Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)


PPS23-01 Room:A02 Time:May 25 14:15-14:30

# High permittivity regions in Oceanus Procelluram and Mare Imbrium found by SELENE (Kaguya)

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**Introduction:** The effective permittivity of the lunar surface material is important for discussion of their composition and porosity. Based on the Maxwell-Garnett mixing model, the bulk density of the lunar surface materials can be derived from their effective permittivity by using the following equation [Fa and Wieczorek, 2012]: $\rho$ [g/m$^3$] = 4.61 ($\varepsilon_r$ - 1) / ($\varepsilon_r$ + 2). Bulk density of the lunar surface material depends on the abundances of voids and heavy components such as ilmenite. The dataset obtained by Lunar Radar Sounder (LRS) onboard SELENE (Kaguya) [Ono et al., 2010] enables us to perform global high-resolution mapping of the lunar surface permittivity because the observation was performed from the polar orbiter at an altitude of about 100 km, and in a frequency range around 5 MHz where thermal emissions is negligible. We should note that the echo powers from the lunar surface depends not only on the permittivity but also on the roughness of the lunar surface. As for the roughness, we can use SELENE Digital Terrain Model (DTM) based on Terrain Camera (TC) observation [Haruyama et al., 2008]. We can therefore calculate expected echo powers by applying Kirchhoff Approximation (KA), and compare them with observed echo powers in order to determine the effective permittivity.

**Analyses Method:** The global distributions of the intensity of the off-nadir surface echo in a frequency range of 4 - 6 MHz in an incident angle range from 10 to 20 degrees were derived from the SELENE/LRS dataset. The median of off-nadir echo intensities were derived in 360 x 180 areas of 1 degree (longitude)x 1 degree (latitude). In addition, we have derived the global distribution of the surface roughness parameters. The RMS height $\nu$ can be derived from the SELENE TC/DTM. If we assume the self-affine surface model, the roughness parameters H and s can be obtained by the least square fitting: $\nu$ = s $\Delta$x$^H$ in a baseline length $\Delta$x range from 30 m to 3 km. The off-nadir surface echo power was then calculated by using the radar equation. Assuming KA, the backscattering coefficient in the radar equation can be obtained from the roughness parameters H, s [Bruzzone et al., 2011]. In calculation of the expected echo powers, we have to assume some effective permittivity also. We compared the observed and calculated echo powers with changing effective permittivity assumption, and determined the most plausible effective permittivity.

**Results:** By applying the analysis method mentioned above, we could obtain the observed and calculated off-nadir surface echo powers. Based on them, we could estimate the effective permittivity of the lunar surface materials. The estimated effective permittivity is 2 - 3 in the highland, 3 - 4 in the maria. In addition, it was found that there areas whose effective permittivity reaching ˜5 in the eastern part of Oceanus Procellarum and the western part of Mare Imbrium.

**Discussion:** By using the estimated effective permittivity of the lunar surface, we can derive the bulk density of the lunar surface materials. The derived bulk density is 1.2 - 1.8 g/cm$^3$ in the highlands, 1.8 - 2.3 g/cm$^3$ in the maria, and approximately 2.6 g/cm$^3$ in the high-permittivity areas in Oceanus Procellarum and Mare Imbrium. The differences of estimated bulk density among the previous studies [Wiezorek et al., 2013; Carrier et al., 1991] and this study could be explained by the depth dependence of the bulk density of the lunar surface soils and rocks. The areas of high permittivity in the eastern part of Oceanus Procellarum and western part of Mare Imbrium coincide with young lava flow units in PKT region. We can consider two possible reasons: (i) The regolith layer is thinner than other mare regions due to short exposure to the meteorite impacts. (ii) The bulk density is higher than other mare regions due to high abundance of the ilmenite.

Keywords: SELENE(Kaguya), Lunar Radar Sounder (LRS), permittivity, Oceanus Procelluram, Mare Imbrium, Digital terrain model (DTM)

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PPS23-02 Room:A02 Time:May 25 14:30-14:45

# Relationship between topography and latest mare volcanism at 2.0 Ga of the moon

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Lunar mare basalts, the most common volcanic feature on the Moon, provide insights into compositions and thermal history of lunar mantle. According to the radiometric ages of the lunar basalt samples and the model ages of mare basalt units determined by crater counting with remote sensing data, the great extent of mare basalts was formed at 3.2 to 3.8 Ga. Temporal variation of the mare basalt eruptions also indicates that 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 is characterized by high abundances of heat-producing elements. In order to understand the magma source of the latest volcanism and mechanism for causing the second peak, we examined the correlation between the titanium contents and eruption ages of mare basalt units using compositional and chronological data updated by SELENE/Kaguya. Although the systematic relationship is not observed globally, 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 eruptions can be correlated with the second peak of volcanic activity at ~2 Ga. The latest volcanic activity can be induced by a high-Ti super hot plume originated from the core-mantle boundary. If the super hot plume was occurred, the topographic features formed by the super hot plume may be remained. Then, 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. Moreover, mare ridges in this region seem to connect with the plateau. Using detailed models of the flexural response of the lunar elastic lithosphere, we estimated the elastic thickness at the time of occurrence of the super hot plume. From our results, the effective elastic thickness at the period of latest volcanism is estimated 20 – 30 km, which is thinner than that of the period before ~2 Ga. These results suggest that the up lift of lithosphere caused by the super hot plume.

