月起源イオンと月表面環境の相関

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Relation between the Moon originating ions and the lunar surface structure

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The solar wind impacts the lunar surface except when the Moon stays in the Earth's magnetosphere. Since the Moon has neither global magnetic field nor thick atmosphere, the solar wind ion bombardment causes the secondary ion emission from the lunar surface. Although the initial energies of such secondary ions are several electron volts, they are accelerated up to several hundred electron volts by the solar wind convection electric field and are detected by ion detectors on the spacecraft. Since the ion composition depends on the lunar surface structure, they are expected to be used for remote sensing of the lunar surface composition. The lunar alkali ions (Na+ and K+) are the major Moon originating ion species when the Moon stays in the solar wind, the major generation mechanism of these ions are photon-stimulated desorption. However, the quantitative observation of the non-alkali heavy ions generated by the solar wind sputtering is necessary to understand the relation between the generated secondary ions and the lunar surface composition.

MAP-PACE-IMA on Kaguya performed energy and mass observation of the Moon origin ions. Since Kaguya is a three-axis stabilized spacecraft, IMA is always faces the lunar surface. Therefore, IMA measures ions coming from the Moon. We have compared the secondary ion flux generated by the solar wind ion impact on the lunar surface obtained by IMA and the solar wind ion flux (H+ and He++).

In order to understand the relation between the secondary ions and the lunar surface composition, we have made secondary ion flux maps for each ion species. H+ and He++ are clearly observed over the lunar magnetic anomalies because the solar wind H+ and He++ are reflected by the strong crustal magnetic field. In contrast, the observed amounts of the secondary ions are decreased over the lunar magnetic anomalies since the strong magnetic field can prevent the solar wind from impacting the lunar surface. We have investigated the ratio of the secondary ions such as Si+/O+ and Ar+/O+ in order to understand the correspondence between the generated amount of each ion species and the location of the moon surface. We will report the features of the lunar secondary ion distribution for different species. This study can contribute not only to understand the plasma environment around non-magnetized solar system objects, but also to remotely observe the surface materials.

月は地球磁気圏内に存在する時期以外は、太陽風に常時曝されている。このとき月には固有磁場も十分な大気も存在しないため、太陽風イオンが月表面に衝突し二次イオンが放出される。このとき生成された二次イオンは数 eV 程度のエネルギーしか持たないが、太陽風中の電場によって数 100eV 程度まで加速されて衛星高度まで到達し観測することができる。この二次イオンの組成は月表面組成に対応していることから、二次イオン観測は月表面の遠隔探査への応用が期待されている。太陽風中において最も顕著に生成される月起源イオンはアルカリイオン (Na+や K+) であり、これらは主な生成メカニズムは太陽光による脱離である。しかし、二次イオンと月面構造との対応を具体的に理解するためには、太陽風スパッタリングによって生成される非アルカリ重イオンの定量的な観測が必要不可欠である。

月探査衛星「かぐや」に搭載されたイオン観測装置 MAP-PACE-IMA は月起源イオンのエネルギー観測や質量分析を行った。「かぐや」衛星は 3 軸姿勢制御衛星であり、衛星本体のある一面が常に月面を向くようになっている。そのため IMA は常に月面を向いており月方向から飛来するイオンの質量分析を行うことができる。本発表では、IMA の質量分析を用いて太陽風イオンの月面衝突で生成される二次イオンについて解析し、太陽風イオン (H+や He++) と二次イオンの比較も行った。

月表面環境と二次イオンの関係を理解するために、IMA の観測データを用いてイオン種毎の分布マップを作成した。H+や He++といった太陽風中に多く存在するイオンは磁気異常上空で強く観測されるのに対し、それ以外の重イオンでは観測フラックスが周囲の非磁気異常領域よりも少なくなる傾向が見つかった。これは、月磁気異常による磁気反射によって月面衝突する太陽風が減少するため、二次イオンの生成量も減少したためと考えられる。また、Si+/O+比や Ar+/O+比のような二次イオン同士の定量比較を行い、各イオン種の生成割合の変化と月表面の位置の対応を調べた。これらにより得られた複数種の二次イオン分布の特徴について報告する。この結果は小型天体の周辺プラズマ環境の理解と同時に、固体表面構造の遠隔探査の可能性について寄与すると言える。

