SELENE-2 に向けた月広域地震計システムの開発
Development of a lunar broadband seismometer system for SELENE-2

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

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

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

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

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

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

キーワード: 地震計, ノイズ, 干渉, 月震, 地動, 計測
Keywords: seismometer, noise, interference, moonquake, ground motion, measurement
SELENE-2 搭載を目指したマクロ分光カメラおよび研磨装置の開発
Development of an in-site rock observation system onboard the next lunar landing mission SELENE-2

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

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

Keywords: visible-SWIR macro camera, rock abrasion tool
SELENE-2/月電磁探査装置 (LEMS)：電磁応答に対する月地殻の影響
SELENE-2/Lunar ElectroMagnetic Sounder (LEMS): The effect of lunar crust on electromagnetic response

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

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

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

キーワード: 電磁探査, 月内部構造, SELENE-2

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

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

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

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


Keywords: igneous activity, basaltic volcanism, radioactive elements, Kaguya (SELENE), gamma-ray spectrometer
The relationship between compositions and ages of lunar mare basalts

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Keywords: Moon, lunar mare basalts, titanium content, lunar mantle, the Procellarum KREEP Terrane, mantle over turn
Development of evaluating method of Spatial distribution of craters on Lunar Surface for detection of secondary craters

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

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

Keywords: Moon, Secondary crater, Cluster analysis
月・地球型惑星の軽元素等内部保存の新モデル研究
Study on New Model of Interior Reservoir of Light Elements on the Moon and Earth-Type Planets

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月と地球型惑星（創成期の地球及びその他の無海水圏惑星）における軽元素の内部保存と循環などについては下記の様な問題点がある。

1）元素供給と太陽系天体（月・地球型惑星・小天体）に統一的な形成過程のモデルがなく、創世期と現代の天体間の形成過程を残存している固体岩石の時空データによる形成中心の研究が多い。
2）月面には創成期の破砕岩石が残存しているが、広大で基盤峡谷地形は発見されてなく、広く厚く多孔ガラス質表土ソイルに覆われている。
3）無大気・無海水圏の月面内部に蓄えられている軽元素がほとんど同じ大きさの火星内部と同じように埋蔵しているはずであるが、月は乾燥して高温の鉱物岩石が多く残存している。
4）月や創成期の地球型惑星（無海水圏）内部に重力に抗して軽元素が進入内蔵される形成モデルが提案されていない。

本研究では、これらの問題点の解明を下記のように提起する（Miura, 2013; in press）。
1）固体岩石は、微細粒子から衝突で気体・液体相から固体相になる過程を繰り返して固結残存した破砕状に固体部分を混在する「衝突成長」モデルで長い時空情報を考える。
2）現代の地球の大陸基盤は、プレート運動・地下沈降・マグマ溶融と噴出火山で固結して大きく成長した基盤岩であり特殊なでき方をしているので、それをすべての無海水圏の古い月・惑星に直接適用できない。
3）月面の大きさに小天体からもたらされる軽元素量は、火星と同じように内部に残存できているが、月面の岩石には軽元素が少なく高温の鉱物岩石が多く残存しているので、通常衝突だけでなく、巨大な惑星間衝突過程で多量の軽元素が欠損（段階 1）したと考えられる（地球上有壤化）。
4）軽元素が破壊した集合体で月面全体が形成されたが、その後不均質で微細に破砕した月面表面に衝突貫入して、内部に軽元素が蓄えられた（段階 2）が、その全重量は炭酸ガス圏を形成する程ではないと考えられる。

以上から、月面の軽元素は初期（段階 1）から未期（段階 2）までに多量に消失したが、岩石固体内または月内部に一部残存していると考えられる。海水圏を持たない金星や火星も同じ軽元素の衝突内部保存からの数段階経年由、炭酸ガス圏を形成したと思われる。

地球惑星の軽元素は、三圈循環過程で大幅に状態変化して、その形式タイプ（短周期）である生命圏を形成している。そのため、現代の水惑星地球のデータは、系統的に月・地球型惑星の創成期のモデルには無理があると考えられる。

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

Keywords: Moon, radon gas, alpha particle, lunar crust, SELENE
Heterogeneity of lunar mantle composition estimated by spectral analyses of Dark Mantle Deposits

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The lunar mantle makes up 90% of the lunar volume. Therefore, it is important to determine the mantle composition for understanding the lunar bulk composition and the process of its differentiation from the lunar magmatic ocean. However, the composition of the lunar mantle remains unclear. On the other hand, pyroclastic beads which are volcanic glass or partially crystallized spheres provide a direct clue to lunar mantle composition. Previous studies suggested that pyroclastic beads are the result of an explosive fire-fountain originating deeper (300 to 500 km) in the mantle than basaltic magma and retain the original composition of the magma because the beads have higher Mg# than mare basalts and do not completely crystallize during eruption, due to the high upward speed. It is also reported that the color variation of pyroclastic beads correspond to their composition, in particular TiO$_2$ content, and the crystallinity of the beads. Also, the crystallinity of the beads correlates with quenching rate of the erupted magma formed them and the volatile content in the magma.

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

In this study we estimated the TiO$_2$ content and crystallinity of the largest 20 DMDs distributed globally over the Moon and investigates the compositional relationships of the magmatic sources, among DMDs and between DMDs and the surrounding mare basalt using spectral data obtained by the Multiband Imager (MI) on SELENE. First, we selected DMD locations which have the lowest reflectance and spectral absorption features of pyroclastic beads. Second, we judged the types of pyroclastic beads by comparing the spectral absorption shapes of DMDs in the MI data with that of the laboratory-measured data for Apollo pyroclastic beads. Finally, by comparing the spectra of different mixing ratios of glass and crystallized beads, we estimated the crystallinity and TiO$_2$ content of the DMD. We also estimated the TiO$_2$ content of mare basalts surrounding the DMDs in order to compare the composition of the DMDs with that of the mare basalts by producing Ti-maps based on MI spectral data.

