Japan Geoscience Union Meeting 2013
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PPS23-01 Room:201A Time:May 23 09:00-09:15

Development of a lunar broadband seismometer system for SELENE-2

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SELENE-2 is planed to be the first Japanese landing mission on the moon. As a strong candidate for an onboard instrument, we propose a lunar broadband seismometer system (LBBS). We have already presented the necessity of the broadband seismic observation beyond the Apollo seismic observation, requirements for the system, scientific objectives from the analyses of Apollo seismic data and the status of the development of LBBS. In this presentation, we introduce the recent progress in the development.

LBBS is a seismometer system having a broader bandwidth of 0.02 to 50 Hz and higher sensitivity than the seismic sensors of the Apollo project. To achieve the required performance at low risk, we decided to integrate an existing short period sensor (SP) and long period sensor (LP) in one package. The SP sensor is based on the velocity sensor developed in the course of the former Lunar-A project and has very high shock durability. The LP sensor is the VBB seismometer developed in France for the ExoMars project of ESA. These sensors shall be modified to satisfy the requirements of very high sensitivity and high stability against the severe surface environment on the moon. In addition, LBBS is composed of measurement and control electronics (ETHZ, Switzerland), leveling system (MPI, Germany) and a thermal shield, called survival module, with a recorder, communication circuits and batteries (JAXA, Japan).

We have carried out interface tests of 7 combinations among the components since autumn of 2010. In particular, we confirmed wellness of a partially integrated system of the SP sensor, measurement electronics and leveling system in an interface test at Zurich from Dec 2010 to Mar 2011. We successfully observed faint seismic tremors in ground motions. In July 2012, we carried out an interface test in which we integrated the SP, LP and leveling system at the Black Forest Observatory, Germany. For comparison, we also recorded outputs of a standard broadband sensor STS-2. All data outputs were recorded by an acquisition system of Quanterra Q330HR.

We analyzed the data so obtained, and found that waveforms obtained by LP and STS-2 almost similar one another and confirmed that LP can faithfully acquire ground motions irrespective of the neighboring SP. It, however, sometimes shows different waveforms from those of STS-2. The cause of this phenomenon is under investigation. On the other hand, SP data show very noisy time series not considered as ground motions. Spectra of the SP data show a flat shape and we cannot recognize spectral features of seismic tremors. Moreover, two horizontal SP sensors with an eigenperiod of 1 sec commonly took boxcar type off sets in the long period waveforms low-pass-filtered with a corner frequency of 0.1 Hz. This is an unacceptable result. They should show independent noises at such a low frequency much below 1 Hz. Thus we conclude that the SP data were polluted from an unknown source.

Potential causes of this phenomenon is (1) noises and instability in a 20 times amplifier, (2) an interference due to output impedance of the 20 times amplifier which may be out of range of the guarantee of Q330HR and (3) an electro-magnetic interference of LP on SP. We have already excluded the possibility of (1) by measuring the response of the amplifier using another acquisition device. In order to distinguish (2) and (3), we plan to obtain SP data without LP using Q330HR which will be rented.

In addition to the report on the above interface test, we also report results of vibration and thermal environment tests for two new manufacturing SP sensor models, and conceptual design of the survival module.

Keywords: seismometer, noise, interference, moonquake, ground motion, measurement

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PPS23-02 Room:201A Time:May 23 09:15-09:30

Development of an in-site rock observation system onboard the next lunar landing mission SELENE-2

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Compositional information of the lunar and planetary surface is important for understanding the bulk composition and evolution of the lunar and planetary bodies. For example, the information of the lunar highland could help us to know the solidification of the lunar magma ocean and to estimate the internal structure of the Moon. Previous studies had been done by using the lunar returned samples which have bias composition, so, it is important to select samples for well-understanding of more primitive highland materials by an in-situ observation.

We are now planning to develop a visible-SWIR macro camera with rock abrasion tool (RAT) which is required to establish a light-weighting for setting on a head of rover's arm. The RAT system will be required to observe the rock sample's texture and composition. An important issue is to grind the surface of rock under vacuum condition. We examined to make a grind test which was done to grind an anorthosite rock sample under a very low pressure of atmosphere by using a RAT developed by HONEYBEE ROBOTICS. As a result, we could confirm to be able to grind the rock sample with very low preload (< 5 N), however, additional bit development work is required to increase the bit life margin (more than 10 grinds). We'll report the details of the examinations about the RAT system, optical design of a visible-SWIR macro camera, and a dark current test of a visible-InGaAs sensor.

Keywords: visible-SWIR macro camera, rock abrasion tool

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PPS23-03 Room:201A Time:May 23 09:30-09:45

SELENE-2/Lunar ElectroMagnetic Sounder (LEMS): The effect of lunar crust on electromagnetic response

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In the SELENE-2 mission, we propose a lunar electromagnetic sounder (LEMS) to estimate the electrical conductivity structure of the Moon, from which the thermal structure in the lunar interior can be deduced. This means that electromagnetic sounding of the Moon provides any constraints on the lunar origin and evolution. It should also be noted that the electrical conductivity structure is independent of the seismic velocity structure derived from seismic measurements. Hence multiple mission instruments for geophysical exploration of the Moon are significant to investigate the lunar interior from various angles.

Magnetometers onboard a lunar orbiter measure temporal variations in the magnetic field of lunar external origin (the inducing field), which induce eddy currents in the lunar interior depending on the electrical conductivity distribution and frequencies of magnetic field. Magnetometers onboard a lunar lander measure temporal variations in the magnetic field of lunar internal origin (the induced field) generated by the eddy currents, as well as those in the inducing field. Electromagnetic response of the Moon can be obtained from these magnetic field measurements, and the response function is used to estimate the electrical conductivity structure by solving an inverse problem.

We have so far paid attention to the electrical conductivity structure of mantle which is the bulk of the Moon. We have investigated electromagnetic response of the Moon for prescribed conductivity models. The response function at higher frequencies obviously depends on the shallow structure, such as lunar crustal thickness and its electrical conductivity. Hence we examine the effect of lunar crust on electromagnetic response of the Moon. The result suggests that crustal thickness at the landing site may be estimated electromagnetically.