Keywords: titanium content, super hot plume, selenoid, effective rlastic thickness, lunar mantle, the Procellarum KREEP Terrane

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PPS23-03 Room:A02 Time:May 25 14:45-15:00

# Impact history in the last 3 billion years based on the lunar rayed craters

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The Moon preserves the impact history in the last 4.0 Ga as the cratering record, which provide important information to understand collisional and orbital evolutions of small bodies in the solar system. Standard lunar cratering chronologies have been based on combining radiometric ages of Apollo and Luna samples and crater densities of landing sites. However, the impact history cannot be resolved in the past 3.0 Ga because of the absence of samples with radiometric age ranging from 3.0 to 1.0 b.y. On the other hand, from crater density of lunar rayed craters and statistics of terrestrial craters it has been suggested hypotheses that the cratering rate has increased or decreased in recent.

In this study, we determined relative ages of rayed craters using SELENE/TC image data to place constraints on the cratering rate in the last $\sim$1 Ga. Formation age of the surface of the planet can be estimated by crater counting, based on the idea that old area have more craters than young area. We performed crater counting on the ejecta blanket of 67 rayed craters larger than 20 km in diameter. The results indicate that 27 rayed craters are younger than the crater Copernicus, whose the formation age is estimated as 0.81 Ga from the Apollo 12 samples.

Based on the crater density of rayed craters younger than Copernicus, the average cratering rate for craters larger than 10 km in diameter in the past 0.81 Ga is estimated to be $5.56\times10\text{-}4\ km^{-2}y^{-1}$, which is 0.66 times lower than that in the past 3.2 Ga. The main source of impactors in the Earth-Moon system is the main asteroid belt located between the orbits of the Mars and Jupiter. The decreasing cratering rate revealed in this study indicates that the total number of asteroids in the main belt has been decreasing for last 3.0 Ga.

Keywords: Moon, crater, cratering chronology

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PPS23-04 Room:A02 Time:May 25 15:00-15:15

# Lunar surface areas with featureless reflectance spectra revealed by 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 (0.5 by 0.5 km footprint) on the Moon in the visible and near-infrared wavelength ranges. Using a data ming approach with all the SP data (SP data mining), we have revealed the global distributions of several-kilometer-wide sites with exposed end members of various minerals on the lunar surface: olivine-rich sites, purest anorthosite (PAN) sites, orthopyroxene-rich sites, clinopyroxene-rich sites, and spinel-rich sites. These results are based on the analysis for the diagnostic absorption bands of $\lambda$ = 1$\mu$m and 2$\mu$m in the continuous reflectance data for the lunar major minerals. On the other hand, it has also been reported that there are several sites on the Moon exhibiting no absorption band for 1$\mu$m and 2$\mu$m (hereafter, featureless spectra or FL-spectra). However, it still remains unclear what is the origin for the FL spectra on the Moon. For the interpretations of the origin of the FL spectra, we need to understand the global occurrence trends of FL sites on the Moon. In this study, we conducted the global survey to reveal the global distribution of the FL sites using the SP data ming. From the global distribution data, we will discuss the possible mechanisms and its implications for the lunar primordial crust.

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

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# Mineralogy of the lunar highland crust based on the Kaguya reflectance spectra

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Introduction: The composition of the lunar highland crust is among the most important information for understanding the formation mechanism of the lunar highland crust and the composition of the lunar magma ocean. Previously, the composition of the lunar highland crust was estimated mainly based on measurements of the lunar returned samples. Measurements of returned lunar samples and meteorites indicate that the lunar highland crust typically consists of plagioclase and low-Ca pyroxene with minor amounts of other mineral phases. However, it is not clear if the low-Ca pyroxene really is a major mafic silicate component of the highland crust because the returned samples may not be a representative material of the entire highland crust. Therefore, this study investigated the mafic silicate phase and estimated its composition within the highland crust by using remote sensing reflectance spectra of the lunar surface.

Method: We used reflectance spectra acquired by the Kaguya Spectral Profiler (SP), which has a spectral coverage of 500 to 2600 nm in 300 bands and a spatial resolution of 500 x 500 m. Among the global SP data, all of the 570 purest anorthosite (PAN) [1] spectra identified and reported by [2] were analyzed by using the modified Gaussian model (MGM) [3]. Several MGM parameters, a number of fitted peak and peak parameters (center wavelength, width, and strength) of each peak at the starting point were tried, and the results were cross evaluated. The compositions of silicate mafic minerals were estimated by comparing the peak fit results and the known correlation between absorption center wavelength and mineral composition.

