A reconsideration of the lunar wake boundary based on Kaguya observations

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Refilling of the tenuous lunar wake by solar wind plasma has been one of the fundamental phenomena of planetary plasma sciences. Because a portion of the solar wind electrons has much higher speed than protons, it has been widely accepted that suprathermal electrons precede protons to come into the wake along the interplanetary magnetic field. In this model, ambipolar (inward) electric fields around the wake boundary generated by the charge separation attract the surrounding solar wind protons into the central lunar wake. However, such treatment has implicitly assumed one-dimensional motion of the solar wind plasma along the magnetic field perpendicular to the solar wind flow. Here we propose a new model of the wake boundary close to the Moon, based on Kaguya observations in orbit around the Moon; Solar wind protons come into the lunar wake owing to their gyro motion and large inertia without help of suprathermal electrons, and those protons form positively charged regions and outward electric fields around the wake boundary that should attract surrounding solar wind electrons. This new model well explains electron signatures around the wake boundary detected by Kaguya at ~100 km altitude from the lunar surface.

Keywords: Lunar wake, Solar wind, Electric field, Kaguya (SELENE)

Global mapping of the lunar magnetic anomalies by electron reflection method

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Crustal magnetic fields are known to exist on Earth, Mars, and the Moon, and they may also exist on various astronomical bodies in the Solar System. Although the Moon has no global magnetic field, there exist locally magnetized regions called lunar magnetic anomalies. Therefore incident solar wind directly impacts the lunar surface, except for the case where the crustal magnetic field prevents it from penetrating into the lunar magnetic anomalies. Interaction between the lunar magnetic anomalies and plasma particles give important information about the distribution of plasma environment and space weathering. Electron reflection measurement is one of the methods for observing the lunar magnetic anomalies. This measurement makes use of the magnetic mirror effect. By the existence of the lunar magnetic anomalies, if the pitch angle of an incident electron reaches 90 degrees before the electron impacts the lunar surface, it is reflected back to the satellite. The crustal magnetic fields on the lunar surface can be estimated by measuring the cutoff pitch angle of the reflected electrons and the magnetic field around the satellite. This method can infer the lunar surface field strength with sensitivity that is independent of spacecraft altitude.

Apollo revealed hundreds of localized crustal magnetic fields. Lunar Prospector made a global map of the crustal magnetic fields for the first time. Kaguya observed the more detailed global crustal magnetic fields with higher time resolution and higher spatial resolution than the previous observations.

We have analyzed the reflected electron data and magnetic field data around the satellite obtained by low energy charged particle analyzers (MAP-PACE) and magnetometer (MAP-LMAG) on Kaguya. Using the electron reflection method, we will report the global map of the lunar surface magnetic fields with high spatial resolution (˜8 km). Some of the observations of the reflected electron distributions showed energy-dependent loss cone by the effects of electrical potential differences between the lunar surface and Kaguya. We corrected the influence of the electrical potential difference on our result. By comparing our result of electron reflection method with the magnetic field measured by the magnetometer, we will discuss the behavior of the electron reflection over the lunar surface.

Keywords: Moon, Magnetic anomaly, Kaguya, Electron reflection method

Secondary ions of carbon, nitrogen and oxygen from the Moon

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Since the Moon has no global intrinsic magnetic field and only has a very thin atmosphere, the solar wind continuously bombard the lunar surface except when the Moon stays in the Earth's magnetosphere. The solar wind ion hitting causes the secondary ion emission from the lunar surface.
Although the initial energies of such secondary ions are low around several electron volts, the solar wind electric and magnetic fields pick up the ions and sometimes transport them to the outer space.
MAP(Magnetic field and Plasma experiment)-PACE(Plasma energy Angle and Composition experiment) on the Kaguya spacecraft performed the first direct ion measurements of three-dimensional energy and mass information. KAGUYA is a Japanese lunar orbiter which had conducted 1.5-year observation around an altitude of 100 km in 2008-2009. MAP consists of LMAG (Lunar MAGnetometer) and PACE. MAP-LMAG is a triaxial flux gate magnetometer which measures the vector magnetic field with a sampling frequency of 32 Hz and a resolution of 0.1 nT. MAP-PACE consists of four sensors: two electron sensors and two ion sensors. The two ion sensors are the IMA and the IEA. The IMA, the IEA and the two electron sensors have hemispherical FOVs and cover the full three-dimensional phase space of low-energy ions and electrons. Because Kaguya is a three-axis stabilized satellite, the IMA continuously faces the Moon. Thus, it measures ions that mostly come from the Moon, whereas the mounted IEA on the opposite side of the spacecraft measures ions from outer space. The nadir-pointing IMA measured ions which originated from the lunar surface and were at least composed of He+, C+, O+, Na+, K+ and Ar+. The measurements of ions from the Moon provided us with abundance mapping of the lunar secondary ions by the solar wind.
We report the features of the lunar secondary ion abundance, especially of C+, N+ and O+ because such light species are well distinguished. We also discuss the feasibility of the remote observation of small bodies' surface materials by measuring secondary ions by the solar wind.

Keywords: Moon, Secondary ions, Mass analyses

KAGUYA observation of terrestrial oxygen transported to the Moon

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Oxygen, the most abundant element of Earth and Moon, is a key element to understand the various processes in the Solar system, since it behaves not only as gaseous phase but also as the solid phase (silicates). Here, we report observations from the Japanese spacecraft Kaguya of significant 1-10 keV O^+ ions only when the Moon was in the Earth' s plasma sheet. Considering the valence and energy of observed ions, we conclude that terrestrial oxygen has been transported to the Moon from the Earth' s upper atmosphere (at least 2.6×10^4 ions $cm^{-2} sec^{-1}$). This new finding could be a clue to understand the complicated fractionation of oxygen isotopic composition of the very surface of lunar regolith (particularly the provenance of a ^{16}O-poor component), which has been a big issue in the Earth and Planetary science.

Keywords: The Earth-Moon system , KAGUYA (SELENE), Oxygen, Magnetosphere, Solar Wind, Earth Wind

10-year summary of the studies based on global subsurface radar sounding of the Moon by SELENE (Kaguya) Lunar Radar Sounder (LRS)

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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 pulsecompressed) 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). Even after the SELENE operation ended, subsurface explorations of the Moon were carried on by several missions such as GLAIL and Chang'E-3. Detailed comparisons among subsurface datasets with different scale and different coverage will be important in future studies.

Keywords: SELENE, LRS, Lunar volcanic activity

Detection of the Lava Tubes by SELENE(Kaguya) Lunar Radar Sounder

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Intact lava tubes on the Moon are potentially the best candidates for constructing lunar bases, where people and instruments are protected from micrometeorites and cosmic ray radiation, and the thermal conditions are stable. Recently, vertical holes were discovered in the lunar surface image data acquired by the high-resolution Terrain Camera onboard SELENE (Kaguya). The holes are possible entrances to subsurface lava tubes. However, whether lava tubes really exist underground on the Moon is still unknown.

We here report the results of our investigation of subsurface lava tube existence using the SELENE Lunar Radar Sounder (LRS) data. We first explored LRS echo wave data obtained near the Marius Hills Hole (MHH) on the “rille-A” in the Oceanus Procellarum of the Moon, and found a reflection peak signature after a sharp drop in echo power, which possibly indicates the existence of a subsurface void such as a lava tube. Then, we expanded the investigation area to 13-15°N and -58.25-55.75°E, including the MHH, and discovered several locations where the LRS echoes show similar wave patterns to that seen at the point near the MHH. We note that four of them are identified along the rille-A and on the extension of the rille, and are also on a long, narrow, sinuous mass deficit found in the GRAIL data.

The present result suggested that subsurface lava tube do exist in the vicinity of MHH, because of discovered wave patterns correspond to the existence of a subsurface lava tube.

Keywords: Lunar Radar Sounder, Lava tubes, Marius Hills Hole, SELENE

Composition of olivine-bearing rocks and their estimated origin

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Introduction: Remote sensing data obtained by the SELENE (Kaguya) Spectral Profiler (SP) found exposures with olivine-rich spectral features, globally distributed on the lunar surface[1], and it was suggested that they are possibly originated from the mantle.

