Studies based on global subsurface radar sounding of the Moon by SELENE (Kaguya) Lunar Radar Sounder (LRS): A summary

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The Lunar Radar Sounder (LRS) onboard the SELENE (Kaguya) spacecraft successfully performed subsurface radar sounding of the Moon and passive observations of natural radio and plasma waves from the lunar orbit. The operation of LRS started on October 29, 2007. Until the end of the operation on June 10, 2009, 2363 hours worth of radar sounder data and 8961 hours worth of natural radio and plasma wave data were obtained [Ono et al., 2010]. We found subsurface regolith layers at depths of several hundred meters, which were interbedded between lava flow layers in the nearside maria. [Ono et al., 2009]. Using the measured depths and structures of the buried regolith layers, we could determine several key parameters on tectonics, surface layer evolution, and volcanism in the maria: Base on the determined parameters such as the formation age of the ridges, effective permittivity of the uppermost basalt layers, and the lava flow volumes in the nearside maria, we made the following suggestions: (1) Global cooling, which forms ridges in southern Serenitatis, became dominant after 2.84 Ga. [Ono et al., 2009], (2) The porosity of the uppermost basalt layer in Mare Humorum was estimated to be 19-51%, much more than the average of Apollo rock samples (7%) [Ishiyama et al., 2013], and (3) The average eruption rate of the lava flow in the nearside maria was 10^{-3} km^{-3}/yr. at 3.8 Ga and decrease to 10^{-4} km^{-3}/yr at 3.3 Ga [Oshigami et al., 2014]. Thanks to the high downlink rate from the SELENE/LRS (0.5 Mbps), we could obtain almost raw (simply pulse-compressed) waveform data from the lunar subsurface radar sounding. Using this dataset, synthetic aperture radar (SAR) processing was applied with trying several permittivity models in the analyses on the ground [Kobayashi et al., 2012]. This dataset is provided via SELENE Data Archive (http://l2db.selene.darts.isas.jaxa.jp/index.html.en), which will be useful for researchers who have new ideas for applying them to the investigations of the lunar surface structures and there evolutions.

Keywords: SELENE (Kaguya), Lunar Radar Sounder (LRS), Tectonics in the maria, Volcanism in the maria

Global Survey of Exposure Areas of Volcanic Glass-Rich Sites on the Moon based on Hyperspectral Remote Sensing

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Spectral Profiler (SP) onboard SELENE/Kaguya has obtained continuous spectral reflectance data (hyperspectral data) for about 70 million points on the Moon in the visible and near-infrared wavelength ranges. Using a data ming approach with all the SP data, global distributions of large area sites with exposed end-member of various lunar major minerals have been revealed: olivine-rich sites, purest anorthosite sites, high Ca pyroxene-rich sites, low Ca pyroxene-rich sites, and spinel-rich sites. In addition to these sites, it is expected that there are exposure sites of quenched glasses from volcanic eruptions on the lunar surface. Although several remote-sensing observations for the volcanic glasses on the Moon have been reported, the global distribution of the glass-rich sites on the Moon has been unknown. Thus, we conducted the global survey using SP data to reveal the global distribution of the glass-rich sites on the Moon. From the global distribution data, we will discuss the compositional variation of the lunar mantle and/or the distribution of the amount of volatiles in the mantle.

Keywords: remote-sensing, hyperspectral, Moon, Kaguya/SELENE

Compositional estimation of the lunar interior based on the mineralogy of impact melt pool of South Pole-Aitken basin