Results: Most (93%) of peak, which corresponds to the mafic silicate phase, has a center wavelength shorter than 980 nm, suggesting that these mafic silicates in the PAN rocks are low-Ca pyroxene (65% are shorter than 950 nm). Note that the low-Ca pyrox-ene in this study implies pyroxene having less than a 0.2 molar ratio of Ca/(Ca+Mg+Fe) smaller than 0.2. Data points having a center wavelength shorter than 980 nm had a strong absorption band and were not a product of weak ambiguous absorption spectra. Six percent of the data have center wavelengths between 980 nm and 1040 nm, which correspond to the high-Ca pyroxene composition. The remaining 1% of the data with longer center wavelengths around 1050 nm possibly corresponds to olivine or glass. No apparent phase difference (low-Ca and high-Ca pyroxene difference) is observed between the nearside and the farside.

Discussion: Our results indicate that the majority of the PAN layer in the lunar highland crust globally consists of anorthite and small amounts of low-Ca pyroxene, the major mafic silicate component, rather than high-Ca pyroxene or olivine. This result is consistent with the previous work based on measurements of the lunar material from the lunar surface mixing layer with limited global coverage and confirms the homogeneous modal abundance within the lunar highland crust. The short center wavelengths of the PAN rocks at Jackson crater, which located at the farside highland suggest relatively higher Mg# (Mg/(Mg + Fe) in mole per cent) (around 70) in this region than the near side. This evidence is in good agreement with previous work [4], which suggests the presence of magnesian anorthosite in the farside highland.

References: [1] Ohtake, M. et al. (2009) Nature, 461, 236-240. [2] Yamamoto, S. et al. (2012) Geophys. Res. Let., 39, L13201. [3] Sunshine, J. et al. (1990) J. Geophys. Res. 95, 6955-6966. [4] Ohtake, M. et al. (2012) Nature GeoSci. 5, 384-388.

Keywords: Kaguya, Moon, crust, reflectance spectra

PPS23-06 Room:A02 Time:May 25 15:30-15:45

# Unsupervised Classification of the Moon's Surface Reflectance Spectra and Geological Significance (1)

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Great successes of recent lunar missions provide vast amount of varieties of remote sensing data. Analysis of those new data provide some new key evidences, such as pure-plagioclase rocks (e.g., Ohtake et al., 2009) and olivine rich rocks (e.g., Yamamoto et al., 2010), for studying solidification process of the Lunar Magma Ocean (LMO) and following lunar evolutions. Those key evidences require us to reconsider the LMO solidification process. One approach to study this problem is requiring following step, reconstruction of compositions and structures for primitive crust by removing influences of volcanisms, impact cratering, and other geological effects. For reconstructing primitive crust, we have to generate a global geological map covers recent findings, so we started a project to build a new lunar geological map to reconstruct structures and composition of the lunar primitive crust. Because of huge volume of recent data set, fully manual classify by expert researchers is not realistic, and then, we have been trying to use some data mining methods for basic unit candidate estimation.

In this study, we show some classification results of SELENE Multiband Imager (MI) data and Spectral Profiler (SP) data applied data mining methods, and compare them with a fully manual classification result for a limited area. Our classification procedure consists of two steps; Independent Component Analysis (ICA) and Iterative Self-Organizing Data Analysis (ISO-DATA). Detail strategy of our procedure is presented by Hareyama et al. in this meeting.

Our procedure generally works well. The classification results in mare region indicate that could detect some types of mare basalt flows. Especially high-Ti basalt in Oceanus Procellarum and the Mare Tranquillitatis are clearly identified. Ejecta deposits of fresh ray craters are also clearly identified. In addition, we compare classification results our procedure around the Aristarchus region with that of fully manual classification result by a researcher (M.O.). These two agrees each other generally. Then, we consider our procedure capture the lunar geological context and useful for the first step of building lunar geological map.

Keywords: Moon, Geological Map, Unsupervised Classification

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PPS23-07 Room:A02 Time:May 25 15:45-16:00

# Study of carbon-bearing materials formed by impact process on the Moon

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Introduction:

In the solar system (terrestrial planets), it is required to study overall processes of volatile carbon between planets (with and without global air and water) and the Moon without global air. Recently author has studied such complicated and unsolved problems [1-4]. In the present paper, the collision formation of carbon-containing materials is mainly to discuss it on celestial bodies without global air (the moon, asteroids and Mercury) that do not have the atmosphere, especially on the moon [3].

Volatiles in the Moon :

The Moon has original reservoirs of carbon-bearing volatiles from successive growth of fine dust particles to become celestial body size. However, the Moon is close to planet Mars size, but the volatiles- reservoirs are difficult to keep during characteristic abrupt collision process to be escaped away[1-3].

Problem of carbon dioxides atmosphere :

Water vapor changes liquid phase by quenching process. However, carbon dioxides-rich atmosphere keeps in a gaseous state by relative cooling, so that it should be taken into something to hot air estimated from the experimental results. In this sense, Mars and Venus with carbon dioxides-rich atmosphere are difficult to form global water system if a global water should be present before global gas-rich system[3]. The Moon is therefore celestial body to discuss the interior carbon-bearing volatiles [3].