Previous studies of returned lunar samples and the lunar magma ocean differentiation model indicate that olivine-rich rocks have the following three major origins: 1) mantle material, 2) volcanic material with olivine-rich composition, and 3) crustal material including rocks intruding into the crust (troctorite) [2]. Though most of the olivine exposures identified in [1] were located near basin rings, the origins of individual olivine sites may not be the same. Furthermore, no mantle material and only a small number of olivine-rich mare materials are available in the lunar sample collection. Therefore, understanding the origin of individual olivine exposures and advancing our knowledge about the distribution and composition of the three types of olivine-rich materials are important for understanding the composition and evolution of the lunar interior.

To address these issues, we geologically and morphologically investigated all of the identified olivine exposures in detail to assess the origin of each site in this study.

Methods: All of the 70 million latest calibrated reflectance spectra obtained by Kaguya SP [3] were used to re-identify olivine-rich exposures on the lunar surface by finding diagnostic absorption features of olivine around 1050 nm as described in [1]. Data of the Kaguya Multiband imager (MI) [4], Lunar Reconnaissance Orbiter Camera (LROC) [5], and SLDEM2013 (digital elevation model generated using the Kaguya Terrain Camera [6], MI, and Lunar Orbiter Laser Altimeter aboard LRO) of each of the identified olivine sites were used to evaluate reflectance, space weathering, geologic context, distribution and size of the exposures, composition, surface texture, and local slopes.

Results: About 150 SP reflectance spectra were re-identified as having unambiguous olivine-rich absorption features. Locations of the spectra were grouped into 50 sites located within the same latitude and longitude. We also evaluated the origin of all grouped sites. Note that we identified the clearest olivine-rich spectra among SP datasets, therefore olivine-rich material with less clear spectra may be present at other areas. We categorized their origins as likely mantle, volcanic, crustal, and “unclear”. About 60% of the sites are estimated to be mantle origin, and 5% are volcanic, 30% are crustal, and 5% are of unclear origin respectively. Mantle origin sites surround large basins whereas volcanic origin sites are within mare, and crustal origin sites are either surround or far from large basins.

Discussion: Though the percentage of each origin is not necessarily proportional to the volumes (surface area) of each category, at least there are many olivine sites of mantle origin around Crisium, Imbrium, and Nectaris. Estimation of excavation depth of these basins indicates it is likely they reach the mantle, which is consistent with the estimation of mantle origin for these olivine sites. We also identified volcanic olivine-rich sites, which have not been reported previously.

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Keywords: Moon, mantle, Kaguya

High resolution lunar mineral maps using Kaguya Multiband Imager data

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We determined the abundance of olivine, low-calcium pyroxene, clinopyroxene and plagioclase for the entire lunar surface at ˜80 m/pixel (512 ppd) using 1°x1° mosaics of the Multiband Imager reflectance data [1,2] corrected for the shading effects of topography (MAP level 02 [2]) and Hapke’s radiative transfer equations. We constructed a spectral lookup table of the reflectance spectra of 6601 mixtures of olivine, low-calcium pyroxene, clinopyroxene and plagioclase, at 7 amounts of submicroscopic iron (SMFe), an Mg# (Mg/Mg+Fe) of 65, and a grain size of 17 microns. We also modeled the reflectance spectra of these mixtures for a grain size of 200 μm for plagioclase to account for the band depth observed in the Multiband Imager data [4], for a total of 92,414 spectra. We compared the modeled spectra that contained ±2 wt% FeO of a given pixel [5], and assigned the composition to the best spectral match (in terms of correlation and absolute difference in continuum removed reflectance). We then validated the mineral abundances we obtained with global elemental maps from Lunar Prospector [6]. We also produced global maps of FeO using the algorithm of Lemelin et al. [5], and global maps of OMAT based on the algorithm of Lucey et al. [7].

The mineral maps obtained using the Multiband Imager data shows some notable differences with the mineral maps obtained using Clementine data [1]. The Multiband Imager data suggests there is much more low-calcium pyroxene than what Clementine suggested, and that low-calcium pyroxene is by far the dominant mafic mineral found in the South Pole-Aitken basin. The data also suggests that Mare Serenitatis contains much more olivine than Mare Tranquilitatis, in agreement with Mare Serenitatis having excavated mantle material [8]. The highest olivine abundances (˜25 wt.%) are found in the Procellarum KREEP Terrane. High abundances (˜50 wt.%) of low-calcium pyroxene and clinopyroxene are also found in the Procellarum KREEP Terrane and in Mare Tranquilitatis. Plagioclase abundances are very high in the Feldspathic Highland Terrane, but mature surface should be analyzed with caution. Indeed, there is currently a mineral identification for every pixel in the Multiband imager data. However, mature surfaces exhibit subdued absorption bands, which can lead to an overestimation in plagioclase abundances, even though we included the presence of SMFe in our modeling. Therefore, the mineral maps presented herein should be interpreted with the aid of the OMAT map. Also, we provide global mineral maps for the complete range of latitudes, but the Multiband Image data has been better calibrated within 50° in latitude [5], therefore caution should be taken when interpreting regions at higher latitudes.

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Keywords: Lunar, Mineral, map

Abundance and characteristics of impact melt on lunar crater central peaks

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The Moon’ s crust has been penetrated and modified by impact craters of all sizes over its history, ranging from micron-sized pits to basins thousands of kilometers in diameter. These craters provide a valuable three-dimensional view of the lunar crust by exposing material from depth, making material from throughout the crustal column and perhaps even the lunar mantle accessible to remote sensing observations. However, the same cratering processes that expose subsurface material also act to obscure the true local composition by contributing to extensive mixing of the surface at all scales and by producing impact melt, even on the steep slopes of central peak craters (e.g. Ohtake et al., 2009, Dhingra et al., 2016)

Taking two central peak craters (Jackson and Tycho), we isolate impact melt regions on and off the central peaks using the geologic maps of Dhingra et al. (2016) and analyze their spectral, compositional, and physical properties utilizing datasets from the Kaguya Multiband Imager (MI) and Terrain Camera (TC), the LROC Narrow Angle Camera (NAC), and the Diviner Lunar Radiometer.

Consistent with previous work (Ohtake et al., 2009; Kuriyama et al., 2012), we find that the regions of Jackson’ s central peak identified as impact melt are compositionally distinct, with higher iron (avg. FeO 5%) and lower modeled plagioclase content (avg. plagioclase 79%) than the rest of the very plagioclase-rich central peak (avg. FeO 2%, avg. plagioclase 90%). This indicates that for central peaks like Jackson with substantial impact melt, it is important to exclude melt from compositional analyses to understand the true local composition. However, the impact melts mapped on Tycho’ s central peak are not substantially different in iron content than the average central peak (both average 6% FeO).

While detailed geologic maps based on high resolution imagery such as Kaguya Terrain Camera or LROC Narrow Angle Camera are an effective tool for eliminating potentially contaminated regions of central peaks, this approach is time consuming and subjective. For large-scale surveys, a quantitative metric for narrowing data to areas less affected by mixing and contamination is needed in order to ensure only the most reliable spectra are interpreted. We investigated three possible discriminators (LOLA/TC slope, Diviner rock abundance, optical maturity) for identifying fresh and uncontaminated surfaces, and find that rock abundance may be a promising metric.

The rock abundance of the impact melt deposits on Jackson’ s central peak is very low, with average rock fractions near 0.03, in contrast to the rest of the central peak, which has an average rock abundance of 0.056. The rock abundance distributions for the melt regions both on and off the central peak are also skewed strongly to the right, with skewness values greater than 1, whereas the average central peak and mapped boulder regions have skewness values below 1. The slopes and optical maturity values for the impact melt units vary, and do not appear to provide a diagnostic measure of the presence of melt.

While our analysis suggests that rock abundance is an effective discriminator of impact melt, at least for

Jackson crater, it may only be applicable to central peak craters within a certain age range, as older craters have much lower rock abundances, and regolith development throughout the central peak might mask the anomalously rock-free signature of melts. Efforts are underway to map impact melt on older central peaks and compare melt rock abundance distributions with average central peak values for these more weathered craters.