Our results suggest that the TiO$_2$ estimates of DMDs had 2 groups including intermediate-Ti group ranged from 5.4 to 6.3wt% and high-Ti group with 9.1wt%. Also, the crystallinity of the pyroclastic beads of DMDs had 2 groups, including low crystallinity group ranged from 3 to 35%, and high crystallinity group ranged from 72 to 85%.

In addition, a comparison of Ti estimates for DMDs and the surrounding mare basalts indicated that DMDs tend toward higher TiO$_2$ content than mare.

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

The possibility of azimuthal compositional heterogeneity in the lunar mantle is consistent with and may suggest compositional diversity after a mantle overturn, which is the vertical transport of the mantle caused by gravitational instability of the high-Ti cumulate layer produced during the final solidification step of a magma ocean.
深発月震の発生原因と月マントルの不均質構造に関する考察
Consideration of causes of deep moonquake generation and heterogeneity of the lunar mantle

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NASA の Apollo 月震測定により、月深部 700-1400km の間である特定の震源から、月地震（深発月震）が繰り返し発生する事が確認された。深発月震は、月-地球-太陽の位置関係、すなわち月内部に作用する潮汐力に関与して周期的に発生することが分かっている（e.g., Lammlein, 1977, Bulow et al., 2007）、その発生原因には諸説あり（e.g., Cheng and Toksoz, 1978, Araki, 2001）、いまだその発生メカニズムについては不明な点が多い。

本研究では、特に Apollo 観測時に活発で震源位置が良く決まっている深発月震源 15 個を選びそれぞれの震源で深発月震イベントの発生特性を調べ、その発生メカニズムに関しての考察を行った。これまでの Apollo 地震データの解析から、深発月震はそれぞれの震源で、異なる振幅値のイベントを発生している事が分かっている（e.g., Lammlein, 1977）。そこで、まずその振幅値の変動の状況と、震源ごとの違いを調べるため、観測された各深発月震波形から地震モーメントを導出した。その結果、深発月震の地震モーメントは震源ごとに明らかに違いがあり（最大 1 桁程度）、特に地域性を示す事が分かった。

次に、各震源での地震モーメントの大きさと時間変動が潮汐応力と関係するかどうか調べるため、Apollo 観測当時の各震源域に加わる潮汐応力を計算した。この計算の結果、潮汐応力と地震モーメントの大きさとの間に高い関連性は見られなかったが、地震モーメントの大きいイベントを発する震源ほど、潮汐応力の時間変動との間に低い相関を示す傾向にある事が分かった。以上の結果は、深発月震の発生メカニズムが震源によって異なるか、もしくは同時に震源域付近の弾性特性（マントル内部構造）が各震源域で異なる可能性を示唆している。

本発表では更に多くのデータを加えて解析した結果を示して、これまでの結論を検証するとともに、深発月震の発生メカニズムや月マントル内部の不均質構造についての更なる考察結果を示す。

キーワード: 深発月震, 地震モーメント, 潮汐応力, 月震発生メカニズム, 月内部構造, 月探査
Keywords: Deep moonquake, Seismic moment, Tidal stress, Generation mechanism of deep moonquake, Lunar interior structure, Lunar exploration
粘弾性変形解析から示唆された古い衝突盆地形成年代
Early formations of lunar impact basins inferred from their viscoelastic states: Implication for the heavy bombardment

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

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

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

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

References:

Keywords: Impact basin, Thermal evolution, Viscoelasticity, Magma ocean, Late Heavy Bombardment
Formation mechanism of the lunar highland crust indicated by correlation between Mg# and Th content

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月高地地殻の形成過程推定：Mg#とTh濃度相関からの考察

月高地地殻の主要構成相である斜長岩は、マグマオーシャンが約80%程度固化した後にマグマから斜長石が結晶化し、浮上・集積して形成したと考えられており、斜長岩がマグマから結晶化した時点でのマグマの分化程度を知る事は、高地地殻の形成過程（成長順序等）を知る上で重要である。我々はこれまでに、月周回衛星かくや（SELENE）搭載スペクトルプロファイル（Spectral profil; SP）データを用い、月高地地殻斜長岩中に微小量含まれる苦鉄質鉱物のMg#（モル比でのMg/(Mg+Fe)×100）の値が大きいほど未分化なマグマから結晶化した事、すなわちより早い段階でマグマから結晶化したことを示す（推定）の提案を行った。その結果、高地地殻のMg#は月の表層で低く、より分化したマグマから結晶化し、月の裏側では表側に比べて高く、より未分化なマグマから時期的には表側よりも先に結晶化した岩石からなる事が示唆された。一方で、同じくかくや搭載のD線分光計による観測結果からも、液層濃縮元素であるThの濃度が月高地で表側に比べて裏側ではなく低く、月裏側がやはり先に結晶化した岩石からなる事が報告されている。

本研究では、これら斜長岩中の苦鉄質鉱物のMg#とTh濃度の間にどのような相関が有るかを調べる事により、月高地地殻の固化・形成過程の推定（表と裏での固化時期の違いを異なる元素組成を用いて検証し、該当時期におけるマグマ組成の変化を推定する）を試みた。手法としては、Mg-MgマップをTh濃度データの空間分解能に合わせて平均化した上で、月面上各地点でのMg#値とTh濃度の相関を得る。その後、各組成領域の面積情報と合わせて場所による地殻形成時期の推移を推定する。

解析の結果、Mg#とTh濃度の間には地殻が形成したマグマの分化過程から推定される相関（マグマの分化が進むに従ってMg#が減少し、一方でTh濃度が上昇する）が緩く見られる事が解った。この事から、月裏側高地のMg#が高くかつTh濃度が高い領域は、表側高地に比べてより未分化なマグマから形成された事が、独立する2つの観測機器データを統合的に解析する事により確かめられた。これは、地殻物質の固化が月裏側で表側より早い時期に起こった事を示唆するとともに、これら固化過程が連続的に生じた証拠となる。

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

Keywords: remote-sensing, hyperspectral
月への大規模衝突によって形成された「マグマの海」の分化過程
Differentiation of impact-induced magma seas on the Moon