Formation of carbon-containing materials of the Moon:

Because the Moon has no atmosphere globally, two-stages growth of separated carbon-rich macro-grains with high-pressure form cannot be expected because of no collision with global air on the airless Moon [3]. It is only possible to growth macro-scopically in the shallow interiors (from dust-growth or fragments of air planet separated) by successive meteoritic collisions on the surface[4]. Carbon-bearing materials on the Moon are localized and minor contents of carbon-bearing materials in the glass, carbon, carbide and carbonates related with shock-wave processes[1-3].

Problem of global water on the Moon:

It might discuss possible formation of global air and water on the Moon and celestial bodies from experimental results. From laboratory experiments, carbon-bearing air which might be possible to generate a global water on air- planets of Mars and Venus is generally difficult, but it is not impossible by the proposed two methods ideally. On the other hand, formation of global water on air-less Moon (also Mercury and asteroids) is relatively very difficult, but it might be not impossible if the Moon becomes global air-bearing celestial body prepared by any proposed process[3].

Summary:

1) Formation of the atmosphere and seawater to any celestial body such as the Moon, can be discussed from experimental results of carbon-containing materials formed.

2) Carbon dioxides atmosphere can be reduced or cooled from state-condition of hot gas by any proposed experiments.

3) Lunar carbon-bearing grains of glass, carbon, carbide and carbonate can be grown microscopically and locally in the interior by successive process of impacts.

Reference:[1] Miura Y. (2011): LPSC 42(2011), #2817.
[2] Miura Y. et. al. (1996) Antarctic Meteorites XX1(Tokyo), 107-110.
[3] Miura Y. (2015): LPSC2016 (LPI), #1811, #1666.
[4] Miura Y. (2009): Patent application.

Keywords: The Moon, Carbon-bearing materials, Impacts, Volatiles, Experiment, Global air and water

PPS23-08 Room:A02 Time:May 25 16:15-16:30

# Solar wind-regolith interaction in space: Observations at Moon and Phobos

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In this presentation, we discuss whether the backscattering of plasma particles is a common physical process of plasma-surface interaction in space. The backscattered protons were first discovered by a plasma package, MAP/PACE, on board the Japanese lunar orbiter, Kaguya. Later, the backscattered protons and neutral hydrogen atoms have been frequently reported near the Moon, for example, by the SARA sensor on Chandrayaan-1. We first review the characteristics of the backscattered protons observed in the lunar environment.

Then, we report the survey of the dataset from the ion sensor (IMA) on board Mars Express recorded during its close encounters to Phobos. During one of the closest encounters (~60 km) we could clearly identify proton signal apart from the solar wind. Careful assessment has lead us to conclude that the signal is the Phobos origin. The characteristics of the Phobos protons are quite similar to those of the reflected lunar protons. The observation provides the first evidence proving that the backscattering is a common process for regolith-plasma interaction in space.

Keywords: solar wind, proton reflection, regolith, Moon, Phobos, backscattering

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PPS23-09 Room:A02 Time:May 25 16:30-16:45

# Exploration of the lunar internal structure using a small-sized penetrator and its perspective

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Information about the lunar interior has been obtained by the seismic exploration through the Apollo mission, the gravimetric explorations of the Kaguya and GRAIL missions, and other geodetic observations such as the Lunar Laser Ranging (LLR). However, we have not sufficiently constrained the lunar deep mantle and the core from available geophysical data, and the material and temperature in the lunar deep region are still uncertain. In addition, we have some uncertainties even about lunar crustal thickness and structure. Clear detections of lunar seismic phases which pass through the lunar deep and crustal regions will be required to reveal the structures. The penetrator, a hard-landing probe with a high sensitive seismometer developed in the former LUNAR-A project, is a powerful tool to carry out new lunar seismic observation.

To demonstrate utility of the penetrator system for scientific observations, we proposed a mission plan, named APPROACH, in which one penetrator is loaded onto a small satellite launched by the 3rd Epsilon Launch Vehicle. In this proposal, we had some plans to perform scientific observations; those are determination of the lunar crustal thickness using travel time data from meteoroid impact events located by the ground observation of the impact flashes, current lunar seismic activities compared with that during the Apollo-era and the first heat flow measurement on the lunar highland. However, the proposal could not be accepted because the success rate of the observation with only one penetrator was insufficient for acceptance.

In this situation, we currently make a modification to the mission plan so as to load two small-sized penetrators onto the small satellite. We aim to reduce the size of the penetrator to two-thirds size keeping the already established high shock durability. In this presentation, we firstly report some plans to reduce size of the penetrator and the effect of the downsizing on scientific observations. Then, we describe scientific expectation from the seismic and heat-flow observation using the small-sized penetrator. Finally, we will discuss future plans to study the lunar origin and evolution by the lunar seismic observations using the penetrator system after the achievement of first observation by the system.