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Keywords: Moon, Impact Processes, Central Peaks, Spectroscopy, Kaguya, Lunar Reconnaissance Orbiter

Global classification map of lunar absorption spectra and new impression of lunar crust formation.

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This report presents the global classification map of lunar absorption spectra by unsupervised classification methods and new impression of lunar crust formation based on the map.
Geologic map is an important tool to understand formation process of lands. Many Moon’s geologic maps has been made by many researchers based on their own criteria. Therefore we are hard to compare different sites on the Moon far from each other.
In order to solve such problem, the study of making global geologic map of the Moon has been started 3 years ago, and we made the global classification map of lunar absorption spectra based on hyper spectrum data of Spectral Profiler/Kaguya. Since this map was produced by both K-means and ISODATA of unsupervised classification methods under unified criteria for whole Moon, we can easily compare a region with others far from there.
The entire Moon was divided into 66 classes of lunar absorption spectra. The entire Moon was divided into 66 classes of lunar absorption spectra by unsupervised classification methods and those were categorized as 5 regional groups based on major corresponding location, which were Mare (M) group, Highland (H) group, South Pole-Aitken (S) group, Boundary between groups of M/S and H (B) group and Ejecta from fresh highland craters (E) group.
Some local class distributions showed good agreement with past those such as Aristarchus region, Orientale region, SPA region and highland region. Also, it was found that some area of B group covered cryptomaria and some spectrum classes corresponded to craters itself in maria and highland region.
Furthermore, some new impressions of the lunar crust formation related to cryptomaria and/or layer structure of subsurface were found through comparison of different sites far from each other based on the presenting global map.

Keywords: Moon, geologic map, crust formation

Near-Far Asymmetry of Magma Production and Conditions of Magma Eruption of the Moon: Constraints from Mare Volumes within the Impact Basins

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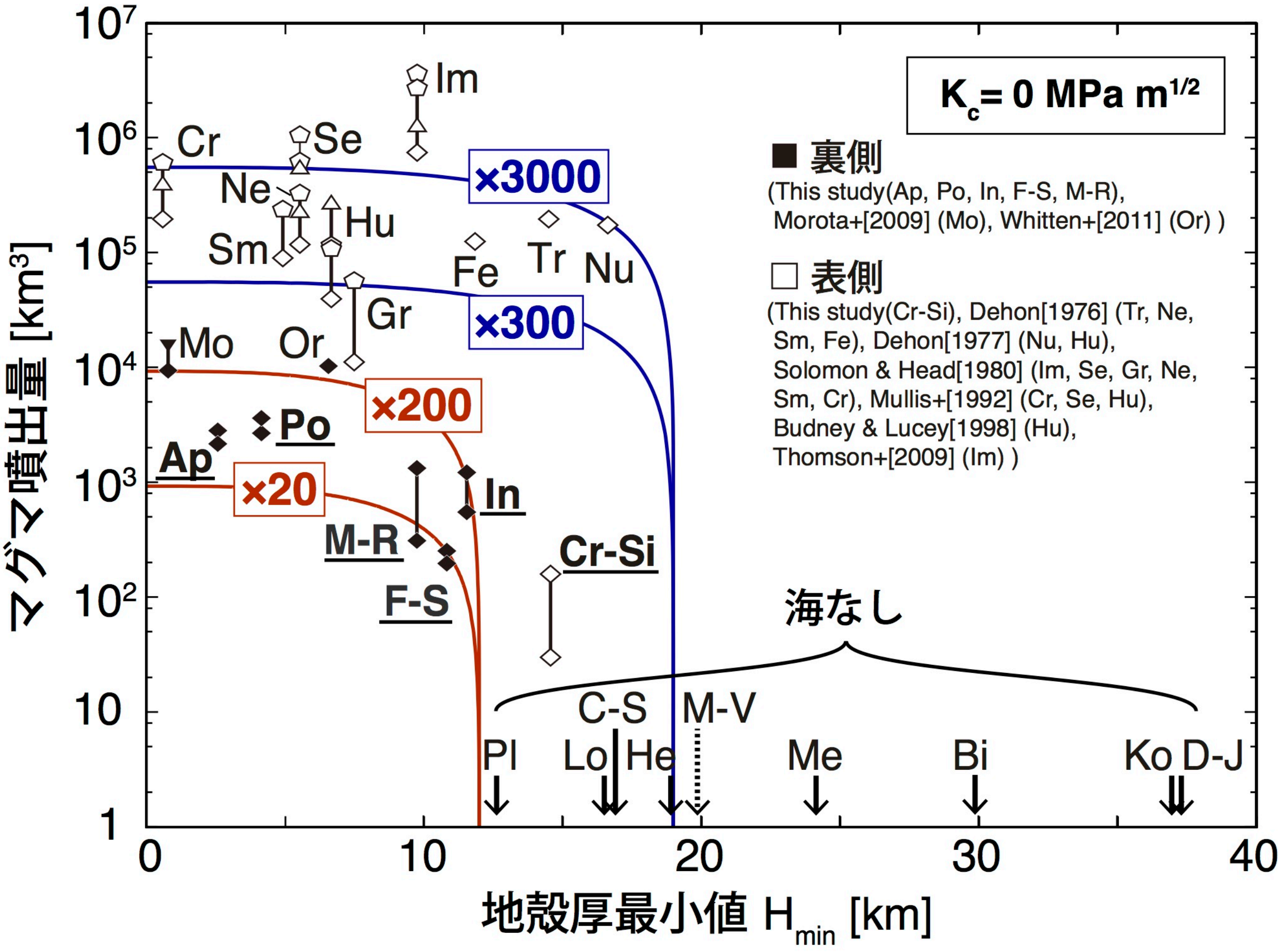
To understand the thermal conditions of the lunar mantle and its lateral heterogeneity, estimates for volumes of mare basalts are essential. However, because of the absence of high-resolution remote sensing data on the lunar farside, accurate volume estimates of farside maria had been limited until recently. In this study, we estimated the volumes of mare basalts within five farside basins, Apollo, Ingenii, Poincare, Freundlich-Sharonov, and Mendel-Rydberg, and one nearside basin, Crüger-Sirsalis, using topographic and multiband image data obtained by SELENE (Kaguya). Furthermore, using the high-resolution crustal thickness model constructed from GRAIL gravity data and LRO topography data, we investigated the crustal thickness of major impact basins and the relationship with the magma eruption. The results of volume estimates indicate that farside mare volumes are ~100 times smaller than those of the nearside. From a relationship between the mare volumes and the crustal thicknesses of each basin, it was also found that the minimum crustal thicknesses within the basins were a dominant factor that determined whether magma erupted at the surface and that the critical crustal thickness for magma eruption were ~12 km for the farside and ~20 km for the nearside. In the areas with thinner crust than the critical thicknesses, the total mare volumes do not depend on the crustal thickness. These results suggest that the lunar diapirs had typical sizes for the nearside and the farside, respectively. The diaper radii were estimated to be 3.5–4.4 km for the nearside and 2.2–3.3 km for the farside based on a simple magma ascent model considering the balance of the positive buoyancy of the diaper at the crust-mantle boundary and the negative buoyancy of a dike in the crust. The ratio in the diaper volumes between the nearside and the farside is only 2.6–4.0, much smaller than the observed ratio of mare volumes (100 times). Therefore, the observed ratio of mare volumes should be explained by difference in frequencies of magma eruption. The eruption frequencies were calculated to be 200–3000 for the nearside and 10–200 times for the farside based on the observed total volumes of mare basalts. Furthermore, from the estimated diaper sizes and eruption frequencies, we estimated that magma production in the farside mantle might be ~15-20 times smaller that of the nearside mantle. This result implies a stronger near-far dichotomy than previously estimated.

Keywords: Moon, Mare volcanism, Lunar dichotomy, Mare basalt, Crustal thickness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10
1
0
10
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30
40
マグマ噴出量 [km^3]
地殻厚最小値 H_{min} [km]

Characteristics of mineral compositions of lunar late mare volcanism revealed from Kaguya data

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In order to understand the crystallization of lunar magma ocean and following evolution of the lunar mantle, reconstructing the volcanic history of the Moon is important. The relation between compositions and ages of lunar mare basalts provides insights into the compositional structure and the thermal history of the lunar mantle. According to previous studies of crater counting analysis using remote sensing data, the age distribution of mare basalts shows a second peak at ~2 Ga, which concentrated in the Procellarum KREEP Terrane (PKT). To understand the mechanism for causing the second peak and its magma source is essential to constrain the thermal history of the moon.

