variations above an altitude of 60 km. In particular, the mid-latitude zonal wind jet was about 10 m/s stronger in the winter hemisphere than in the summer hemisphere. For the mean meridional circulation, both a direct circulation in low-latitudes and an indirect circulation in the mid-latitudes are stronger in the winter hemisphere. The enhancement of the indirect circulation suggests the enhancement of baroclinic instability. However, eddy fluxes of the angular momentum are poleward from the jet's core and work to weaken the jet. On the other hand, along the direct circulation in low-latitudes, an isomomentum region extends poleward. This suggests that, like the subtropical jet in the Earth atmosphere, the jet was enhanced as a result of increased angular momentum transport due to the enhanced and expanded low-latitude direct circulation (Hadley circulation). Such a north-south asymmetry of about 10 m/s in zonal winds is also suggested by the Akatsuki observations (Horinouchi et al., 2018). Thus, analyses considering Venusian seasons are coming to be important both for observational and numerical studies.

金星の自転軸の傾きは約 2.6 度と非常に小さいために、その影響 (季節変化) はほとんど着目されてこなかった。地表付近では、放射緩和時間は数万地球日にもなるため、季節変化はほとんどないと考えられる。一方、高度 60 から 70 km 付近では放射緩和時間は数十から数地球日程度であり、地球大気のそれと大差がなく、自転軸の傾きの影響が無視できるとは限らない。Yamamoto and Takahashi (2007) は、数値実験で金星大気循環に対する自転軸の傾きの影響を調べ、2.6 度の傾きではスーパーローテーションの強さは影響を受けないことを示した。この結果に基づき、また設定の簡素化のために、国内外のグループによる金星大気シミュレーションにおいて、自転軸の傾きは省略されてきた。一方、金星探査機の Venus Express や「あかつき」によって、雲頂高度 (65 km 付近) の水平風分布が推定されるようになった。また、金星大気シミュレーションの高解像度化によって、細かな循環構造が表現されるようになった。すなわち、スーパーローテーションを含めた金星大気循環に対して、その空間構造を含めた議論ができるようになってきている。

そこで本研究では、改めて自転軸の傾きを入れた金星大気シミュレーションを行った。数値モデルには AFES-Venus (Sugimoto et al., 2014) を用いた。AFES-Venus は放射過程を簡略化し、雲微物理や地形を省略した力学モデルではあるが、雲層付近の低安定度層を導入し、高解像度で計算することで、周極低温域 (Ando et al., 2016) や惑星規模筋状構造（Kashimura et al., 2019）など観測と整合的な構造を再現することに成功している。今回は、水平 1.4 度× 1.4 度 (T85) 鉛直 120 層 (dz = 1 km) の解像度で、自転軸の傾きを 2.6 度に設定し、理想化したスーパーローテーション流を初期値として、6 金星年分の時間発展計算を実施した。その他の（解像度に依存しない）設定は、Kashimura et al. (2019) と同じで

ある。

計算の結果、高度 60 km より上空では、有意な季節変化が示された。特に中緯度の東西風ジェットが、冬半球で夏半球よりも 10 m/s 程度強くなった。また平均子午面循環は、冬半球において、低緯度の直接循環と中高緯度の間接循環がともに強化されていた。中高緯度の間接循環の強化は、傾圧不安定の強化を示唆するものだが、角運動量の渦フラックスはジェットを弱化する向きに存在しており、中緯度ジェット強化とは整合しない。一方、低緯度の直接循環に沿って、等角運動量の領域が極向きに伸びていた。これは、地球大気の亜熱帯ジェットと同様に、低緯度の直接循環（ハドレー循環）の強化拡大による角運動量輸送の増加の結果として、ジェットが強化されたことを示唆している。このような、東西風で 10 m/s 程度の南北非対称は、あかつきの観測結果 (Horinouchi et al., 2018) にも見られている。今後は、観測とシミュレーションの両面で季節を意識した解析が重要となるだろう。

R009-30
B 会場 ：11/7　PM1 （13:45-15:30）
14:30〜14:45

あかつき LIR による金星の惑星規模の波動の鉛直構造と変動の研究

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Long-term variation and vertical structures of planetary-scale waves of Venus observed by Akatsuki LIR

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Venus is a planet with a very long rotation period, but it has a very fast cruising wind that can reach 100 m/s at an altitude of 70 km (Schubert et al., 1980). This wind is called superrotation. Superrotation is predicted to be caused and maintained by momentum transport by non-axisymmetric vortices(Gierasch, 1975; Rossow and Williams, 1979).

As one of the mechanisms for the excitation and maintenance of superrotation, the contribution of planetary-scale waves such as Rossby waves, which are distributed at mid- and high latitudes and propagate slower than the period of superrotation, and Kelvin waves, which are distributed at low latitudes and propagate faster than the period of superrotation, has been suggested. As one of the excitation processes of these planetary-scale waves, it has been suggested that the Rossby-Kelvin instability is responsible for equatorward momentum transport (Iga and Matsuda, 2005; Wang and Mitchell, 2014). Recent GCM calculations have also suggested that Rossby and Kelvin waves appear simultaneously near cloud tops and can be excited by Rossby-Kelvin instability (Takagi et al., 2022).

In this study, we focus on the possible contribution of planetary-scale waves and aim to clarify the structure of planetary-scale waves on Venus from Akatsuki's observations. The existence of planetary-scale waves with a wavenumber of 1, such as Kelvin waves with a period of ˜4 days and Rossby waves with a period of ˜5 days, has been confirmed so far by previous Venus missions (Del Genio and Rossow, 1990; Kouyama et al., 2015; Imai et al., 2019; Kajiwara et al., 2021).

The amplitudes of these planetary-scale waves vary over time scales of several months, as revealed by an analysis of cloud-tracked winds obtained by the Ultraviolet Imager onboard Akatsuki (Imai et al., 2019). Observations by Akatsuki's Longwave Infrared Camera (LIR) have also revealed that waves with different periods appear simultaneously at high latitudes (Kajiwara et al., 2021). However, the long-term evolution of these planetary-scale waves and the structure of their vertical propagation have not been revealed from observations until now. In this study, we improved the method of Kajiwara et al. (2021) and used the LIR data to detect planetary-scale waves from brightness temperature changes. We compared the results for different observation periods and tried to clarify the vertical structures of planetary-scale waves by using the fact that the observation altitude depends on the emission angle.

These periodic analyses revealed the stable existence of periodic waves that appear to be Rossby waves, and that the amplitude of the planetary-scale waves differs depending on the time when the data was taken, and the angle of incidence used in the analysis. These results may be related to variations in background wind velocity and may contribute to the elucidation of the excitation mechanism.

金星上空には，高度 70km で約 100m/s もの速さになる非常に高速の巡行風が吹いている (Schubert et al., 1980)。この風は超回転と呼ばれている。非軸対称渦による運動量の輸送によって引き起こされ，維持されると予測されている (Gierasch, 1975; Rossow and Williams, 1979)。

超回転の励起と維持のメカニズムのひとつとして，中高緯度に分布し超回転の周期より遅く伝播するロスビー波や，低緯度に分布し超回転の周期より早く伝播するケルビン波といった惑星規模の波動の寄与が示唆されている。これらの惑星規模の波動の励起プロセスのひとつとして，ロスビー・ケルビン不安定によって，赤道方向への運動量輸送が担われていることが示唆されている (Iga and Matsuda, 2005; Wang and Mitchell, 2014)。また，最近の GCM 計算によって雲頂付近にロスビー波やケルビン波が同時に出現し，ロスビー・ケルビン不安定によって励起されうることも示唆されている (Takagi et al., 2022)。

本研究では，惑星規模の波が寄与しているこれらの可能性に着目し，観測から金星の惑星規模の波の構造を明らかにすることを目指す。惑星規模の波動はこれまでに，周期 4 日のケルビン波や周期 5 日のロスビー波など，波数 1 の惑星規模の波の存在が金星探査によって確認されている (Del Genio and Rossow, 1990; Kouyama et al., 2015; Kajiwara et al, 2021)。これらの惑星規模の波動は，振幅が短い時間スケールで変化しているということが日本の金星探査機「あかつき」の紫外線イメージャーによる雲追跡の観測から明らかになっている (Imai et al., 2019)。また，「あかつき」の中間赤外カメラによる観測で，高緯度側に複数の周期の波が同時に見えていることも明らかになっている (Kajiwara et al., 2021)。しかし，これらの惑星規模の波動が長期的に変化する様子や，鉛直伝播の構造についてはこれまで観測から明らかにされていなかった。本研究では Kajiwara et al. (2021) の手法を改善したうえで「あかつき」の中間赤外カメラ (LIR）を用い，輝度温度変化から惑星規模の波を検出した。長期間の観測データから得られる結果を比較し，観測高度が光の出射角に依存することを利用して，惑星規模の波動の鉛直構造を明らかにする。

これらの周期解析によって，ロスビー波と見られる周期の波が安定して存在することや，データを取得した時期や解析

に用いた出射角の違いによって惑星規模の波の振幅が異なっているといった結果が得られた。これらは背景の風速の変動と関係がある可能性があり，励起メカニズムの解明に寄与する可能性がある。

R009-31
B 会場 ：11/7　PM1 （13:45-15:30）
14:45〜15:00

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A new constraint on HCl abundance at the cloud top of Venus

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We provided a new constraint on HCl abundance at the cloud top of Venus by infrared spectroscopy using a cross-dispersed high-resolution echelle spectrograph, iSHELL, mounted on the NASA Infrared Telescope Facility (IRTF). This study aimed to investigate the inconsistency in HCl abundance reported by previous ground-based observations and solar occultation measurements by Venus Express. Venusian dayside observations at a solar phase angle of ˜90 deg were conducted during August 6-7, 2018 and August 18-20, 2020 (UT), when the Venusian afternoon and morning sides were visible, respectively. The high spectral resolving power of ˜80,000 and large Doppler shift (˜13 km/s) enabled us to measure the Venusian lines with less contamination by terrestrial ones. We analyzed the $H^{35}Cl$ P(5) and $H^{37}Cl$ P(6) lines at 2775.8 and 2750.1 cm^{-1}, respectively in the 1-0 band together with $^{16}O^{12}C^{18}O$ P- and R-branch lines of the 20001-00001 band, which fell in the same spectral orders as the HCl lines. The $^{16}O^{12}C^{18}O$ lines were used to derive the cloud top altitude, as the upper clouds had a significant impact on retrieving HCl abundance. The cloud top had an equatorially symmetric structure. The average altitude was 70.8 $\pm$ 0.6 km in the region equatorward of 30 deg and decreased toward higher latitudes. HCl volume mixing ratio was derived as 0.379 $\pm$ 0.013 ppm at an effective altitude of 70.6 $\pm$ 1.1 km and showed no significant latitudinal dependence over latitudes of $\pm$ 70 deg. A small difference of ˜0.02 ppm between 2018 and 2020 would result mainly from a temporal variation. The $H^{35}Cl/H^{37}Cl$ abundance ratio was 3.01 $\pm$ 0.16, with no prominent latitudinal dependence. The obtained HCl volume mixing ratio agreed with the results of previous ground-based measurements, which were approximately one order of magnitude larger than those derived from the solar occultation measurements by Venus Express. This significant inconsistency cannot be explained by systematic uncertainties in our retrieval analysis. To solve this issue, the impact of forward scattering by aerosols on the retrieval method for solar occultation measurements should be investigated further.