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The South Pole-Aitken (SPA) basin is the largest basin (2400 x 2050 km) that is clearly identified on the Moon. The basin impact is very large, so it has been suggested that most of the crustal material within the SPA was excavated, and it is likely that the mantle materials have been exposed within the basin. However, the mineralogy of the SPA basin was not well known previously because it is one of the oldest basins (pre-Nectarian in age), and its surface has become obscured by intensive cratering and mixing since its formation. Therefore, it is very important to investigate the mineralogy and composition of the impact melt pool and to evaluate if the impact melt pool had undergone magmatic differentiation to acquire rare direct information of the lunar interior (possibly mantle) composition. In this study, we used a mineralogical map based on high-spatial-resolution reflectance spectra using the SELENE (Kaguya) Multiband Imager (MI). We investigated not only the mineralogy but also the layer thickness, distributions, chemical abundance, and stratigraphy within the central area of the basin.
As the results, we classified the rock types for six units as, 1) LCP-dominant unit (L1) located around the central depression, 2) HCP-dominant unit (H1) located within the depression, 3) HCP-dominant unit (H2) with relatively deeper spectral absorption at 1050 nm than the 950 and 1000 nm and tends to have longer wavelengths in the band center than the H2 unit, 4) an LCP-dominant unit (L2) observed at the central peaks of the large craters, which formed after the SPA basin impact, 5) the HCP-dominant unit (MB) having even longer wavelengths in the band center and higher iron content than H1 and L2 units, 6) plagioclase dominant rock (An). HCP-dominant rock types (H1 and H2) have the largest coverage in the central depression. Based on the crater wall and floor observation on the L1 unit, it is clear that the H1 unit extends under the L1 unit. The L1 thickness is estimated to be 100 to 500 m based on the estimated excavation depth of the observed craters. Based on the crater central peak observation of the H1 unit, the LCP-dominant L2 unit underlays the H1 unit, and the H1 thickness is from 6.5 to 6.9 km. Similarly, H1 extends under the H2 unit and is up to 2 km thick. The thickness of L2 is at least 8 km thick, based on the diameters of the smallest and largest craters that have central peaks of the red layer. As a result, columnar sections of the area are determined as L2> H1> (L1/H2) from bottom to top.
We interpreted the L1 unit as mantle material ejected by an SPA formed impact event based on its spectra, thickness, and chemical composition. We also interpreted the H1 and L2 units as the impact melt of the SPA basin that had undergone magmatic differentiation because this layer is larger and thicker than the normal mare basalt observed on the Moon. In addition, the average FeO abundance is 2 wt.% lower than that of mare basalt.
Hurwitz and Kring (2014) studies SPA impact melt differentiation and derived estimated stratigraphy considering the different lunar bulk composition (different impact melt composition) and mantle overturn. Stratigraphy of our observation (lower LCP layer of at least 8 km and upper HCP layer of 6~7 km) is matched to the stratigraphy of a post-overturn model in their study, which estimated relatively thick olivine layer (~30 km)> LCP layer (12 km)> HCP layer (5 km) from bottom to top in the differentiated column. This suggest that the composition of the SPA impact melt indicates the

lunar upper mantle after the mantle overturn. In other words, the SPA impact event occurred after the LMO cumulate overturn. This is possibly direct evidence that the mantle overturn occurred early in the history of the Moon.

Keywords: Moon, interior, composition, mineralogy, impact melt

Spectral charactaristics of possible antipodal ejecta deposits of Tycho crater

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Recently, melt deposits have been identified at the antipode of crater Tycho on the lunar farside. Because of absence of a potential source crater nearby this region, these deposits are formed by concentration of ballistic ejecta from Tycho crater at its antipode. Coincidence of model ages by crater counting of these deposits and impact melt deposits on Tycho ejecta also supports this interpretation.
We examine multi spectral data of the Tycho antipode region to describe spectral characteristics and regional extent of these possible antipodal deposits of Tycho crater. Global spectral cube data of Spectral Profiler (SP-Cube) is used in this study. SP-Cube provides lunar spectral reflectance and band depth from 510 nm to 1600 nm covering the whole surface of the Moon with 0.5 x 0.5 deg. mesh. Independent Component Analysis (ICA) is applied to SP-Cube to identify spectral characteristics of the target materials. ICA can extract significant spectral components from original spectral cube data as independent components.
Pseudo color composite of the ICA component can visualize a distinct structure at the Tycho antipode. A white circular spot with a ~150 km of diameter is located on 167.25E and 43.25N and a dark red-pink tail extending over 1000 km to the west. Shorter light pink streaks are also found. The location and size of the white spot exactly correspond to a rocky region found in Diviner rock abundance map. The associating tail and streak structures have not been reported in previous works. The Tycho antipode structure has spectral characteristics of 1) low albedo, 2) bluish spectral slope in a VIS range, and 3) weak or no 1-um absorption feature.
As possible ejecta from Tycho, the antipode deposits have unique spectral characteristics. Morphological observations suggest that they are rich in impact melt, but a dark ring material around Tycho, in which many melt pond deposits exist, has redder spectral slope. Difference of reflectance spectra may originate from variation of source materials or cooling history of impact melt. Impact melt on the dark ring near the crater rim is ejected with slower velocity, while that reaching to the antipode has a higher ejection velocity. Considering excavation process of crater cavity, slow ejecta should originates from a deeper region of impact point, while fast ejecta does from shallower region. Mixing with local materials on the farside is potentially affected chemical composition of the antipode deposits.

