# 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

 

# Carbon Contribution of the dark moon samples: Quenched solids of the lunar materials

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The extraterrestrial bodies without the atmosphere (including the Moon) can usually be seen wholly blackish dark color. The lunar black and white surface is explained simply by the differences of colored minerals the albedo by smooth and irregular topographic surface. This explanation can be generally understood by descriptive terminology and formation, but is clearly main reason that it cannot be developed further study and challenges in future. Recently author has analyzed comparatively that based on terrestrial rocks and artificial analyses with carbon contents and micro-textures, the lunar samples of the Apollo (USA) and lunar meteorites (including present analyzed samples) show significant carbon contents and carbon-bearing textures, which indicate large contribution of blackish carbon on the Moon surface.
Difference of rock minerals on the Moon surface, has been explained generally by colored dark minerals of pyroxene, olivine and metallic mineral on the Mare basalt (Earth volcanic type) and the Highland gabbro-to-anorthosite (Earth plutonic type). However, the lunar minerals reveal blackish dark color by limited rock-composition range, which cannot be compared with whitish minerals of silica quartz and various feldspars on the water-planet Earth evolved widely.
The moon minerals which are also observed in two lunar meteorites (NWA4483 and Y-86032) , show comparatively low crystallization, very few kinds of minerals and rocks caused by poor fluids, hydrous mineral, silica-feldspar variety on the Moon surface, which might be lower activity in the Moon.
In the present study, it is resolved finally big differences of carbon contents obtained not only at mineral-rocks on the Mare and the Highlands, but also on regolith soils and breccias.
Earth's rocks are obtained in this study that carbon contents and textures by bulk analyses and SEM observation, are increased on colored minerals and volcanic rocks. It indicates in this study that carbon contents are changed directly by cooling process, which is not simply caused by a depth of unknown Earth's interior explained by descriptive explanation.
It is experimentally confirmed in author's study that a carbon-bearing solids and textures are formed newly by artificial laser experiments reacted as quenching sputtering.
The present results of Moon's color study are summarized as follows.
1) The colors of the Earth's rocks are classified with the silica contents (and feldspar), whereas the lunar rocks can be classified with carbon contents by the different cooling process not mainly by mineral variety.
2) Lunar quenched rocks of regolith soil and breccias have much content of lunar carbon. On the other hand, terrestrial carbon can be obtained relatively in volcanic rocks quenched rapidly.
3) Carbon increases formed by carbon-bearing solids have been obtained by the laser irradiation experiment, which can be confirmed strongly by formation of carbon-bearing materials and textures on the Moon rocks studied in this study..
4) From comparative study of the Moon and water-planet Earth, the isolated Moon body surface shows finally blackish dark color including carbon-bearing local solids and micro-textures formed by quenched processes of brecciated reaction.

Keywords: Blackish dark color of lunar sampes, Carbon content effect, Quenched solids formation

 

# Stratigraphy of mare basalts and topographic features in the central region of the Procellarum KREEP Terrane of the Moon

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Reconstructing the volcanic history of the Moon is essential to understand the solidification process and subsequent thermal evolution of lunar mantle. Lunar mare basalts provide insights into compositions and thermal history of lunar mantle. According to previous crater counting analysis with remote sensing data, magma activity has a second peak at the end of mare volcanism (~2 Ga), and the latest eruptions were limited in the Procellarum KREEP Terrane (PKT), which has high abundances of heat-producing elements. To understand the mechanism for causing the second peak and its magma source is important to constrain models of lunar thermal evolution. We have examined the correlation between the titanium contents and eruption ages of mare basalt units using compositional and chronological data updated by SELENE/Kaguya. As a result, we found that a rapid increase in mean titanium (Ti) content occurred at 2.3 Ga in the PKT, suggesting that the magma source of mare basalts changed at that time. The high-Ti basaltic eruption, which occurred at the late stage of mare volcanism, can be correlated with the second peak of volcanic activity at ~2 Ga. The latest volcanic activity can be explained by a high-Ti hot plume originated from the core-mantle boundary. If the hot plume was occurred, the topographic features formed by the hot plume may be remained. We calculated the difference between topography and selenoid and found the circular feature like a plateau in the center of the PKT, which scale is ~1000 km horizontal and ~500 m vertical. We investigated the stratigraphic relationship between mare basalts and mare ridges in the PKT by using Kaguya TC and MI data. We found that the mare ridges were formed before and after the high-Ti basaltic eruptions and seem to be along with the plateau. Considering that ridges were formed during formation and relaxation of the plateau, the timing of the plateau formation is consistent with the timing of ridge formation.