Keywords: electromagnetic sounding, lunar interior structure, SELENE-2

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PPS23-04 Room:201A Time:May 23 09:45-10:00

Constrains on the igneous activity of basaltic magma based on the distribution of radioactive elements on the Moon

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Investigation for the eruption ages and causes of mare volcanism on the Moon is essential for understanding the thermal evolution inside the Moon. Morota et al. [1] estimated the eruption ages of mare basalt units in the nearside of the Moon by using the image data obtained by the Terrain Camera (TC) [2] onboard Kaguya. In addition, Kaguya Gamma-Ray Spectrometer (KGRS) [3] successfully observed global distributions of radioactive elements (K, Th, and U) on the Moon [4, 5]. These observations present that most of the relatively young basalt units ($<$ 2.5 Ga) locate in the Procellarum KREEP Terrane (PKT) [6] enriched in radioactive elements. The radioactive heating produced by the decay of the radioactive elements in KREEP may affect the volcanic activities in the PKT [e.g., 7]. Studies of lunar basaltic meteorites indicate that the younger basalt is more enriched in K and Th than the older basalts. However, such an investigation has not been conducted for globally distributed maria using remote sensing data. Therefore, we investigated the relationship between the abundance of radioactive elements and eruption ages of mare basalts by Kaguya data in this study. Moreover, we discussed the effect of radioactive heating for the igneous activity of the Moon.

We used the gamma-ray spectral data obtained by the KGRS at the low altitude (50 +- 20 km) from February to May, 2009. The gamma-ray counts observed by the KGRS were integrated on each of basalt units defined by previous studies [e.g., 8]. The peaks at 1461 keV (^{40}K) and 2615 keV (^{232}Th-^{208}Tl) were used to estimate their intensities. The eruption ages of each mare basalt unit are derived by [e.g., 1]. The counting rates of gamma-rays from K and Th were calibrated to elemental concentrations by an empirical method using returned samples as ground truth. We have chosen Apollo and Luna soil samples as ground truth [9].

The K and Th contents of mare basalts in PKT are higher than those of mare basalts outside PKT. In the PKT, the eruption lasted for a long time, and each unit is enriched in K and Th. As the eruption ages of basalt units in the PKT are younger, their K and Th contents increased more. It seems reasonable that a region in PKT has more heat source elements, more magma might have been generated. The partial melting zone below the layers enriched in heat source elements might last longer time than other regions in PKT. The source regions of younger magma needed more heating by the decay of radioactive elements for its remelting to offset cooling associated with heat loss of the Moon as a time went on. Thus, the younger basalts contain more K and Th contents than the older basalts.

In contrast, most of the basalt units outside the PKT have low abundances of K and Th. This implies that the effect of radioactive heating by the KREEP layer is small. In other words, there must be no or very small volume of KREEP layer outside the PKT. Moreover, most units erupted by 2.5 Ga. This result implies that the mare eruption without heat from KREEP layer drastically decreased around 2.5 Ga. Previous calculations of lunar thermal evolution suggest that the volume of partial melting zone decreases with time and may be very small around 2.5 Ga without KREEP layer [e.g., 10]. Our results of mare basalts outside the PKT are supported by the assumption inferred from thermal evolution calculations.

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Keywords: igneous activity, basaltic volcanism, radioactive elements, Kaguya (SELENE), gamma-ray spectrometer

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Relationship between compositions and ages of lunar mare basalts

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Toward a systematic understanding of the formation and evolution of terrestrial planets, it is necessary to understand the early evolution of the Moon, an endmember of differentiated planetary bodies. However, the process of magma ocean solidification and the thermal and structural evolution of the mantle are still unknown.

Lunar mare basalts provide insight into horizontal and vertical compositional structure and the thermal history of the lunar mantle. In this study, we investigated titanium contents of mare basalts using high-resolution image data obtained by Kaguya Multi-band Imager. Our results show that mare basalts exhibit typical variations in titanium content, which may reflect differences in chemical composition of the magma source.

Previous studies with remote-sensing data have suggested that no simple relationship exists between titanium contents and ages of mare basalts. However, our new analysis indicates an obvious increase in mean titanium content at 2.3 Ga, implying that the mechanism for magma production changed at that time. The high-titanium basaltic eruption, which occurred at the late stage of mare volcanism, can be correlated with a peak of volcanic activity at ˜2 Ga revealed from crater counts for mare basalts. One possible explanation for the massive eruption of high titanium basalt is the development of hot super-plume rising into the mantle from the core-mantle boundary.

Keywords: Moon, lunar mare basalts, titanium content, lunar mantle, the Procellarum KREEP Terrane, mantle over turn

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PPS23-06 Room:201A Time:May 23 10:15-10:30

Development of evaluating method of Spatial distribution of craters on Lunar Surface for detection of secondary craters

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Secondary craters are impact craters formed by ejecta blocks that were thrown out of a primary crater formation. The secondary craters give a biased spatial distribution of craters. For a crater chronology, researchers extract the secondary craters from the surface including primary and secondary craters based on his or her subjective views.

The purpose of this research is to develop an algorithm for evaluating spatial distribution of craters on lunar and planetary images. In our algorithm, clustering analysis (S-LINK, Group average etc.) applies to ideal spatial distribution of craters and observed spatial distribution of craters, and evaluates whether a non-random portion in obtained image by comparing clustering analysis results of ideal and observed craters. We demonstrated for two regions in Mare Crisium and some Apollo landing sites. As a result, most of clustered secondary craters are detected quantitatively by our algorithm.