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B 会場 ：11/7　PM1 （13:45-15:30）
15:00〜15:15

金星の雲頂温度と紫外反射率の緯度構造と長期変動

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Latitudinal distributions of the cloud-top temperature and UV albedo and their long-term variations

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Clouds have a large albedo and cooling effect on the planet as a whole. In addition, an unknown absorber near the cloud-top of Venus has a broad absorption range from ultraviolet to visible wavelengths with a peak around 360 nm and is considered to play an important role in the absorption of solar energy. Therefore, the sulfuric acid clouds that cover the entire surface of Venus are important for considering the climate on Venus.

Previous observations have revealed that the albedo of Venus fluctuates on a multi-year scale, and it has been further suggested that the fluctuations might be related to periodic solar activity (Lee et al., 2019). The following series of physical processes can be considered as expected climatic feedback in Venus's climate system. The atmospheric cell changes the albedo as a result of the transport of chemicals and cloud particles in the cloud layer and changes the atmospheric temperature by altering the radiation balance of the planet as a whole. This change in atmospheric temperature alters atmospheric cells. However, it is still unclear what the latitudinal distributions in cloud-top height and cloud-top temperature reflect. The possible feedbacks include cloud physics, radiative transport, and Hadley cell, but no combined observational data have clarified them.

In this study, we aim to investigate the causal relationship between different physical processes occurring on Venus by analyzing long-term data acquired by multiple instruments onboard AKATSUKI at the same time. We have derived the interannual variations of the mean latitudinal distributions of the cloud-top temperature and the albedo, and the time-series variation over 8 Venusian years at each latitude, by analyzing the long-term data consisting of images continuously taken by the 10 μ m wavelength Longwave Infrared Camera (LIR) and the 365nm wavelength UltraViolet Imager (UVI) onboard AKATSUKI. The results show that both mean latitudinal distributions are generally symmetric or asymmetric, and their structures differ depending on the period averaged over 1 Venusian year. The time series of each latitude showed quasi-periodic variations on the scale of a few years. In the future, we plan to examine the vertical profile of atmospheric temperature obtained from radio occultation, which is complementary to the horizontal profile of LIR, to discuss the factors that contribute to the latitudinal distribution of cloud-top temperature in the horizontal and vertical directions. In addition to the qualitative discussion so far, in order to conduct quantitative analysis, we will derive the annual average of cloud-tracked winds using LIR (Fukuya et al., 2021), which can observe cloud-top temperature day and night. We will also discuss how the wind speed is related to the albedo and cloud-top temperature.

雲は大きなアルベドをもたらし惑星全体で大きな冷却効果を持つ. また金星の雲頂付近に存在する未知の吸収体は波長 360 nm 付近をピークとする紫外から可視までの幅広い吸収特性をもち, 太陽エネルギー吸収に重要な役割を担うとされている. そのため金星全球を覆う硫酸の雲は金星の気候を考える上で重要となってくる.

これまでの観測から金星の紫外アルベドが数年スケールで変動していることが明らかになっており, さらにその変動が周期的な太陽活動と関係している可能性が示唆されている（Lee et al.,2019）. ここで金星の気候システムを考えるうえで予想される気候フィードバックとして, 大気循環により雲層内の化学物質や雲粒が輸送された結果アルベドが変化し, 惑星全体の放射収支が変化することで大気温度が変化し, さらにその大気温度変化が大気循環を変えるといった一連の物理プロセスが考えられる. しかし雲頂温度の緯度による違いが何を反映するのかについては未だわかっていない. そこで考えられるのは雲物理・放射輸送・ハドレー循環を含むフィードバックであるが, これらを明らかにする複合的な観測データはこれまでなかった.

そこで本研究では, 金星探査機「あかつき」に搭載された複数の観測機器が同時期に取得した長期的なデータを解析することによって金星で生じている異なる物理プロセス間での因果関係を突き止めることを目的とする. 現在我々は「あかつき」搭載の波長 10 μ m の中間赤外カメラ（LIR）と波長 365nm の紫外カメラ（UVI）が連続的に撮影した画像からなる長期的なデータを解析することにより, それぞれ雲頂の温度と紫外アルベドの平均緯度分布の年々変動, 及び各緯度での 8 金星年に渡る時系列変化を導出した. その結果, どちらの平均緯度分布も概ね対称な時期と非対称な時期があり,1 金星年に渡って平均した期間によってその構造は異なることがわかった. また各緯度の時系列変化については, 数年スケールで準周期的な変動が見られた. 今後は水平分布が得られる LIR とは相補的である, 電波掩蔽観測から得られた大気温度の鉛直分布も見ていくことで, 雲頂温度緯度分布の要因を水平鉛直方向に切り分けて議論していく予定である. またこれまでの定性的な議論に加えて定量的な解析を行なっていくために, 昼夜問わず雲頂温度を観測できる LIR を用いた雲追跡（Fukuya et al.,2021）を行うことで, 雲追跡風の年平均を導出しそれが紫外アルベドや雲頂温度とどのような関わりがあ

るのか考察していく予定である.

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B 会場 ：11/7　PM1 （13:45-15:30）
15:15〜15:30

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Spectroscopic and imaging observation of Venus for identification of an unknown absorber by a balloon-borne telescope FUJIN-2

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Gaseous species that absorb solar light in the wavelength region of 280 – 500 nm exist in the Venusian atmosphere. It has been known that SO2 absorbs light with wavelengths shorter than 320 nm, whereas it has not yet been identified what gas species are responsible for absorption with wavelength longer than 320 nm. A recent study suggests S2O and OSSO are the most plausible candidates as the unknown absorber [Perez-Hoyos et al., 2018].

A balloon-borne stratospheric telescope FUJIN-2 will obtain near-ultraviolet to visible spectra and images of Venus to identify the unknown absorber. From the upper stratosphere at an altitude of ˜32 km where absorption by the ozone layer is much weaker than the ground level Venus reflection spectra down to 290 nm can be measured. The reason why the unknown absorber has not been identified for a long time is that the spectral resolution of the past spectral observations of Venus was too low to resolve the characteristic absorption features by gaseous species. FUJIN-2 enables us to observe Venus in the near ultraviolet region where observation is impossible from the ground, with a high spectral resolution at a far low cost compared with an orbiter or a satellite telescope.

The gondola is 3.5 m high and weighs 1.23 t including the weight of ballast of 550 kg. The spectrometer onboard FUJIN-2 covers a spectral range of 200 – 550 nm with a spectral resolution of ˜0.5 nm, which is high enough to resolve characteristic absorption features by the candidate molecules. A Cassegrain telescope with a clear aperture of 400 mm is mounted on the gondola, of which attitude is stabilized with respect to the inertial space by an active decoupling mechanism and control moment gyros. Geomagnetic sensors and GPS are used to determine attitude and position of the gondola. A target object is found by wide and narrow star sensors and tracked by the telescope mount so that the object is always at the center of field-of-view of the telescope. Guiding error is detected by a position sensitive PMT and corrected by a tip/tilt mirror (TTM) installed between the secondary mirror and the main focus in real time. A power supply unit with Li-ion batteries, onboard computers, a power supply for TTM, and an Iridium satellite communication receiver/transmitter are installed in a pressurized chamber in which temperature and pressure are kept at a room condition.

The balloon experiment will be conducted in Alice Springs in Australia in March/April, 2023. An image of Venus at the wavelength of 365 nm where the absorption contrast is the highest in the near ultraviolet and visible regions will be acquired to distinguish dark and bright regions seen in the ultraviolet. During 4 hours of the expected level flight duration spectra and images at low, middle and high latitudes of Venus will be obtained. From the spectra obtained by the experiment the unknown absorber will be identified, and a solar heating rate in the cloud layer will be estimated with a chemical dynamical atmospheric model.

R009-P01
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

#笠原　慧 [1)], 吉岡　和夫 [2)], 坂谷　尚哉 [3)], 亀田　真吾 [4)], 松岡　彩子 [5)], 村田　直史 [6)], 原田　裕己 [7)], 船瀬　龍 [3)], 河北　秀世 [8)]
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The Comet Interceptor mission: JAXA's mission definition review and system requirement review completed

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Comets are pristine small bodies and thus provide key information about the solar system 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 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 (24 U) 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. In June 2022, ESA formally adopted Comet Interceptor as the first mission of the Fast class. Subsequently in July 2022, JAXA completed mission definition review and system requirement review, and the team is now referred to as a pre-project in JAXA. Meanwhile several advances have been made in hardware development, and here we will report some details of them.

R009-P02
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

火星 GCM によるレゴリス-大気間の水交換が水蒸気カラム量に与える影響

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Effect of the regolith-atmosphere water exchange on water vapor column simulated by a Mars GCM

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The global distribution of atmospheric water on Mars is controlled by transportation of water vapor and ice clouds, gravitational sedimentation and surface accumulation of water ice clouds, and sublimation of water ice on a surface with the primary source from the northern polar cap. In addition to them, the absorption and desorption by surface regolith are also thought to regulate the diurnal water cycle (e.g., Jakosky et al., 1997). For example, a recent mesoscale simulation (Steele et al., 2017) with an active regolith reproduced the diurnal variations in relative humidity consistently with the measurements by the Rover Environmental Monitoring Station (REMS) onboard Curiosity under the assumptions of several adsorption isotherms. As for the study of global regolith-atmosphere water exchange using a Mars General Circulation Model (GCM), Bottger et al. (2005) implied that regolith exchange only about 10% of the atmospheric water vapor column and cannot contribute to reproducing the diurnal variations of water vapor column, which was a different claim from the studies using mesoscale models about the importance of an active regolith. However, the sensitivity of adsorption isotherms has not been discussed well. We started to study the regolith-atmosphere interaction using a GCM to clarify that. We have newly implemented a regolith scheme based on Zent et al. (1993) and Bottger et al. (2005) into our Mars GCM with the water cycle (Kuroda, 2017). We performed two kinds of simulations using two different adsorption isotherms, which are defined by Fanale and Cannon (1971) and Jakosky et al. (1997) to check the sensitivity to them. The former has been used in previous GCM studies, and the latter has been said to be the most appropriate in mesoscale models. We ran the GCM for a Mars year and showed that the adsorption likely occurred in the areas with high water vapor and lower temperatures. Regolith adsorbed water vapor efficiently in the northern summer (Ls ˜90 degrees), which is consistent with the previous study (Bottger et al., 2005). Also, the amount of water in the subsurface can vary reasonably depending on the defined adsorption isotherms. When the adsorption isotherm with a large temperature dependence of adsorption at low temperatures (Fanale and Cannon, 1971) was defined, the water vapor flux on the surface became large, which indicated that previous GCM studies with an active regolith presumably overestimated the amount of adsorbed water at night and early morning. Our results also suggested that the regolith less contributed to the diurnal variation of water vapor column. In the presentation, we will discuss why the implications of the active regolith contribution were not consistent between the GCM and mesoscale models.