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我々は月探査機「かぐや」に搭載された Spectral Profiler (SP) データの解析を行い、かんらん石・低カルシウム輝石の
全体マッピングを行った。その結果、（1）かんらん石はモスクワの海・危険の海といった地殻の薄いと比較の小さい衝突
盆地周辺に（2）低カルシウム輝石は月の三大衝突盆地、すなわち南極＝エイトケン盆地・南の海・プロセラム盆地
の周辺に、それぞれ存在することが明らかとなった。通常のマグマオーシャンの固化モデルでは、最初にかんらん石が
晶出して底に沈み、その後に低カルシウム輝石が固化する。つまり SP による観測とは逆に、より深くまで掘削する大規
模な衝突盆地の周辺にかんらん石が存在し、地殻の直下まで掘られている大規模な地殻では低カルシウム輝石が分
布するはずである。この観測結果とモデルの不一致を説明するには、以下の3つの仮説が考えられる。

(i) マグマオーシャンが十分に深かったため、三大衝突盆地でも最初に晶出したマントル中のかんらん石層には到達し
なかった。あるいは月のパルク組成は地球とは異なる (Mg+Fe)/Si が低いため、マントルの大部分が低カルシウム輝石
で構成されている。
(ii) オーバーティールによってマントルの下が逆転し、かんらん石が低カルシウム輝石の上に来た。このため、より小
さい遠心力で上の方のかんらん石マントルが放出され、深部まで到達した三大盆地だけが低カルシウム輝石を露出させた。
(iii) 大衝突によって生じた大規模なメルトによってマグマの海が形成され、その後の固化の時に、マグマオーシャンと同
様の分化が起こった。

(i)の場合、小規模盆地周辺のかんらん石はマントルに由来するものではなく、下部地殻中の Mg-suite であると考えら
れる。両者の主な違いは斜長石の含有量であるが、SP の観測する可視赤外域では斜長石の吸収帯は低カルシウム輝石 / 鉄
かんらん石によって隠されててしまうため、別の観測手段が必要となる。具体的には (a) X 線 / ガンマ線による元素分布観
測 (b) SiO2 の割合を制約できる熱赤外放射観測 (e.g., LRO/Diviner) などがあるが、SP で検出した領域の空間的な広
がりはせいぜい数 km であるため、(b) がより有力な手法となる。なお三大盆地周辺の低カルシウム輝石はマントル起源
であるため、斜長石の混入比は低いと予測される。

(ii) の場合は、マグマオーシャンの固化やマントルオーバーティールの規模や時期に重要な制約が与えられる。表側の
Procollerum KREEP Terrain (PKT) が KREEP 成分に富むということは、マグマオーシャンの残余成分 (urKREEP) がオー
バーティールで沈み込みよりも先に大規模衝突が起こり、その成分を表面で露出させたということである。一方、裏側の
South-Pole Aitken Terrain (SPAT) で KREEP 濃度が低いのは、この衝突が起こった時には urKREEP がすでにオーバーティ
ール裏部へ (あるいは先に起こった Procollerum 役割の影響で表側へ) 移動していたため解釈するのが自然である。
このモデルが正しいとすると、SP が同定した低カルシウム輝石およびかんらん石に富む岩体はいずれもマントルに起源
を持つため、斜長石をほとんど含んでいないはずである。よって、(i)の場合と同様に、X・ガンマ線による元素組成分
および熱赤外放射による SiO2 量の観測が重要な役割を果たす。

衝突スケーリング則によれば、プロセラム盆地や南極＝エイトケン盆地の内部には、数 km の広がりと数十 km の
深さを持つマグマの海が形成されたと推測される。このメルトが再結晶する際の分化によって、低カルシウム輝石およ
びかんらん石が形成されたとするのが (iii) の説である。メルトの主成分は上部マントルだが、一定量の地殻の混合に
よって Ca/Al 成分が増えることが考えられる。このメルトが再結晶すると、地殻が形成される。現在も PKT / SPAT の地下に存在する斜
長岩地殻は、Feldspathic Highland Terrain (FHT) のようにマグマオーシャンから直接固化したものではなく、マグマの海
から形成されたかごべき地殻である可能性が高い。かくや探査マルチバンドイメージャー (M1) の観測により、PKT の中央
に位置するアリスタルコスケーラーの中央丘に有彩色物質をほとんど含まない純粋な斜長岩が露出している。この岩体
がマグマの海から形成されたとすると、その年代はマグマオーシャンから晶出した斜長岩よりも若いはずである。またこ
のモデルでは、SP によって同定された低カルシウム輝石およびかんらん石に富む岩体が (ア) 斜長石を含んでいる (イ)
斜長岩と隣接している、ことがありうる。SP による全観察データを複数の礫物種が隣接する領域を同定し、その複雑
な地質を M1 多色画像で調べた結果は、この (ii) 説を強く支持する。
キーワード: 月、スペクトル、赤外線、マントル、衝突、地殻
Keywords: Moon, Spectra, Infrared, Mantle, Impact, Crust
Radar observation of lunar surface by KAGUYA LRS

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We present recent result of lunar surface observation of KAGUYA Lunar Radar Sounder (LRS). Extracting nadir surface echoes out of LRS observation data, we made a surface echo map of the Moon, i.e. LRS lunar surface image. Nadir surface echo was defined as the most intense peak of an A-scope data. More than 10⁸ observation data was used. The LRS lunar surface image has a wide dynamic range of 20 dB, and shows variety of radar surface features as follows;

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

Keywords: KAGUYA, LRS, Moon, Surface, Radar
Determination of the permittivity of the lunar surface based on the radar echo intensity observed by the Kaguya

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

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

The obtained Hurst exponent $H$ is less than 0.5 in the maria, and about 0.9 in the highlands. The parameter $s$ is about 1 in the maria, and about 0.3 in the highlands. The global distribution of $H$ is similar with that reported by Lunar Reconnaissance Orbiter (LRO) laser altimeter [Rosenburg et al., 2011]. By applying the analysis method mentioned above, we could obtain the observed and calculated surface echo powers in the regions where $0.25 < H < 0.35$, and $0.85 < H < 0.95$. Based on them, we could estimate the average permittivity in the maria ($H\approx0.3$) to be 4-5, and that in the highlands ($H\approx0.9$) to be 2.