Keywords: Moon, Secondary crater, Cluster analysis

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PPS23-07 Room:201A Time:May 23 10:30-10:45

Study on New Model of Interior Reservoir of Light Elements on the Moon and Earth-Type Planets

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The following problems are existed interior reservoir and circulation of light elements on the Moon and Earth-type planets (i.e. primordial Earth and water-less planets of Mars and Venus) as follows:

1)Few systematic models of light elements and the Solar System materials of the Moon, Earth-type planets and smaller bodies are proposed, but only time and location data of the remained solid rocks are obtained at the primordial to the present bodies.
2)Little hard and wide rocks on the water-less Moon are existed except the breccias and fine void-rich regolith soils.
3)Light elements on the Moon are lost to form high-temperature minerals and rocks.
4)Few models of light elements to penetrate and reserve in the interior against the gravitational forces are proposed on water-less Moon and other planets.

The following models of impact growth process are proposed to explain the above problems (Miura, 2013; in press).
1)Impact growth model is applied to remained solid rocks from fine-grains to breccias.
2)Wide and hard continental rocks which have been formed by plate-movements, subduction and magmatic melting with lift-up eruption of ocean-planet Earth, cannot be applied for the Moon and other water-less planets.
3)The Moon rocks without light elements and high-temperature minerals and rocks are not formed by continuous smaller impacts, but by giant impacts with two planetary bodies with much light contents), called as step 1 process.
4)On the later Moon surfaces with mixed with smaller blocks, light elements are penetrated and stored in the interior by later impact, called as step 2 process.

In short, there are major two types light elements of steps 1 and 2 processes on solidified rock and regolith on the Moon The process of light elements as multi-steps are applied to wat4erless Venus and Mar.
The present Earth light elements are not used for the Moon and primordial Earth-type planets model, because the Earth is changed so much by ocean water system.

Keywords: The Moon, Earth-type Planets, Light elemets, Interior reservoir, New model, Giant planetary impact

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PPS23-08 Room:201A Time:May 23 11:00-11:15

Sites of radon gas emission on the lunar surface obtained from the SELENE Alpha-Ray Detector (ARD)

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We report results from the observations by Alpha Ray Detector (ARD) onboard SELENE. ARD observes the alpha-particles from Rn-222 and its radioactive decay products including Po-210. Rn-222 is in the decay sequence of U-238. Since radon is rare gas, it diffuses through the fissures or porosity of the lunar surface structure upon its production and decays with the half life of 3.8 days. About half of the daughter nuclei are adsorbed on the lunar surface, and Po-210 is produced after several radioactive decay stages of which time scale is regulated by one of the intermediate products' half life of 22 years. Thus, the intensity of Po-210 alpha-particles gives information on the radon gas emission integrated over the last several decades whereas that of Rn-222 alpha-particles is an indicator of the current gas emission. By analyzing the ARD data, we obtained the Rn-222 and Po-210 distribution on the lunar surface with the spatial resolution of about 80 km (FWHM) which is about a factor of 4 or 5 times better than the observations in the past. One of the most intense peaks of the alpha-particle signal was at the Aristarchus region where Apollo 15, 16, and Lunar Prospector reported detection of radon alpha-particles. Another peak of Po-210 alpha-particle intensity was discovered in the region of Mare Moscovience on the far side of the moon, where the crust thickness has been found to be exceptionally thin. In terms of large-scale intensity distribution of the Po-210 alpha-particles, northern part of the PKT region showed higher intensity than the southern part of the PKT and FHT regions. This trend is not in complete accordance with the U-238 distribution on the lunar surface derived from gamma-ray observations which shows the highest intensity in the southern part of the PKT region. This is probably because the radon alpha-particle intensity reflects the subsurface distribution of U-238. We will discuss the overall picture of the radon gas emission on the lunar surface based on the results of the ARD observations.

Keywords: Moon, radon gas, alpha particle, lunar crust, SELENE

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PPS23-09 Room:201A Time:May 23 11:15-11:30

Heterogeneity of lunar mantle composition estimated by spectral analyses of Dark Mantle Deposits

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The lunar mantle makes up 90% of the lunar volume. Therefore, it is important to determine the mantle composition for understanding the lunar bulk composition and the process of its differentiation from the lunar magmatic ocean. However, the composition of the lunar mantle remains unclear. On the other hand, pyroclastic beads which are volcanic glass or partially crystallized spheres provide a direct clue to lunar mantle composition. Previous studies suggested that pyroclastic beads are the result of an explosive fire-fountain originating deeper (300 to 500 km) in the mantle than basaltic magma and retain the original composition of the magma because the beads have higher Mg# than mare basalts and do not completely crystallize during eruption, due to the high upward speed. It is also reported that the color variation of pyroclastic beads correspond to their composition, in particular TiO_2 content, and the crystallinity of the beads. Also, the crystallinity of the beads correlates with quenching rate of the erupted magma formed them and the volatile content in the magma.

Dark Mantle Deposits (DMDs) are darkest regions on the Moon and are believed to contain pyroclastic beads. Thus, by estimating the composition and crystallinity of DMD based on remote-sensing data, we can investigate the composition and volatile content of the magma generated in the deeper lunar mantle on a global scale.

In this study we estimated the TiO_2 content and crystallinity of the largest 20 DMDs distributed globally over the Moon and investigates the compositional relationships of the magmatic sources, among DMDs and between DMDs and the surrounding mare basalt using spectral data obtained by the Multiband Imager (MI) on SELENE. First, we selected DMD locations which have the lowest reflectance and spectral absorption features of pyroclastic beads. Second, we judged the types of pyroclastic beads by comparing the spectral absorption shapes of DMDs in the MI data with that of the laboratory-measured data for Apollo pyroclastic beads. Finally, by comparing the spectra of different mixing ratios of glass and crystallized beads, we estimated the crystallinity and TiO_2 content of the DMD. We also estimated the TiO_2 content of mare basalts surrounding the DMDs in order to compare the composition of the DMDs with that of the mare basalts by producing Ti-maps based on MI spectral data.

Our results suggest that the TiO_2 estimates of DMDs had 2 groups including intermediate-Ti group ranged from 5.4 to 6.3wt% and high-Ti group with 9.1wt%. Also, the crystallinity of the pyroclastic beads of DMDs had 2 groups, including low crystallinity group ranged from 3 to 35%, and high crystallinity group ranged from 72 to 85%.