火星における大気中の水の分布は、水蒸気や水氷雲の輸送、重力沈降と地表蓄積、北極冠を主要な供給源とする地表での水氷の昇華によって制御されている。それらに加えて、地表レゴリスによる吸着・脱着も水循環の日内変動を制御していると考えられている (e.g. Jakosky et al., 1997)。例えば、レゴリス-大気間の交換を考慮したメソスケールシミュレーション (Steele et al., 2017) では、いくつかの吸着等温線を用いて、キュリオシティ搭載のローバー環境モニタリングステーション (REMS) による測定値と一致する相対湿度の日周変動が再現された。火星大循環モデル (GCM) を用いたレゴリス-大気間の水交換の研究では、Böttger et al. (2005) が、レゴリスは大気水蒸気柱の 10 %程度しか交換せず、水蒸気カラム量の日内変動の再現には寄与しないことを示唆しており、レゴリスの重要性について、メソスケールモデルによる研究とは異なる主張をしている。しかし、吸着等温線の感度については、これまであまり議論されてこなかった。それを明らかにするために、GCM を用いたレゴリス-大気相互作用の研究を開始した。我々は Zent et al. (1993) と Böttger et al. (2005) に基づくレゴリススキームを、水循環を考慮した火星 GCM に新たに実装した (Kuroda, 2017)。Fanale and Cannon (1971) と Jakosky et al. (1997) で定義された 2 種類の吸着等温線を用いてシミュレーションを行い、その感度を確認した。前者はこれまでの GCM 研究で用いられてきたものであり、後者はメソスケールモデルにおいて最も適切であると言われてきたものである。モデルを 1 火星年分走らせたところ、水蒸気が多く、温度が低い領域で吸着が起こった可能性が高いことが示された。レゴリスは北半球の夏 (Ls ˜90 ☒) に効率よく水蒸気を吸着し、これは以前の研究 (Böttger et al., 2005) と整合的であった。また、地下の水量は定義された吸着等温線によって有意に変化することがわかった。低温での吸着の温度依存性が大きい吸着等温線 (Fanale and Cannon, 1971) を定義すると、表層の水蒸気フラックスが大きくなり、レゴリスが活発なこれまでの GCM 研究では夜間から早朝の吸着水量が過大評価されていた可能性がある。また、レゴリスが水蒸気カラム量の日内変動にあまり寄与していないことも示唆された。発表では、なぜレゴリスの寄与が GCM とメソスケールモデルの間で整合しなかったのかについて議論する。

R009-P03
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

金星大気雲層下部における二酸化硫黄の高度分布の導出

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Derivation of vertical profiles of sulfur dioxide in the Venus cloud layer by the Akatsuki radio occultation measurements

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On Venus, clouds exist at the altitudes from 45 to 70 km, covering the entire planet. This thick cloud layer plays a key role in controlling the heat budget in Venus atmosphere. One of the missing information is the vertical distribution of the sulfur dioxide (SO_2) which is the main chemical compound in forming the sulfuric acid clouds.

The previous observations of SO_2 vertical distribution in the cloud layer have been limited to the in-situ measurements of the VEGA probes and the radio occultation (RO) measurements of the Venus Express. The former showed only two vertical profiles of the SO_2 mixing ratio from the surface to 60 km. The latter derived the mean SO_2 mixing ratio at 51-54 km.

In the present study, we estimated the SO_2 vertical profiles in the cloud layer (50-55 km) using the data obtained by the RO measurements in the Japanese Venus climate orbiter mission, "Akatsuki". Provided that sulfuric acid vapor cannot be supersaturated in the cloud layer, we attributed any attenuations of radio waves that exceed the saturation curve of sulfuric acid vapor to the attenuations by SO_2. We examined the SO_2 errors by estimating the dependence of the sulfuric acid saturation mixing ratio on the concentration of sulfuric acid in cloud particles and by considering the noise of the radio wave intensity.

The averaged profile showed the mixing ratio of about 200 ppm at 50 km and 50 ppm at 55 km, decreasing with increasing altitude. Our results are consistent with the previous results of the VEGA probes and Venus Express RO measurements. Additionally, we found a local time dependence of SO_2 mixing ratio that tends to decrease during the daytime in the cloud layer, similar with previous observations conducted above the cloud layer. Long-term variations were not found in the present analysis.

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。この雲の主材料である硫酸蒸気の生成には二酸化硫黄（SO_2）が不可欠であり SO_2 の時空間分布に関する情報は金星の雲物理を理解する上で重要と言える。

SO_2 の分布に関しては、雲層上空では多くの観測に基づいた統計的な研究が行われているが、雲層内の観測は極めて少なく、VEGA プローブ観測と Venus Express 電波掩蔽観測に限られる。前者は、地表面から高度 60 km までの SO_2 混合比の高度分布を示したが、その観測数は 2 本のみである。前者は、北極域を中心に全球で観測を行い高度 51-54 km における SO_2 混合比の平均値を導出した。また、雲頂では SO_2 混合比のローカルタイム依存性や長期変動が報告されている一方で、雲層では観測が極めて少ない。

本研究では、Venus Express 電波掩蔽観測で採用された手法を拡張し、あかつき電波掩蔽観測データから高度 50-55km での SO_2 の高度分布を得ることを試みる。電波掩蔽観測では、大気分子が電波を吸収することを利用して、探査機から地球に送信した電波の減衰率からその大気組成の濃度を導出できる。電波掩蔽観測で利用される周波数帯に関して、金星において電波吸収に寄与する気体種は、CO_2、N_2、SO_2、硫酸蒸気である。また、電波減衰の要因には、大気による吸収の他に発信機のアンテナの指向誤差、ディフォーカシングロスが挙げられる。受信強度の時系列から、後者の２つの影響を除去することで残りの減衰量から大気による吸収率を推定することができる。その後、CO_2 と N_2 による吸収率を差し引き硫酸蒸気と SO_2 の混合比を導出する。Venus Express 電波掩蔽観測データを解析した Oschlisniok et al. (2021) の解析では飽和蒸気圧が小さく硫酸が気体の形ではほぼ存在できないと考えられる高度領域 (51-54km) での減衰は全て SO_2 に起因すると仮定することで、雲層における平均的な SO2 混合比を得ていたが、本研究では硫酸蒸気が過飽和しないと仮定することで、雲層の SO_2 高度分布の推定を試みた。

SO_2 導出過程においては、硫酸飽和混合比の雲粒硫酸濃度への依存性を検討した結果 98 %の硫酸濃度を計算に用いることとした。また、掩蔽前の受信強度のばらつきを金星大気以外のすべての要因に起因する効果だとみなし、それをノイズとして掩蔽中の受信強度に加えた上で SO_2 を導出したところ、その差は 50ppm 程度であった。そのため、この値を金星大気以外の要因による誤差とみなすこととした。

導出された SO_2 混合比の高度 50 km における平均値は 200 ppm 程度であり、高度が上がるにつれて混合比は減少し、高度 55 km では 50 ppm 程度であった。混合比の値は、Venus Express 電波掩蔽観測結果の先行研究と整合的であり、また、高度変化についても VEGA プローブ観測と整合している。また、雲頂で報告されているような昼で減少し夜に増加するというようなローカルタイム依存性が今回導出した高度域（雲層）でも示唆された。一方で、長期変動に関しては、雲頂のような明確な変動は見られなかった。

R009-P04
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

TGO/NOMAD 火星大気観測データを用いた $^{13}CO/^{12}CO$ 比解析の初期結果

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Carbon isotope ratio in CO on Mars observed by TGO/NOMAD: Preliminary results

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It has been suggested that Mars once had a thick atmosphere with a surface pressure of more than about 0.5 bar around 4 Ga (e.g., Kurokawa et al., 2018). The isotopic compositions of atmospheric components have been used to constrain the Martian atmospheric evolution. In particular, carbon isotope ratios are the important tracer to constrain the origin of the organic on Mars. The isotopic ratio can be fractionated by degassing, condensation, photodissociation, molecular diffusion, and atmospheric escape to space. However, the previous observations of carbon isotope ratios are limited to CO_2, the main component of the Martian atmosphere. Schmidt et al. (2013) suggests that $^{13}C/^{12}C$ (δ 13C) in ^{13}CO theoretically decreases by around 200 per mil through the isotopic fractionation by photodissociation of CO_2 by the quantum mechanical methodology. Thus, in order to fully understand the carbon isotopic cycle of the atmosphere, we also need observation of the carbon isotope ratio in CO. ExoMars Trace Gas Orbiter (TGO), which started science operation in 2018, has two high-spectral resolution spectrometers that carry out solar occultation measurements, which allows us to perform a sensitive measurement of trace gas on Mars. The characterization of the isotopic ratios are one of the main science goals. In fact, previous studies with TGO measurements have shown the isotopic ratios of carbon, oxygen, and hydrogen in CO_2 from 70 to 100 km and in water vapor from surface to 50 km (Vandaele et al., 2018; Alday et al., 2020, 2021; Villanueva et al., 2021, 2022). In this study, we attempt to derive the carbon isotopic ratios in Martian CO for the first time, using infrared spectral data observed by Nadir and Occultation for MArs Discovery (NOMAD) on board TGO. Moreover, we will investigate the vertical profile of carbon isotopic ratios in CO to constrain how isotopic ratios in the lower atmosphere are transported vertically to the upper atmosphere, where the atmosphere escapes into space.

Thanks to the solar occultation technique and high spectral resolution (R～17,000) achieved by simultaneous use of an echelle grating and Acousto-Optic Tunable Filter (AOTF), NOMAD enables us to perform a high-precision remote sensing analysis of atmospheric trace gas species and isotopic ratios. First, in this study, we have selected the best absorption lines for derivation of the isotope ratios. In order to derive the isotope ratio accurately, we need to use a set of ^{12}CO and ^{13}CO absorption lines that have similar weighting functions along the line of sight. There are many strong absorption lines of ^{12}CO and ^{13}CO in 4100-4250 cm^{-1} and we can observe a set of ^{12}CO and ^{13}CO absorption lines that have similar intensities in 4157-4190 cm^{-1}, which is echelle grating of NOMAD diffraction order 185. Furthermore, considering the temperature dependence of the absorption lines and contamination of light from other diffraction orders, we chose 4180.28 cm^{-1} for ^{12}CO and 4180.86 cm^{-1} for ^{13}CO to derive isotope ratios because these lines allow the smallest uncertainty.

Solar occultation observations by order 185 of NOMAD is a new observation mode, which started from February in 2022. In this study, we have analyzed 13 orbits data from 2022/2/24 to 2022/4/8. For the retrieval, we use a radiative transfer and inversion code, ASIMUT (Vandaele et al., 2006), which were used in the previous studies with the NOMAD data. This code uses Optimal Estimation Method (OEM) (Rodgers, 2000) to find the best parameters to fit the data. Temperature and pressure profiles in the Martian atmosphere for radiative transfer calculations are obtained from the theoretical predictions by GEM-Mars GCM (Daerden et al., 2019). We use the total amount of ^{12}CO and ^{13}CO along the line of sight as free parameters, and performed the retrievals for each altitude independently. We further selected the results retrieved in each altitude by the two following criteria - (1) in order to distinguish between absorption and noise, we only selected data in which the absorption features of ^{12}CO and ^{13}CO being 5 times larger than instrumental noise (i.e., SNR $>$5); (2) in order to ensure the similar weighting functions along the line of sight, optical depth of absorption lines of ^{12}CO and ^{13}CO is smaller than unity. As a result of these post-selections, we found that we can derive the $^{13}CO/^{12}CO$ from 20 km to 50 km. The retrieved isotope ratios show a strong depletion of ^{13}CO, δ ^{13}C being between -300 and -800 per mil from 20 km to 50 km in all of the 13 orbits. When we take the average in the altitude direction for all orbits, the averaged value of δ ^{13}C = -634 per mil and its standard derivation is 141 per mil. The degree of the depletion of ^{13}C in CO evaluated by this preliminary result is much stronger than the theoretical estimates of the photo-induced isotopic fractionation suggested by Schmidt et al. (2013). We plan to evaluate the effects of temperature, instrumental calibration and retrieval method on these preliminary results in order to verify the validity of our observation and consider the cause of the gap with theoretical research.