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

Based on the bulk permittivity and grain permittivity determined in this study, we also estimated the porosity in the maria ($H\approx0.3$) to be 30% and that in the highland ($H\approx0.9$) to be 60%. It is considered that the surface of the highlands is older than that of the maria. Due to the longtime exposure to the impacts of the meteorites, the porosity of the lunar basalt in the highlands can be larger than that in the maria.

Keywords: Kaguya (SELENE), Lunar Radar Sounder (LRS), Terrain Camera (TC), Electric permittivity, Porosity, Surface roughness.
Estimation of the permittivity and porosity of the lunar uppermost basalt layer based on the SELENE observation data

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

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

We have used data sets obtained from three instruments onboard SELENE: LRS, Multiband Imager (MI), and Terrain Camera (TC). We first focused on the ejecta composition (FeO and TiO2) around two types of impact craters (the haloed crater and non-haloed crater) due to the estimation of T. The non-haloed crater has the same ejecta composition with the surface composition of uppermost subsurface layer, while the haloed crater has the different ejecta composition from the surface composition of uppermost basalt layer. The haloed craters would be formed when meteorites excavate a lower basalt layer with the different composition from the uppermost basalt, which is lied on the lower basalt layer. The haloed crater and non-haloed crater are identified on the basis of FeO and/or TiO2 maps created from the MI data. We would therefore constrain T from the depths of haloed crater and non-haloed crater (d_h and d_{non}) measured from the TC data: d_{non}<T<d_h. We note that the distance between haloed crater and non-haloed crater should be as short as possible. The true lunar subsurface boundary is probably oblique, so that the oblique subsurface boundary produces a bad limitation of T. In this study, the distance is limited within 6 km. D is also determined within 6 km from these craters by using the LRS data.

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

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

キーワード: 電子サイクロトロン高調波. プラズマ波動. かぐや. 月
Keywords: Electron cyclotron harmonic waves, Plasma waves, KAGUYA, moon
かぐやで観測された月周辺電静孤立波 (ESW) と電子ビーム
Electrostatic Solitary Waves (ESWs) and electron beams observed by Kaguya near the Moon

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観測された波形を、理想的な ESW 波形や、その生成過程と考えられている磁場に垂直な成分を含めて近似し、さらに、モノポール観測の場合には、伝搬速度やポテンシャルのスケール等に関する情報も評価してきた。

今回は、Geotail で観測された ESW の解析 [6] に依り、電子の速度分布関数の磁場に垂直な成分を積分した、積分成分の分布関数から背景の熱電子の分布関数を差し引くことによって電子ビーム成分を導く。太陽風中、磁気異常上空、ウェイク境界、ウェイク内といった ESW が受信されている場所依存性と ESW, 磁場環境との関係を吟味する。

References

キーワード: かぐや, 静電孤立波, 電子ビーム
Keywords: Kaguya, ESW, electron beam
Type-II entry of solar wind protons into the lunar wake as a general phenomenon

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

Keywords: Solar wind-Moon interaction, Lunar wake, SELENE, Wave-particle interaction, Plasma entry into wake
かくや衛星によって発見された月ウェイク中央部のELF帯磁場変動について
Magnetic fluctuations detected by Kaguya in the central wake

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月には地球のような大規模な固有磁場が無いため、太陽風粒子は直接月面に衝突する。そのほとんどは月面で吸収され、ごく一部（0.1%以下）の太陽風プロトンが月面に衝突し、月表面の磁場で反射される。この反射プロトンは月周辺の磁場に擾乱を与える。特に周期100秒程度の低周波の波と、0.03-10Hz程度のELF帯の波が特徴的である。後者は特に、月が太陽風中にある衛星が月の昼間側にあるときにはほとんど常に観測される。一方、月の夜側の、太陽風プラズマが入らないウェイク領域では、そのような磁場変動はほとんど見られないのが常である。

しかしながら、100km程度の高層大を通りの軌道上のかくや衛星搭載磁気計MAP/LMAGによって、0.1-10Hz程度のELF帯の磁場変動が月の夜側中央部（ウェイク中央部）付近に時折見られることが発見された。このような波の15例中、少なくとも12例は、真夜中でありながら、同時にイオンが観測されている。このイオンは日照側月面で反射したプロトンが太陽風の磁場を横切って回転を始め、ウェイク中央部に到達したも（タイプIIエントリー、Nishino et al., 2009）と考えられる。波の継続時間（数分程度）は、イオンの観測時期より短程だが短いことが多かった。

これらの磁場変動には明確な回転方向は見られず、むしろ1次元的な変動であり、振動方向は背景磁場の方向に近いことが多かった。これらの変動が観測されるのは、背景磁場のy方向成分（GSE座標）が卓越している時に多かった。以上のように後、この磁場変動は、タイプIIエントリーのプロトンビームによって生じたビームモデルの磁気音波ではないかと考えられる。

キーワード: ELF, かくや, MAP/LMAG, MAP/PACE, ウェイク, 月
Keywords: lunar wake, SELENE, magnetic fluctuations, solar wind, nightside, type-II entry
ブラズマ粒子シミュレーションによる太陽風・小型ダイポール磁場相互作用の解析とそのReiner Gamma磁場への応用
PIC simulation on the solar wind interactions with meso-scale magnetic dipole and its application to Reiner Gamma

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我々は、宇宙ブラズマの運動論的効果を考慮したブラズマ粒子シミュレーションにより太陽風と小型所磁場ダイポール磁場との相互作用について研究を行っており、本講演では、その結果の一部を紹介するとともに月面ライナーガンマの局所磁場への応用事例を報告する。我々が対象としている代表的なダイポール磁場は、その中心と太陽風動圧の釣り合い点との距離が太陽風イオンの慣性長よりも小さくかつ電子ジャイロ半径よりは十分大きい、いわゆるメソスケール規模を想定している。地球規模のダイポール磁場と違い、メソスケール磁場の場合、磁場に対する電子とイオンのダイナミクスの違いが磁気圏形成やそれに関連するブラズマ現象に大きく影響すると予想される。すなわち、磁場を媒介した電子とイオンのスケールカップリングが重要となる。しかし、このような小型磁場構造と太陽風の間でのどのような相互作用が生じるかという点については、いまだ定量的な理解が進んでいない。