In our previous study, we investigated the relation between eruption ages and titanium contents of mare basalts. As a result, we found that a rapid increase in mean titanium content occurred near 2.3 Ga, suggesting the magma source transition. Moreover, the high-titanium basaltic eruptions are correlated with the second peak in volcanic activity at around 2 Ga. We designate volcanisms before and after 2.3 Ga as Phase-1 and Phase-2 volcanism. We propose that Phase-2 volcanism can be explained by the three possible scenarios: (1) the ilmenite-bearing cumulate rich layer in the core-mantle boundary formed after the mantle overturn, (2) the basaltic material layers beneath the lunar crust formed through upwelling magmas, and (3) ilmenite-bearing cumulate blocks remained in the upper mantle after the mantle overturn. We also searched the evidence of the magma source transition in topographic features. As a result, we found a feature like a plateau in the central region of the PKT where most of Phase-2 mare basalts erupted, suggesting that the origin of the plateau might be related to Phase-2 volcanism.

To understand the magma source transition around 2.3 Ga, reconstructing the history of the volcanic activity in the PKT is essential. In this study, we focused on the central region of the PKT and make new geological map of this region. Then, we performed spectral analysis of mare basalts to investigate mineral compositions of mare basalts. At first, we made geological map of the central region of the PKT using KAGYA Multiband Imager (MI) data and digital terrain model (DTM) derived from KAGUYA Terrain Camera data and investigated mineral compositions of mare basalts using KAGYA Spectral Profiler (SP) data. We calculated absorption depths of 950, 1050 and 1250 nm reflectance data from MI to divide highland and mare regions in the central region of the PKT. Also, topographic roughness was calculated from DTM to identify highland regions. We performed principal component analysis for MI 8 band reflectance data to identify each mare basalt unit.

To deconvolute an observed spectrum into individual mineral components, the modified Gaussian model (MGM) is generally used. However, it is difficult to fit the spectrum of complicatedly mixed material such as mare basalts by the MGM because each mineral has multiple absorption bands. Nimura (2011) improved the MGM by investigating the relations between chemical compositions of minerals (the ratio of Fe/(Fe+Mg) in olivine and the ratios of Ca/(Ca+Fe+Mg) and Fe/(Ca+Fe+Mg) in pyroxene) and absorption band parameters (center, width and strength ratio of Gaussian curves). This method was applied to the spectra of asteroids in the previous study and successfully could model mineral and chemical compositions. In this study, we applied this method to the spectra of mare basalts obtained by KAGUYA SP. To avoid the effect of the space weathering, we used spectra of fresh crater wall.

At present, we enhanced the field of the geological map of the PKT and we are performing spectral

analysis of mare basalts. In this presentation, we show the updated geological maps of the PKT and the result of spectral analysis of Phase-1, Phase-2 mare basalts in the Oceanus Procellarum and Mare Tranquillitatis.

Keywords: Moon, volcanism, mineral composition, spectrum

Re-evaluation of deep moonquake source parameters and implication for thermal condition of deep lunar interior.

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While deep moonquakes are seismic events commonly observed on the Moon, their source mechanism is still unexplained. The two main issues are poorly constrained source parameters and incompatibilities between the thermal profiles suggested by many studies and need for brittle properties at these depths. In this study, we reinvestigated the deep moonquake data and uncover the atypical feature of deep moonquake that completely differs from those of the Earth. We first improve the estimation of source parameters through spectral analyses using virtual “new” broadband seismic records made by combining those of the Apollo long and short period seismometers. We use the broader frequency band of the combined spectra to estimate corner frequencies and DC values of spectra, which are important parameters that constrain the source mechanism. We use the spectral features to estimate seismic moments and stress drops from 3 deep moonquake source regions. Secondly, we show that the large strain rate from tides makes the use the new sets of source parameter and re-evaluate brittle-ductile transition temperature at deep moonquake source regions. We finally take the temperature as an additional constraint and estimate the temperature profile that is compatible with deep moonquake occurrence and other geophysical observations such as surface heat flow measurements and geodetic observations.

Keywords: Lunar Science, Seismology, Planetary Science

Re-determination of lunar crustal thickness around the Apollo landing site by analyzing Apollo artificial impacts’ seismic data combined with LRO’s products

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It has been about 50 years since the seismometers were deployed on the Moon in the Apollo missions. Since then, some topics have been studied by analyzing the lunar seismic data. For example, core size, composition of the Moon, velocity structure of the lunar interior and so on. The lunar internal structure gives us important information about origin and evolution of the Moon. For instance, we can estimate bulk abundance of Al from lunar crustal thickness and it gives constraints for the lunar formation. In the previous lunar seismic analyses, the artificial impacts were often used to constrain the lunar crustal thickness because of known source locations and impact times from the tracking of the impactors. Five S-IVB rocket boosters and four Lunar Module impacts were deliberately impacted on the surface of the Moon to generate the seismic waves. All of them were succeeded to track except for Apollo 16 S-IVB booster. Loss of radio contact between the Apollo 16 S-IVB left large uncertainties on the location of the impact. However, the precise source locations of the five S-IVB impacts were updated with Lunar Reconnaissance Orbiter(LRO) image data recently. The updated locations resulted in change in the reference source locations for the travel time analysis with these artificial impacts. Especially, as for Apollo 16 S-IVB, we found that its impact site estimated in Apollo era was different from the precise one by about 30 km. In this study, we re-analyzed artificial impacts’ seismic data using the precise source locations to determine more accurately the crustal thickness of the Moon. We will present the crustal thickness around the Apollo landing site and discuss the effect of local structure that might affect the travel time analyses. We will also discuss implications for future lunar seismic exploration for better understandings of lunar crustal structure.

Keywords: Moon, Apollo lunar seismic data, Lunar interior exploration, LRO

Studies for the source region of lunar basaltic brecciated meteorites, Northwest Africa 773 group on the geochemical, mineralogical and petrological analyses

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Lunar meteorites originate from craters that are randomly distributed on the surface and thereby provide valuable information on geochemistry, mineralogy, and petrology of the source regions that are not obtained from the Apollo and Lunar mission samples. The recent-improved remote sensing data (e.g., Kaguya, LRO, Chandrayaan-1) are very powerful tool to interpret their source regions. Identification of the source region of lunar meteorite could be almost equivalent to the sample return from that region. Lunar meteorites, Northwest Africa (NWA) 773 clan consist of a group of paired meteorites with different lithologies (NWA 773, 2727, 2977, 3160, 3333, 6950, and more). Some of them contain olivine cumulate gabbro (OC) as lithic clasts in a basaltic breccia, while NWA 2977 and NWA 6950 entirely consist of OC. Furthermore, NWA 773 clan contains a variety of clasts other than OC: olivine phyric basalt, pyroxene phyric basalt, pyroxene gabbro, ferroan symplectite, alkali-rich phase ferroan rocks, and silicic rock. Such a variable lithological types indicated the complex igneous petrogenesis and subsequent brecciation of the source region of NWA 773 clan. In this work, the geochemical, mineralogical and petrological characteristics of their source region were discussed by comparing the lunar sample and Kaguya observational data.

Lunar meteorites, Northwest Africa 773 clan were investigated with geochemical, mineralogical and petrological microanalyses: 1) the bulk chemical compositions were obtained by neutron-induced prompt gamma-ray analysis (PGA) and instrumental neutron activation analysis (INAA) in the Japan Atomic Energy Agency; 2) mineralogical and petrological data of NWA 773 clan were investigated by Scanning Electron Microscope (SEM) and Electron Prove Micro-Analyzer (EPMA) at Waseda Univ., visible and near-infrared reflectance spectra obtained by a JASCO reflectance spectrometer at JAXA; 3), where their radiogenic ages were discussed by references of several literatures.