40 億年前の火星は 0.5 気圧以上の現在よりも非常に厚い大気に覆われていたと推定されており (Kurokawa et al., 2018)、大気の同位体組成は火星大気の進化を制約するために用いられてきた。特に炭素同位体比は、有機物の起源を制約する重要なトレーサーであると考えられており、それらは、脱ガス・凝縮・光解離・分子拡散・宇宙空間への散逸などによって変化し得ると考えられている。しかし、これまでの炭素同位体比の観測研究は、火星大気の主成分である CO_2 に限定されてきた。一方、Schmidt et al. (2013) では、CO_2 の光解離によって生成される CO の $^{13}C/^{12}C$ 比 ($\delta\ ^{13}C$) が約 200 ‰減少することが理論的に示唆されており、火星大気の炭素同位体比循環を総合的に理解するためには、CO 中の炭素同位体比も合わせて導出することが求められている。2018 年から稼働している、欧州火星探査衛星 ExoMars Trace Gas Orbiter (TGO) は、高い波長分解能を有する赤外分光器を用いた太陽掩蔽観測を実施し、そのような同位体比の観測研究が主要な科学目標の一つである。実際、これまでの研究では、70-100km における CO_2 や 0-50km における水蒸気の炭素・酸素・水素の同位体比が調べられてきた (Vandaele et al., 2019; Alday et al., 2021, 2022; Villanueva et al., 2021, 2022)。本研究は欧州の火星探査衛星 TGO に搭載された赤外分光器 Nadir and Occultation for MArs Discovery (NOMAD) で得られた赤外スペクトルデータを用いて、火星大気 CO 中の炭素同位体比の初導出を試みた。さらに、CO 炭素同位体比の高度分布も導出し、下層大気の同位体比が、大気が宇宙空間へ消失する上層大気へ、どのような分別を経て鉛直輸送されるかの制約も目指す。

本研究で用いる赤外分光計 NOMAD は、輝度の高い太陽を背景光とした太陽掩蔽観測手法と、音響光学可変素子とエッシェル回折格子の併用により達成された高波長分解能 (R〜17,000) により、大気微量成分や同位体比の高精度リモートセンシング分析が可能となっている。本研究ではまず同位体比導出に用いる最適な吸収線の選定を行った。正確な同位体比の計測には、観測視線方向に同じような感度を持つ ^{12}CO と ^{13}CO の吸収線を選ぶ必要がある。^{12}CO と ^{13}CO の強い吸収線は、4100-4250 cm^{-1} に豊富に存在するが、NOMAD のエッシェル回折格子次数 (order) 185 に相当する 4157-4190 cm^{-1} の波長帯では同等の線強度で ^{12}CO と ^{13}CO が観測可能である。さらに、吸収線の温度依存性や、他の次数の光からのコンタミを考慮し、同波長域に存在する ^{12}CO・^{13}CO それぞれ 7、9 本の吸収線のうち、12CO は 4180.28cm^{-1}、13CO は 4180.86cm^{-1} の吸収線を解析することが、最も不確定性が少なくなることを明らかにした。

NOMAD の Order185 による太陽掩蔽観測は、2022 年 2 月から運用に追加された新しい観測モードである。本解析では、2022/2/24-2022/4/8 に取得された 13 軌道について解析を行った。解析には、NOMAD データによる先行研究でも使用されている放射伝達・反転解析コード ASIMUT (Vandaele et al., 2006) を用いた。同コードは、最尤推定法 OEM (Rodgers, 2000) を用いて観測データに合う最適な変数を調べる。放射伝達計算に用いる、火星大気の温度・圧力分布は、GEM-Mars GCM による理論計算 (Daerden et al., 2019) を用いた。^{12}CO と ^{13}CO の観測視線方向の積算量を変数とし、リトリーバルを各高度で取得されたスペクトルに対して独立に行った。得られた各高度でのリトリーバル結果は、以下の 2 つの基準でさらに選定を行った - (1) シグナルとノイズの混同を防ぐため、^{12}CO と ^{13}CO の吸収線の深さがノイズレベルの 5 倍以上; (2) 視線方向に同じような感度であることを担保するため、^{12}CO と ^{13}CO の吸収線の光学厚さが 1 以下。これらの選定の結果、^{12}CO と ^{13}CO の比を導出できる高度範囲が 20-50km であることがわかった。導出された同位体比は、解析した 13 軌道の全てにおいて、20-50km で $\delta\ ^{13}C$=-800 から-300 ‰と比較的大きな同位体分別を示した。全ての結果を平均すると、$\delta\ ^{13}C$=-634 ‰、標準偏差は 141 ‰となった。この初期結果は、Schmidt et al. (2013) により予想された同位体分別よりも大きい。今後は、気温・装置・リトリーバルなどが結果に与える影響について定量的に評価し、初期解析結果の妥当性を検証すると共に、理論予測とのギャップの原因を考察していく予定である。

R009-P05
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

あかつき水平風速データ同化を用いた金星大気大循環モデルによるコールドカラーの再現

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([1] 京都産業大学,[2] 慶應義塾大学,[3] 東京学芸大

Cold collar reproduced by a Venus GCM with the Akatsuki horizontal wind assimilation

#Hiroki Ando[1)], Yukiko Fujisawa[2)], Norihiko Sugimoto[2)], Yoshihisa Matsuda[3)]
([1]Kyoto Sangyo University,[2]Keio University,[3]Tokyo Gakugei University

The atmospheric thermal structure in the Venus upper polar region is reproduced by the assimilation of horizontal winds derived from the Akatsuki ultra-violet images. The obtained structure is well consistent with infrared and radio occultation measurements. In particular, the unique thermal structure in the Venus polar vortex such as cold collar and warm polar region in our model is realistic: the level where the cold collar is located and the temperature difference between cold collar and warm polar region are consistent with the measurements. The reasons why the thermal structure in the upper polar region is realistic are that the zonal wind distribution around the cloud top level and the structure of the residual mean meridional circulation induced by the thermal tide are improved. Our results also suggest that the thermal structure in the Venus upper polar region is closely related to the atmospheric dynamics.

あかつき紫外イメージャ（UVI）で得られた雲頂付近の水平風速データの同化をした金星大気大循環モデルを用いて、金星上層の極域の熱構造を再現した。再現された構造は赤外観測や電波掩蔽観測と整合している。特に、コールドカラーやそれに取り囲まれた温暖な極周辺の温度構造は、実際の観測と極めて良く一致している。金星上層の極域の熱構造が現実的なものになった理由は、雲頂付近の東西風や熱潮汐波により励起される残差子午面循環の構造が改善されたためであると考えられる。本研究の結果は、金星上層の極域の熱構造は主に大気の運動が決めていることを示唆する。

R009-P06
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

金星探査機あかつきによる電波掩蔽観測で得られた気温擾乱に関する研究

#萩野　藍霞 [1)], 野口　克行 [2)], 安藤　紘基 [3)], 今村　剛 [4)], 杉本　憲彦 [5)], 藤澤　由貴子 [6)], 高木　征弘 [7)]
([1] 奈良女大・理・環境,[2] 奈良女大・理・環境,[3] 京産大,[4] 東京大学,[5] 慶大・日吉物理,[6] 慶應大,[7] 京産大・理

A study of the temperature perturbations obtained from the radio occultation measurements by the Venus Climate Orbiter Akatsuki

#Aika Hagino[1)], Katsuyuki Noguchi[2)], Hiroki Ando[3)], Takeshi Imamura[4)], Norihiko Sugimoto[5)], Yukiko Fujisawa[6)], Masahiro Takagi[7)]
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We analyzed the small-scale (vertical wavelengths of 4km or less) temperature perturbations between 45N and 45S in the Venus atmosphere using the radio occultation measurements conducted by the Akatsuki spacecraft. We found a characteristic structure in the local time-height distribution around 80 km altitude. The possible mechanisms generating such structures includes the spontaneous gravity wave radiation (Sugimoto et al. [2021]) and thermal tidal waves themselves with small vertical wavelengths that were suggested to exist at higher altitudes (Pechmann and Ingersoll [1984]).

本研究では、赤道周回軌道である「あかつき」の電波掩蔽観測にて取得された気温の高度分布データを用いて、北緯 45 度から南緯 45 度における小規模な (鉛直波長 4 ㎞以下の) 気温擾乱を解析した。2016 年から 2022 年までのデータを用いて解析を行ったところ、高度 80km 付近の地方時-高度分布に特徴的な構造が見られた。このような構造が見られる原因としては、まず大規模な大気運動から自発的に放射された大気重力波 (Sugimoto et al. [2021]) が挙げられる。また、線形解析によると熱潮汐波の鉛直波長が高高度ほど小さくなる可能性が示唆されており (Pechmann and Ingersoll[1984])、熱潮汐波そのものである可能性も考えられる。講演では、大気安定度との関連についても議論する。

R009-P07
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

MAVEN/STATIC の観測に基づくダストストーム期間の火星電離圏イオン密度の周期変動の研究

#長内　大河 [1)], 益永　圭 [2)], 原　拓也 [3)], 寺田　直樹 [1)], 堺　正太朗 [1)], 吉田　奈央 [1)]
([1] 東北大・理・地物,[2] 宇宙研,[3]SSL, UC Berkeley,[4] 東北大・理・地球物理,[5] 東北大・理・地物

Periodic variations of ion density in the Martian ionosphere during dust storms observed by MAVEN/STATIC

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Due to no intrinsic magnetic fields on Mars, a state of Martian upper atmosphere is highly controlled by the solar wind and solar EUV flux. However, recent studies showed that the compoition of various atmospheric components in the Martian thermosphere and exosphere fluctuates in response to Martian dust storms (e.g., Yoshida et al., 2021). Recently, HISAKI space telescope observations during a major dust storm period have shown that the total amount of hydrogen and oxygen atoms in the upper atmosphere varies periodically, likely imposed by the atmospheric waves in the lower atmosphere (Masunaga et al., submitted). However, it is unclear how the variations of thermospheric and exospheric abundances affect ion abundances in the upper atmosphere during dust storms.

Using the SupraThermal And Thermal Ion Composition (STATIC) on the MAVEN spacecraft, we analyzed the variation of the number density of two ion species (H^+, O^+) observed, during a major dust storm that occurred in September 2016.

To remove the solar zenith angle effect on the density variations, we only used the data in which the solar zenith angle of the MAVEN position was 100 degrees considering dependency on the solar flux. We studied diurnal variations of H^+ and O^+ number densities in the ionosphere and found that H^+ increase by a factor as the day passes and O^+ fluctuate constantly. Furthermore, periodicity in the density variations was determined using the Lomb-Scargle periodogram method. We found that H^+ and O^+ show characteristic periodic variations in the ionosphere (180-250 km).