Keywords: Penetrator, Lunar intarnal exploration, Moonquake observation, Heat flow observation, Small-sized exploration satelite

PPS23-10 Room:A02 Time:May 25 16:45-17:00

# Present status of the active X-ray spectrometer development for future lunar landing mission

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The Active X-ray Spectrometer (AXS) consisting of an active X-ray generator and a silicon drift detector (SDD) has been developed for future lunar landing missions. The AXS can determine the elemental composition of rock samples by X-Ray Fluorescence spectroscopy which provides the geochemical data of rock samples. The AXS has each outstanding features as excellent energy resolution, compact and light weight, low power consumption, and no high voltage power supply and no radioisotopes. The X-ray generator is made of some pyroelectric crystals, peltier device and thin metal target. The instrument of the AXS and the present status of its development are presented and discussed.

Keywords: X-ray fluorescence spectroscopy, active X-ray spectrometer, lunar landing mission, elemental analysis

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# Study on X-ray Fluorescence for Future Lunar Landing Mission - Surface Roughness and Ratios of Characteristic X-ray -

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Landing and roving observation for planetary bodies provides more detailed local information of geochemistry, mineralogy and petrology with remote sensing observation[1]. An X-Ray Fluorescence spectroscopy (XRF) is a powerful method on/around the landing point in-situ measurement of chemical abundance. Lunar surface is so heavily weathered by meteorites, micrometeorites, the solar wind, and the cosmic rays that surface grindings of lunar samples should be performed by a rock abrasion tool to remove the weathered surface before the XRF measurements. The relations between surface roughness of sample and ratios of observed characteristic X-ray intensity are studied on the basis of both experiments and simulations[2, 3]. In this presentation, the results of experiments and simulations of grinding level needed for the XRF measurements on planetary surface are compared and discussed.

[1] T. Hashimoto et al., 2011, Acta Astronautica 68, 1386-1391. [2] H. Kusano et al., 2013, Proc. SPIE 8852, 88520B. [3] M. Naito et al., Nucl. Instrum. Methods Phys. A, to be published.

Keywords: Lunar sample, X-ray fluorescence, Active X-ray Spectrometer, Surface roughness

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PPS23-12 Room:A02 Time:May 25 17:15-17:30

# Visual Tracking using SIFT to Solve Time-Delay Problem in Remote Operation

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This paper proposes and describes a method to solve a time-delay problem when a direction of a camera in the wide angle fovea vision system (WAFVS) equipped on a lunar exploring rover is contorlled remotely from the ground control station on the earch. That is, we need to control the camera view direction acculately in order to obtain visible ray band images of a target in detail using WAFVS, but the time-delay often causes WAFVS to fail to capture the target in the central field of view of the input image when the rover is moving around. The authors acheive correct camera view direction control by applying SIFT operator to track a target candidate from past images to future images storaged temporarily in the computer on the rover. Experimental results show this implementation is successfully done and indicate how to apply WAFVS for this task.

Keywords: Exploring Rover, Remote Operation, Visual Tracking, SIFT, Wide Angle Fovea Sensor, Time Delay

PPS23-13 Room:A02 Time:May 26 09:00-09:15

# Toward a 3D spherical modeling of lunar mantle convection

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Earlier two-dimensional models of coupled magmatism-mantle convection system raise two issues concerning the evolution of the lunar mantle. One is to understand why lunar magmatism continuously occurs with a characteristic time of several hundred million years. When the Rayleigh number of the lunar mantle Ra exceeds the critical value for the onset of thermal convection Rc, earlier two-dimensional models suggest that a positive feedback, called the magmatism-mantle upwelling (MMU) feedback, operates to make magmatism episodic and vigorous; magmatism occurs continuously and mildly as observed on the Moon only when Ra <Rc. Another issue is to understand why mare magmatism continued until as recent as about a billion years ago. Magmatism extracts heat producing elements (HPEs) and earlier two-dimensional models predicts that lunar magmatism should have waned much earlier because of this HPEs extraction. A possible solution to this issue is that the lunar mantle contains a reservoir that is enriched in HPEs and compositionally dense at depth. The nature of thermal convection in a basally heated mantle with a small core, however, has not been investigated enough to resolve these issues. To estimate Rc and to understand the nature of thermal convection in the lunar mantle, we are carrying out a linear perturbation analyses and numerical simulation of thermal convection in a spherical shell with a small core.