Keywords: Moon, Volcanism, Lunar mare, Topography, Mare ridge, Stratigraphy

 

# Broadband noise and associated electron heating observed by Kaguya around the Moon in the solar wind

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Broadband electromagnetic noise in the frequency range up to ~10 Hz has been detected around the Moon at ~100 km altitude [Halekas et al., 2008; Nakagawa et al., 2011; Tsugawa et al., 2012]. Halekas et al. [2008] suggested that the waves are associated with electron energizations and are basically generated through the interaction between the solar wind plasma and crustal magnetic field. Nakagawa et al. [2011] studied the characteristics of the broadband waves by considering properties of whistler-mode waves propagating in the solar wind frame of reference. Tsugawa et al. [2012] showed that the statistical distributions of the intense noise are clearly located at the magnetic anomalies. While they discussed the possible generation process of the waves through resonant or non-resonant instability by ions reflected from the lunar surface, details of the generation process of the waves have not been clarified yet.
We analyzed the broadband noise observed by Kaguya statistically, and suggest that the absolute condition to observe the noise at altitudes ~100 km are 1) the spacecraft is connected to the Moon through the magnetic field, and 2) the solar wind ions are reflected considerably in the connected region on the Moon. The fluxes of reflected ions depend on the solar wind parameters and the magnetisms of the lunar crusts. In a usual solar wind condition (roughly the dynamic pressure < 2 nPa), the second condition is mostly satisfied above the magnetic anomalies. In the solar wind with larger density and faster speed than usual (roughly the dynamic pressure > 2 nPa), the second condition can be satisfied above not only magnetic anomalies but also unmagnetized surface. Electrons are often energized perpendicular to the ambient magnetic field or isotropically in association with the noise and reflected ions. The electron heating above the lunar magnetic anomalies are also associated with the broadband electrostatic noise in the frequency range up to ~10 kHz [Kasahara et al., 2011]. Their correlation is suggested in analogous to the transverse ion acceleration due to broadband extremely low frequency noise in the Earth's auroral region [e.g., Andre et al., 1998].

 

# Formation process of linear gravity anomalies of the Moon

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Gravity data obtained from the Gravity Recovery and Interior Laboratory (GRAIL) have revealed linear gravity anomalies (LGAs), which might be formed by the early global expansion of the Moon and subsequent magma intrusion. If the formation process of the LGAs is true, the surface exposure of mafic rock originated from ancient dykes is expected around large craters, which excavated deep material in the crust. We carried out a compositional investigation to examine existences of intrusion associated with the LGAs using SELENE (Kaguya) high-resolution spectral datasets obtained by Multiband Imager (MI) and Spectral Profiler (SP). Here we investigated LGA2 because the LGA2 is one of the largest LGAs and is superposed by the 150 km-diameter crater Roche, which might excavate intrusion. Clustered small-scale basaltic exposures in the highland are found in the northern outer region of Roche crater across the LGA2. The basaltic exposures exist not at topographic lows but at fresh crater rays and slopes. This indicates that the clustered basaltic exposures originate from the intrusion in the crust and/or ancient maria.

Keywords: Moon, volcanism, linear gravity anomaly, intrusion

 

# Evaluation of chronological measurement method of geological units by collapsed crater on the Moon

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The age of the moon is an important clue in understanding the former state of igneous activity of the moon. To explore the time course of the scale and the eruption of the magma leads to pursue the internal evolution of the moon. Generally, exploring crater size frequency distribution is used to determine the model ages of lunar geological units. However, this age determination is susceptible to the influence of secondary craters, and an error is likely to occur in the measured age. Therefore, by using another age determination, it is necessary to confirm whether the measurement age by the age determination that is free from influence of the secondary crater should be investigated. The way based on the status of crater collapse is another expected method for age determination of lunar geological units. In order to establish this method, it is needed to investigate the correlation between the age of the geological units and a parameter value expressed by F which is corresponding to the total amount of impacted objects disrupting the craters. Since the F value is a numerical value determined by the most collapsed crater in a geological unit, it does not include the effects of secondary craters probably occurring after the formation of the oldest most collapsed craters. Here, we explore the correlation relationship between the F values and the model ages based on crater size frequency distribution for several lunar geological units, and discuss the possibility of the way based on crater collapse as an age determination of lunar geological units.