Keywords: Tycho, antipode, ejecta, SELENE/Kaguya, spectroscopy

Heterogeneity in magma eruption on the lunar farside

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Lunar maria are limited to the topographic low and/or thin crust regions. It implies that magma eruptions on the Moon are largely controlled by the surface structure as well as the lateral heterogeneity in magma production in the upper mantle. Morota et al. (GSL Special Publications, 401, 127-138, 2015) conducted a global survey of regional differences in magma eruption on the lunar surface. As a result, they found that the South Pole-Aitken (SPA) region has high mare ratio compared to the Feldspathic Highlands Terrane (FHT) even they have same crustal thicknesses. Their explanation for the result is that crustal density of SPA is higher than that of FHT. In contrast, our estimate of magma volume in the SPA provides the result that there are no significant difference in magma volume between maria in the SPA and the FHT (Taguchi et al., JpGU Meeting 2015, PPS23-P0). Morota et al. (2015) considered only crustal thickness as an indicator of condition for magma eruption. However, altitude is also an important indicator for the ease of magma eruption to the surface, thus systematic investigation of both crustal thickness and altitude on the mare region is required.
In this study, we aim to reveal the relationship between magma eruption and surface structure on the lunar farside maria and put constraints on a condition of magma eruption. Therefore, we redefined mare region and investigated their crustal thickness and altitude.
As a result, we found that magma erupted selectively in the area that has thin crust and low altitude, as have been reported by previous studies. However, in comparing the SPA and the FHT, magma eruption can occur at higher altitude in the FHT than in the SPA. In addition, there is a spatial variation in mean crustal thickness and altitude of the mare regions in the SPA compared with the FHT, indicating heterogeneity in conditions for magma eruption in the SPA. For example, there is much volume of magma in the Ingenii basin, but not in the Apollo basin. Also, a latitudinal dependence of magma eruption is confirmed within the SPA.
The spatial distribution of magma observed on the surface reflects amount of magma production and/or easiness for magma eruption to the surface. In particular, the latter depends on both density structures in the crust and magma density. Since the SPA crust consists of relatively high-Fe rocks, it is expected that the SPA was better place for magma to erupt to the surface compared to the FHT. However, our results show opposite trend, implying that magma production within the SPA was less than that within the FHT.

Keywords: lunar farside, mare volcanism, South Pole-Aitken basin

Lunar geologic map based on auto classification of Kaguya spectral data

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Geologic mapping is essential to understand the history of the crust formation and the volcanic activity of its plant or satellite. For the Moon, many researchers have made the lunar geological map. Those work were mainly based on albedo, texture and topography of the lunar terrain, and relative age from crater counting, which were obtained in the Apollo era. There is no mineral and chemical composition-oriented geologic map of the entire Moon up to today, while those have been reported about many local area.
By using reflectance spectrum data set obtained by the Spectral Profiler (SP) and Multiband Imager (MI) aboard Kaguya, we have started a project to make a new geological map that is mineral and chemical composition-oriented. The SP observed lunar reflectance with 296 bands in the wavelength range of 510 to 2600 nm with footprint of 500 m×500 m. The SP data of 160 bands between 510 and 1600 nm was averaged pixel by pixel of 0.5 degree interval in longitude and latitude and was removed a continuous part from each reflectance spectrum, called as SP-Cube Depth. And, the abundance map of titanium oxide calculated from MI data was also used for this work.
To construct the geologic map, the unsupervised clustering methods as K-means and ISODATA were adopted to classify the SP-Cube Depth. These are similar algorithm, but the input parameters for the classification are different. One of them is the final number of class. While the K-means needs it, the ISODATA do not need it. Since nobody knows the true number of class as the lunar spectral surface unit, the ISODATA is more suitable for this work than the K-means. However, comparing with the K-means, the ISODATA requires more calculation time, as the data increase. Therefore, at first, we divided the entire Moon into 7 classes by K-means, which correspond approximately to two mare regions, South Pole-Aitken (SPA), two highland regions, boundary regions between mare/SPA and highland, and relatively fresh crater ejecta. Then, the 3 classes corresponding to the mare regions and the boundary region between mare and highland were divided into 5 classes in each by the titanium content, because the sensitivity for that is small in the SP-Cube depth. Finally, all classes were applied to the ISODATA to classify the SP-Cube Depth. As a result, the SP-Cube Depth was divided into 66 classes in total.
Focusing on the Aristarchus and Marius regions, Aristarchus crater, the Aristarchus plateau and the Marius hills can be classified as other classes. At Aristarchus crater, inside and outside of the crater was divided into other classes. The crater ejecta in the outside were recognized as some classes near the crater and one of their classes has SPA-like spectrum as low calcium pyroxene type.
This report presents the analytical procedure and the result of automatic classification of lunar reflectance spectra.