In addition, a comparison of Ti estimates for DMDs and the surrounding mare basalts indicated that DMDs tend toward higher TiO_2 content than mare.

This variation of composition and crystallinity of DMDs indicates the presence of an azimuthal heterogeneity of composition and volatile content in the lunar mantle, assuming that the depth of the magma source for each DMD has the same range.

The possibility of azimuthal compositional heterogeneity in the lunar mantle is consistent with and may suggest compositional diversity after a mantle overturn, which is the vertical transport of the mantle caused by gravitational instability of the high-Ti cumulate layer produced during the final solidification step of a magma ocean.

Keywords: Dark Mantle Deposit, Moon, SELENE, pyroclastic beads, Ti, crystallinity

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PPS23-10 Room:201A Time:May 23 11:30-11:45

Consideration of causes of deep moonquake generation and heterogeneity of the lunar mantle

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The Apollo lunar seismic experiments have revealed that lunar seismic events; deep moonquakes, occur repeatedly from specific source regions at depth of 700-1400 km in the lunar interior. The deep moonquake occurs periodically related with positions of Earth, Moon and Sun; that is tidal forces (e.g., Lammlein, 1977, Bulow et al., 2007), but the generation mechanism of deep moonquake is not understood well regardless of some theories (e.g., Cheng and Toksoz, 1978, Araki, 2001).

In this study, we investigated characteristics and mechanism of deep moonquake generations from active well-located 15 deep nests. From previous analysis of Apollo seismic data, we know that deep moonquake occurs with different amplitudes among each deep nest (Lammlein, 1977). We, therefore, derived seismic moment from each deep moonquake event and analyzed the variation of the amplitude and the difference among deep nests. This investigation showed that amplitudes of seismic moments of the deep events are different among the active nests and they have regional characteristic.

Then, we calculated tidal stresses worked on region of each active nest during Apollo-era to reveal the correlation between the seismic moments and the tidal stress in terms of the amplitude and the time variation. From this analysis, we do not clearly identify the correlation between amplitudes of the seismic moments and those of the tidal stresses, but the deep nests occur the events with large seismic moment tend to have lower correlation between the occurrences and time variation of the tidal stresses than the nests with lower seismic moment. These results indicate that generation mechanism of deep moonquake may be different among each deep nest and/or the lunar mantle may have different elastic characteristics around each region of deep nests.

In this presentation, we will show the results derived from further analysis of more deep moonquake events and validation of previous results. Then, we will progress the discussion about the mechanism of deep moonquake generations and heterogeneity of the lunar mantle.

Keywords: Deep moonquake, Seismic moment, Tidal stress, Generation mechanism of deep moonquake, Lunar interior structure, Lunar exploration

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Early formations of lunar impact basins inferred from their viscoelastic states: Implication for the heavy bombardment

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Formations of impact basins are major geologic processes that had occurred on the early Moon [e.g., 1]. Because the upper part of the Moon probably cooled rapidly during its early history, the viscoelastic relaxation of topography would have occurred more vigorously immediately after the basin formation than later [e.g., 2]. Consequently, topographic undulations both at the surface and at the Moho (i.e., the boundary between the crust and mantle) around impact basins would reflect the thermal state of the lunar interior during basin formation ages. Thus, global survey of deformation states of impact basins is important for investigating the early thermal state of the Moon.

Using recent Kaguya geodetic data, Kamata et al. [3] investigate viscoelastic states of major lunar impact basins and obtain upper limit values for surface temperature gradient and for temperature at the Moho. However, no significant information about the thermal state for impact basins earlier than pre-Nectarian (PN) 5 is obtained. In this study, we investigate the thermal structure that can reproduce current crustal structures around early PN impact basins.

Our results indicate that a Moho temperature higher than the solidus of peridotite is necessary to reproduce early PN impact basins when the surrounding crustal thickness is thinner than 60 km. Both our crustal thickness model and a recent crustal thickness model based on LRO and GRAIL data [4] suggest that surrounding crustal thicknesses around degraded impact basins are less than 60 km. Consequently, if such degraded topographies for early PN ”basins” are actually remnants of ancient impact basin topographies, the mantle underneath these basins around their formation ages may be partially melted. This result further suggests that the timing of the complete solidification of the lunar magma ocean corresponds to the boundary between PN 4 and 5. Considering the duration of liquid magma ocean [e.g., 5], this boundary is about 4.1-4.3 Gy ago.

An important implication for the impact history of the Moon is obtained from our results. Based on Apollo sample analyses, a large increase in impact flux on the Moon around 3.9-4.1 Gy ago is proposed [e.g., 6]. This event is often called the Late Heavy Bombardment (LHB) and is very important for understanding the surface environment of the early Earth and the dynamical evolution of the Solar System [e.g., 7]. The absolute formation ages of impact basins, however, are still controversial [e.g., 8]. Because of this, the impact rate on the Moon during the LHB is highly unknown. Ryder [9] suggests an extremely large impact rate during the LHB and suggests that almost all impact basins are formed during the LHB. This speculation, however, is not consistent with our result because our results suggest that 20 out of 45 impact basins are formed before 4.1 Gy ago. This result is further consistent with recent E-belt impactor model [10, 11].

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Keywords: Impact basin, Thermal evolution, Viscoelasticity, Magma ocean, Late Heavy Bombardment

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Formation mechanism of the lunar highland crust indicated by correlation between Mg# and Th content

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Mg# (Mg/[Mg+Fe] in mole percent in mafic minerals) is a key geochemical parameter of lunar highland rock for addressing the crustal formation process because it provides the degree of differentiation of the magma ocean at the time of its solidification. In a previous study, we reported the Mg# distribution of the lunar highlands by using spectral data obtained by Kaguya, which clearly indicates a dichotomic distribution, with a higher Mg# in the far-side highlands than in the near-side highlands. A simple yet plausible model for interpreting the observation is dichotomic crustal growth from the magma ocean (the farside crustal material solidified from a less evolved magma than did the nearside crustal material). Th abundance data obtained by Kaguya also suggested similar solidification of the highland crustal material (less evolved on the farside than on the nearside).