Keywords: chronology, lunar craters, status of crater collapse

 

# Water-rich lunar upper mantle as recorded in lunar meteorites

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Bulk water analyses of the Apollo samples have revealed almost scant water (<1 ppb), which has resulted in the post-Apollo view of a dry Moon. However, with the discoveries of OH species in lunar secondary minerals by mass spectrometry, questions concerning water in the mantle have been revived. Some recent studies of lunar samples proposed a water-rich mantle (9–585 ppm) based on carefully considered assumptions. However, the wet mantle hypothesis has remained inconclusive because the inferences made must be taken with caution as the result of the unreliability of the tentative assumptions used. Recent isotopic analyses of chlorine and oxygen in lunar second minerals predict the dry lunar mantle (<10 ppb), but this hypothesis was build up based on the indirect evidences (not in the direct way using hydrogen mass spectrometry). In this study, we measured water in gabbroic clinopyroxene and olivine of the gabbro lithic lunar meteorites using *in-situ* transmission FTIR heating absorption spectroscopy to determine the actual water content of the upper mantle beneath the Procellarum basin without the unreliable assumptions.
*In-situ* FTIR heating measurements at 120 °C represent water bands at ~3750, ~3600 and ~3500 $cm^{-1}$ for clinopyroxene and at ~3550, ~3500 and ~3250 $cm^{-1}$ for olivine in the gabbroic lithologies. The *in-situ* FTIR spectra of clinopyroxene and olivine entrained on the shock veins and fusion crusts include similar water bands but with obviously lower absorbances. This behaviour appears to be the result of the dehydration of intrinsic water due to the post-shock annealing in an impact event for the shock vein, and due to aerodynamic heating during the atmospheric entry for fusion crust. Therefore, the abundant water in the gabbroic minerals appears to be derived from the Moon and not the Earth. The *in-situ* FTIR heating measurements of the gabbroic clinopyroxene and olivine at 200–550 °C demonstrated that the absorbances show almost no change up to 300 °C but drastically decrease in temperature from 300 to 550 °C. This result can be attributed to the dehydration of tightly bound molecular water. The other water bands remained after heating to 550 °C, and exhibit anisotropies of the absorbance during rotation of the polarizer. Therefore, the remaining bands can be assigned to structurally oriented OH species.
A conversion using the Beer-Lambert law of the integral absorbance into the water contents revealed that the gabbroic clinopyroxene and olivine contain >339–1363 and >199–1152 ppm water, respectively. Based on these water contents, a mode composition of the constituent minerals determines the mantle water content without the previously proposed assumptions. As a result of our findings, we conclude that there is a water-rich part of the upper mantle that spreads >631 ±498 ppm at depth of >30 to >400 km beneath the Procellarum basin; such water concentrations are as plentiful as that found in the Earth’s mantle. Notably, however, the wet mantle hypothesis requires further consideration because there are some evidence concerning water depletion in the lunar

 

mantle as reported in the previous studies. A tentative theory that explains this discrepancy proposes that the indigenous water is heterogeneously distributed and partly included in the lunar mantle. The heterogeneously and partly water-rich lunar upper mantle proposed here supports recent lunar evolutionary models; accretion and cooling processes of the primary materials in the aftermath of the Giant Impact, differentiation in the lunar magma ocean, the cause of a deep moonquake, and a share of common water sources between proto-Earth and Moon. Our findings also promises new insights into future lunar missions and, particularly into landings on and sample returns from the mantle-originated olivine-bearing sites found by the SELENE mission on the Procellarum basin and South Pole Aitken.

Keywords: Moon, Lunar mantle, Lunar meteorite, Mantle water content, Infrared absorption spectroscopy, Procellarum basin

 