太陽風ブラズマ、特にイオンのラーマ半径がダイポール磁場構造の大きさとほぼ同程度もしくは大きくなるため、この定常的解析を行うにはMHDモデルシミュレーションではなくブラズマの運動論的効果を考慮した粒子シミュレーションが適している。これまでのシミュレーション結果では、イオンラーマ半径より小さい尺度磁場構造においてもメソスケールの磁気圏が形成されることがわかった。太陽風動圧と磁場の釣り合い点近傍において、イオンと電子の電荷分離が生じ、その結果生じる局所電場により、本来このスケールでは非磁化とみなされるイオン流も大きく影響を受けを明かにした1。また、ここを中心にダイポール磁場が圧縮される点、および、その磁場圧縮領域で電子による境界層電流が流れその領域の厚さは電子のラーマ半径程度である点も粒子シミュレーションから明らかになった。ただし、惑星間空間磁場（IMF）の影響を考えると、前面では衝突波構造に似た擾乱領域の生成、また磁力線リコネクションによる小型ダイポール磁場の構造的変化などが考えられる。

今後、月面磁気異常の一例としてライナーガンマをモデルとして用いてそのブラズマ粒子シミュレーションを行った。太陽風に対してダイポール磁場がほぼ垂直に位置するため、ライナーガンマ上空でのブラズマおよび磁場密度の増加がみられるが、IMFの方向によってその違いがみられた。また磁場の影響により太陽風イオンがライナーガンマ領域の月面にほとんど達しないことも明らかになった。これらの現象について月面上空でのブラズマダイナミクスや電界構造を考慮しつつ議論する。

キーワード: ブラズマ粒子シミュレーション, 磁気異常, 小型ダイポール磁場, 太陽風, ライナーガンマ
Keywords: Plasma particle simulation, magnetic anomaly, small-scale magnetic dipole, solar wind, Reiner Gamma
The effect of magnetic anomalies on the detection of Moon originating ions

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月周辺には太陽風プラズマの他、月表面や月外気圏に由来する重イオン（月起源イオン）が存在することが地上観測などにより知られてきた。月起源イオンの生成・輸送過程は今から提案されてきたが、そのプロセスが支配的であるかなど詳しいことはまだよくわからない。定性的には月表面からは太陽光による脱離や太陽風によるスパッタリング、熱脱離によって、外気圏からは中性大気の電離によって発生し、月が太陽風中にあるときは太陽風によるコンベクション電場や月表面の帯電によるポテンシャル電場で月面に戻るか宇宙空間に輸送されると考えられている。月周回衛星「かぐや」に搭載された低エネルギーイオン観測器 MAP-PACE IMA は世界で初めて月起源イオンの現場観測を行い、月が太陽風中にあるときに高度 100km において C^+, O^+, Na^+, K^+, Ar^+ のイオンを同定した。検出されたイオンのエネルギーはおよそ数百 eV であり、概ね太陽風によるコンベクション電場で加速されたとして説明できるものであった [Yokota et al, 2009]。

本研究では、IMA が検出する月起源イオンの量の変動から、月起源イオンの生成輸送過程の手掛かりを得ることを目的としている。特に、イオンには電磁場の影響が強いと考えられるため、コンベクション電場の影響と磁気異常の影響について解析を行った。

コンベクション電場と高度 100km 月起源イオンのフラックスを比較したところ、電場の北西方向・東南方向との相関は平均でほぼ 0 であったのに対し、動径成分はやや正の相関がみられた。検出されたフラックスの変動は、およそ電場の動径方向の変動で説明することができるが、「かぐや」が磁気異常上空を通過する際、ごく低エネルギーの月起源イオンフラックスの検出量について電場の変動だけでは説明できない減少がみられた。このことから、磁気異常が月起源イオンに及ぼす影響について考察する。

キーワード: 月, プラズマ, 磁気異常
Keywords: Moon, plasma, magnetic anomaly
最新のSELENE、LROデータによる月数値標高モデル(DEM)
The newest lunar digital elevation model (DEM) from SELENE and LRO data

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2007年に我々が打ち上げた月探査機SELENE（かぐや）に搭載された地形カメラによる月球全体の10m画素の解像度で視覚データに基づいて、SELENE搭載マルチバンドイメージジャデータならびに米国月探査LROに搭載された高度計データ（LOLA）によって補完された月球の数値標高モデル（DEM）の最新版について、本講演では紹介する。

これまで、SELENE地形カメラのステレオ視覚箱を基にした数値地形モデル（Digital Terrain Model）データが、画像データとともに、SELENEレベル2データベース（LINK参照）で配布されている。また、これらを基に、月球についてモザイク処理を施したDTMマップとオルソ画像マップも公開されている（LISM高次プロダクト；プロダクト名は、DTMマップ、TCオルソマップ）。これらモザイクデータは、極端にいたるまで等経度線図で表された3deg x 3degのタイル状となっている。1画素あたりの解像度は、赤道域では7m画素となるような、リサンプリングを施している。

地形カメラデータは、ほぼ月球全体の観測を行ったが、裏側の高地等に、隣接軌道で数%以下程度ながら抜けが生じた。ただし、月球に対する被覆率は1%未満である。また、極端については、陰が多く数値地形モデルが作成出来ないところが多い。そこで、地形カメラデータを基に、抜けの部分を他データによって埋めて、より被覆率の高い地形標高モデルが作成されている。この時利用されたのは、SELENE搭載マルチバンドイメージジャ（MI）可視域（VIS）データからのDTMと、LRO搭載LOLA（高度計）のデータである。MI-VISデータは、数値解像度20mである。MI-VISは、二次元の検知器について、5つのラインを残し、後はマスクすることで、各ラインが、あたかも二次元センサーのようにして月面をスキャンし、二次元画像を得る。その結果を、後で、MI-VISの異なるラインの間には、視差が生じることになる。この視差を用いて、DTMが作成できる。最も前方と最も後方のライン間の画角は、5.48 degである。MI-DTMによって、特に裏側の高地で抜けたところが補完された。