Current balance at the lunar night-side surface in the terrestrial foreshock

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There forms a tenuous region called the wake behind the Moon in the solar wind, and plasma entry/refilling into the wake is a fundamental problem of the lunar plasma science. High-energy ions and electrons in the foreshock of the Earth's magnetosphere were detected at the lunar surface in the Apollo era, but their effects on the lunar night-side environment have never been studied. Here we show the first observation of bow-shock reflected protons by Kaguya (SELENE) spacecraft in orbit around the Moon, confirming that solar wind plasma reflected at the terrestrial bow shock can easily access the deepest lunar wake when the Moon stays in the foreshock (We name this mechanism 'type-3 entry'). In an intermittent type-3 entry event, the kinetic energy of upward-going field-aligned electron beams decreases from 80 eV to 20 eV or electron beams disappear as the bow-shock reflected ions come accompanied by enhanced downward electrons. According to theoretical treatment based on electric current balance at the lunar surface including secondary electron emission by incident electron and ion impact, we deduce that incident ions would be accompanied by a few to several times higher flux of an incident electron flux, which well fits observed downward fluxes. We conclude that impact by the bow-shock reflected ions and electrons raises the electrostatic potential of the lunar night-side surface.

太陽風イオンの月磁気異常領域侵入のエネルギー依存性

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Energy dependence of solar wind ion penetration into the lunar magnetic anomaly region

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Since the Moon has neither a thick atmosphere nor a global dipole magnetic field, it has been thought that the solar wind plasma directly impacts the lunar surface. Although the solar wind is almost absorbed by the lunar surface, a part of it is reflected by the strong crustal magnetic field, called lunar magnetic anomalies. To study the interaction between the solar wind and the lunar magnetic anomalies is very important for understanding the lunar plasma environment and the space weathering. Although the ion energy and incident direction are important parameters of the magnetically reflection process, they are still unclear.

We have analyzed the data obtained by low energy charged particle analyzers MAP-PACE and magnetometer MAP-LMAG on Kaguya. IMA and IEA have hemispherical field of view (FOV) and cover the full FOV of low-energy ions. Since Kaguya is a three-axis stabilized spacecraft, one of the spacecraft panels on which IMA is installed always faces the lunar surface. Therefore, IMA measures ions coming from the Moon, and IEA on the opposite side of the spacecraft measures the solar wind ions. We have analyzed the difference of reflection process with different ion species by using the data of the mass profile mode of IMA.

We have found that there is a correlation between the energy flux of reflected ions and the polar angle direction. Although the mass profile mode of IMA has no directional information about the azimuthal direction, we can constrain the particle trajectory by comparing polar angle distributions of different ion species considering mass dependence. By comparing the reflected protons and the reflected alpha particles, we have found that the observation of the reflected ions is strongly related to their gyro motion. In addition, by measuring the bulk velocity of the reflected ions at different solar zenith angles, we examined the solar zenith angle dependence of the reflected ions. We will report how the incident solar wind ions penetrate into the lunar magnetic anomalies, and will discuss the condition that determines their fate : to impact the lunar surface or to be magnetically reflected.

月には全球的な固有磁場も大気も存在しないため、月表面は太陽風に曝されている。月近傍に侵入した太陽風のほとんどは月表面に衝突し吸収されるが、月磁気異常領域では磁場によって衝突せずに反射する場合がある。この月磁気異常と太陽風の相互作用は、月周辺プラズマ環境や月表面の宇宙風化作用の理解に繋がる重要な物理過程である。しかしこの太陽風イオンの反射メカニズムにはイオンのエネルギー依存性や月磁気異常領域に対する角度依存性が存在すると考えられるが、これまでに十分な理解が得られているとは言えない。

本研究では、月探査衛星「かぐや」に搭載された低エネルギーイオン計測器 MAP-PACE-IMA、IEA と磁場観測装置 MAP-LMAG によって観測されたデータを用い、磁気異常上空で反射されたイオンについて解析を行った。両イオン分析器は共に半球の視野を確保していて、2 台で全方向に対しての視野を確保している。「かぐや」衛星は 3 軸制御の探査機であるため、IMA は常に月面を向いている。従って IMA は月方向から飛来するイオンの質量分析を行い、IEA は月に向かって飛来する太陽風イオンを計測する。今回は IEA の太陽風観測データと IMA の質量分析モードの反射イオン観測データを用いて、異なるイオン種で反射特性の違いについて解析した。