In this presentation, we will discuss the periodic density variations of H^+ and O^+ in the ionosphere observed by STATIC and compare with those of H and O in the thermosphere found in previous studies.

固有磁場を持たない火星において、超高層大気の状態変化は太陽風や太陽 EUV フラックスの影響が支配的であると考えられてきた。しかし、近年の研究により火星の熱圏や外気圏の組成がダストストームに応じて変動することが明らかになり (e.g., Yoshida et al., 2021)、ダストストームが火星超高層大気へ及ぼす影響が重要視され始めている。

近年、ダストストーム期間におけるひさき衛星の分光観測により、火星超高層大気中の水素原子や酸素原子の総量が下層大気中の大気波動と同期するように周期変動している様子が観測された (Masunaga et al., submitted)。このように熱圏や外気圏に大規模な変化が起これば、中性大気を起源とする電離大気にも同様の影響を及ぼすと予想される。しかし、ダストストーム期間中の電離圏イオンの数密度変動の周期性については調べられていない。そこで本研究の目的は、火星探査機のイオン質量分析器の観測データを用い、ダストストーム中に発生する熱圏・外気圏大気の周期変動が火星電離圏イオンにどのような影響を及ぼしているのか明らかにすることである。

我々は火星探査機 Mars Atmosphere and Volatile EvolutioN (MAVEN) 搭載の SupraThermal And Thermal Ion Composition (STATIC) を用い、2016 年 9 月の大規模ダストストーム期間に火星超高層で観測された 2 つのイオン種、(H^+, O^+) の数密度の変動、周期性について解析を行なった。電離圏領域 (180-250km) でそれぞれのイオン種に対し 1 日ごとの平均数密度変動を調べ、H^+ は数倍で増加、O^+ は一定で推移する変動が見られた。この際、イオン数密度の太陽天頂角依存性の影響を取り除くため、日照領域のみのデータを解析し、さらに Lomb-Scargle periodogram 法を用いて周期を求めた。その結果、電離圏 (高度 180-250km) において H^+, O^+ に特徴的な周期変動が見られていることを発見した。

本発表では、ダストストームで観測された電離圏 H^+ と O^+ の周期的密度変化と先行研究によって発見された熱圏大気の H と O の周期変化に関して比較を行い、電離圏と熱圏の関係について議論する。

R009-P08
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

金星夜面に見られる巨大な雲の不連続（ECC）の測光にもとづく研究

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A photometric study of the Enormous Cloud Cover (ECC) seen in the Venus' night-side disk

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The 2-um infrared camera (IR2) onboard Akatsuki observed a remarkable cloud feature in the Venus' night-side disk, a sharp discontinuity of cloud opacity which subtends latitudinally to some thousands of km (Peralta et al., 2020). Though obvious and seemingly common in the Venus' atmosphere as similar features can be identified in imagery since the beginning of the night-side observations (Allen and Crawford, 1984), the mechanism of this enormous cloud cover (ECC) has not yet been explained.

To characterize this ECC (aerosol size parameters and column numbers), we have analyzed the Akatsuki/IR2 data, as well as the Venus Express/VIRTIS data. Six sets of the Akatsuki/IR2 data (MM-DD = 03-27, 07-22, 08-09, 08-18, 08-27, and 09-06) are measurable with varying photometric uncertainties, due to contaminations from the intense day crescent. Seven VEx/VIRTIS data, as tabulated in Peralta et al. (2020), are also measured by the consistent method with that for IR2 data. A reference region, which is just west of the discontinuity and is seemingly not affected by the ECC, is defined as the background cloud (BC) region. Radiances at the BC and the ECC regions are measured for two IR2 filter passbands (1.735 and 2.26 um). They are plotted in the correlation plot (radiance at 2.26 um in horizontal axis and radiance at 1.735 um in vertical axis). The BC-to-ECC slope can be used to infer the aerosol size and abundance that changes the BC region to the ECC region. Comparison of obtained characteristics of the ECC for different observing times will be presented and implication to the possible mechanism of this large-scale phenomenon will be discussed.

あかつき搭載の 2-um 赤外線カメラ IR2 は金星の夜面に、南北へ数千 km もの広がりをもつ巨大な雲の不連続構造を観測した（Peralta et al., 2020）。過去に地上観測等で得られた画像を見返すとそれらの中にも同様の現象が見られ（Allen and Crawford, 1984）、金星大気の中ではこの構造を生じやすい何かがあるはずだが、そのメカニズムは未解明である。われわれはその見かけから Enormous Cloud Cover (ECC) と名付け、それに影響されない通常雲領域 Background Cloud (BC) 領域との違い（雲粒子サイズなど）を、放射伝達計算を用いた解析で調べた。

あかつき IR2 は観測期間が限られていてデータが多くない（2016 年の 3/27, 7/22, 8/9, 8/18, 8/27, 9/6）ので、Venus Express/VIRTIS データも合わせて解析することとした。ECC の西側に影響を受けていない BC 領域をとり、各々の 2 色測光（IR2 の 1.735um と 2.26um フィルター）を実施した。得られた放射輝度を 2 色の相関グラフにプロット（ただし特殊な座標系を導入）し、BC から ECC への変化を説明する雲モデルを構築した。IR2 データおよび VIRTIS データ全体を比較することで、BC → ECC の標準的なモデルが示唆され、また 2016 年 8 月 18 日は特異な性質を示す日であることも分かった。

R009-P09
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

金星探査機あかつきの紫外画像と放射輸送計算を用いた SO2 輸送の研究

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Study of SO2 transport using UV images taken by Akatsuki and radiative transfer calculation

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The distribution of H2SO4 clouds in the Venus atmosphere is an important factor that influences the solar energy absorbed by Venus. Understanding the sequence of process that SO2, the precursor of cloud, is transported from the lower layers to the cloud top and photochemically changed to H2SO4 is essential for understanding the climate system of Venus.

To observe the spatial distribution of SO2, the Venus orbiter Akatsuki has been taking UV images of the Venus disk from orbit, and because SO2 absorption is mainly around 280-300 nm, the bright and dark patterns in the 283 nm UV images taken by Akatsuki are thought to reflect mainly the SO2 content. However, to quantify the SO2 content, retrievals considering the scattering of solar ultraviolet radiation by H2SO4 aerosols and CO2, which is a major atmospheric constituent, are needed.

In this study, we developed a new method to estimate the SO2 mixing ratio at the cloud top from UV images using a newly developed radiative transfer code under various conditions and estimated the SO2 mixing ratio during the period from 2016 to 2020. We compared the local time-latitude distribution of the SO2 mixing ratio with the atmospheric general circulation model by Takagi et al. (2018), and the dependence of the SO2 mixing ratio on local time was consistent with that of the vertical wind and vertical movement of air calculated by the GCM. The results show that the SO2 variations and the vertical air movements caused by the thermal tidal waves are on the same scale. However, we need to consider the effect of unknown UV absorber as well as SO2 at 283 nm in the future.

金星大気中の硫酸エアロゾルで構成されたの雲の分布は，金星が吸収する太陽エネルギーに影響する重要な要素である．雲の前駆物質である SO2 が下層から雲頂まで輸送され，光化学的に硫酸へ変化する一連のプロセスを理解することは，金星の気候システムを理解する上で不可欠である．

SO2 の空間分布を観測するために，金星周回機あかつきは軌道上から金星ディスクの紫外画像を撮影し続けている．SO2 は 280-300nm 付近に吸収の中心を持つため，あかつきが撮影した 283nm 紫外画像に見られる明暗の模様は主に SO2 の量の大小を反映すると考えられるものの、SO2 の定量のためには硫酸エアロゾルや大気主成分である CO2 による太陽紫外光の散乱を考慮したリトリーバルが必要である．

そこで，本研究では，あかつきが様々な幾何学条件の下で撮影した紫外画像から，新たに開発した放射輸送コードを用いて雲頂での SO2 混合比を推定する手法を開発し，2016 年から 2020 年までの期間の SO2 混合比を推定した．SO2 混合比の局所的な時間緯度分布を Takagi et al. (2018) による大気大循環モデルと比較したところ、SO2 混合比のローカルタイムに対する依存性は、GCM により計算された鉛直風や空気の鉛直速度によるものと矛盾はなかった。ただし，283nm には SO2 だけでなく未同定の紫外吸収物質の影響があるため，その効果も今後考慮する必要がある．

R009-P10
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

月面低周波電波干渉計による科学：太陽系科学・惑星科学の課題

#土屋　史紀 [1)], 岩田　隆浩 [2)], 山田　亨 [2)], 磯部　直樹 [2)], 関本　裕太郎 [2)], 宮崎　康行 [2)], 佐伯　孝尚 [2)], 森　治 [2)], 吉光　徹雄 [2)], 高橋　慶太郎 [3)], 井口　聖 [4)], 大西　利和 [5)], 山内　大介 [6)]
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Science with Lunar Low-Frequency Radio Interferometry: Solar System and Planetary Science

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Non-thermal radio emissions in the low-frequency range below several tens MHz provide a means of understanding the magnetic activity in the stellar and planetary magnetosphere, as well as sensing the plasma density in the propagating media. Because of shielding by the Earth's ionosphere, spacecraft have been used to observe radio waves below 10 MHz. On the other hand, low-frequency radio waves require longer antenna elements, making it difficult to increase the aperture size of the radio antennas mounted on a spacecraft. For this reason, low-frequency radio telescopes on the lunar surface and radio interferometry using formation flights of spacecraft have been considered as future tools of the low frequency radio astronomy.

A feasibility study (FS) to realize a lunar low-frequency radio interferometer is currently underway. In this presentation, we will describe the scientific objectives for solar system and planetary sciences which will be addressed by the future lunar low-frequency radio interferometer.

The FS targets a prototype antenna to be carried on a lander and a prototype interferometer with several self-standing antenna units. The main observation targets in the solar system are non-thermal radio sources from the Sun, Earth, and Jupiter. These radio sources have been studied for many years, and the prototype antennas will be used to evaluate their influence on weak radio wave observations from distant radio sources. On the other hand, the seamless frequency band across 10 MHz and the long-baseline interferometer with Earth's stations are expected to provide new insights on solar and planetary radio emissions. The prototype interferometer will also enable observations of the structure and temporal variation of the lunar ionosphere. The formation of the ionosphere is related to the interaction of the Moon with charged dust and plasma and is expected to provide knowledge related to the lunar environment and science. When a high-sensitivity interferometer with many antenna units is realized in the future, it will be possible to obtain information on lightning activity in planetary atmospheres, auroral radio emissions of ice giant planets, the magnetic activity of stars with habitable planets, and exoplanet radio emissions.