LROに搭載されたLOLAは、スポット半径20mの5つのビームが打たれる仕様になっており、各スポットの衛星進行方向の出射間隔は10–20mである。緯度方向の水平解像度は軌道間隔で決まるが、極端には、非常に密なデータが得られることになる。地形カメラの数値地形モデルデータより、緯度約85 deg以上で、LOLAの水平方向のデータ密度が上回る。

これらのMI-DTMとLOLAデータを統合して、新たに全球の数値標高モデル（Digital Elevation Model:DEM）SLDEM2012が作成されている。ただし、これまでの検証で、地球の数mのオフセットがLOLAデータと、SLDEM2012との間に残っていた。そこで、このオフセット処理を取り除く補正処理を行い、新たなDEMの作成を試みてみた。このDEMが出来れば、これまでの月面全体を覆うDEMマップとしては、世界最高精度のものとなる。このDEMマップは、月科学研究、更には将来の月探査において、非常に重要かつ有意義なものとなることが期待される。

【LINK】
SELENEデータアーカイブサイト
（日本語）http://i2db.selene.darts.isas.jaxa.jp/
（英語） http://i2db.selene.darts.isas.jaxa.jp/index.html.en

キーワード: 月、数値標高モデル、デム、地形カメラ、セレーネ、かぐや
Keywords: Moon, digital elevation model, DEM, Terrain Camera, SELENE, Kaguya
Mare volcanism: Reinterpretation based on Kaguya Lunar Radar Sounder data

Shoko Oshigami, WATANABE, Shiho, Yasushi Yamaguchi, Atsushi Yamaji, Takao Kobayashi, Atsushi Kumamoto, Takayuki Ono

Units, the ages of which have been estimated by several researchers, to evaluate the volumes of the units. Regions of lunar maria. Using the technique of Ono et al. [2009], we correlate subsurface reflectors with the surface geologic and its time dependence. Therefore the LRS data have great potential to determine a lava effusion volume during a series of magmatism in lunar maria between basalt units with different FeO contents, suggesting that buried regolith layers were responsible for the radar returns. The LRS detects, using FM-CW radar (4-6 MHz), echoes from subsurface horizons with abrupt changes in dielectric constants at the apparent depths smaller than about 1 km. Oshigami et al. [2012] concluded that the reflectors correspond to the interfaces derived for only limited areas in Oceanus Procellarum and Mare Serenitatis.

At present, the geological structures under the lunar maria are directly investigated using sounder observations. The Lunar Radar Sounder (LRS) onboard Kaguya (SELENE) detected widespread horizontal reflectors under some nearside maria. The LRS detects, using FM-CW radar (4-6 MHz), echoes from subsurface horizons with abrupt changes in dielectric constants at the apparent depths smaller than about 1 km. Oshigami et al. [2012] concluded that the reflectors correspond to the interfaces between basalt units with different FeO contents, suggesting that buried regolith layers were responsible for the radar returns. Therefore the LRS data have great potential to determine a lava effusion volume during a series of magmatism in lunar maria and its time dependence.

Thicknesses of mare basalt units with different ages and compositions are directly estimated from the LRS data in the several regions of lunar maria. Using the technique of Ono et al. [2009], we correlate subsurface reflectors with the surface geologic units, the ages of which have been estimated by several researchers, to evaluate the volumes of the units.

The estimated thicknesses of the geologic units were of the order of 10^{1}-10^{2} meter, and showed a positive correlation with their ages. The resolution of our estimation was limited by the range resolution of the LRS data. Previous studies indicated that the typical thicknesses of single basalt flows were about 10 m or less in most of the studied sites. These estimations suggest that the geologic units are made up of dozens of lava flows.

Weider et al. [2010] estimated the thicknesses of a number of mare basalt units in Oceanus Procellarum and Mare Serenitatis, ranging from about 80 to 600 m. For the purpose of comparison, we took the unit S15 in Serenitatis defined by Hiesinger et al. [2000]: Weider et al. concluded that the representative thickness was about 500 m although individual data derived from craters located on the unit showed a wide variation, implying large uncertainty of their estimation. In contrast, the LRS data exhibit that the averaged thickness of the unit S15 is about 150 m.

The volumes of the geologic units estimated in this study were of the order of 10^{3} km^{3}, and showed a clear positive correlation with their ages. Again, the resolution of our method was limited by the range resolution of the LRS data. This volume range is consistent with flow volumes derived from numerical simulations of thermal erosion model for lunar sinuous rilles formation. The large sinuous rilles are estimated to have formed by thermal erosion with sustained lava flows of volume in the range 300-1200 km^{3}. The volume range derived from our study also comparable to the average flow volumes of continental flood basalt units forming after the Paleozoic and calculated flow volumes of Archean komatiite flows, both possibly originated from mantle plume activities on the Earth. The estimated volumes of the geologic mare units and their age variation on each maria potentially constrain key factors for the thermal evolution of the Moon; magma buoyancy and crustal thickness, impact basin topography effects on the ascent of magma, and thermal evolution trend.

Keywords: Kaguya, Lunar Radar Sounder, Lunar maria, Subsurface structure, Volcanism
Despite recent insight regarding the Moon from satellite sensing and analyses of Apollo-era seismic data, there are still several unknown issues on the deep lunar interior. It is suggested that the Moon has a small iron-rich core with a radius between 220 and 450 km based on the calculated value of the mass and moments of interior (Konopliv et al., 1998), but the question about its feature is still under debate. Recent studies suggest the presence of a solid inner core and liquid outer core in the Moon (Weber et al., 2011). If we could constrain the temperature and composition of the lunar outer core, this would help us for better understanding of the lunar interior. Here, we focused on the interaction between liquid iron-alloy and solid silicate, and revealed the nature of the outer core of the Moon. The lunar mantle is characterized by high FeO content compared to the Earth’s mantle. This implies that Moon is oxidizing and oxygen can be in the lunar core. Therefore, Fe-O-S system is considered and we performed the partition experiments of oxygen between silicate and molten metal in this study.