Keywords: the Moon, mantle evolution, 3D spherical shell, mantle convection, numerical simulation

PPS23-14 Room:A02 Time:May 26 09:15-09:30

# Flow patterns in spherical mantles with small size of core; the effect of temperature dependent viscosity

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Clarifying the effects of three-dimensional spherical geometry on mantle convection is a major issue of mantle dynamics in terrestrial planets. We study in detail the nature of thermal convection of a variable viscosity fluid in the basally heated spherical mantle of small planets with a small core, keeping in mind the application of our numerical models to the Moon. Spherical geometry affects mantle convection mildly when the ratio of the core-radius to the planetary radius $r_{CMB}$ takes an Earth-like value of 0.55, while it is thought to affect strongly when $r_{CMB}$ is small like Moon around 0.2. Here, we investigate the flow pattern systematically for $r_{CMB}$ from 0.1 to 0.6 with small to large viscosity dependence on temperature. We first estimate the critical Rayleigh number $Rc$ for the onset of convective motion at various $r_{CMB}$ and the magnitude of temperature-dependence of viscosity by a linear perturbation analysis. Then, we study the convective flow pattern of thermal convection above $Rc$ by numerical simulation. The result of our simulation is in good agreement with the linear analysis. The nature of convective flow pattern considerably changes as $r_{CMB}$ smaller than about 0.4. The flow pattern has smaller number of up- and down-wellings. We established regime diagrams of convection pattern in relation to the Rayleigh number and the temperature dependence of viscosity, for various value of $r_{CMB}$. Stronger temperature dependence of viscosity is necessary for realizing the stagnant-lid regime of convection for smaller $r_{CMB}$. It is due to the relatively smaller volume of high temperature region near the CMB. The horizontally averaged temperature at mid mantle remains low despite the strong temperature variation of viscosity when $r_{CMB}$ is small.

Keywords: Moon, 3D spherical shell, mantle convection, size of the core, flow pattern

Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)


PPS23-15 Room:A02 Time:May 26 09:30-09:45

# Formation of anorthosite on the Moon through magma ocean fractional crystallization

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Geological records of the moon have a potential to reveal early evolution of the earth. 4.4Ga anorthosite on the Moon formed as by fractional crystallization of the lunar magma ocean (LMO). It has been generally accepted that the lunar bulk composition is enriched in FeO compared with the bulk silicate earth, which is critical to make large plagioclase/melt density difference enough to form the anorthosite. However, the bulk moon composition likely has the same composition of the earth, which is supported by isotopic similarities for the two bodies and recent giant impact modeling. In this study, critical condition of fractional crystallization of plagioclase is assessed for the BSE composition by taking into account crystal/melt density difference, viscosity of melt, crystal size, and Rayleigh number of the magma ocean. This study modeled solidification process of the LMO and calculated change of melt composition by use of MELTS/pMELTS. Density and viscosity of melt were calculated by use of first-principles simulations.

Results of thermodynamic calculations indicate that melt is basaltic (Mg# = 0.59) when plagioclase starts to crystalize. Viscosity of the basaltic melt ranges 20 - 10 Pa s whereas density ranges 2.60 - 2.71 g/cc for 0 - 1 GPa where plagioclase crystallizes. Comparison between critical crystal diameter calculated from the viscosity and density and crystal diameter of plagioclase (5 - 18mm) of anorthosite suggests that crystal fraction of magma, $\varphi = 0.55$ is required to make convection of magma ocean moderate enough that plagioclase could separate from the melt. Results of critical crystal diameter for olivine/pyroxene indicate that the crystallized mafic minerals would also be entrained in the viscous basaltic melt until $\varphi = 0.55$ is attained. In that case, large amount of mafic minerals are entrained in the magma along with plagioclase, which is enough to account for the $\varphi = 0.55$ in the magma. For the melt composition when crystal fraction $\varphi = 0.55$ is attained, the basaltic melt is enriched in FeO enough that plagioclase could float to the surface of the moon. Application of the discussion to the terrestrial magma ocean has insight into the surface evolution of the Hadean Earth, which would be related to the evolution of life.

Keywords: Moon, Anorthosite, Magma ocean, Density and viscosity of melt, Hadean Earth

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PPS23-16 Room:A02 Time:May 26 09:45-10:00

# High pressure phase relationships of the Fe-Ni-C system and its implications to the lunar core structure

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We investigate the phase relationships of the Fe-Ni-C systems at 5 GPa equivalent to the lunar core condition using multi anvil high pressure apparatus. We determined the precise melting relationships of the Fe-Ni-C system at 5 GPa. We also elucidate the stability field of $(Fe,Ni)_3C$ and $(Fe,Ni)_7C_3$ carbide phase. In the meeting we will discuss the composition and the structure of the lunar core using the present data based on the seismic model of Weber et al. (2011).

Keywords: high pressure, lunar core, Fe-Ni-C system, phase relationships

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PPS23-17 Room:A02 Time:May 26 10:00-10:15

# Particle simulations on plasma and dust environment near lunar vertical holes

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Japanese lunar explorer "Kaguya" has discovered vertical holes on the Moon surface. The diameter and depth of the holes are both in a range of 50 through 100 m, which produces a higher depth-to-diameter ratio than typical impact craters. The holes are thus expected to create characteristic plasma and dust environment around it. It is of practical importance to assess such a distinctive environment, reminding that a future landing mission plans to explore the lunar holes and caverns associating to the holes.