Keywords: Moon, geologic map, spectroscopy, unsupervised clustering, SELENE/Kaguya

The detailed distributions of Th and K in the high-Th concentration regions of the Procellarum KREEP terrane observed by Kaguya Gamma-ray Spectrometer

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Thorium (Th) and potassium (K) are incompatible elements that remained in the melt phase during the crystallization process of the lunar magma ocean. Therefore, the distributions of these elements on the lunar surface provide valuable information regarding magmatic activity and differentiation of the Moon.

Kaguya Gamma-ray Spectrometer (KGRS) [*Hasebe et al.*, 2008] onboard Japanese lunar explorer Kaguya determined elemental composition of the lunar surface with the high precision among previous gamma-ray remote sensing missions. The KGRS, which employed a high-purity germanium (Ge) detector, observed lunar gamma rays from the high altitude (100±20km) from December 14, 2007 to December 10, 2008. Subsequently, the KGRS resumed observation from the low altitude (50±20km) from February 10, 2009. The energy resolution of gamma-ray lines at 2615 keV was ~0.8% in full width at half maximum throughout the low-altitude phase, which was better than that of the high-altitude phase and was ~9 times better than that of Lunar Prospector Gamma-Ray Spectrometer (LP-GRS). It contributed to unique and high-precision identification of Th and K lines. Furthermore, the spatial resolution of the KGRS was ~$(67km)^2$ throughout the low-altitude phase, which was ~4 times better than that of the high-altitude phase. It enabled us to produce higher spatial resolution maps of Th and K.

Global distribution maps of Th and K on the lunar surface derived from the data acquired by LP-GRS and the data acquired by the KGRS during the high-altitude observation have been reported. According to them, there are several areas where Th concentration is prominently higher than their surrounding regions on the lunar surface. Th concentrations in some of the high-Th regions located in the province known as the Procellarum KREEP terrane (PKT) of the near side (e.g., Aristarchus crater, Aristillus crater, Mairan crater, La Condamine crater, Birmingham crater, and Archytas crater) are 7-12 ppm, whereas they are 3-5 ppm in their surrounding regions. In this study, using the low-altitude data set of KGRS, we derive higher spatial resolution maps of Th and K abundance of the PKT, based on 3°× 3°pixels, and we discuss the detail distributions of Th and K in the high-Th concentration regions of the PKT.

Keywords: Moon, gamma ray spectroscopy, thorium, potassium, the Procellarum KREEP terrane

Time variation of radon gas emanation on the lunar surface observed by Kaguya/ARD

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We analyzed the data obtained by the Alpha-Ray Detector (ARD) onboard the lunar orbiter Kaguya and detected intensity increases of alpha-particles from ^{222}Rn on the lunar surface. Although the time variation of the radon alpha-particle intensity was implied by the observations of Apollo 15, 16, and the Lunar Prospector, we observed the variation directly for the first time. We divided the entire observation period of January to June 2008 into the time periods of 2 weeks which approximately corresponds to the time necessary for Kaguya/ARD to observe the entire lunar surface. Then, we evaluated the ^{222}Rn alpha-particle intensity using the sliding-window algorithm for each period and detected at least 7 events of statistically significant signal higher than 4s. In all cases, duration of the alpha-particle intensity increase was less than 2 weeks. The result implies that the observed radon gas emanation is a sporadic event caused by opening of some path to the lunar surface after subsurface accumulation of gas. We examined the timing of the events relative to the passage of the terminator and found that 5 out of 7 events were within 5 days around the terminator passage. Thus, at least some of the gas emission events are possibly triggered by the stress due to the temperature gradient in the lunar crust.

Keywords: Moon, radon, alpha-particle, Kaguya, ARD

Mass dependence of solar wind ion reflection over lunar crustal magnetic anomalies