High pressure experiments were conducted at 5 GPa from 760 C to 1400 C using 3000 ton Kawai-type multi-anvil apparatus of Tohoku University. We used powder mixtures of Fe, FeO and FeS as the metallic component of the starting material. Olivine crystals with Mg number of about 83 from Miyakejima, which is similar to the lunar mantle olivine, were used for the silicate component of the starting material. The sulfur content was 24 wt.% and the oxygen content varies 0 ˜ 7 wt.% for the starting iron-alloys. Scanning electron microscope (SEM) was used for the texture observation of the recovered samples, and the electron probe micros-analyzers (EPMA) with Energy-dispersive X-ray spectroscopy (EDS) and wavelength-dispersive X-ray spectroscopy (WDS) were used to obtain the chemical compositions of recovered run products.

Some differences in reactions between the experiments made at 1000 C and at 1400 C were observed in the recovered samples. At 1000 C, the metallic sample melted partially and liquid phase had magnesiowustite crystals were observed at the boundary between the molten iron alloy and olivine. The Mg number of the olivine crystals increased with increasing the distance from the metal phase. At 1400 C, the metallic sample was totally-melted. Pyroxene and olivine crystals with reverse zoning were observed in the silicate phase, whose Mg number was higher than starting materials. The effects of oxygen content in metallic phase on silicate phase were not observed in this experimental condition. We calculated the distribution coefficient D of FeO between metal liquid and olivine crystal. Using this value, the amount of FeO in the lunar liquid outer core is 4.45 at.% at 1000 C and 1.63 at.% at 1400 C when the mantle Mg number is 80. If the amount of FeO is 4.45 at.%, the lunar outer core might have two layers because of existence of the immiscible two-liquid regions in the Fe-S-O system.

Keywords: lunar core-mantle boundary, Fe-O-S system, olivine, melting, high pressure
Mare Imbrium周辺の地殻物質
Crustal materials around Mare Imbrium: result of Kaguya data integration science

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In order to understand lithological distribution and geological structure of the lunar crust, it is important to conduct analysis of spectral images with high spatial resolution considering 3D geological structure by using high-spatial resolution topographic map. In this presentation, lithological distribution and it relationship with geological structure around Mare Imbrium will be discussed by using the Kaguya data acquired by MI, TC, KGRS and LALT. As well known, Imbrium basin is situated in Procellarum KREEP Terrane (PKT). Therefore this investigation would contributes to understand lithological structure of the PKT and influence of Imbrium basin formation on the PKT evolution. In addition to discussion on crustal materials around the PKT, implication for origin of high-Th (i.e. KREEPy) crustal materials will be discussed.

キーワード: 月. 地殻. かくや. Procellarum KREEP Terrane, マグマオーシャン. 初期進化
Keywords: The Moon, Lunar crust, Kaguya/SELENE, Procellarum KREEP Terrane, Magma ocean, Early evolution
Presence of impact melts on central peaks of lunar craters and its implications

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Introduction: Impact melts within complex impact craters are known to be flat and smooth deposits filling the floors or wall terraces [1]. Recent studies suggest that compositionally different layers with smooth surfaces are present on the central peaks in several lunar craters, implying impact melts [2, 3]. Impact melts on the central peaks could constrain the central peak formation timescale because impact melts will flow out if peaks are uplifted too quickly. However, little evidence and few examples of impact melts on the central peaks were reported. In this study, we investigate the central peaks of the all lunar complex craters listed by [4] to check for the presence of impact melts morphologically and compositionally.

Methods: Central peak morphologies and topographies are identified using SELENE data obtained by the Terrain Camera (TC, 7.4 m/pixel) and Multiband Imager (MI, visible: 20 m/pixel and near- infrared: 60 m/pixel); MI spectral data also provide compositions of geologic units. Impact melt textures are identified by characteristic features, such as cooling cracks and flowing features (lobes or levees), using data from the Narrow Angle Camera (NAC, 0.5-1.2 m/pixel) aboard the Lunar Reconnaissance Orbiter (LRO) in addition to SELENE data.

Results: At least 13 of the analyzed central peaks have distinctive impact melt morphologies on their slopes. Seventy craters (including the above mentioned 13 craters) have spectrally unique geologic units on their gentler slopes with smooth surfaces exhibiting low albedo and weak absorption depth similar to their floor melts. The 70 craters vary in setting, diameter, and formation age, while almost all the 13 distinctive melt morphologies are observed in the craters formed in Copernican period [4], which is the latest selenogical period.

Discussion and Conclusions: Our observation that impact melts are found on the central peaks of more than half of the Copernican period craters implies that many central peaks could have impact melts. My analysis suggests that the unique geological units on the 70 central peaks are possibly impact melt origin, and melt morphologies on the older central peaks are probably obscured by erosion, which implies it is common that impact melts did not flow out completely from the central peaks when the peaks were uplifted. This suggests that impact melts already had relatively high viscosity but were not completely solidified when central peaks were uplifted.


Keywords: central peak, moon, SELENE, impact crater, impact melt
Estimating the origin and thickness of high-thorium-content rock units on the lunar surface

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The abundance and distribution of thorium, an incompatible element, within a planetary body are very important for understanding the thermal history of a terrestrial planet because it correlates to the heat-source elemental abundance of these planets. Gamma-ray remote-sensing data depicts the global distribution of thorium of the lunar surface, in which thorium concentrates in the western hemisphere of the lunar near side around the mare region. Within this high thorium area are several hot spots, which have significantly higher thorium content. Lunar rocks containing abundant incompatible elements are called KREEP-rich rocks based on the Apollo sample analyses. KREEP should be formed in the boundary area between the lower crust and the upper mantle. However, the KREEP-rich rock is exposed on the lunar surface. Two processes were proposed as the mechanism for transporting KREEP-rich rocks from under the crust to the surface. One is an igneous process, in which KREEP-rich basalts erupt from magma generated in a deep area at the bottom of the crust. The other mechanism is the ejecta origin of Imbrium basin, in which a basin-formation event excavated the lower crust including KREEP-rich rocks and spread it as ejecta on the surface. The thorium hot spots can be considered to have been formed by either mechanism. However, because of a low spatial resolution of gamma-ray observation from orbit, we cannot identify the corresponding rock types of the thorium hot spots. Therefore, the actual distribution of the high thorium unit and its thorium abundance has not been well understood.