In the present study, we apply our original particle-in-cell simulator EMSES, which have been used to study spacecraft-plasma interactions, to assessment of day-side plasma environment around lunar vertical holes. We have a three-dimensional computational domain including a simplified lunar hole structure and introduce a solar wind plasma inflow to the lunar surface. We also simulate the photoelectron emission from the lunar surface by taking into account the presence or absence of sunlight illumination, and its incident angle. We will show simulation results on the properties of lunar surface charging near the hole and its dependence on changing solar wind plasma conditions. We also report the progress of further investigations into dust grain environment around the hole, based on the electrostatic environment self-consistently computed by our simulator.

Keywords: Moon, vertical hole, space plasma, lunar surface charging, dust grain, PIC simulation

PPS23-18 Room:A02 Time:May 26 10:15-10:30

# Full Particle-In-Cell 3D simulation on the solar wind response to a lunar magnetic anomaly

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The objectives of the current research is to reveal the plasma environment disturbed by the magnetic anomaly found on the moon surface by considering the plasma kinetics. In this study, by performing three-dimensional full Particle-In-Cell simulations, we will discuss the plasma response to Reiner Gamma which is one of the typical and famous magnetic anomalies on the moon. The size of a magnetic anomaly is characterized by distance L from its center at which the equilibrium is satisfied between the pressure of the magnetic field of the dipole and that of the solar wind. In the Earth's magnetosphere, L implies the magnetopause location. We particularly focused on meso-scale magnetic dipoles in which L is smaller than the gyroradius of ions in the solar wind but larger than the electron Larmor radius. Contrary to the Earth's magnetosphere, difference of dynamics between ions and electrons with respect to the local magnetic field play an important role in the magnetosphere formation. In other words, electron-ion coupling through a dipole field becomes important. The simulation results show that a meso-scale magnetosphere is clearly created even if the ion gyroradius is larger than L. We found that electron dynamics are important in the process of meso-scale magnetosphere formation. Around the distance of L from the dipole center, charge separation occurs because of the difference of dynamics between electrons and ions. Then intense electrostatic field is locally induced and ions, which are assumed unmagnetized in the meso-scale magnetic dipole, are eventually influenced by this electric field. We also examined the plasma dynamics at dayside magnetosphere. Ions which encounter the magnetic anomaly start to gyrate around the local magnetic field. However, electrons which are basically magnetized make drift motion with ExB velocity. This difference of the plasma dynamics causes intense boundary current in the dayside region. In the case of Reiner Gamma, the magnetic field is almost perpendicular to the solar wind. In such a situation, increase of plasma and magnetic field densities is found in the dayside region in the simulation results. We are also interested in the plasma response when the direction of IMF changes because the magnetic field reconnection occurring in the dayside region will affect the formation of the meso-scale magnetosphere. One of the interesting findings is that the solar wind ions do not reach the moon surface in Reiner Gamma. We will discuss this point by considering the plasma dynamics as well as the electrostatic field observed over the Reiner Gamma region.

Keywords: Magnetic anomaly, Reiner Gamma, Meso-scale magnetic dipole, Solar wind response, Plasma particle simulation

PPS23-19 Room:A02 Time:May 26 10:30-10:45

# Ion cyclotron waves observed by Kaguya/LMAG around the moon in the Earth's magnetosphere

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Narrowband ion cyclotron waves as found by Apollo 15 and 14 Lunar Surface Magnetometers were detected in the magnetic field data obtained by MAP/LMAG magnetometer on board Kaguya at an altitude of 100 km above the moon in the tail lobe of the Earth's magnetosphere. The frequency of the waves was near the local proton cyclotron frequency. They had a significant compressional component. They were detected on the dayside, on the nightside, or above the terminator of the moon. Analysis of the waves detected by Kaguya would contribute the understanding of the moon-plasma interaction.

Keywords: ion cyclotron wave, Kaguya, LMAG, moon, cyclotron frequency, lobe

PPS23-20 Room:A02 Time:May 26 11:00-11:15

# Observation of the solar wind protons and alpha particles over lunar magnetic anomalies

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Lunar surface is directly affected by solar wind because the Moon has neither thick atmosphere nor global magnetic field. However, there exist locally magnetized regions called lunar magnetic anomalies on the lunar surface. Strong lunar magnetic anomalies can prevent solar wind from impacting the lunar surface. Research on the interaction between solar wind and lunar magnetic anomalies has been carried out by in-situ observations, numerical simulations and laboratory experiments, since the discovery of the lunar magnetic anomalies in 1960s. Since lunar magnetic anomalies greatly affect the incident solar wind plasma and plasma around the Moon, investigation on the interaction between solar wind and lunar magnetic anomalies is quite important.

The solar wind consists of protons as a major component and several percent of alpha particles as a second major component.

The flux of the magnetically reflected solar wind ions is about several tens percent of the incident solar wind ion flux. So far, nobody has ever investigated the reflected solar wind ions over lunar magnetic anomalies in terms of the ion species. Since more than 90% of the solar wind ions are protons, the current knowledge of the interaction between solar wind ions and lunar magnetic anomalies is highly dependent on the behavior of protons. Note that the incident solar wind alpha particles can be detected clearly, but the reflected alpha particles are not easily observed. Thus analysis of both proton and alpha particles will led us to more detailed understanding of the plasma structure over lunar magnetic anomalies.