This study investigates the correlation between the Mg# and Th abundances of the lunar highland crust of the same area by combining Kaguya spectral and gamma-ray data to check the validity of the previous interpretation derived by the Mg# and Th abundances of the highland material.

The results indicate a weak negative correlation of the Mg# decrease with increasing Th abundance, which is consistent with a prediction based on the magmatic evolution process. This result confirms the suggested process based on the individual observation (Mg# and Th abundances) of the highland formation of the farside material solidifying earlier than did the nearside material.

Keywords: Kaguya, moon, highland crust

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

PPS23-13 Room:201A Time:May 23 14:30-14:45

Global Survey of Lunar Spinel-Rich Exposures by Satellite Hyperspectral Remote Sensing

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The studies using the spectral data obtained by Spectral Profiler (SP) and Multiband Imager (MI) onboard the Japanese lunar explorer SELENE/Kaguya revealed the global distributions of the purest anorthosite (PAN), olivine-rich materials, and orthopyroxene-rich materials over the entire Moon. These results were based on the diagnostic bands of these lunar major minerals in spectral data with wavelength less than 1.7 micron. Recently, a prominent Mg-spinel-rich material (hereafter, Mg-spinel) on the lunar surface has been identified by Moon Mineralogy Mapper onboard Chandrayaan-1. Since the Mg-spinel is characterized by a strong absorption band around 2 micorn, the spectral data with wavelength longer than 1.7 micron are needed to find the Mg-spinel by remote-sensing spectral data. We have recently updated the radiometric calibration for SP NIR 2 data with wavelength longer than 1.7 micron. Based on the entire data set of SP, including the SP NIR 2 data, we conducted the global survey to find the Mg-spinel on the Moon. Here, we report the global distribution of the Mg-spinel sites based on this survey.

Keywords: remote-sensing, hyperspectral

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PPS23-14 Room:201A Time:May 23 14:45-15:00

Differentiation of impact-induced magma seas on the Moon

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It is widely accepted that a huge impact on the Moon, such as the South Pole-Aiken (SPA) basin forming event, entirely removed the feldspathic crust and melted the mantle below . The tremendous amount of impact melt must have formed a magma sea in the excavated basin. Such magma seas likely have experienced a significant differentiation as global magma ocean. In this presentation, we summarize recent results of global hyperspectral mapping of the Moon by Spectral Profiler (SP) onboard Kaguya and discuss the implications on the differentiation processes of magma seas.

Keywords: Moon, Spectra, Infrared, Mantle, Impact, Crust

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(May 19-24 2013 at Makuhari, Chiba, Japan)

PPS23-15 Room:201A Time:May 23 15:00-15:15

Radar observation of lunar surface by KAGUYA LRS

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We present recent result of lunar surface observation of KAGUYA Lunar Radar Sounder (LRS).

Extracting nadir surface echoes out of LRS observation data, we made a surface echo map of the Moon, i.e. LRS lunar surface image. Nadir surface echo was defined as the most intense peak of an A-scope data. More than 10^8 observation data was used. The LRS lunar surface image has a wide dynamic range of 20 dB, and shows variety of radar surface features as follows;

1. Highland surface appears darker while mare surface appears brighter.
2. Statistical property of surface echoes is different in highland and mare.
3. A crater whose diameter is larger than a few tens of kilometers can be recognized in the image.
4. The central peak of a middle sized crater is recognized as a dark spot.
5. Wrinkle ridges in maria appeared dark linear features.
6. Surface echo intensity of mare surface has a strong correlation with the surface age.

Keywords: KAGUYA, LRS, Moon, Surface, Radar

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PPS23-16 Room:201A Time:May 23 15:15-15:30

Determination of the permittivity of the lunar surface based on the radar echo intensity observed by the Kaguya

Atsushi Kumamoto[1*], Takayuki Ono[1], Takao Kobayashi[2], Junichi Haruyama[3]

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The permittivity of the lunar surface is considered to depend on the compositions and porosity of the surface materials. Therefore the determination of the permittivity is important for discussion of the geological conditions of the lunar surface. If we are going to use echo power for determination of the permittivity, we should note that the radar echo intensity depends not only on the permittivity but also on the roughness of the surface. Therefore, we have determined the permittivity of the lunar surface with considering the surface roughness. In the analysis, the permittivity is determined by using the radar echo intensity obtained by Kaguya Lunar Radar Sounder (LRS) [Ono et al, 2000; 2008; 2010], and the surface roughness parameters derived from Digital Terrain Model (DTM) based on Kaguya Terrain Camera (TC) observation [Haruyama et al., 2008].

The global distributions of the echo powers in a frequency range of 4-6 MHz were derived from the Kaguya/LRS dataset. We have used the intensity of off-nadir echoes in an incident angle larger than 3 degree. The reason why nadir echoes are not used in the analysis is because the echo intensity changes drastically in small incident angle especially at the smooth surface. The echoes arrived after the arrival of the nadir surface echo were identified as off-nadir echoes in this study. In addition, we have also derived the global distribution of the surface roughness parameters. The RMS height sigma of the surface can be obtained by $sigma^2 = <(h(x+dx)-h(x))^2>$, where h(x) is height of the surface derived from the Kaguya TC/DTM, dx is baseline length, and <> denotes the average. If we assume the self-affine surface model, the roughness parameters H and s can be obtained by the least square fitting of the RMS heights to $sigma = s(dx)^H$. The off-nadir surface echo power can be calculated based on the radar equation. Assuming Kirchhoff Approximation (KA), the backscattering coefficient in the radar equation can be obtained from the roughness parameters H and s, and permittivity [cf. Bruzzone et al., 2011]. Using the roughness parameters H and s obtained by Kaguya TC/DTM and changing the assumed permittivity, we can calculate the expected off-nadir surface echo powers and compare them with observed off-nadir surface echo power. Based on the comparison, we can determine most plausible permittivity.