Rare Earth Element (REE) compositions from NWA 773 breccia have similar KREEP-enriched patterns of their light-REE-enriched and heavy-REE-depleted patterns, and negative Eu anomaly. The NWA 773 clan breccias show the wide range REE values among each portion of NWA 773 clan breccias (La = 40 –170 × CI chondrite), which probably reflects variable abundances of KREEP-rich clasts in the breccia. In fact, we observed an evolved igneous clast (high-silica) in NWA 2727 breccias. Silica-rich rocks (e.g., felsite, granite) from the Apollo missions are highly enriched in incompatible elements (REE, K, Th).

NWA 773 clan represents the following characteristics: 1) the included igneous clasts derived from basaltic to rhyolitic magma composition on the Moon, 2) NWA 773 clan breccias represent high-Th (max 5.15 μg/g), -FeO (>15wt%), and very-low-Ti (<1wt%) composition, 3) the included OC lithologies represent one of youngest crystallization ages (3 Ga) among lunar samples. The first suggests that the silica-rich rocks in NWA 773 clan could be associated with putative silicic volcanism observed by the recent remote sensing data. The above features of NWA 773 clan were permitted in Procellarum KREEP Terrane (PKT), as putative silicic volcanism mostly occurs in PKT. NWA 773 clan allows us knowledge of complex igneous activities in PKT. Furthermore, the source region of NWA 773 clan will be narrowed down within PKT region by comparing with the following data: 1) bulk FeO, CaO, TiO_2, K, Th contents of NWA 773 clan breccia vs. elemental distribution maps obtained by Kaguya gamma-ray spectrometer; 2) visible and near-infrared reflectance spectra of NWA 773 clan vs. reflectance spectra obtained by Kaguya spectral profiler, 3) the crystallizaition ages of NWA 773 clasts vs. the eruption ages obtained by Kaguya Terrain Camera. As described here, the source regions can be well interpreted on the basis of the combination of data from lunar meteorite and remote sensing observations.

Keywords: meteorite, KREEP, volcanism

Moganite in lunar meteorite, Northwest Africa 773 clan: Trace of H_2O Ice in the Moon’s Subsurface

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Lunar water locally concentrates as a result of the migration of H_2O molecules on the sunlit surface towards the colder regions. The molecular water is subsequently cold-trapped as ice on the permanently shadowed regions, the poles and theoretically Moon’s subsurface. Although a few trace of subsurface H_2O has been observed by remote sensing spectrometers (e.g., LCROSS), it has not been reported in the Apollo and Luna samples and lunar meteorites yet. In this study, lunar meteorites, the Northwest Africa (NWA) 773 clan, were investigated and thereby moganite, a monoclinic SiO_2 phase precipitated from alkaline fluids, was discovered by various microanalyses. A formation process of this lunar moganite was also interpret to evaluate origin of the Moon’s subsurface H_2O.

Lunar meteorites of the NWA 773 clan were selected for Raman spectroscopy, electron microscopies and synchrotron X-ray diffraction (SR-XRD). The KREEP-like NWA 773 clan commonly consists of gabbroic and/or basaltic clasts.

Silica occurred as anhedral micrograins between the constituent minerals in the lunar meteorite. Raman spectra of the silica micrograins exhibited pronounced peaks at 128, 141, 217 and 503 cm^{-1}, which corresponded to those of moganite. Coesite Raman peaks were also identified together with the moganite signature. Raman intensity mapping revealed that the silica micrograins contain abundant moganite in its core, surrounded by coesite. SR-XRD of several silica micrograins also confirmed moganite and coesite. Transmission electron microscopy clarified that the silica micrograins consist of nanocrystalline particles with an average radius of 4.5 nm. Most of the SiO_2 nanoparticles were identified as moganite by selected area electron diffraction (SAED) patterns. Moganite was accompanied by small amounts of coesite, according to SAED analyses of the SiO_2 nanoparticles.

Moganite-bearing silica micrograins in the NWA 773 clan precipitated from lunar alkaline fluids rather than terrestrial weathering for the following reasons: (1) Occurrence only in a part of the NWA 773 clan. (2) Moganite surrounded by the coesite rim. (3) High moganite content contradicting reduced content to <20 wt% under dry desert condition over terrestrial age.

A formation process for lunar moganite can be explained as follows. A host gabbroic and basaltic rock of the NWA 773 crystallised within the Procellarum KREEP Terrene (PKT). Subsequently, carbonaceous-chondrite collisions occurred on the surface of the PKT, followed by ejection of the host rock due to the impact events. The alkaline water delivered by the carbonaceous chondrite was captured as a fluid during the brecciation on the impact basin. Below the freezing point, this fluid got cold-trapped as H_2O ice in the subsurface. Simultaneously, the moganite-rich silica micrograins precipitated from the captured alkaline fluid on the sunlit surface. The NWA 773 clan was launched from the PKT by the latest

impact event, thus producing transformations to coesite from moganite.

Keywords: Lunar meteorite, Moon, Subsurface water, H2O ice

Origin and evolution of Moon

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The ABEL model, newly proposed to discuss the history of the Moon. The core of this new model is characterized by two steps:(1) a Dry-Earth Moon system formed at 4.53Ga, and (2) ABEL Bombardment, which delivered volatiles to the Moon’ s interior and atmospheric and oceanic components to the Earth at 4.37-4.20 Ga with the minor bombardment continuing up to 3.9 Ga. During the ABEL Bombardment, asteroids bombarded the nearside of the Moon, selectively causing frictional mantle heating down to the deep mantle. The largest impact at around 4.37 Ga resulted in such effect even at Aitken on the opposite side of the Moon through mantle to the surface, which included the transferal of volatiles into the deep mantle and lowering the viscosity of the hydrated mantle. About 200 million years after the bombardment, the mantle rebounded upwards to generate a series of basalts within the craters. This kind of rebound did not occur on the farside because bombardment was less on the farside.

A new model of the history of the Moon includes the following seven major events: (1) giant impact to form the Moon-Earth system;(2) formation of a magma ocean and its consolidation; (3) injection of water into the Moon through 4.37-4.20 Ga ABEL Bombardment;(4) widespread isostatic-rebound magmatism over the Procellarum KREEP Terrane (PKT) on the nearside Moon (extension on the nearside caused compression on the farside by thrusting); (5) strong magnetism;(6) Copernican bombardment; and (7) gaseous eruption combined with Moonquakes up to now.

Keywords: ABEL Model, Geology of Moon, secondary accretion of volatiles

The heterogeneities in Lunar interior: Role of High Titanium materials

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Tomographic images of the lunar mantle have been reported by Zhao et al. (1) using the Apollo seismic data. They reported existence of P and S-wave anomalies in the lunar mantle which could relate also to the epicenters of the deep moonquakes. There is a possibility that the cause of the lunar P and S-wave anomalies is completely different from that of the Earth’s mantle. In the Earth, slow seismic anomalies are the signature of hot plumes ascending in the Earth’s mantle. On the other hand, the seismic anomalies in lunar mantle may be caused by compositional heterogeneities. Elkins-Tanton et al. (2) presented a model of solidification of the lunar magma ocean. In their model, titanium rich cumulates were formed in the later stage of its solidification, and gravitational overturn occurred in the early Moon. This overturn provided titanium rich regions in the lunar deep interior. Some of these materials might have stagnated and could have produced chemical heterogeneities in the lunar mantle. Titanium enriched materials are denser and slower in seismic wave velocity compared to that of the normal lunar mantle, which causes slow seismic velocity anomalies. Previous measurements of density and sound velocity of Ti-rich materials and magmas (3) indicate clearly that the Ti-rich materials which are remnant of the early overturn can cause slow velocity anomalies. Igrashi et al. (4) measured the solidus temperature of the Ti enriched materials at around 3-5 GPa corresponding to the base of lunar mantle, and showed the solidus temperature is lower than the lunar geotherm, i.e., the partial melting occurs in the lunar lower mantle generating dense magmas at the depths (3). Thus, the molten high Ti melts can cause high attenuation and slow seismic velocity regions at the base of the lunar mantle. More precise seismic tomography studies of the moon and mineral physics studies of the lunar materials are essential to clarify the heterogeneities of the lunar mantle in the future lunar exploration. It is very important to separate the chemical and thermal heterogeneities in the lunar mantle and to compare the difference from those of the Earth’s mantle.