IMA の観測データから月磁気異常によって反射されたイオンを解析した結果、反射イオンのエネルギーフラックスと仰角方向に相関があることが分かった。なお IMA の質量分析モードでは方位角方向の情報を記録しておらず仰角方向のみ角度情報を持つが、異なるイオン種の仰角分布を比較し質量依存性を考慮することで、粒子軌道について考察することができる。反射プロトンと反射アルファ粒子の観測を比較したところ、反射イオンの観測には各イオンのジャイロ運動が強く関係していることが分かった。また、太陽天頂角毎の反射イオンの速度を求め、月磁気異常領域への太陽風入射角度による反射イオンの振る舞いも調べた。これらの結果から、入射太陽風イオンのパラメータによってどのように月磁気異常領域に侵入し、月面衝突と磁気反射の選択がされるのかについて議論する。

R011-P02 **会場: Poster** **時間: 10 月 18 日**

True polar wander of the early Moon estimated from small isolated magnetic anomalies on the SVM map

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Recent studies on the lunar magnetism indicate that the global magnetic field was generated by a core dynamo of the early Moon, although the present Moon has no global magnetic field. Since the crustal magnetic anomaly could record the early Moon's magnetic field as remanent magnetization, probably TRM, the magnetization directions of the lunar magnetic anomalies (LMAs) may yield information on the core dynamo of the early Moon.

Runcorn (1982, 1983) argued clusters of magnetic pole positions from the magnetization directions estimated by Hood et al. (1980), which were determined by fitting magnetized disks to the LMA observations of Apollo 15 and 16 subsatellites. Takahashi et al. (2014) applied dipole approximation to 24 isolated LMAs observed by Kaguya and Lunar Prospector at 20-40 km altitudes. These studies suggest the true polar wander by several tens of degrees in the early Moon. However, the observation data used in the previous studies could generally be affected by the crustal fields within relatively wide area. Thus it is not evident whether the individual LMAs consist of a single magnetic source or not.

We use the global maps of the LMAs on the spherical lunar surface with the Surface Vector Mapping (SVM) method [Tsunakawa et al., 2015]. The SVM data with high spatial resolution (0.2 degrees on the map) are useful for finding small isolated anomalies to be approximated with a single dipole or a small magnetic source body. We have studied single isolated LMAs [Ikeuchi et al., 2016 in SGEPSS Fall Meeting]. We found 82 LMAs of diameter ˜2 degrees, suggesting the true polar wander of the early Moon at 3-4 times through the cluster analysis.

In the present study, we have selected 154 small isolated LMAs and approximated them with a single dipole source or a small magnetic source body (magnetized disk or vertical prism). These LMAs include a new dataset of 72 smaller LMAs (diameter ˜1 degree). We estimated the magnetic poles from the magnetization directions of LMAs and applied a cluster analysis based on the Ward's method.The result shows four clusters of magnetic poles associated with the polarity reversal: the one is located near the selenographic north pole (P1; Takahashi et al., 2014), the one is at low-to-mid latitude on the far side (P2; Takahashi et al., 2014), the one is at low latitude on the eastern hemisphere (P3; Tsunakawa et al., 2015), the one is at low latitude area on the near side (P4; present study). These magnetic pole clusters imply that the dipolar field would be generated by a core dynamo, while the true polar wander like switching a pole position might occur more than once in the early Moon and its angle might be 40˜90 degrees.