# A spatio-temporal change of the density structure beneath impact basins of the Moon

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Impact basin, a large-scale structure on the surface of the Moon, is formed by a giant impact in the past and is considered to affect the evolution of not only the surface but also the internal structure of the Moon. Recent analyses of GRAIL data of the all mission phases provide the gravity field model with the spherical harmonics up to degree and order of 900 [Lemoine et al. 2014; Konopliv et al., 2014]. We can, therefore, expect to obtain detailed information of the interior of the Moon from this gravity model. In this study, from the latest selenodetic data, we estimate the density structure (i.e., Moho) beneath the impact basins and discuss differences of the density structure.We use the topographic model of LRO_LTM01_PA_1080 with the spherical harmonics of degree and order of 1080 [Neumann, 2013]. Bouguer anomaly is calculated from the topographic data and the gravity potential data of GRGM900C [Lemoine et al., 2014] with the Bouguer correction density of 2560 kg/m3 and is expanded by the spherical harmonics of degree and order of 600 (wavelength ~9km). We estimate the depth of the lunar Moho using the gravity inversion method of Wieczorek and Phillips (1998). In the estimation of the Moho depth, considering the values of crustal density reported by Han et al. (2014), we set the crustal density of 2750 kg/m3 and the mantle density of 3360 kg/m3 [Ishihara et al., 2009], respectively, so that our estimation coincides with seismological estimations of the crustal thickness at Apollo 12/14 sites and the average crustal thickness reported by previous works. We apply a downward continuation filter with the half-power degree of 100. The crustal structure is expanded by the spherical harmonics of degree and order of 600. We call the density structure calculated by this method as global model.We estimate the local Moho relief using the gravity inversion method of Rama Rao et al. (1999) for each impact basin. The crustal density and mantle density are the same as the case of the global model and we set a spatial resolution to 10 km. We set the initial boundary depth to the deepest point of the global model and the shallowest point of the density structure to the deepest point of the topography for each impact basin. We call the density structure obtained by this method prism model.To evaluate the prism model structures quantitatively, we take following four steps.(1) We make the azimuthally averaged cross section of the prism model within 1.5 times of the positive Bouguer anomaly area [Neumann et al., 2015] for each impact basin.(2) We define the area within the radius of the positive Bouguer anomaly as the inner region and the outside area as the outer region.(3) We define the distance from the center to the farthest point within top 15% of the depth width as D_upper and that from the center to the intersection between the linear fitting line of the outer region data points and the cross section profile as D_lower.(4) We calculate D_upper/D_lower.We found that the distribution of the value of D_upper/D_lower showed positive correlation with the size of the impact basins and have regional characteristic. We suggest that the latter is controlled by the difference of the internal temperature structure, because it is consistent with the distribution of radioactive elements [Jolliff et al., 2000] and the thermal state at the time of basin formation estimated based on viscoelastic deformation calculation [Kamata et al., 2013]. In the presentation, we discuss the major control on subsurface structure, together with calculation results of viscoelastic deformation.

Keywords: impact basin, inversion, viscoelastic deformation

 

# Paleomagnetic poles of the early Moon estimated from small isolated magnetic anomalies

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Paleomagnetic measurements and satellite observations indicate that the global magnetic field existed in the early Moon, in probable, a core dynamo field. Using the Kaguya and Lunar Prospector observations at 20-40 km altitudes, Takahashi et al. (2014) estimated magnetization directions for 24 lunar magnetic anomalies, suggesting the polar wandering of the early Moon. Although they applied a dipole approximation, the observations at high altitudes are generally affected by the crustal field at relatively wide area. Thus their estimation includes some ambiguity of the dipole approximation. In the present study, we use the global maps of the lunar magnetic anomalies on the surface with the Surface Vector Mapping (SVM) method [Tsunakawa., et al. 2015]. The SVM data with high spatial resolution are useful for finding small isolated anomalies like a single dipole. As a result, we have selected several tens of magnetic anomalies to be approximated with a single dipole source. The magnetic poles in the present analysis show two main clusters: one is near the selenographic north pole and the other is on the eastern hemisphere.

Keywords: Moon, magnetic anomaly, paleomagnetic pole

 

# Kaguya observation of oxygen ion precipitation from the Earth to the Moon

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It is widely believed that the Moon was formed due to the impact between the Earth and a planet-sized body, which we have called Theia. In order to confirm that the impact had taken place, many studies was done by numerical modeling and measuring the ratios between the isotopes. Theoretical models proposed that the Moon would form mostly from Theia, and thus would be expected to be compositionally different from Earth. However measured isotope ratios are similar between the Earth and Moon. Measured isotope ratios and theoretical models had conflicted with each other. Recent isotope measurements used lunar samples from the Apollo 11, 12 and 16 missions and found significantly higher levels of 17O/16O than Earth's counterparts.
One of the reasons of the similarity of the isotope ratio is isotope exchange with water from the Earth especially in lunar samples arrived via meteorites. We propose the other reason, oxygen ion transport from the Earth to the Moon, because many satellites such as GEOTAIL and STEREO observed the oxygen ion escape from the Earth in the Earth's magnetotail.
KAGUYA, a Japanese lunar orbiter, conducted scientific observation in 100 km altitude in 2008. An ion mass analyzer on KAGUYA detected oxygen ions coming from the Earth to the Moon in the Earth's magnetosphere. Here we show the amount of the oxygen ion transport estimated by using KAGUYA data and discuss the effect to measuring the isotope ratios.