References: (1) Zhao et al. (2008), Chinese Sci. Bulletin, 53, 3897-3907, Zhao et al. (2012), Global Planetary Change, 90-91, 29-36, (2) Elkins-Tanton et al. (2011), EPSL, 304, 326-336 (3) Sakamaki et al. (2010), EPSL, 299(3), 285-289, (4) Igarashi et al. (This meeting abstract)

Keywords: Tomography, High titanium material, Lunar magma ocean, Heterogeneity, lunar mantle

Possible observation of free core nutation of the moon

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The Earth has a fluid core and it can rotate around the axis different from that of the mantle because it is fluid.
If the axis of rotation of the fluid core and that of the mantle incline a little to each other for some cause, they begin rotation around the other axis anticlockwise because forces acting on the core mantle boundary (CMB) are asymmetrical to the figure axis of the mantle. This phenomenon is called the Free Core Nutation (FCN).
In case of the Earth tides, the period of FCN is about 460 sidereal days, and when seeing on the rotating coordinate fixed to the Earth, the angular velocity becomes 1-1/460 (turns/ sidereal day), which is close to the period of 1 sidereal day.
There are a lot of components of diurnal Earth tides near the period of 1 sidereal day, and the amplitudes of these components are magnified according to the resonance of the period of FCN, which is called fluid core resonance.

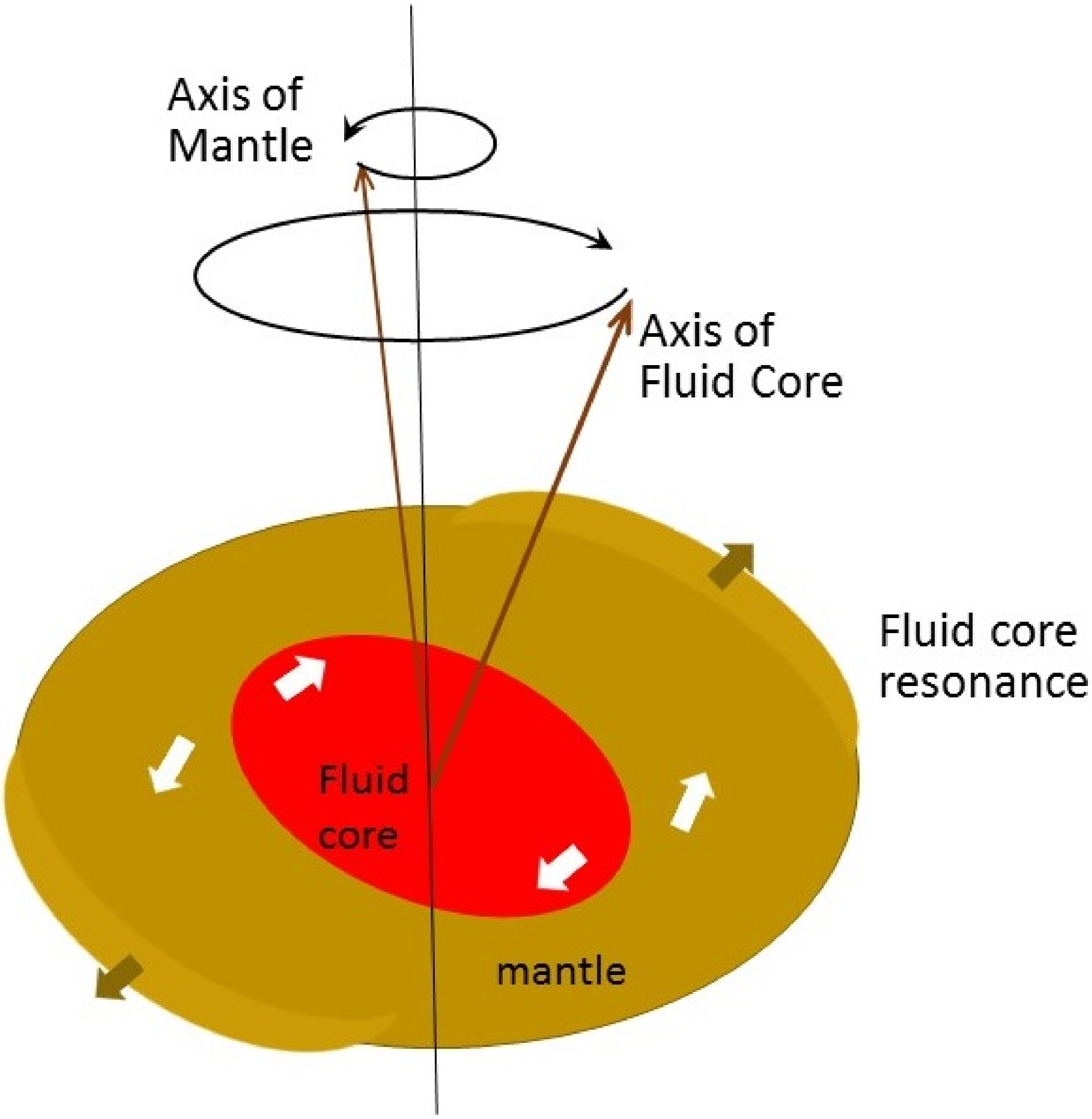
Whether the Moon has a fluid core or not is still unclear although it is an important issue which is related to existence or non-existence of paleo magnetic field and thermal history of the Moon. There were researches which suggested energy dissipation inside of the Moon from the analysis of Lunar Laser Ranging data (Williams et al, 2001) and which suggested partial melting inside of the Moon from the theoretical estimation of tidal heating (Harada et al., 2014). However there has been no observation which directly show the existence of the fluid core.

The period of FCN is estimated to be from several to 20 decades according to lunar model and the amplitude is less than 16 arc seconds (Gusev et al., 2016). Astronomical observations of FCN might be very difficult because its period is too long. However observations of deformation or gravity variation affected by resonance of FCN appear on the lunar surface are more practical like the Earth. Supposing the mean angular velocity of the Moon be Ω_L, angular velocity of FCN relative to inertia space be n_L, then FCN is observed on the Moon as the angular velocity of Ω_L-$n_{L.}$ It becomes 0.0366-1 / (200×365) = 0.03660099-0.00001370=0.03658729 (27.331 days) for the period of 20 decades..

Because there are a lot of components of lunar diurnal tides around the 27.3 days, there is possibility that the amplitudes are magnified by the resonance of FCN. Not only the tidal variations but the forced physical librations which are caused by the same forces must be affected by the resonance. Actually there are some evidences of resonance in the result of analyses of Lunar ephemeris DE421 expanded to over 1000 years (Rambaux&Williams, 2010). However, there are free modes such as the precession (about 24 year period), the Chandler like polar-motion (about 75 years), the free librations (about 100 years for latitudinal mode and 2.9 years for longitudinal mode) as well as FCN (Gusev et al., 2016), and the resonance effects must be complicated.

We try to estimate the effect of resonance existence of FCN, and we propose to observe tidal deformation and gravity tides on the moon surface.

Keywords: Lunar interior, Free core nutation, Free core resonance, Lunar tides



Classification of deep moonquakes using machine learning technique and application of it to lunar science and exploration

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A lot of lunar seismic events had been observed by 4 seismic stations deployed at Apollo 12, 14 15 and 16 sites through NASA Apollo mission from 1969 to 1977. Deep moonquake which occurs at depth of about 700-1200 km is most frequent lunar seismic event, and 106 sources have been located. The deep moonquake events occurred from the located source have been analyzed to investigate the lunar deep structure (e.g., Lognonn et al., 2003, Matsumoto et al., 2015). We know that the deep moonquakes occur repeatedly related with tidal force worked on the lunar interior and the waveforms of the events generated from the same source are similar (Nakamura et al., 1982). The sources of many deep moonquake events have been identified using the similarity of the waveforms (e.g., Nakamura, 2003). On the other hand, about 20% of the discovered lunar seismic events are still unclassified and about several hundreds of the deep events are unlocated. This fact indicates that the previous identification of the deep moonquake sources using the waveform similarity is not necessarily sufficient. In the previous studies, the waveforms of deep moonquake in time series are mainly analyzed to classify the sources using the similarity (e.g., Nakamura, 2003, Bulow et al., 2005), and they would not be enough to classify the sources. Therefore, we have investigated new parameters to classify the deep moonquake sources efficiently using the supervised machine learning technique.