Possible mechanisms of an ESW excitation in the lunar wake boundary

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The electrostatic solitary wave (ESW) is one of the plasma waves commonly seen in space, and it is observed as broadband electrostatic noises (BENs) in frequency-time spectrograms. It has been pointed out that the ESWs are generated by a bi-stream electron beam instability or a bump-on-tail instability driven by an electron beam in a warm thermal plasma. In the last decade, Kaguya (SELENE) spacecraft in orbit around the Moon detected ESWs in the wake boundary, but its generation mechanism has not been understood yet. Here we analyze an ESW event in the wake boundary reported by Hashimoto et al. (2010), showing velocity distribution functions of electrons. In the event, the Kaguya spacecraft at 100 km altitude is magnetically connected to the lunar night-side surface, and detects upward-travelling field aligned electron beams (at 100-150 eV). The upward electron beams form a bi-stream distribution function with the solar wind strahl-electrons going down toward the lunar night-side surface along the interplanetary magnetic field. A statistical study also shows dependence of BENs in the wake boundary on the downward electron distribution and upward electron beams. We discuss a possibility of ESW generation by a bi-stream instability by the upward lunar electrons and the downward solar-wind strahl-electrons.

1 次元静電ブラソフシミュレーションを用いた電離圏飛翔体ウェイク近傍のプラズマ不安定に関する研究

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Study of plasma instabilities around the wake of an ionospheric sounding rocket by a 1D Vlasov-Poisson simulation

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Artificial satellites and sounding rockets travel in the ionosphere at supersonic velocities, which makes rarefied regions called 'plasma wakes'. Through some recent rocket experiments, it has been suggested that plasma waves are excited around the rocket wake as reported by Yamamoto [PhD. thesis, Tohoku University, 2001]. From the results of the S-520-26 rocket experiment, Endo et al. (JGR, 2015) have concluded that the waves observed in the wake were electrostatic waves such as electrostatic electron cyclotron harmonic (ESCH) waves and UHR mode waves. The intensities of these waves, as well as of whistler mode waves observed in the same experiment, had spin-phase dependence, which was different depending on kinds of plasma waves. These results indicate that there was inhomogeneous spatial distribution of hot electrons with some anisotropic velocity distribution functions around the rocket wake. Singh et al. (JGR, 1987) have shown that two-stream type electron distribution functions are obtained on the wake axis of spacecraft by using a 1D numerical simulation. However, they have not discussed near the wake edges and the tail of the near-wake, and thus the wave data from the S-520-26 rocket experiment cannot be understood clearly.

In order to investigate inhomogeneity of hot electrons around the rocket wake, we are now developing a Vlasov-Poisson code. In the simulation with this code, we can calculate wake filling process of ambient ions and electrons in one-dimensional space along the X-axis, which is parallel to the ambient magnetic field. If we assume that the plasma is also flown in the y direction, the plasma distribution along the x-axis as a function of time can be understood as that as a function of distance in the y direction. Although this simplified model is also used in Singh et al. (JGR, 1987), plasma parameters are changed in our simulation to discuss an environment around the rocket wake. In addition, we adopt the rational CIP method [Xiao et al., CPC, 1996] in order to suppress the effect of numerical diffusion.

In our current code, electric oscillations whose amplitudes increase with time are observed outside the wake near the wake boundaries, which makes the CFL condition be unsatisfied at up to t=469dt (corresponding to 3.4 mm downstream; 0.8 % of the near-wake). Those electric oscillations are considered to be not physical, and their origin is now under study. For the purpose of suppressing the growing electric oscillation, we perform four test simulations, which are the cases of (1)using absorbing boundaries, (2)damping the longest-wavelength electric fields, (3)reducing the ion-electron mass ratio ($m_i/m_e=2.9*10^4$ is change to 40), and (4)increasing the initial densities in the wake ($n_{wake}/n_0 = 0$ is change to 0.3). As a result, it is found that the growth rate of the oscillation becomes smaller in the cases (3) and (4) although the growth rates are still positive in all of the four cases. In the case (3), for instance, we can proceed the simulation until t=612dt (corresponding to 4.4 mm downstream; 27.6 % of the near-wake), getting closer to the tail of the near-wake.

Even in the calculation described above, several hot electrons can be seen such as multi-stream electrons on the wake axis, and a single beam component outside the wake. The multi-stream electrons are considered to be composed of electrons periodically coming into the wake from the outside, and the single electron beam may be owing to the reflection of electrons by the polarized electric field at the wake boundaries. We need to introduce test particles to investigate the origin of the energetic electrons responsible for non-Maxwellian components.

In this presentation, we will describe the configuration, schemes, and our simulation results first. Then, we will discuss the generation process of anisotropic electrons and will compare the simulation results with the wave data obtained in the S-520-26 rocket experiment.