低周波数帯の非熱的電波は、恒星・惑星磁気圏の磁気活動を把握する手段であるとともに，群遅延から伝搬経路上のプラズマ密度観測が可能となる．10MHz 以下の電波は地球の電離圏により遮蔽されるため，人工飛翔体が観測を担ってきた．一方，低周波ではアンテナ素子が長くなり，飛翔体に搭載するアンテナの大型化が困難になる．このため，月面への低周波電波望遠鏡の建設や，探査機の編隊飛行による電波干渉計が検討されてきた．

現在，月面低周波電波干渉計の実現を目指すフィジビリティスタディ (FS) が進められており，本講演では，太陽系科学・惑星科学の研究対象について，月面低周波電波干渉計により実現する科学課題を述べる．本 FS は，着陸機に搭載するプロトタイプアンテナと，自立型アンテナユニット複数台によるプロトタイプ干渉計を対象としている．太陽系内の主な観測対象は，太陽，地球，木星の非熱的電波となる．これらの電波源は長年の研究の蓄積があり，プロトタイプアンテナでは，遠方電波源からの微弱電波観測への影響評価を行う．

一方，10MHz を跨ぐシームレスな周波数帯や地球局との長基線干渉計により、科学価値の高い観測の実施も期待できる．プロトタイプ電波干渉計では，月の電離層の構造や時間変動の観測が可能となる．電離層の形成には帯電ダストやプラズマと月の相互作用が関係しており，月面環境や月の科学に関連した知見の獲得が期待される．将来，多数のアンテナからなる高感度干渉計が実現した時には，惑星大気の雷電波や外惑星のオーロラ電波に加え，ハビタブル惑星を持つ恒星の磁気活動の把握や，系外惑星電波を通した惑星磁場や自転周期情報の獲得が視野に入る．

R009-P11
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

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Next UV space telescope, LAPYUTA: instrument overview and technical developments

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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 cm2) and a high spatial resolution (0.1 arc-sec) and imaging with a wide field of view in an 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. Two main instruments are installed on the focal plane of the telescope: a spectrometer and a UV slit imager. The spectrometer contains a movable slit with different slit width, a holographic toroidal grating with 2000 lines/mm, and an MCP detector coupled with CMOS imaging sensors. Spectral resolution of <0.01 nm and field-of-view of 100 arc-sec will be achieved. A UV slit imager consists of imaging optics, several bandpass filters with a 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 are studying the concept of LAPYUTA and preparing a proposal of it to JAXA's M-class category. Here we present the updated LAPYUTA concept design, the overview of the spacecraft and instruments, and the status of technical developments.

R009-P12
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

LAPYUTA による惑星オーロラ観測に向けた科学検討

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Scientific feasibility study for planetary auroral observations for the LPYUTA mission

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We made a feasibility study for observations of planetary auroras with the next generation planetary ultraviolet (UV) space telescope LAPYUTA. Based on current dataset from the Hubble Space Telescope and the Hisaki satellite, simulations for the LAPYUTA spectroscopy and imaging were made for Jupiter's auroral emissions. It was confirmed that under the current design of LAPYTUA telescope, both the spectroscopy and imaging have enough sensitivity for detections of Jupiter's auroral emissions. Now we are narrowing down the imaging filters specifications and planning the observation modes. In this presentation, the current status of the above feasibility studies are presented.

次世代紫外線宇宙望遠鏡 LAPYUTA による惑星オーロラの分光、及び、撮像観測のフィージビリティスタディを実施した。既存のハッブル宇宙望遠鏡やひさき衛星の観測データと、LAPYUTA の観測器設計データに基づき、木星オーロラの分光観測・撮像観測のシミュレーションを行った。その結果、現状の LAPYUTA の基本設計において、分光観測、撮像観測ともに、科学目的達成のために必要な有意な感度を持っていることが確認できた。現在は分光器及び撮像器の試験モデル作成に向けた、必要な撮像フィルタ特性の絞り込みや、観測モードの検討等を行っている。本発表では、上記のフィージビリティスタディの現状を報告する。

R009-P13
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

Kaguya/LRS のオーロラキロメータ放射観測を用いたパッシブレーダーによる月面地下構造探査手法の検討

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Method to explore the lunar subsurface structure by passive radar using auroral kilometric radiation with Kaguya/LRS

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The Lunar Radar Sounder (LRS) was installed on KAGUYA(SELENE). The purpose of the LRS is to perform radar soundings of the lunar surface and subsurface structure to understand the evolution of the Moon. The LRS consists of three subsystems: the sounder transmitter and receiver (SDR), the natural plasma wave receiver (NPW), and the VLF wave form capture (WFC). LRS-NPW is capable of natural wave observations in the frequency range of 20kHz to 30MHz. With this receiver, natural radio wave observations such as aurora kilometer radio waves (AKR) originating from the Earth's auroral latitudes and Jupiter radio waves in the hectometer band (HOM) have been successfully carried out [Kumamoto et al. 2016]. Recently, using echoes of these natural radio waves, investigations of the subsurface structure and ionosphere of Jupiter's icy satellites are being considered for implementation with the JUICE spacecraft. Such an observation technique is called a passive radar. Although there have been studies on the Moon applying AKR to ionospheric probes [Goto et al. 2011], there has been no investigation of lunar subsurface structure using AKR. The objective of this study is to investigate a method to probe the lunar subsurface structure from AKR data obtained by LRS-NPW. To probe the subsurface structure, we use interference fringes between AKR direct waves propagating from the Earth and AKR reflections on the lunar surface and subsurface structure. In this presentation, we will show the preliminary results of the feasibility study. AKR is observed in a low frequency range from several tens to several hundred kHz and has the potential to probe deeper subsurface structures than an active radar sounder (LRS-SDR) which was operated in 4-6MHz. According to Ono et al.2010, interference fringes between direct waves and surface reflected waves have already been observed in the LRS. To calculate the interference fringes produced on the radio spectrum by the direct waves from the Earth and the reflected waves from lunar surface and subsurface, the following assumption were made. In this preliminary study, for simplicity, the incident angle of AKR to the lunar surface is set to 0deg and two-layer subsurface structure whose, relative permittivities are 4.0 for the first layer and 8.0 for the second layer. The attenuation in the first layer is not considered. KAGUYA's altitude from the lunar surface is set to 100 km and the thickness of the first layer is set to 1 km. Based on the above assumptions, the frequency spacing [kHz] and amplitude [dB] were determined for interference fringes due to direct and surface-reflected waves, and for those due to surface-reflected waves and subsurface-reflected waves, respectively. As a result, the interval and amplitude of interference fringes due to direct and surface-reflected waves were 1.5 kHz and 6.0 dB, respectively. The interference fringe interval between the surface-reflected and subsurface-reflected waves was 75 kHz, and the amplitude was 8.3 dB. The interference fringes actually captured by KAGUYA is a combination of direct, surface-reflected, and subsurface-reflected waves; the calculated interference fringes of the three waves show that the frequency interval of the interference fringes between the surface and subsurface reflected waves on the lunar surface is 75 kHz and their amplitude is 2 dB. Since the frequency resolution of LRS-NPW is 6 kHz, interference fringes due to direct and surface reflected waves cannot be resolved in the region near (0deg E, 0deg N), where the incident angle is 0deg, but interference fringes between surface and subsurface reflected waves could be detectable. Since a frequency spacing of interference fringes become wider as the AKR incident angle is larger [Kumamoto et al. 2016], it is expected that the LRS-NPW will be able to capture the interference fringes due to the direct waves and the reflected waves. In order to reproduce the fringe under more realistic conditions, it is necessary to add the attenuation term in the first layer, which is currently not taken into account, and also to enable calculations at arbitrary angles of incidence, depending on KAGUYA's latitude and longitude, for comparison with LRS-NPW observation data. In this presentation, I will discuss the progress of the research and prospects for deep structure exploration of the Moon.

月周回衛星「かぐや」には、月レーダーサウンダー LRS(Lunar Radar Sounder) が搭載されている。LRS の目的は、月表面および地下構造のレーダーサウンディングを行い、月の進化について理解することである。LRS はサウンダー送受信部 (SDR)、HF 帯自然波動受信部 (NPW)、VLF 帯波形受信部 (WFC) の 3 つのサブシステムから成っている。LRS-NPW では 20kHz〜30MHz の周波数帯で自然波動観測が可能である。この受信機により地球のオーロラ帯を起源とするオーロラキロメータ電波（AKR）やヘクトメートル帯の木星電波 (HOM) 等の自然電波観測に成功している [Kumamoto et al., 2016]。 近年、このような自然電波のエコーを用いて、木星探査機 JUICE での実施を想定した木星の氷衛星の地下構造や電離圏探査の検討が行われている。この様な観測手法をパッシブレーダーと呼ぶ。月では AKR を電離層探査機に適用した研究はあるものの [Goto et al.,2011]、AKR を用いた月面地下構造探査の検討は未だ行われていない。本研究の目的

は、LRS-NPW で得られた AKR 観測データから、月の地下構造を探査する手法を検討することである。AKR の地下エコーから月の地下構造を探査するため、地球方向から伝搬する AKR の直達波と、月面及び地下構造で反射した AKR の干渉パターンを利用する。今回は、予備的な検討結果について発表する。AKR の周波数は数 10〜数 100kHz と低周波であり、4-6MHz のアクティブレーダーサウンダー (LRS-SDR) よりも深い地下構造を調べられる可能性がある。Ono et al.,2010 によると、AKR の直達波と表面反射波の干渉縞が LRS で既に観測されている。地球からの AKR の直達波と、月面と地下からの反射波により、電波スペクトル上に生じる干渉縞を計算するため、以下の仮定を行った。

今回の予備検討では、簡単のため、２層の地下構造を仮定し、AKR が月面に対して入射角 0° で入射する場合を考える。月面から 1 層目の比誘電率を 4.0、２層目を 8.0 と設定した。1 層目での伝搬減衰は考えないものとする。かぐやの月面からの高度を 100km、１層目の厚さを 1km とする。以上の仮定の上、直達波と表面反射波による干渉縞と、表面反射波と地下反射波による干渉縞について、周波数の間隔 [kHz] と振幅 [dB] をそれぞれ求めた。その結果、直達波と表面反射波による干渉縞の間隔は 1.5kHz、振幅は 6.0dB であった。また、表面反射波と地下反射波による干渉縞の間隔は 75kHz、振幅は 8.3dB であった。実際にかぐやが捉えるのは直達波、表面反射波と地下反射波の３つを組み合わせた干渉パターンである。３つの波の干渉縞を計算した結果、月面の表面反射波と地下反射波の干渉縞の周波数間隔は 75kHz でその振幅は 2dB となった。LRS-NPW の周波数分解能は 6kHz なので、入射角 0° となるような (0° E, 0° N) の付近の領域では直達波と表面反射波による干渉縞を十分な分解能で観測できないが、表面反射波と地下反射波の干渉縞は検出できる可能性がある。一方で、AKR の入射角が大きくなるような領域では干渉縞の間隔が大きくなるので [Kumamoto et al., 2016]、直達波と表面反射波の干渉縞も捉えることができるようになる。また、LRS-NPW が観測する典型的な強度の AKR はノイズレベルの差が 15dB 程度であるので、干渉縞の 2dB の振幅を検出できる可能性がある。

今後は、より現実的な状況を再現するために、現在は考慮していない月面内での伝搬減衰項を加え、さらに、LRS-NPW の観測データと比較するために、かぐやの緯度・経度に応じて、任意の入射角での計算を可能にする必要がある。

本講演では、研究の進捗状況および月の深部構造探査に対する展望等について述べる。

R009-P14
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

ARTEMIS 衛星で観測される月周辺の電子サイクロトロン高調波の解析

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Analysis of electrostatic cyclotron harmonic waves observed by the ARTEMIS satellite

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Electrostatic Cyclotron Harmonic (ECH) waves are a type of plasma wave, which is characterized by a harmonic structure with a spectral peak between integer multiples of the electron cyclotron frequency. It has been confirmed that ECH waves are excited under the electromagnetic environment around the Moon formed by the interaction between the Moon and space plasma, which has no large-scale intrinsic magnetic field and no atmosphere.