In this study, we analyzed the deep moonquake events occurred from the known active sources observed at Apollo12 station. Firstly, we have investigated effectivity of power spectral density (PSD) in frequency domain to classify the deep sources using one of conventional machine learning technique; Support Vector Machine (SVM). This result has shown that the PSD using 15 minutes' data from arrival of P-wave are more effective to classify the sources compared with waveform in time series (Goto et al., 2013, Kato et al., 2016). Secondary, most effective machine learning technique for classification of the deep source has been studied, and we found that Neural Network has the best availability among five representative method. Then, it is often difficult to extract the effective parameters from the waveforms due to small amplitude and strong scattering of the waveforms. From the reason, we have investigated positional relation between the Moon and other planets at occurrence time of each deep moonquake as the parameters for the classification without using the waveforms, because it is known that deep events occur related with relative position (that is tidal force) among the Moon, the Earth and the Sun (e.g., Lammleign, 1977). This investigation has shown that relative position and velocity between the Moon and the Earth were important to identify some deep moonquake sources (Kato et al., 2017).

We found that these new parameters and method for classification of the deep sources are available to identify the source of the unlocated deep events (Kikuchi et al., 2017). Most deep moonquake source have been located in lunar near-side and there are only small number of sources in lunar far-side. However, Nakamura (2005) describes that some deep moonquake events which may occur from undiscovered far-side sources are detected at only one or two Apollo stations. Though this number is insufficient to locate the source from travel-time analysis, if we can identify that the unclassified events generate from the same far-side source and increase the observation points using our new method, we may be able to locate that and discover new far-side sources. This discovery will give new knowledge about activity of far-side deep events, internal structure in lunar far-side and the lunar dichotomy. Then, it can be expected that we can discover a lot of new deep moonquakes in sequential seismic data observed during about 7 years using the new parameters such as PSD. In future lunar seismic experiments such as SELENE-2 (Tanaka et al., 2008) and Approach (Yamada et al., 2016), we can deploy only one or two seismic stations, and the number is insufficient to locate the deep moonquakes. In this case, if we can identify the source of detected deep events using the positional relation between the Moon and other planets, we will be able to obtain new travel time data of deep moonquakes on the future missions in spite of a few seismic stations.

Keywords: Deep moonquake, Machine learning technique, Analysis of moonquake waveform, Lunar interior structure, Lunar exploration

A simulation study of Lunar Farside Lander positioning with a Four-way Lander-Orbiter Relay Tracking Mode

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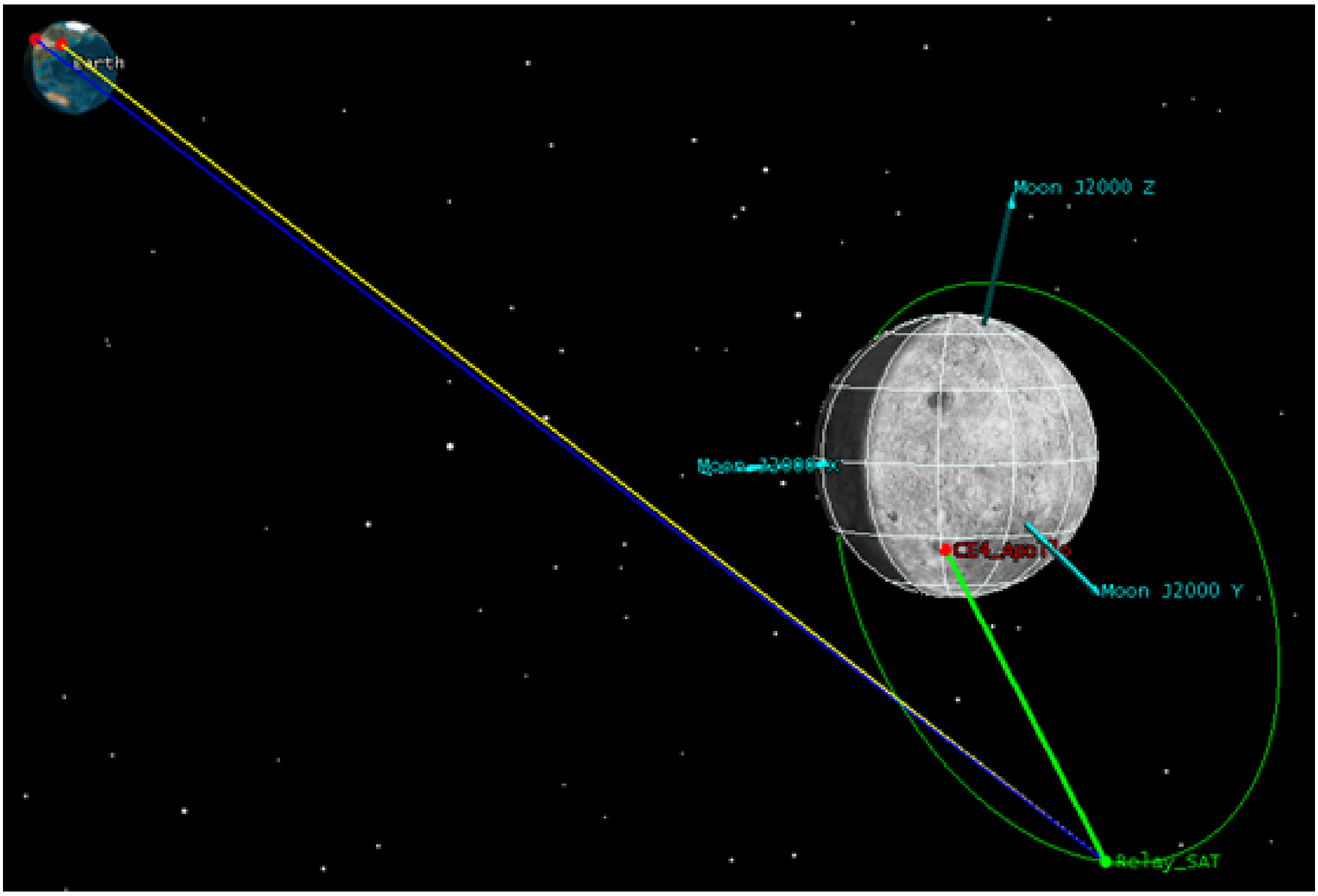
The in-situ exploration of lunar farside is still an international blank until now. The reason is the synchronous rotation of the moon, which results in the unachievable between the lunar farside lander and earth tracking station. The traditional direct tracking mode, such as two-way range/range rate, VLBI delay/delay rate, will be ineffective for the farside lander tracking, therefore it is essential to relay the signal using a relay satellite. In this paper, we firstly give the updated mathematical formulas and the partials for the Four-way Lunar-Orbiter relay tracking measurement. Then, based on the independent precise orbit determination software system WUDOGS, the precise positioning of the lunar farside lander is studied with simulated tracking data. The results show that: with 0.1 mm/s measurement level, the positioning precision of the farside lander could reach the maximum of centimeter level using a circumlunar relay satellite (Fig. 1a); while for the L2 halo relay satellite (Fig. 1b), its accuracy could reach about 10 meters level. The conclusion could provide an important reference for the future lunar farside landing mission, especially for Chinese lunar exploration mission Chang’E-4.