Keywords: Isotope of the Moon, Kaguya spacecraft, Mass analyses

 

# Instrumental performance and present status of development of Active X-ray Spectrometer for future lunar landing mission

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Recent Chinese lunar landing mission (Chang'E 3) was successful in landing on the surface of the Moon after their twice successful remote observations. The landing mission investigated the elemental compositions of landing sites in more detail, and obtained new "ground truth" by using alpha particle X-ray spectrometer, which could have not been provided by any returned samples. The compositions of major elements as Mg, Al, Si, K, Ca, Ti, Fe of landing site help us to understand its petrogenesis and evolution. In Japan, the global investigation of Kaguya promoted our knowledge and understanding of the origin and evolution of the Moon. The landing and/or sample-returned missions in the future will be followed in order to investigate the geology in more details, in the next.
We have been developing the active X-ray spectrometer (AXS) as elemental analyzer on site, in order to prepare for future lunar landing mission. Present AXS consists of active X-ray generators with pyroelectric crystal ($LiTaO_3$), and a silicon drift detector (SDD). Here, the present status of development is reported, and the instrumental performance of AXS and the observation targets of AXS will be discussed.

Keywords: Active X-ray spectrometer, landing mission

 

# One-dimensional crater chronology: A method of estimating the termination age of faulting

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The timing of the tectonic deformation will be a clue to distinguish the origins of geological structures among global cooling (Solomon and Chaiken, 1976), orbital evolution of the Earth-Moon system (Melosh, 1980) and subsidence by the loads of mare basalts (e.g., Solomon and Head, 1980). There are a number of deformed and undeformed craters on a fault on the lunar surface. Undeformed craters mean that they were formed after the fault ceased its tectonic activity. In order to estimate the termination age of faulting, we propose a new method named one-dimensional crater chronology. The method converts the linear density of the undeformed craters on a fault into the termination age. By means of numerical experiments we estimate the relationship between one-dimensional crater size-frequency distribution and the termination age.

Keywords: Moon, Tectonic history, Crater chronology, Mare ridge

 

# Enhancement of lunar topographic data with statistical voting algorithm

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In addition to terrestrial planets, grabens and ridges that are typical topographic features on the moon indicate stress activity of the lunar surface. The grabens, which show negative channel-like reliefs result from tensile stress in lunar subsurface. On the other hand, the ridges, which show positive riliefs, result from compressive stress in the lunar subsurface. Especially, grabens and ridges have been supposed to be indicators of thermal evolution of the moon, because these feature result from expansion and constriction of the moon.
In order to find grabens and ridges by visual inspection, images taken by exploration camera are usable. However, some of ridge have gentle slope and some of graben have shallow channel-like relief, so it is difficult to identify these degraded features by visual inspection. In addition to degraded features, visibility of these topographic features is affected by spatial resolution and sun-lighting condition. Therefore, we use the Digital Terrain Model (DTM) of the moon for production of enhanced topographic data. The DTM provides elevation data of the lunar surface and is not generally affected by sun-lighting condition. However, it is difficult to identify small grabens and ridges with DTM data. In previous research with a similar purpose, roughness parameter (Root Mean Square Slope, here after RMS) with DTM data was utilized to identify several topographic features such as craters, ridges, and lava flows. The RMS with DTM data depends on a parameter set of calculation window size and data sampling step size. Appropriate parameter combination of these two parameters was needed to adjust to every scale of topographic features. In this study, on the basis of topographic data, we developed new calculation algorithm based on statistics named as “statistical voting algorithm”. In this algorithm, we calculated an average and standard deviation in calculation window and it vote to each pixel which has a significant difference comparing with the average value. Continuously, we do same procedure along with moving calculation window. We expect that this algorithm is good at identifying small degraded or small-scale topographic feature.
As a result, and an availability of the statistical voting algorithm with DTM data to enhance the contrast of DTM data at the topographic features was confirmed. The appropriate parameter of this algorithm is window size 640 pixels in both case of grabens and ridges. This algorithm is useful to identify not only normal topographic features but also small and indistinct ones. However, small target superposed on large topographic feature could not be identified by visual inspection with our statistical voting algorithm data.