The obtained Hurst exponent H is less than 0.5 in the maria, and about 0.9 in the highlands. The parameter s is about 1 in the maria, and about 0.3 in the highlands. The global distribution of H is similar with that reported by Lunar Reconnaissance Orbiter (LRO) laser altimeter [Rosenburg et al., 2011]. By applying the analysis method mentioned above, we could obtain the observed and calculated surface echo powers in the regions where $0.25<H<0.35$, and $0.85<H<0.95$. Based on them, we could estimate the average permittivity in the maria (H˜0.3) to be 4-5, and that in the highlands (H˜0.9) to be 2.

It is inferred that the lunar basalt below the surface consists of grains and voids. The bulk permittivity of the lunar uppermost basalt layer depends on the permittivity of the grains and the ratio of the voids, or porosity. According to the previous studies based on the Apollo lunar samples [cf. Shkuratov et al., 2001], the grain permittivity can be estimated based on the ilmenite abundance. The ilmenite abundance can be derived from the Clementine multiband image data [Lucey et al., 2000].

Based on the bulk permittivity and grain permittivity determined in this study, we also estimated the porosity in the maria (H˜0.3) to be 30 % and that in the highland (H˜0.9) to be 60 %. It is considered that the surface of the highlands is older than that of the maria. Due to the longtime exposure to the impacts of the meteorites, the porosity of the lunar basalt in the highlands can be larger than that in the maria.

Keywords: Kaguya (SELENE), Lunar Radar Sounder (LRS), Terrain Camera (TC), Electric permittivity, Porosity, Surface roughness

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PPS23-17 Room:201A Time:May 23 15:30-15:45

Estimation of the permittivity and porosity of the lunar uppermost basalt layer based on the SELENE observation data

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Permittivity is an important parameter for understanding the results obtained from various radar observations. For the investigation of lunar subsurface structures, Lunar Radar Sounder (LRS) onboard the SELENE (KAGUYA) spacecraft emitted the electromagnetic wave (4 - 6 MHz), and measured the delay (dt) between the electromagnetic waves reflected at a lunar surface and at subsurface boundaries [Ono et al., 2009]. In this study, we define an apparent radar depth (D), which is expressed as a function of D=(c∗dt)/2, where c is the speed of light in vacuum. The apparent radar depth relates to the thickness (T) between the surface and subsurface boundaries, at which the electromagnetic wave is reflected. However, we must note that the apparent radar depth is not equal to its thickness. Because the lunar subsurface layer has a bulk permittivity (E_{bulk}), it varies the velocity (v) of the electromagnetic wave in the subsurface layer. The thickness can thus be given as T=v∗dt/2=(c/(E_bulk)$^{0.5}$)∗dt)/2=D/(E_{bulk})$^{0.5}$. In radar observations, the information of the thickness of lunar basalt layer is significant for discussing the lunar volcanic activity [e.g., Hiesinger et al., 2003].

The values of the bulk permittivity (4 - 11), based on Apollo basalt samples, have been used in previous works [e.g., Peeple et al., 1978; Cooper et al., 1994; Oshigami et al., 2009]. We, however, cannot easily use the bulk permittivity. Because Apollo samples were collected on the lunar surface, we suspect whether the bulk permittivities based on Apollo basalt samples reflect the bulk permittivity of the lunar basalt layer. In this study, the bulk permittivity of the lunar uppermost basalt layer is estimated from the rate of D and T. In general, the subsurface bulk permittivity relates to the subsurface porosity [e.g., Shkuratov and Bondarenko, 2001]. The information of the porosity is important for discussing lunar geological conditions, so that the porosity is also estimated by using an empirical relationship between the bulk permittivity and porosity [Shkuratov and Bondarenko, 2001; Huang and Wieczorek, 2012].

We have used data sets obtained from three instruments onboard SELENE: LRS, Multiband Imager (MI), and Terrain Camera (TC). We first focused on the ejecta composition (FeO and TiO_2) around two types of impact craters (the haloed crater and non-haloed crater) due to the estimation of T. The non-haloed crater has the same ejecta composition with the surface composition of uppermost subsurface layer, while the haloed crater has the different ejecta composition from the surface composition of uppermost basalt layer. The haloed craters would be formed when meteorites excavate a lower basalt layer with the different composition from the uppermost basalt, which is lied on the lower basalt layer. The haloed crater and non-haloed crater are identified on the basis of FeO and/or TiO_2 maps created from the MI data. We would therefore constrain T from the depths of haloed crater and non-haloed crater (d_h and d_{non}) measured from the TC data: $d_{non}<T<d_h$. We note that the distance between haloed crater and non-haloed crater should be as short as possible. The true lunar subsurface boundary is probably oblique, so that the oblique subsurface boundary produces a bad limitation of T. In this study, the distance is limited within 6 km. D is also determined within 6 km from these craters by using the LRS data.

As the results, the bulk permittivity was estimated to be 2.3 - 4.2 in Unit 85 of Mare Humorum and 1.8 - 13.1 in Unit S13 of Mare Serenitatis. In particular, the bulk permittivity of Unit 85 of Mare Humorum was limited within a low bulk permittivity. This low bulk permittivity is indicative of a porous basalt layer with a porosity of 36 - 58%. This estimated porosity would be explained mainly by two different sources: intrinsic voids (vesicles and micro cracks) and impact-induced cracks (micro and macro cracks).

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PPS23-18 Room:201A Time:May 23 15:45-16:00

ARTEMIS observations of lunar dayside plasma in the terrestrial magnetotail lobe

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We report observations by the dual-probe ARTEMIS mission of Moon-related electron and ion signatures obtained above the dayside lunar surface in the terrestrial magnetotail lobes. While the Moon is often thought of as a passive absorber, recent observations from Kaguya, Chandrayaan, Chang'E, and ARTEMIS indicate that plasma of lunar origin can have significant effects on the near-lunar environment. We now present new observations from ARTEMIS showing that lunar plasma can play a dominant role in the low-density environment of the terrestrial magnetotail. Two-point observations reveal that the density of plasma of lunar origin is higher than that of the ambient lobe plasma even several hundreds of kilometers above the Moon's dayside. Meanwhile, the distributions of incoming electrons exhibit modifications correlated with Moon-related populations, suggesting direct or indirect interactions of the lobe electrons with plasma of lunar origin. We also observe high-energy photoelectron emission from the dayside lunar surface, supporting the existence of large positive potentials on the lunar surface. Pickup ions with nonzero parallel-velocity components provide further evidence for positive surface potentials of tens of volts or more. ARTEMIS data reveal not only the existence of the large surface potentials first inferred from Apollo CPLEE measurements, but also their significant implications for the dynamics of both the dominant Moon-originating ions and the tenuous ambient plasma populations in the tail lobe.