Keywords: lunar farside, lander positioning, precise orbit determination, four-way relay tracking, Chang’E-4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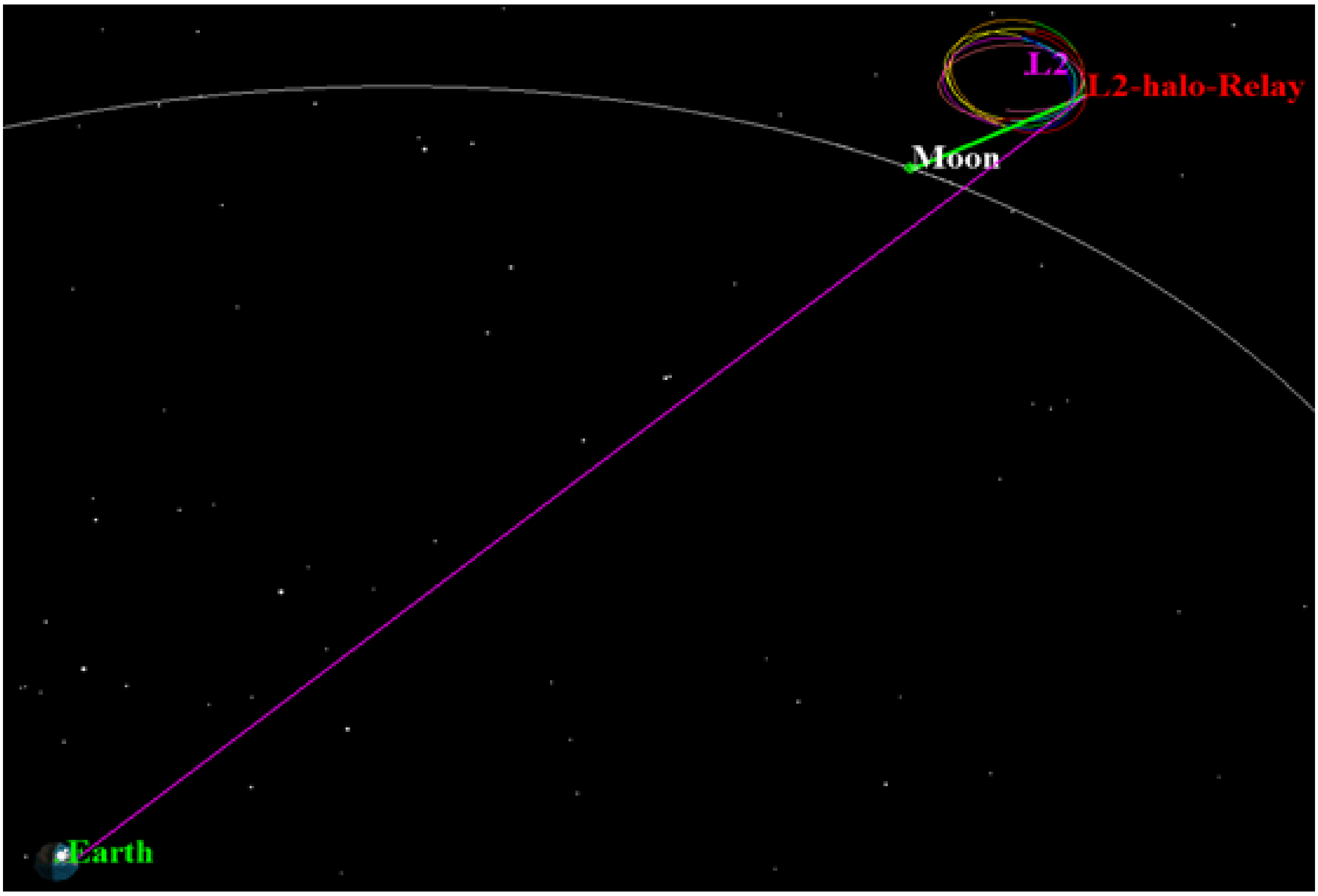
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Design and development of Multi-band Camera proposed for SLIM mission

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Smart Lander for Investigating Moon (SLIM) is being planned by Japan Aerospace Exploration Agency (JAXA). SLIM aims to research and demonstrate the engineering key issues related to the smart landing on the gravitational planets. They are precise guidance algorithm, vision based navigation, smart landing gear. By doing SLIM mission, we expect to achieve the paradigm shift in the field of celestial body landing from ‘landing where easy to land’ to ‘landing where desire to land’. This paradigm shift requires a number of novel technologies, and it is reasonable to demonstrate with the small lander at first. We proposed Multi-Band Camera (MBC) for SLIM lander. MBC is a compact VIS-NIR camera composed of an imaging sensor (InGaAs), a filter-wheel with 10 band-pass filters, and a movable mirror for panning and tilting. Scientific objectives of MBC are rock-forming mineral identification and rock texture observation for rocks around the lander. The design of MBC, the state of development, and the idea of scientific operation will be presented.

Keywords: the moon, SLIM, remote sensing

SSERVI: Merging Science and Human Exploration

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1. NASA Solar System Exploration Research Virtual Institute

NASA's Solar System Exploration Research Virtual Institute (SSERVI) represents a close collaboration between science, technology and exploration, and was created to enable a deeper understanding of the Moon and other airless bodies. SSERVI is supported jointly by NASA’ s Science Mission Directorate and Human Exploration and Operations Mission Directorate. The institute currently focuses on the scientific aspects of exploration as they pertain to the Moon, Near Earth Asteroids (NEAs) and the moons of Mars, but the institute goals may expand, depending on NASA's needs, in the future. The nine initial teams, selected in late 2013 and funded from 2014-2019, have expertise across the broad spectrum of lunar, NEA, and Martian moon sciences. Their research includes various aspects of the surface, interior, exosphere, near-space environments, and dynamics of these bodies.

NASA anticipates additional team selections in early 2017 with a further Cooperative Agreement Notice (CAN) likely to be released in 2017. Calls for proposals are issued every 2-3 years to allow overlap between generations of institute teams, but the intent for each team is to provide a stable base of funding for a five-year period. SSERVI's mission includes acting as a bridge between several groups, joining together researchers from: 1) scientific and exploration communities, 2) multiple disciplines across a wide range of planetary sciences, and 3) domestic and international communities and partnerships.

The SSERVI central office is located at NASA Ames Research Center in Mountain View, CA. The administrative staff at the central office forms the organizational hub for the domestic and international teams and enables the virtual collaborative environment. Interactions with geographically dispersed teams across the U.S., and global partners, occur easily and frequently in a collaborative virtual environment. This talk will consist of an overview of SSERVI’ s mission and the current US teams.

Keywords: Solar System, Virtual Institute, Lunar, NEA, Martian Moons

NASA’ S SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE: BUILDING COLLABORATION THROUGH INTERNATIONAL PARTNERSHIPS

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1. NASA Solar System Exploration Research Virtual Institute

Abstract

The NASA Solar System Exploration Research Virtual Institute (SSERVI) is a virtual institute focused on research at the intersection of science and exploration, training the next generation of lunar scientists, and community development. As part of the SSERVI mission, we act as a hub for opportunities that engage the larger scientific and exploration communities in order to form new interdisciplinary, research-focused collaborations.

This talk will describe the international partner research efforts and how we are engaging the international science and exploration communities through workshops, conferences, online seminars and classes, student exchange programs and internships.

Introduction

NASA’ s Solar System Exploration Research Virtual Institute (SSERVI) represents a close collaboration between science, technology and exploration that will enable deeper understanding of the Moon and other airless bodies as we move further out of low-Earth orbit. The Institute is centered on the scientific aspects of exploration as they pertain to the Moon, Near Earth Asteroids (NEAs) and the moons of Mars. The Institute focuses on interdisciplinary, exploration-related science centered around all airless bodies targeted as potential human destinations. Areas of study reported here will represent the broad spectrum of lunar, NEA, and Martian moon sciences encompassing investigations of the surface, interior, exosphere, and near-space environments as well as science uniquely enabled from these bodies.

We will provide a detailed look at research being conducted by our ten international partners. In addition, we will discuss the process for developing internatioal parterships with NASA.

Summary and Conclusions

As the Institute’ s teams continue their proposed research, new opportunities for both domestic and international partnerships are being generated that are producing exciting new results and generating new ideas for scientific and exploration endeavors. SSERVI enhances the widening knowledgebase of planetary research by acting as a bridge between several different groups and bringing together researchers from: 1) scientific and exploration communities, 2) multiple disciplines across the full range of planetary sciences, and 3) domestic and international communities and partnerships.

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Keywords: NASA International Partnerships, SSERVI, Virtual Institute