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The Moon is located outside the Earth's magnetosphere at a rate of about 80% except for the full moon period. The solar wind can directly interact with the lunar surface since the Moon has neither thick atmosphere nor global magnetic field. Since the discovery of locally magnetized regions called the lunar magnetic anomalies in 1960s, the interaction between the lunar magnetic anomalies and the solar wind is one of the typical science targets of the lunar plasma environment research. The solar wind consists of H+ as a major component, several percent of He++ as a second major component, and a small amount of heavier ions. It is known that the flux of the magnetically reflected solar wind ions is about ten percent of the incident solar wind ion flux. Although ion mass is an important parameter of the magnetic reflection process, mass dependence of the reflected ions is not known at all.
The purpose of this study is to understand the ion reflection process over lunar magnetic anomalies, using the data obtained by low energy charged particle analyzers MAP-PACE and magnetometer MAP-LMAG on Kaguya.
As a result of the analysis of the reflected ions, we have found that solar wind H+ and He++ are both reflected by magnetic anomalies. Although the reflected ions have higher temperature than the incident solar wind ions, the reflected He++ ions have lower velocity and flux than the reflected H+ ions. The temperature of reflected ions is related to the energy difference between vertical and tangential directions. Since the vertically reflected ions can penetrate to low altitude, the vertically reflected ions are more significantly heated and decelerated than the tangentially reflected ions. It clearly indicates the existence of a non-adiabatic interaction between solar wind ions and lunar magnetic anomalies. Since high energy ions have larger larmor radius, the high energy ions can penetrate deeper into the magnetic anomalies than the low energy ions. Therefore, the amount of the solar wind ions that impact the Moon surface depends on the ion species.
Ion reflection occurs at all astronomical bodies that has intrinsic magnetic field. Lunar magnetic anomaly is one of the examples that have the smallest scale in the solar system. The knowledge acquired by this study is useful not only to understand lunar plasma environment, but also to understand plasma environment around various astronomical bodies.

Keywords: Moon, solar wind, magnetic anomaly

Excitation of selenogenic ion cyclotron waves: Implications from ARTEMIS observations and dispersion analysis

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A unique type of electromagnetic waves can occur when the Moon is inside the Earth's magnetotail. First detected by the Apollo Lunar Surface Magnetometers, these waves are narrowband ion cyclotron waves (ICW's), and their occurrence is due to the presence of the Moon. The exact generation mechanism of these narrowband ICW's at the Moon is still an open question. Here we investigate the excitation of ICW's at the Moon through ARTEMIS observations near the Moon and wave dispersion analysis. Two types of narrowband ICW's have been observed by ARTEMIS. The first type is found when ARTEMIS was close to and magnetically connected to the Moon. The ESA instrument aboard ARTEMIS detected keV ions that are typical of the Earth's plasma sheet. The velocity distribution of ions shows a half-sphere geometry, except for ions with higher energies that can come over from the other side of the Moon through gyration motion. The second type is detected when ARTEMIS was several lunar radii from the Moon and was not magnetically connected. The ESA instrument detected ions at energies of around 100 eV, and the ion velocity distribution was mostly symmetric with a net flow velocity. With the dispersion analysis by WHAMP, we find that the observed particle distributions for both types of wave events are ion cyclotron unstable. These wave and particle observations support the hypothesis that each of two different processes near the Moon could lead to ion cyclotron waves. First, the ICW events at locations near and magnetically connected to the Moon strongly hint a wave generation through the absorption of ions by the Moon. This process is similar to the loss-cone-induced ion cyclotron instability in the inner magnetosphere, and it implies that the presence of the Moon can modify the local plasma condition in the Earth's magnetotail. Second, the ICW's located at several lunar radii from the Moon are likely caused by PUI's that originate from the lunar exosphere. Because PUI's are one of the major loss mechanisms of the lunar exosphere, the observations of ICW's at the Moon can help understand the loss of volatiles from the Moon.

Keywords: Lunar exosphere, Ion cyclotron waves, Terrestrial magnetotail

Simulation analysis on the electron dynamics in the magnetosphere boundary above a lunar crustal magnetic anomaly

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The objective of this research is to study the response of solar wind plasma to a lunar crustal magnetic anomaly, particularly the electron behavior in the boundary current of a mini-magnetosphere by performing three-dimensional full particle-in-cell simulations. In the simulation domain, we set one magnetic dipole under the lunar surface as the Reiner Gamma magnetic anomaly. We define the size of the magnetic anomaly L as the distance between the dipole center and a position where the solar wind dynamic pressure balances the magnetic pressure. At the location of L above the magnetic anomaly, the Larmor radius of electrons is much smaller than L while that of ions is larger than L. As reported in the previous works, we confirmed the formation of a mini-magnetosphere above the magnetic anomaly. In the simulations, we observed strong current around the boundary layer of the magnetosphere. The boundary current mainly consists of electrons flow.
In the low latitude region, electrons flux points to the dawn-to-dusk direction. In the mid- and high- latitude regions, on the other hand, the direction of the electron flux is reversed. It seems that a rotational current structure is formed in the dayside magnetopause both in the Southern and Northern hemisphere. Along the equator from the dawn to the dust region intense electron flux is observed. The flux splits at the dusk side and each flux turns to the higher latitude region in both hemispheres, returning to the dawn region. We particularly focused on the electron dynamics at the magnetopause in the equator plane to figure out the mechanism of the intense electron flux from the dawn to dusk side. As reported in the previous works, intense electric field is induced by the difference of dynamics between the solar wind electrons and ions at the magnetopause where the electron density decreases to zero. Due to the intense electric field perpendicular to the local magnetic field, the incoming solar wind electrons are accelerated toward the lunar surface and the Larmor radius is eventually enlarged. At the edge of the magnetopause, the maximum velocity to the duskward direction is observed because of the electron gyrations. This maximized velocity of electrons can be the source of the intense electron current in the boundary layer. The width of the intense electron current at the magnetopause approximately agrees with the local Larmor radius of the accelerated electrons.