Keywords: Topographic feature, Digital Terrain Model, Statistical voting algorithm

 

# Scientific observation plan for Smart Lander for Investigating Moon mission

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Main objective of Smart Lander for Investigating Moon (SLIM) mission is to develop and demonstrate technology of high-precision landing on the Moon, which enables us to explore not only the Moon but the other planetary body with gravity. This mission is planned to land on the lunar surface within a hundred meters from the pre-fixed destination, and it is extremely attractive for landing site dependent study themes. Therefore, although weight and other resource budgets are very limited for this mission because the mission aims to develop a challenging light weight and small lander, possibility of a payload have been discussed recently within that strict resource budgets for adding extra result to the mission. Around 20 instruments were proposed for the mission as the results of efforts of instrument team members and candidate instruments and candidate objectives were identified. In this presentation, the candidate instruments and their objectives will be discussed with the information of current status the mission.

Keywords: Moon, SLIM, high-precision landing

 

# Linear mass anomalies going through three volocano complex areas in the Oceanus Procellarum

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In western part of the Oceanus Procellarum of the lunar nearside, there are several large-scale volcanic complexes, in which volcanic geographycal features are highly concentrated. In this study, Gravity Recovery and Interior Laboratory (GRAIL)-derived lunar gravity field data is used to investigate the geophysical relevance of the major volcanic complexes in the region. One of our concerns is whether the volcanisms of these complexes are caused by common factors or not. We estimated Bouguer gravity anomaly in the region and investigated the directions of the linear structure of the anomalies. The result shows that there are linear mass anomalies, which connect the mass anomalies at the volocano complexes of Aristarchus Plateau, Marius Hills and Flamstead Basin. The observed linear structures lie inward of the large quasi-rectangular pattern revealed by Andrews-Hanna et al., and much shallower than the pattern. Considering that, the observed linear structures should have been created later than the quasi-rectangular outer structure. After the quasi-rectangular pattern was created, magma rose to the surface through the cracks. The observed linear structure is supposed to be created through cooling of the overflowed magma. The geological units, which the linear structures go through, are younger than that of the outer quasi-rectangular pattern. The linear cracks created by cooling are weaker than other locations. Therefore, magma probably rose easier than in other area. That may be why the three currently observed volcano complexes lie on the same linear structure.

Keywords: lunar gravity field, GRAIL, volcanic activity

 

# Where did the oldest lunar mare sample come from?

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Introduction: Kalahari 009 is a lunar meteorite classified as a very-low-titanium (VLT) mare basalt breccia and known as one of the oldest mare basalts with the U-Pb age of 4.35 ±0.15 Gyr (Terada et al., 2007). This meteorite provides the information of the lunar oldest mare magmatism prior to the Late Heavy Bombardment around 3.8-4.1 Gyr ago and potentially facilitates understanding of the origin of lunar mare magma activity. Here we report search for the source crater of the Kalahari 009 meteorite and shock products in the meteorite.
Analytical Methods: The source crater of Kalahari 009 was searched in a region from northern latitude of 60 degree to southern latitude of 60 degree using data of the Multiband Imager (MI) and Gamma Ray Spectrometer (GRS) obtained by the lunar explorer SELENE (KAGUYA). We selected candidates of the source crater, of which FeO, TiO2 and Th concentrations are comparable to those in Kalahari 009 (16 wt% of FeO, 0.45 wt% of TiO2 and 0.09 ppm of Th) (Sokol et al., 2008). To estimate the compositions of FeO and TiO2 we used the algorithms for deriving the abundances of FeO and TiO2 based on MI image data (Otake et al., 2012). At the same time, optical maturity parameter (OMAT), which is an index of relative surface age of craters, was also calculated to search for the source crater of Kalahari 009 using the method in Lucey et al. (2000).
To reveal the impact history of Kalahari 009, we observed the thin section of the meteorite using the field emission scanning electron microscope (JEOL 7001F) and Raman spectrometer (JASCO NRS-2000).
Result and Discussion: 254 craters with concentrations of FeO (14-17 wt%), TiO2 (≤ 1 wt%) and Th (≤ 1 ppm) were identified. It was suggested that Kalahari 009 was ejected together with the Kalahari 008 highland breccia (Sokol et al., 2008), and therefore the source crater may be located in a region of cryptomare. 92 out of 254 craters are located in cryptomare. The cosmic exposure age of Kalahari 009 is from 220 ±40 yr to ~0.3 Myr (Nishiizumi et al., 2005), which means that the craters with relatively high OMAT are candidates of the source crater. Thus, the source crater of Kalahari 009 is probably one of 92 craters in cryptomare having relatively high OMAT.
In the thin section of Kalahari 009, shock products such as coesite, ringwoodite, partly mosaicism and planar fracturing in plagioclase and olivine were observed. According to the shock classification in Stöffler et al. (1991), the shock pressure is estimated as 30-35 GPa. The presence of ringwoodite suggests the shock pressure of ~ 7-14 GPa based on the Fe2SiO4 phase diagram (Ohtani, 1979). Thus, it is inferred that Kalahari 009 experienced the shock pressure of ~ 7-35 GPa. The Ar-Ar dating of Kalahari 009 showed that the meteorite experienced significant loss of radiogenic Ar at 1.7 Gyr (Fernandes et al., 2007). Thus, Kalahari 009 has experienced at least one impact which caused loss of radiogenic Ar and/or produced shock-induced minerals.
In summary, we describe a possible ejection scenario of Kalahari 009 based on the results of the present and previous studies. An impact event occurred at 1.7 Gyr, but the ancient basalt clast remained in the impact crater as a breccia. Then, the 2nd impact produced a small crater inside the large crater between ~0.3 Myr and 220 ±40 yr and ejected the meteorite from the small crater.
In the presentation, we will discuss the source crater of Kalahari 009 in conjunction with the impact history of the meteorite.