In previous studies, ECH waves have been analyzed using data observed by the lunar orbiter KAGUYA, which orbits at an altitude of about 100 km from the Moon, but research on ECH at even higher altitudes has not progressed.

The purpose of this study is to elucidate the relationship between ECH wave excitation and the plasma environment around the Moon using data from the ARTEMIS satellite, which orbits the Moon in an elliptical orbit and observes a wider altitude range than KAGUYA.

First, the region where ECH waves are observed was investigated based on plasma and wave data acquired by the ARTEMIS satellite during the year 2021. We found that ECH waves are observed at the altitude of the ARTEMIS satellite only when the moon is located within the magnetosphere.

The observed ECH waves can be classified into three types: those with a spectral peak near the UHR frequency (Type 1), those with multiple spectral peaks between integer multiples of the cyclotron frequency (Type 2), and those with characteristics of both Type 1 and Type 2 (Type 3).

The regions where the classified ECH waves appeared were examined by focusing on the satellite location relative to the moon. The type 3 event is most frequently observed on the night side, although it was also observed on the dayside. The type 1 and 2 events are observed on both the lunar dayside and night side, but are less frequently observed compared to the type 3 event.

We also investigated the magnetic connectivity between ARTEMIS and the lunar surface during the onset of ECH waves, by straight-line extrapolation of the measured magnetic field by ARTEMIS. We confirmed that ARTEMIS is magnetically connected to the lunar surface in most cases of the ECH wave event. This strongly suggests that the observed ECH waves are excited through moon-electron interactions.

Since the analysis of ECH waves with the KAGUYA datasets has revealed that the presence or absence of a magnetic anomaly at the location of the connection of the external magnetic field with the Moon is important for the generation of ECH waves, we plan to discuss the relationship between ECH excitation and the magnetic anomaly on the Moon in this study as well.

電子サイクロトロン高調波 (ECH：Electron Cyclotron Harmonic Wave) とはプラズマ波動の一種であり、電子の Bernstein mode wave が励起したもので、電子サイクロトロン周波数の整数倍の間にスペクトルのピークをもつ高調波構造が特徴である。 大規模な固有磁場を持たず、大気も存在しない月と宇宙プラズマの相互作用によって形成される月周辺のプラズマ環境のもとで、ECH が励起されていることが確認されている。

先行研究においては、月から高度約 100 km を周回する月周回衛星 KAGUYA のデータを用いた ECH の解析が行われているが、さらに高い高度での ECH の研究は進んでいない。

そこで、本研究では、月周辺を楕円軌道で周回し、KAGUYA に比べ広い高度範囲を観測している ARTEMIS 衛星のデータを用いて、月周辺における ECH の励起とプラズマ環境の関係を解明することを目的とする。

まず、ECH が観測される領域を、2021 年の 1 年間、ARTEMIS 衛星によって取得されたプラズマ・波動データをもとに調査した。その結果、ARTEMIS 衛星の高度で ECH が

みられるのは、月が磁気圏内に存在している場合であり、太陽風中では ECH は観測されなかった。また、観測される ECH 波動は、UHR 周波数付近にスペクトルのピークをもつもの (タイプ 1)、サイクロトロン周波数の整数倍の間に複数のスペクトルのピークをもつもの、(タイプ 2)、タイプ 1 とタイプ 2 の両方の特徴をもつもの (タイプ 3) に分類できることがわかった。

分類した ECH の出現する領域を、月と衛星の位置関係に注目して調べた結果、タイプ 1 は日陰側でも観測されたが、日照側で多く観測された。タイプ 2 は日照側と日陰側の両方で観測されたが、観測頻度が少なくい。タイプ 3 は最も多く観測され、日照側でも観測されたが日陰側で多く観測された。

次に ECH の発生時において、ARTEMIS を貫く外部磁場が、月面へ接続しているかを確認した。その結果、観測されたほとんどの ECH において ARTEMIS を貫く外部磁場の月面への接続を確認できた。これは、観測された ECH が月の

影響を受けて励起されている事を強く示唆する。

KAGUYA における ECH の解析により、外部磁場の月面での接続位置の磁気異常の有無が ECH の発生に重要であると明らかとなっているため、本研究においても、ECH の励起と月面の磁気異常の関係についても言及する予定である。

R009-P15
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

BepiColombo みお搭載磁力計 MGF-I データと衛星による磁場ノイズ干渉の評価

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Examination of data from inboard magnetometer (MGF-I) on BepiColombo MIO and interference by the spacecraft

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By BepiColombo mission we aim to understand the essential properties of the Herman intrinsic magnetic field and physical process occurring in the Herman magnetosphere. To achieve our aims, we installed dual magnetometers respectively on Mercury Magnetospheric Orbiter (MMO, MIO) and Mercury Planetary Orbiter (MPO); namely four magnetometers in total are implemented on BepiColombo. MIO spacecraft build in Japan has inboard (MGF-I) and outboard (MGF-O) magnetometers, which are developed by Japanese and European groups, respectively. BepiColombo was launched in October 2018 and is now cruising in the interplanetary space. It will be inserted into the orbit around Mercury in 2025 after swing-by with the earth, Venus, and Mercury.

The MGF-I and MGF-O sensors are placed in the middle and on the top, respectively, of the 5m-length MAST of MIO spacecraft. During the cruising to Mercury the MAST is stored in a container, and the two sensors are located nearby the surface of the spacecraft. Although the magnetic noise radiated from the MIO spacecraft is well restrained, the sensors are considerably interfered by the components on MIO. Moreover, since MIO, MPO (built by ESA) and a transfer module (MTM) are stacked during the cruising, MGF sensors suffer strong magnetic noise from MPO and MTM as well. These magnetic noise varies with wide-range timescale and is difficult to remove. Although we have chances to measure the interplanetary field, draping fields around Venus and Mercury and Herman main fields, the interference noise degrades the accuracy of the measured field.

All of four sets of magnetometers on MIO and MPO are interfered by the magnetic noise, while the magnitude depends on the location and distance from the spacecraft. Comprehensive analysis of data from four magnetometers at different locations nearby and around the BepiColombo module will enable the separation of the natural field from the noise, and improvement of the measurement accuracy. MGF-I sensor is located just inside the surface of the MIO spacecraft. It suffers most strongly the noise from BepiColombo module, and suitable to examine the magnetic interference precisely. We are investigating the method to utilize MGF-I data to improve the accuracy of the magnetic field data obtained by BepiColombo comprehensively.

日欧共同水星探査プロジェクト BepiColombo の主目的に、水星の持つ固有磁場の詳細計測、水星の磁気圏におけるプラズマの物理プロセスの解明がある。これらの目的を達成するために、BepiColombo を構成する 2 機の探査機にはそれぞれ 2 式の磁力計が搭載されている。そのうちの 1 機、日本で製造された Mercury Magnetospheric Orbiter (MMO、みお) には、日本のグループが担当する MGF-I とヨーロッパのグループが担当する MGF-O の 2 式の磁力計が搭載されている。BepiColombo は 2018 年 10 月に打ち上げられ、現在惑星間空間を航行中である。地球、金星、水星とのフライバイを経て、2025 年に水星周回軌道に入る予定である。

MGF-I と MGF-O のセンサは５ｍの長さを持つ伸展マストの中間と先端に搭載されているが、惑星間空間航行中、マストは収納された形態にあり、センサは衛星表面近傍に位置する。磁場の高精度計測のための対策として、みお衛星が出す磁場ノイズは抑制されているが、マストが収納状態の時、センサは衛星が出すノイズの影響を少なからず受ける。また、惑星間空間航行中、みお衛星はヨーロッパで製造された Mercury Planetary Orbiter (MPO) と Mercury Transfer Module (MTM) に連結された状態にあるため、MPO た MTM が出す磁場ノイズの影響も強く受ける。これらのノイズは、様々な時間スケールで変動しており、惑星間空間中の微小な磁場や、金星・水星フライバイ時の draping 磁場や水星の主磁場を正確に測定する上での障害となっている。

みお衛星と MPO に搭載された計４式の磁力計は、程度の差はあるものの、いずれも何らかの磁場ノイズの影響を受けている。BepiCoombo 衛星群の表面、あるいは周囲の異なる４個所で測定された磁場データを総合的に解析し、自然界の磁場と衛星が出す磁場を分離することが、結果的に磁場測定精度の向上につながる。本研究では、みおや MPO の磁場ノイズの影響を最も大きく受けている MGF-I のデータを評価することにより、衛星が出す人工ノイズを正確に評価し、BepiColombo 磁場測定の精度向上への貢献について検討する。

R009-P16
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

水星磁気圏昼間側擾乱に関する粒子シミュレーション

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Particle simulation on the dayside perturbation of the Hermean magnetosphere

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Satellite observations have shown that Mercury's magnetosphere is smaller and more dynamically fluctuating than Earth's magnetosphere because Mercury's intrinsic magnetic field is smaller and more affected by the stronger solar wind than Earth. Since the inertial length and cyclotron radius of solar wind ions are not negligible to the size of each region of the magnetosphere, we need to consider the plasma kinetic effect to investigate Mercury's magnetosphere. In this study, we have started particle simulations of Mercury's magnetosphere, mainly focusing on the daytime side region. We will present some of the simulation results obtained in this study.

We analyze Mercury's magnetosphere using a three-dimensional hybrid simulation in which ions are treated mainly as particles and electrons as fluids. First, we focus on the variation and cross-correlation of the current and magnetic field in the magnetosheath. In the case of Earth's magnetosheath, density and magnetic field variations due to mirror mode instability and competitive excitation of ion cyclotron waves have been studied in detail by satellite observations and numerical simulations. In Mercury's magnetosheath, disturbances in density and magnetic field strength due to mirror mode instability have also been studied. In the hybrid simulation of this study, we also found similar magnetic field strength and plasma density fluctuations in the magnetosheath. In the current flow analysis, we found a complex structure consisting of multiple vortexes in the equatorial plane. In three-dimensional space, we will investigate the relationship between magnetic field strength and current in detail. We will also examine the dynamics of ion particles and check the growth conditions of mirror mode instability by velocity distribution functions and particle trajectories. We also plan to study the ring current near the surface of Mercury's magnetosphere and the ion dynamics at the cusp region.