Keywords: plasma particle simulation, magnetic anomaly, electron dynamics

Particle simulations on charged dust dynamics in the lunar plasma environment

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The moon has no intrinsic magnetic field, and its surface interacts directly with the solar wind plasma, leading to the lunar surface charging. Due to the electrodynamic effect, some portion of micron and sub-micron sized grains on the lunar regolith layer are charging and levitated above the lunar surface, which are known as the Moon dust. It is of practical importance to assess such a distinctive environment, reminding that the dust grains will affect the Moon rover system in future landing missions.
In the present study, we apply our original particle-in-cell simulator EMSES, which have been used to study spacecraft-plasma interactions, to prediction of charged dust dynamics in the day-side lunar plasma environment. For this, we reproduce the near-surface electrostatic environment and develop a numerical model of dust charging in it by conducting the plasma particle simulations. We also consider an effect of characteristic lunar surface topography such as the lunar vertical holes, which are recently discovered by the Kaguya satellite. We will show preliminary simulation results on the charged dust environment near the moon surface.

Keywords: the Moon, dust grains, plasma, lunar surface charging, vertical hole, PIC simulation

Mineralogy and petrology of a rock fragment of felsite in lunar meteorite Northwest Africa 2727 breccia: Implications for silica- and Th-rich volcanism and scientific targets toward a future landing mission on the Moon

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Based on previous study of lunar returned samples and meteorites, the main suites of pristine nonmare igneous rocks have been classified into the following four types: (1) ferroan anorthosite (FAN) or ferroan anorthositic-suite (FAS), (2) magnesian suite (Mg-suites), (3) alkali-anorthosite-suite and (4) KREEP basalt and possibly related rocks such as quartz-monzogabbro (QMG) /monzodiorite (QMD), granite and felsite. The latest suite type, the evolved rock samples related to KREEP, may have been derived from residue of the lunar magma ocean (urKREEP), or from low degrees of partial melting or some other process to account for their high incompatible trace element (high-ITE) compositions. Granite and felsite have Th-rich compositions (10 to 60 ppm), and such lunar samples with bulk SiO_2 content of >60wt% originated from silicic volcanic or exposed intrusive material. Recent global remote sensing data have presented several candidates of silicic volcanism over the Moon based on indicators such as ITE-rich compositions, dome-like topography, characteristic infrared spectra (Christiansen Feature), and high albedo. Silica-rich, broadly granitic samples have been identified in lunar returned samples and lunar meteorites, but are rare. Lunar meteorite Northwest Africa (NWA) 2727 is a breccia paired with NWA 773 and the other meteorites of the NWA 773 clan. An olivine cumulate gabbro (OC) is common to most of these lunar meteorites within the NWA 773 clan; in fact NWA 2977 and 6950 consist entirely of OC lithology. However, in addition to the OC lithology, several clast types, including in olivine phyric basalt, pyroxene phyric basalt, pyroxene gabbro, ferroan symplectite, and alkali-rich-phase ferroan (ARFe) rocks have been discovered from the NWA 773 clan. The ARFe clasts have K-feldspar and/or felsic glass, a silica phase and minerals rich in incompatible elements such as merrillite. In this work, we characterize a felsic clast in NWA 2727 and compare our results with other lunar samples to discuss silicic volcanism.

A polished thin section (PTS) of NWA 2727 was investigated by a combination of petrographic microscopy and electron probe micro-analysis. The NWA 2727 breccia includes a variety of large-scaled lithic clasts (>1mm) including: OC, ferrogabbro, pyroxene-phyric basalt, and the felsic igneous clast. The felsic clast has a modal composition of 37% silica, 34% plagioclase, 14% K-feldspar, 6% high-Ca pyroxene, 5% fayalite, 3% Ca-phosphate, 1% ilmenite, and traces of troilite and chromite. Feldspar compositions of the plagioclase are near An85-90. Two compositional types of pyroxene were identified—one near hedenbergite (Wo46Fs53, Mg#=1 [calculating Mg# as Mg/(Mg+Fe)x100]) and the other with zoning and more magnesian compositions (Wo25-30Fs55-65, Mg#=8~20). The K-feldspar is also zoned with variable concentrations of Ba, clearly detected in elemental X-ray maps (quantitative analyses of Ba are planned). The abundance of silica + feldspars (>80 mode%), the high proportion of K-feldspar to plagioclase, and the very ferroan compositions of mafic minerals attest to the felsic composition of this clast. Subhedral-euhedral olivine crystals up to 0.3 mm in maximum length are preserved, and silica and K- and Ba-feldspar occur in elongate parallel crystals indicating an igneous origin. These observations indicate that this clast was derived from silica-rich magma.