In this study, we have analyzed mass identified low energy ion data observed by a low energy ion mass spectrometer MAP-PACE-IMA on Kaguya. We have newly found that reflected protons and reflected alpha particles show significantly different behaviors over lunar magnetic anomalies. In most cases, the bulk velocity of the reflected ions is slightly reduced from the incident solar wind bulk velocity, and the temperature of the reflected ions is higher than the incident solar wind ions. We have found that the bulk velocity of the reflected alpha particles is much lower than the bulk velocity of the reflected protons. We have also found that the ratio of the reflected alpha particle flux to the incident solar wind alpha particle flux is much less than the ratio of the reflected proton flux to the incident solar wind proton flux. There seems to be multiple reasons why the existence of the reflected alpha particles were not clear; 1) there exists large difference in E/q (E: kinetic energy, q: charge) between incident solar wind alpha particles and the reflected alpha particles and 2) the reflected alpha particle flux is quite low. It clearly shows that the reflection of the solar wind ions is not an ideal magnetic mirror reflection but the reflection includes non-adiabatic processes.

Keywords: Moon, plasma, solar wind, magnetic anomaly

PPS23-21 Room:A02 Time:May 26 11:15-11:30

# Early global expansion of the Moon: constraints from topographic characteristics on linear gravity anomalies

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According to numerical models of the lunar thermal evolution, the lunar radius temporary increased at the lunar early stage because of a thermal expansion resulted from mantle remelting after the magma ocean solidification. However, no clear evidence of lunar early global expansion was observed because many impacts have transformed the lunar surface. Recently, the Gravity Recovery and Interior Laboratory (GRAIL), which was launched in 2011 by NASA, measured the lunar gravity field with high accuracy. Andrew-Hanna et al. [2013] identified large linear gravity anomalies (LGAs) from the analysis of the GRAIL gravity data, and suggested that the LGAs resulted from ancient intrusions or dykes formed by magmatism with the global expansion. To test the hypothesis, we investigated topographical profiles across the LGAs. In addition, we determined formation ages of LGAs to constrain the timing of the global expansion.

We used 1/1024-degree gridded lunar topographic data from LOLA Data Archive [http://imbrium.mit.edu/LOLA.html LOLA_GDR(LRO-L-LOLA-4-GDR-V1.0)]. The topographic profiles across the LGAs were calculated in a range of 300 km from the LGAs. We found graben-like topography along the LGAs, suggesting that the LGAs were formed in the tensile stress field accompanied with the global expansion.

We performed crater counting in areas of 50 km distance from the LGAs to constrain the timing of the global expansion. The estimated formation ages of LGAs are distributed in a range from 4.3 to 3.9 Ga with a peak at 4.1 Ga, corresponding to the oldest ages of the Apollo basaltic samples and lunar basalt meteorites [e.g., Terada et al., 2007]. The results suggest that the lunar global expansion begun at 4.3 Ga.

We estimated the lunar radius change as a function of time based on the estimated ages. We assumed that the topography of the LGAs simply were a dale consisting of two normal faults. The increase of lunar radius is estimated to be ~2.2 km at most, consistent with the estimation from a lunar thermal model [e.g., Zhang et al., 2014].

Keywords: linear gravity anomaly, early global expansion, tensile stress, topography, crater chronology

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PPS23-22 Room:A02 Time:May 26 11:30-11:45

# Magnetic anomalies, dynamo and true polar wander of the Moon

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Applying the latest advanced paleomagnetic technique to the Apollo samples, it is now well established that the Moon once had an ancient core dynamo operated from 4.2 to 3.56 billion years ago, or even younger age. Because these results are based on paleointensity retrieved from unoriented samples, any directional information cannot be obtained. Instead, we focus on the magnetic anomalies on the Moon. Since the magnetization of the lunar crust in the magnetic anomalies could be records of an early core dynamo of the Moon, the magnetic anomalies may yield directional information of the lunar paleomagnetic field. Here we present results of our global survey of magnetic anomalies on the lunar surface using magnetometer data acquired by the Lunar Prospector and Kaguya spacecraft. Using an iterative inversion method, we extract magnetization vectors from well-isolated magnetic anomalies and derive the positions of paleomagnetic poles. We find two distinct clusters of the resultant paleomagnetic poles: one near the present rotation axis and the other at mid-latitude (Takahashi et al., 2014). The result is consistent with a dipole-dominated lunar magnetic field generated by a core dynamo that was reversing the polarity. It is also implied that the Moon experienced a polar wander event. Additional inversion results for well-isolated central magnetic anomalies based on the surface vector mapping method (Tsunakawa et al., 2014) suggest existence of the third cluster of the lunar magnetic pole.

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Keywords: magnetic anomaly, dynamo, core, polar wander