 

Keywords: Moon, Kaguya/SELENE, Cryptomare

 

# The rheological structure of moon interior and the mechanism of deep moonquake.

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Apollo program installed some seismometers on the moon and the seismic data provided us the much information about the moon interior. Analysis of moonquake data supports the following: The moon interior is differentiated, and the crust and mantle are composed mainly of plagioclase and olivine, respectively (reviewed by Wieczorek et al., 2006). Although we have considered the moon interior based on moonquake data, the mechanism of moonquake is debatable problem. Moonquakes is categorized into shallow moonquake, deep moonquake, thermal moonquake, and moonquake by meteoroid impact. We discuss the mechanism of deep moonquakes, which occur at a depth of 800–1200 km, based on the rheological structure of moon interior. Unraveling the mechanism of deep moonquakes is key to understand the heterogeneity and evolution of moon interior.
We calculate the rheological structure of moon interior. In this calculation, thermal structure of moon interior is calculated using the equation suggested by Kuskov et al., (2002). Pressure was calculated using the crustal density of 3000 kg/m$^3$ and mantle density of 3300 kg/m$^3$. Moho depth is assumed to be 60 km depth (Hood and Zuber, 2000). Based on the above assumptions, Byerlee's law is applied to determine the rock strength in brittle deformation regions, and the flow laws are applied to calculate the rock strength in plastic deformation regions. Crustal deformation is calculated by flow laws of plagioclase (Rybacki and Dresen, 2000; Rybacki et al., 2006), mantle deformation is calculated by flow laws of olivine (Karato and Jung, 2003). Strain rate is assumed to be $10^{-14}$ or $10^{-19}$ ($s^{-1}$).
The calculated rheological structure suggests that the deep moonquakes occur in plastic deformation region, where the fracture and slip are generally not occurred. We verified the possibility that the thermal runaway instability causes the deep moonquakes in plastic deformation region (e.g., Karato et al., 2001). The key issues in thermal runaway instability are (1) the strain rate should be large and (2) the degree of thermal feedback must be large (Karato et al., 2001). We calculated the strain rate that produced by the tidal stress in lunar interior under dry and wet conditions, and the degree of thermal feedback (a degree of softening of material). We found it difficult that the thermal runaway instability causes the deep moonquakes under dry conditions because small tidal stress (~0.1 MPa) cannot produce the large strain rate under dry conditions. On the other hand, the large strain rate is produced and the thermal runaway instability can be occurred in moon interior under wet conditions (500–1000 ppm H/Si). It suggests that the water exists heterogeneously in moon interior, and this heterogeneity of water may cause that the deep moonquakes occur in localized regions (clusters).

Keywords: Moon, Deep moonquake, Rheological structure

 