Silicic volcanism is also interesting from the viewpoint of landing site candidates for future

lunar landing mission. Global gamma-ray observations have presented several high-Th regions in PKT, but the main lithology of the Th-rich regions remains a subject of dispute; possibilities include mafic impact-melt breccia, KREEP basalt, QMD, and felsite/granite. If a lander/rover mission to a high-Th region is equipped for analysis of major elements, in situ analyses on the Moon can be compared with silica-rich samples such as the felsic clast in NWA 2727.

Keywords: felsite, lunar meteorite

Origin of water and water reservoirs on the Moon as considered from the perspective of material sciences

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Water-bearing deposits have been discovered on the Moon by the spacecraft missions and the spectral data identified the water species as hydroxyl groups, mineral-bound H_2O and ice. The water supply sources to the surface were suggested to be derived from solar wind and cometary/asteroidal water. However, both of them are insufficient to explain abundant hydroxyl groups, the origin of mineral-bound H_2O and heterogeneous distribution of water on the Moon. Recent studies proposed the wet lunar mantle based on results of various microanalyses of lunar meteorites, and found the mantle-originated olivine-bearing sites and the plutonic Olivine Hill on the South Pole Aitken (SPA) and Procellarum basin by the spacecraft missions. Therefore, the possibility that mantle-originated water significantly act as a new candidate of the water supply source to the surface must be considered from the perspective of meteorite and Apollo samples. Here we identified the water species in lunar meteorites with various lithologies using microanalyses to determine the origin of water on the Moon. The bulk water contents of the lunar soil and the outcrop rocks (anorthosite crust, mare basalt, Olivine Hill, the brecciated layers and olivine-bearing site) were also estimated to clarify the lunar water reservoir.
Gabbroic lunar meteorites include the constituent minerals of olivine, clinopyroxene and plagioclase and the basaltic lunar meteorites typically have clinopyroxene phenocrysts within a fine-grained feldspar-pyroxene-rich groundmass. In the brecciated lunar meteorites, fine to coarse grains of the lithic minerals fill the interstices between the basaltic and gabbroic lithologies as breccia matrix.
In-situ transmission FTIR heating absorption measurements of these lunar meteorites showed pronounced water bands for all gabbroic minerals, but weak water bands for the basaltic clinopyroxene phenocrysts. As a result of the *in-situ* FTIR stepwise heating measurements, the water bands can be assigned to hydroxyl groups and mineral-bound H_2O. According to Lambert-Beer's law, the absorbance of the bands can be converted into the water contents of 663, 627 and 674 ppm in the gabbroic olivine, clinopyroxene and plagioclase, respectively, but only 169 ppm in the basaltic clinopyroxene phenocrysts. Amygdaloidal silica exists in a breccia matrix as nanocrystalline aggregates with ~9.0 nm in grain size under electron microscopy. The silica aggregates originated from the lunar hydrous fluid that was captured in the interstices between the mineral grains during the shock-brecciation.
With corrections of shock-induced water loss and solar wind supply, water amount and mode compositions of the constituent minerals obtained here provide a constraint on the bulk water contents: 757 ppm for Olivine Hill, 25 ppm for mare basalt, 668 ppm for the brecciated layers (780

ppm in the permanent shadow), 808 ppm for olivine-bearing site, 70 ppm for the lunar soil and 23 ppm for anorthosite crust. The olivine-bearing site, Olivine-Hill and the surrounding brecciated layers play a role in the wettest lunar water reservoirs on the Moon rather than the lunar soil. The origin of water on the Moon can be determined as follows: (1) hydroxyl groups supplied mainly from the mantle-originated water and slightly from solar wind, (2) mineral-bound H_2O only from the mantle-originated water and (3) ice from cometary/asteroidal water and mantle-originated hydrous fluid from the shock-brecciation. Since the cometary/asteroidal water were commonly supplied into both the lunar soil and outcrop rocks according to the temperature distribution on the Moon, the outcrops at high latitude tend to contain more abundant bulk water than those at low latitude. The olivine-bearing site and Olivine Hill on the SPA and then Procellarum basin are the most important candidate sites of future lunar landing and sample return missions.