Keywords: Moon, plasma, surface charging, pickup ion, photoelectron

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PPS23-19 Room:201A Time:May 23 16:15-16:30

Electron cycltron harmonic waves observed around the moon

Yumiko Katayama[1], Hirotsugu Kojima[1*], Yoshifumi Saito[2], Yoshiya Kasahara[3], Yoshiharu Omura[1], Tadateru Yamamoto[4], Shoichiro Yokota[2], Masaki N Nishino[2], Kozo Hashimoto[1], Takayuki Ono[5], Hideo Tsunakawa[6]

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The present paper discusses the generation of Electron Cyclotron Harmonic (ECH) waves observed around the Moon. Plasma wave data obtained by the KAGUYA satellite show the existence of two kinds of ECH waves. They are:the

ECH waves with lower order harmonics and ones with higher order harmonics which frequencies are close to the upper hybrid resonance frequency. ECH waves can be observed only when the moon is inside the terrestrial magnetosphere. They never appear in the solar wind. The configuration of local magnetic fields is also important. KAGUYA observes the both types of ECH waves along the magnetic field lines which are connected with magnetic anomalies which are scattered on the moon surface. Furthermore, while the lower order harmonics are observed in the nightside of the Moon in the plasma sheet and lobe regions, the higher order harmonics are observed in the dayside in the lobe region. The correlation studies between waves and particles show that the existence of two components of electrons is essential for the observation of the both types of ECH waves. Two components of electrons mean hot electrons with the loss cone velocity distribution and cold electrons. On the other hand, the generation of cold electrons is classified into two echanisms. One is the acceleration over the nightside moon surface which is negatively charged and the other is the emission of photo electrons while the spacecraft gets sunlight. In order to make sure the relation of ECH waves and electron distribution, we conducted the linear dispersion relation analysis and particle simulation using the realistic plasma parameters of electromagnetic environment based on the KAGUYA observation. The results clearly showed the parametric dependence of the ECH wave growth under the co-existence of the loss cone distribution of hot electrons and cold electrons. We discuss the generation of ECH waves consulting the parametric dependence and explain the relation of the ECH waves with the moon location in the magnetosphere.

Keywords: Electron cyclotron harmonic waves, Plasma waves, KAGUYA, moon

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PPS23-20 Room:201A Time:May 23 16:30-16:45

Electrostatic Solitary Waves (ESWs) and electron beams observed by Kaguya near the Moon

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In KAGUYA (SELENE) LRS[1], WFC-L[2] observes waveforms of plasma waves in 100Hz-100kHz and a lot of electrostatic solitary waves (ESWs) have been observed[3]. Although the orthogonal dipole antennas are generally used in the observations, sometimes a pair of monopole antennas were used. We analyze the magnetic field[4] and plasma environment[5] around the observed regions.

Observed waveforms are fitted to ideal ESW waveforms parallel to the magnetic field and the perpendicular component. The propagation velocities and the potential scales are also evaluated in the case of the monopole observations.

In the present report, electron distribution functions are analyzed. Electron beam components are derived by subtracting background thermal Maxwellian distribution from parallel distribution integrated over perpendicular component based on the electron beam analysis for ESW observed by Geotail[6]. Relation among ESW, electron beam, and magnetic field observed in the solar wind, above the magnetic anomalies, in the wake boundaries, and inside the wake will be discussed.

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Keywords: Kaguya, ESW, electron beam

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PPS23-21 Room:201A Time:May 23 16:45-17:00

Type-II entry of solar wind protons into the lunar wake as a general phenomenon

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We study a type of solar wind entry into the lunar wake under various interplanetary magnetic field (IMF) conditions using SELENE (Kaguya) data. Our recent observations around the Moon revealed that so-called type-II (T2) entry of the solar wind protons into the near-Moon wake occurs when the IMF is dominated by the non-radial components (i.e. B_Y and/or B_Z). Under this condition a part of the solar wind protons scattered/reflected at the lunar dayside surface subsequently enters the central region of the near-Moon wake after a large-scale cycloid motion, which gives rise to electron acceleration and wave generation. The situation handled in the previous studies is that the magnetic field line around which the solar wind protons entering the wake are gyrating is detached from the lunar surface, and thus a possibility of the T2 proton entry into the region where field lines are connected to the lunar surface has not been considered yet. Here we report that the T2 entry process takes place under various IMF conditions, and that the protons can access the central wake region that is magnetically connected to the lunar nightside surface, which we categorize into the T2 entry with magnetic connection to the lunar surface (T2MC). Furthermore we show that the energy of the electron beams associated with the entered protons depends on the magnetic connectivity to the lunar nightside surface. Strong electron acceleration (up to several hundred eV to 1 keV) along the magnetic field associated with the T2 entry is prominent when the field line has its both ends in the solar wind, that is, when the magnetic field is detached from the lunar surface (i.e. the ”original” T2 entry that we rename to T2MD). On the other hand, no significant electron acceleration is found in the T2MC cases, although an enhancement of the electron flux associated with the T2 proton entry is evident. Our results indicate that, while the T2 entry of solar wind protons into the wake itself does not require a special IMF condition but is a rather general phenomenon, the characteristic energy of associated electrons does show a strong dependence on the magnetic connectivity to the lunar surface.