水星は地球と比べて固有磁場が小規模であり、より強い太陽風の影響を受けるため、水星磁気圏は地球磁気圏と比較して小型でダイナミックに変動することがこれまでの衛星観測でわかっている。特に太陽風イオンの慣性長やサイクロトロン半径が磁気圏の各領域の大きさに対して無視できない点は、地球磁気圏とは異なる点である。我々は、水星磁気圏の昼間側、特にマグネトシース、マグネトポーズにおけるプラズマ電磁現象変動に着目し、粒子シミュレーションを用いた解析を開始したのでその進捗を報告する。

本研究では、イオンを粒子、電子を流体として扱う 3 次元ハイブリッドシミュレーションを主に行いて水星磁気圏の解析を進めている。まず、マグネトシースにおける電流と磁場の変動および相互相関に着目した。地球のマグネトシースでは、ミラーモード不安定性及びイオンサイクロトロン波の競合的な励起による密度、磁場強度の変動について衛星観測および数値シミュレーションで詳細研究が行われている。水星マグネトポーズにおいてもこれまでミラーモード不安定性等による密度、磁場強度の擾乱が研究されている。本研究のハイブリッドシミュレーションにおいても、同様の磁場強度変動が確認されておりミラーモード不安定性等の波動粒子相互作用が原因と考えられる。現在、マグネトシースにおける電流と磁場強度の相関解析を進めており上述のプラズマ不安定性の同定を行うとともに、そこでの粒子の密度、電流、磁場の相互関係について定量的に明らかにする予定である。特に、電流については、マグネトシースにおいて小さな渦をいくつも描くような複雑な 3 次元構造が特徴的に観測されており、磁場強度と電流の関係について詳しく調べるとともに、ミラーモード不安定性の成長条件の観点からもイオン粒子のダイナミクスを速度分布関数や粒子軌道により調べる。また、マグネトシースのみならず、磁気圏内部での水星表面に近い環状電流構造やカスプ領域でのイオンダイナミクスについても調べる予定である。

R009-P17
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

3 次元グローバル MHD コードによるタイタン大気散逸の太陽風応答の数値シミュレーション

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Solar wind response of Titan's atmospheric escape simulated with the 3D global MHD code

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Titan is a unique satellite with an environment close to the early Earth: liquid on the surface (methane and ethane), nitrogen-dominated atmosphere, and tick atmospheric pressure around 1 atm on the surface. In order to unveil the atmospheric evolution of the early Earth, it is very important to understand that of Titan, especially the escape of atmosphere to the space. Titan's atmosphere comprises 97% nitrogen, 2% methane and 1% hydrogen which have been observed by the in-situ measurements with the Voyager and Cassini spacecraft (Sagan and Thompson,1984). Titan is blown in the solar wind for a long period in its orbital motion around Saturn. The temporal variation in the solar wind may change Titan's atmospheric escape. However, the global spatiotemporal variations in Titan's atmospheric escape have not been investigated quantitatively. Here we investigate the global response of atmospheric escape to the solar wind by numerically modeling the global non-thermal escape process of Titan's atmosphere using a 3D multi species MHD simulation code. We applied the MHD code for the atmospheric escape for Venus and Mars (Terada et al., 2009a,2009b) to Titan. In a simplified case, we calculated the escape rate from a nitrogen atmosphere in the altitude range of 1000~1400 km and estimated the escape rate to be 5.97e+23-3.76e+24 /s when the dynamic pressure of the solar wind ranges from 1.2 to 6.8 nPa which is comparable with the present value at Earth's orbit. This result is comparable to the non-thermal escape rate of 2-3e+24 /s estimated by 1D Monte Carlo simulations and other methods in the previous studies (Michael et al.,2005). For more realistic estimations, we are currently evaluating the escape rates for the nitrogen and hydrogen atmospheres in the altitude range of 700-3000 km, which includes the ionospheric electron density peak. The solar wind response of nitrogen and hydrogen escape rates will be presented in this poster. We also plan to investigate the nitrogen and hydrogen escape rates when Titan is located in Saturn's magnetosphere.

タイタンは、窒素主体の大気を持ち、地表面付近での大気圧は 1 気圧に及ぶ。また、表層に液体（メタン・エタン）の海洋を持っている。これらは、初期地球に近い表層環境である。地球の大気進化を明らかにする上で、その比較対象としてタイタンの大気進化、特に大気散逸を解明することは非常に重要である。タイタン大気は窒素 97 %、メタン 2%、水素 1% で構成されていることが Voyger 探査機や Cassini 探査機による観測からわかっている (Sagan and Thompson,1984)。また、土星の周りを公転している時間のうち、太陽風中に置かれている時間が長い。地球に類似した大気が太陽風に直接吹き付けられ、宇宙空間へ散逸していると予想されるが、大気散逸の全球的な時空間変動は明らかになっていない。そこで本研究は、3 次元多成分 MHD シミュレーションを用いてタイタン大気の全球的な非熱的散逸過程を模擬することで、散逸の太陽風応答を調べた。Terada et al. (2009a,2009b) の金星・火星用シミュレーションコードをタイタンに応用した。簡単化したケースとして、高度範囲 1000~1400km に窒素大気を配置した条件で散逸率を計算したところ、太陽風の動圧が地球軌道において現在と同程度の 1.2-6.8nPa の時、窒素大気の散逸率は 5.97e+23-3.76e+24 /s となった。この結果は、過去研究の 1 次元モンテカルロシミュレーションなどによる非熱的散逸の見積もり 2-3E+24/s と同等の散逸率となった (Michael et al., 2005)。　現在は、よりリアルな大気分布を考慮するために、電離圏電子密度ピークを含めた高度範囲（高度 700～30000km）に窒素と水素を配置し、散逸率を評価中である。窒素と水素の散逸率について、太陽風の各種パラメータに対する応答を調査中である。本発表では、その調査結果と解釈を発表する。また、今後は、タイタンが土星磁気圏中に位置しているときの、窒素・水素大気の散逸率を調査していく予定である。

R009-P18
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

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Test particle simulation of electron – water molecule ionizations around Enceladus: energy loss of 1keV electrons

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We have examined energy loss of 1 keV electrons through ionization around Enceladus by using a test particle simulation. Saturn's inner magnetosphere is dominated by water group neutrals (H2O, OH, and O) originated from Enceladus. Previous studies suggested that these neutrals are seems to contribute to loss processes of plasma in the inner magnetosphere. Tadokoro and Katoh [2014] focused on the loss process of 1 keV electron through the elastic collision with neutral H2O around Enceladus. With regard to above several hundred eV, ionization cross section for electron electron-H2O collision is greater than elastic collision cross section. We focus on 1keV electron energy loss by the ionization with neutral H2O in this study. Conducting one dimensional test-particle simulation, we calculate the electron ionization collision. We use a Monte Carlo method to calculate collision. We show the preliminary result of the 1keV electron energy loss due to ionization process.

R009-P19
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

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A Test Particle Simulation of Jovian Magnetospheric Electrons Precipitating into Europa's Oxygen Atmosphere

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Europa has a tenuous atmosphere composed mostly of molecular oxygen. Roth et al. [2016] found north-south asymmetric morphology of the oxygen 135.6 nm emissions when Europa is far from the plasma sheet center. The observed north-south brightness ratio is up to 5 on the trailing hemisphere and below 2 on the leading hemisphere. Since the main source of the 135.6 nm emissions is the electron impact dissociative excitation of O2, they concluded that the asymmetry is the result of an inequality of electron energy flux from the Jovian magnetosphere into Europa's atmosphere.

The electron energy flux into Europa's atmosphere depends on (a) the bounce period of magnetospheric electrons moving along a field line, (b) the velocity of the corotating plasma flow, and (c) the magnetic latitude of Europa. Retherford et al. [2003] explained that when the corotating plasma flow slows down by the moon-plasma interaction, most electrons in an intersecting flux tube collide with Io: the electrons above the moon precipitate into the northern hemisphere and those below the moon precipitate into the southern hemisphere. This creates a pronounced asymmetric electron energy flux into the atmosphere when the moon is far from the plasma sheet center. The theory, however, has never been evaluated for the case of Europa quantitatively.

To derive the electron flux into Europa's surface, we use a test particle simulation and trace the motion of magnetospheric electrons around Europa. We assume that Jupiter has a tilted dipole magnetic field and a corotational electric field. The motion of each electron is treated as a superposition of the cyclotron motion around a field line, the bounce motion along the field line and the longitudinal convection in the Jovian magnetosphere. We don't consider the field perturbation around Europa, but electron's longitudinal convection assumingly slows down from the corotating velocity (Ip [1996]). We acknowledge that the applicability of dipole field and the decelerated plasma flow alone is limited. To reduce the computational costs, we trace the trajectories backward in time (e.g., Cassidy et al. [2013]).

We calculate the spatial distribution of the electron number flux to Europa's surface and evaluate the 135.6 nm brightness excited by the derived electron flux. We found that the corotating velocity relative to Europa, 100km/s at Europa's orbit, is required to be decelerated to below 5km/s to create a north-south ratio of electron flux larger than 2. Under this condition, the north-south brightness ratio is estimated at 2.82 on the trailing hemisphere, and 5.56 on the leading hemisphere. However, the estimated north-south brightness ratio is inconsistent with the observation results: the ratio should be larger on the trailing hemisphere than the leading hemisphere. This suggests that the simple dipole field cannot generate the exact morphology of the 135.6 nm and we must consider the perturbed field around Europa and the induced field.

We're now working on the test particle simulation with more realistic field scenarios. In this presentation, we will show how the perturbed field and Europa's induced field affect the trajectories of electrons and the distribution of electron flux and the 135.6 nm brightness.

R009-P20
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

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High spatial resolution simulation of global Jovian magnetosphere for vortex configuration

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For a number of years we have studied the magnetospheres of Jupiter, Saturn and Earth by using 3-dimensional magnetohydrodynamic (MHD) simulations. In the simulation of Saturn's magnetosphere, we have obtained the clear vortex configuration of plasma flow. Using the fastest supercomputer at that time (K-computer), we could represent the vortices in the Terrestrial magnetosphere. However, we have not been able to get the vortex configuration along the magnetopause in the Jovian magnetosphere due to the size of numerical simulation grid spacing. The size of Jovian magnetosphere is huge with its strong intrinsic magnetic field so that the high spatial resolution numerical simulation of the magnetosphere becomes hard to be performed since the requirement of computer memory and CPU is unrealistic.

Considering this situation, we have done the approach that the simulation with the supercomputer in Japan has been performed for over three years to be obtained the time series variation of global magnetosphere. Form the simulation over years we have obtained over 200 hours' time evolution and found the vortex configuration in the Jovian magnetosphere with 0.15RJ grid spacing and 1.5TB simulation data/sampling (totally using over 1PB disk storage). In this study, we will show the results of high-resolution simulation and discuss the configuration vortices.

R009-P21
ポスター 2 ：11/5　AM1/AM2 （9:00-12:30）

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Causalities of occurrence features of Io-related Jupiter's radio emission : Examination of non-uniform energy supply from Io

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The following question; 'How Jupiter's auroral radio emissions are generated?' has been long years of subjects. Especially the Io-related auroral emission component called Io-DAM has shown mysterious nature of characteristic occurrence probability, that is, the occurrence strongly depends on both Io's positional angle and Jupiter's magnetic longitude to an observer. We have investigated this subject based on numerical calculations with a 3D ray-tracing using several kinds of magnetic field and plasma density models including a recently proposed magnetic field model based on the JUNO in-situ explorations near Jupiter. The calculation results show that the new magnetic field model gives more natural explanations for the observed occurrence probabilities, however a hypothesis of some special energy transportations, that is, non-uniform energy supply from Io to the Io-DAM source region, is required to restrict radio emissions to be solely Io-DAM emissions. We have reexamined whether this hypothesis is really needed based on both further numerical calculations including the delay of energy transportation from Io to the Io-DAM source regions and analyses of observation results for Io foot print auroras. In the presentation, we will introduce this numerical and observational approach precisely and discuss necessity of the 'special energy transportation'.