Keywords: Moon, Origin of water, Water reservoir, Lunar meteorite, Olivine-bearling site, Olivine Hill

Review of lunar water studies and the implication to future exploration program.

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Recent geochemical studies on water isotopes trapped in lunar rock samples are reviewed. From the results of the studies, including the problems recently recognized, we discuss how to maximize the performance in future lunar exploration program, particularly in sample return missions.

Keywords: Lunar Rocks, Water Planet, Isotope Composition

On-site isotope laser spectrometry aiming underground lunar water

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It has been long believed liquid water cannot exist at the Moon's surface. However, it is also true that water is continuously supplied to the moon by meteorites or comets and a few studies indicated the existence of water in the moon[1)]. Actually, lunar volcanic glass showed a trace amount of water [2-3)]. Water may also survive in cold permanently-shadowed craters at poles[4)] or deep underground which is not affected by diurnal variation of solar heat[5)]. Now, lunar water is a big concern among researchers.
It is also important to know the origin of the water on the moon. On-site isotope measurements are essential because contamination of terrestrial water should be avoided.We are planning to fabricate a light-weight laser isotope measurement system about several kg in weight. Light weight DFB laser or Er-doped (Er:ZBLAN) fiber laser are candidates, which emit at desirable absorption bands for water isotope around 2.7 Another concern is a sample cavity which consists of a cell and mirrors. In order to resolve the small amount of isotopes, a long path length about km of laser beam must be achieved. In Mars Science Laboratory by Nasa, Curiosity includes the Laser isotope spectrometer with a Herriot cell, while commercial devices using a cavity enhanced cell with ultra-high reflectivity. Our concept and preliminary experiments will be presented.

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Keywords: lunar water, isotope, Laser isotope measurement

Expected results on the lunar science from scientific observations in Approach mission

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The penetrator has been developed through Japanese lunar explorer 'LUNAR-A' mission. The penetrator is a hard-landing probe to deploy on-board sensors on planetary surface by free-fall from an orbiter. Through previous studies, we have already confirmed that the seismometers for the penetrator can maintain the performance to detect moonquakes even after a shock over the impact to the lunar surface (Yamada et al., 2009) and the communication instrument on the penetrator properly operate for data transmission (Tanaka et al., 2010). The penetrator is advanced system to deploy geophysical network on the planetary bodies and it is expected to be applied for future lunar and planetary explorations

To establish utility of the penetrator system and demonstrate scientific observations using the system, we have proposed a mission plan: Approach mission, so as to load two small-sized penetrators on a small satellite launched by the Epsilon Launch Vehicle. In this proposal, we aim to reduce size of the penetrator to two-thirds size keeping the already established high shock durability and the on-board sensors, and two penetrators enable achievement of redundancy and more progress in scientific results.

In this mission, we have plans of seismic and heat-flow observations using two penetrators. Due to small numbers of seismic stations, we apply travel time data from the meteoroid impact events located by the ground observation of the impact flash to determine the lunar crustal thickness. The better determination of the crustal thickness and utilization of recent lunar gravity data enable estimation of the lunar crustal volume and aluminum bulk abundance with better accuracy. If we can identify seismic waves which pass through the lunar deep region using two seismic station data, more information about the deep interior can be also expected. Then, heat flow observations on both areas where the radioactive elements are concentrated and poor are important to estimate bulk abundance of the radioactive elements. In this presentation, we report the results expected from the scientific observations in Approach mission quantitatively, and then discuss how we can progress the study about lunar origin and evolution from the results.

Keywords: Penetrator, Lunar interior exploration, Moonquake observation, Heat flow observation, Small-sized exploration satellite

Direction of “Lunar and Planetary Data Analysis Group” of ISAS

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Japanese lunar orbiting mission, Kaguya, launched in 2007 and successfully finished its mission life in 2009, have brought many scientific discoveries to progress the lunar and planetary science, which has produced the second most published papers among lunar missions in the couple of decades. To maximize outcomes of the lunar and planetary exploration missions with leading the planetary science from now on, both system and environment to handle and to analyze large amount of data obtained by exploration missions. These are also important for designing strategies and technical studies, however, these activities depend on the ability and effort of personal data users while they are implemented systematically such as in NASA and in USGS. With taking this situation into consideration, we will state a new trial of the “Lunar and Planetary Data Analysis Group”, an ISAS organization of which starts at the beginning of FY2016.

Keywords: exploration, large amout of data, analysis