Keywords: Solar wind-Moon interaction, Lunar wake, SELENE, Wave-particle interaction, Plasma entry into wake

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PPS23-22 Room:201A Time:May 23 17:00-17:15

Magnetic fluctuations detected by Kaguya in the central wake

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Since the moon does not have a global magnetic field system, the solar wind particles can access the lunar surface directly. The solar wind particles that hit the moon are absorbed by the dayside lunar surface, and the solar wind plasma are essentially absent on the downstream side of the moon (the lunar wake). Kaguya MAP-PACE instrument has revealed that not all the solar wind particles are absorbed, but 0.1 - 1% of the solar wind protons are reflected by the lunar surface (Saito et al., 2008).

Due to the reflection of the solar wind particles, the magnetic field is almost always fluctuating over the frequency range of 0.03 - 10 Hz (Nakagawa et al., 2011). They were basically absent in the central wake.

Magnetic fluctuations of about 0.1-10 Hz are found by Kaguya MAP-LMAG magnetometer in the deepest wake region, where magnetic fluctuations were rarely expected. The magnetic fluctuations were rather 1-dimensional, showing no preferred polarity. They were often detected when the SSE-y component of the solar wind magnetic field was dominant. At least 80 percent of them were accompanied by ions, which are thought to be the solar wind protons once reflected by the dayside surface, picked up by the solar wind electric field and entered the deepest wake (Type-II entry protons, Nishino et al., 2009). Accordingly, the magnetic fluctuations in the central wake are thought to be generated by the type-II protons.

Keywords: lunar wake, SELENE, magnetic fluctuations, solar wind, nightside, type-II entry

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PPS23-23 Room:201A Time:May 23 17:15-17:30

PIC simulation on the solar wind interactions with meso-scale magnetic dipole and its application to Reiner Gamma

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We have been studying the solar wind interactions with a small-scale magnetic dipole by means of plasma particle simulations. In the current presentation, we will report some of the simulation results including a case of magnetic anomaly found in Reiner Gamma on the moon. If we define the dipole size L as the distance between the dipole center and a position where the solar wind dynamic pressure balances the magnetic pressure, L of our interest is in the meso-scale which implies the size smaller than the ion's inertia length and sufficiently larger than the electron Larmor radius in the solar wind. Contrary to the Earth's magnetosphere, difference of dynamics between ions and electrons with respect to the local magnetic field play an important role in the magnetosphere formation. In other words, electron-ion coupling through a dipole field becomes important. However, very little analysis has been done so far on the interactions between meso-scale dipole field and plasma flows.

Plasma particle simulation is appropriate for the investigation on the interactions between the solar wind and meso-scale dipole magnetic fields because plasma kinetics is considered. The simulation results obtained with the plasma particle simulations we performed so far show that electron interactions are important in the process of meso-scale magnetosphere formation. Around the distance of L from the dipole center, charge separation occurs because of the difference of dynamics between electrons and ions. Then intense electrostatic field is induced and ions, which can be assumed unmagnetized in the present dipole size, are eventually influenced by this electric field. At the distance of L from the dipole center, magnetic fields are also compressed. The width of the boundary current layer as well as the spatial gradient of the local magnetic field compression found on the dayside can be characterized by the electron Larmor radius. When IMF is considered, it is found that the formation of shock structure and magnetic field reconnection can affect the formation of the magnetosphere.

As one application, we studied the solar wind interactions with magnetic anomaly found in Reiner Gamma by performing plasma particle simulations. Since the magnetic field is almost perpendicular to the solar wind, increase of plasma and magnetic field densities is found at the dayside region in the simulation results. When the direction of IMF changes, their increase fluctuates because of the magnetic field reconnection. One of the interesting findings is that the solar wind ions do not reach the moon surface in Reiner Gamma. We will discuss this point by considering the plasma dynamics as well as the electrostatic field observed over the Reiner Gamma region.

Keywords: Plasma particle simulation, magnetic anomaly, small-scale magnetic dipole, solar wind, Reiner Gamma

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PPS23-24 Room:201A Time:May 23 17:30-17:45

The effect of magnetic anomalies on the detection of Moon originating ions

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The Moon has only thin atmosphere and local magnetic field called ”magnetic anomalies”, which makes the Moon intriguing in terms of interaction between the solar wind and surfaces of astronomical bodies. In the second half of the 20th century, the Apollo series and ground-based observation revealed the existence of the thin atmosphere and heavy ions around the Moon. Although the generation / transportation processes of the ions originating from the Moon have long been discussed, they have not been sufficiently understood yet. At present, it is supposed that ions are generated by multiple processes including ionization of neutral exosphere by solar wind, processes at the lunar surface such as thermal desorption, photon / charged-particle / chemical sputtering, meteoric impact, and interior release. The generated ions are accelerated by surface potential / convection electric field in the solar wind, and then released to space [Vondrak, 1988].

An ion energy mass spectrometer MAP-PACE IMA on Kaguya first made in-situ observation of Moon originating ions. Yokota et al [2009] identified heavy ions such as C^+, O^+, Na^+, K^+, Ar^+ in the mass spectra obtained by integrating the ion counts observed by IMA (Ion Mass Analyzer) on Kaguya, when the Moon was in the solar wind. They showed that in general the energies of the ions could be explained by assuming that ions were accelerated by convection electric field in the solar wind.

Since the amount of detected ions would be affected by many factors, including electric field, magnetic field, positional relation between the Sun and the Moon, selenographical features and so on, to understand how detected ions are affected by these factors should be an important clue to reveal the generation / transportation processes.

We study how convention electric field and magnetic anomalies affect the Moon originating ions. Comparing the convection electric field and fluxes of the Moon originating ions detected by IMA at ˜100km altitude, we confirmed that the radial component of convection electric field has relatively good correlation with detected fluxes. This means that the quantity of the transported ions is in general dominated by the direction and intensity of the convection electric field. On the other hand, IMA detected less Moon originating ion fluxes whose energies are under ˜250eV above magnetic anomalies even when the radial component of electric field was positive. This indicates that magnetic anomalies affect generation or transportation of ions originating from the Moon.

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