In this study, we used high-resolution visible to near-infrared band images obtained by Kaguya (SELENE) and combined them with a simulated thorium abundance based on Lunar Prospector gamma-ray data to estimate the origin of the thorium-rich rocks and their thorium concentrations. We selected two hot spots (Aristillus and Copernicus) to analyze as candidates of the two KREEP origins. Aristillus is a crater within the Imbrium basin, while Copernicus is located outside of the Imbrium basin.

Our results indicate that KREEP-rich rocks around Aristillus contain high calcium pyroxene, and its thorium abundance is estimated to 35 ppm, while there appears to be no thorium inside the crater. In contrast, KREEP-rich rocks around Copernicus contain low-calcium pyroxene with 12 ppm thorium content. By combining the results with their geologic contexts, KREEP-rich rocks in Aristillus (Copernicus) are estimated to originate from KREEP basalts (Imbrium ejecta). The KREEP layer around Aristillus is estimated to be 1.6 km thick, and that around Copernicus is estimated to be 9 km thick. These results suggest that the thorium concentration within the crust is not uniform as assumed in a previous model but it forms a layer. It also clearly demonstrates that the previous model assuming constant thorium content within the crust from surface to the bottom (60 km deep) needs modification. Our estimation based on our new thorium abundance model for the Procellarum KREEP terrane derives much lower thorium abundance (50% less) than previously estimated.

Keywords: moon, thorium, thermal history
The formation and reactivation of a mare ridges in northern Imbrium

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Mare ridges are the manifestations of horizontal compressions in the shallow part of the lunar crust. They have been interpreted as the folds that determined the basaltic lava layers in mare basins. Since the distribution of the ridges is usually concentric with respect to basin centers, the compressional stress is thought to be originated from the flexure of lithosphere caused by the loading of mare basalts, which is called mascon tectonics. Possible mantle viscosity allowed such deformations to have had delay time of the order of 0.1 Gyr from the deposition of the basalt, which means the deformation was almost syndepositional. However, recent investigations on the underground structures showed that there is no lateral change of thickness of basalt lava around ridges, and this fact supports the post-depositional formation of ridges. On the lunar surface, the majority of mare basalts deposited before 3.0 Ga. Thus, the most of the ridge formation should have occurred before 3.0 Ga. The timing of the formation will be the clue to distinguish their origin, among global cooling, orbital evolution of the Earth-Moon system and mascon tectonics. This study found a crosscutting relationship between a ridge and a basalt unit, then constrained the formation age of the ridge using depositional ages of basalt lava units derived from the crater-size frequency distribution (CSFD).

By means of optical data taken by the cameras onboard SELENE (Kaguya), an ENE-WSW trending mare ridge that dammed up a relatively high-Ti basaltic unit was found near Sinus Iridum, northern Imbrium. The ridge is 300–400 m high, ~30 km wide and ~150 km long. Relatively high-Ti unit is dammed up by the ridge and relatively low-Ti unit made up the ridge. It was also found that the lowermost part of the ridge is partially covered by high-Ti unit, that is, a part of the ridge was uplifted after the deposition of the high-Ti basalt. In addition, there is a smaller ridge of ~50 m in the younger unit. The smaller ridge runs roughly parallel to the ridge mentioned above. The reactivation and the formation of the small ridge showed that a compressional deformation occurred in the area after the deposition of high-Ti basalt. This study determined the depositional ages of high-Ti unit and low-Ti unit by performing CSFD measurements. The estimated ages were 3.0 Ga and 2.1 Ga for low-Ti unit and for high-Ti unit, respectively. The cross-cutting relationship showed that the major formation age of the ridge was between 3.0 to 2.1 Ga. Furthermore, it was revealed that the reactivation and the smaller ridge formation occurred after ~2.1 Ga. Since most of the mare basalts were deposited before 3.0 Ga in the Imbrium basin and the ridge is a part of concentric ridges of the basin, the formation of the ridge was possibly induced by the latest stage of the mascon loading. However, the reactivation of the large ridge and the formation of the small ridge were too young for the mascon, requiring some mechanisms other than the loading. Global cooling and the increasing Earth-Moon distance are possible explanation.

Keywords: mare ridge, chronology, formation age
Assessment of Hemispherical Spatial Distribution of Craters on the Lunar Farside.

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The impact craters on planetary surface show random spatial distribution. However, lunar surface expect to have a bias of spatial distribution of crater because the Moon have same rotation and revolution periods.

The previous research showed that rayed crater density at the apex (0 N, 270 E) is highest than antapex (0 N, 90 E). I compared crater size-frequency distribution of apex and antapex side about craters of over 20 km in diameter. In the result, the crater size-frequency distribution of the antapex side was higher than the apex side.

Purpose of this research is to develop an algorithm to assess spatial distribution of craters on lunar farside by using clustering analysis for finding where bias of craters is. In this algorithm, I apply the nearest single-linkage clustering (S-LINK) to simulated and actual craters, and assess whether the crater is random or not by comparing both of results. As a result, 2870 of 3112 craters were decided to non-random (1403 craters are at the apex side, and 1467 craters are at the antapex side). I investigated the crater frequency variation with longitude and latitude. The high frequency of non-random craters was found at north high latitude region, apex side (210 to 270 E) and antapex side (90 to 150 E).

Keywords: Crater, Spatial distribution, Clustering analysis, apex
SELENE-2 project has been started from 2007 as the first Japanese lunar lander. The main prior object of the SELENE-2 mission is to develop safe and precise landing system on middle to large planets and satellites such as the Moon and Mars for future lunar and planetary exploration. Another key technologies under investigation are surface mobility by a rover, and long night survival module without using nuclear power. In addition, some instruments for lunar science and future utilization have been so far investigated.

The Strategic Headquarters for Space Policy of Japanese government established "Basic Plan for Space Policy" in June, 2009. Following the plan, a concrete strategy of Japanese lunar exploration had been discussed in "Study group for lunar exploration" of Japanese government which was organized from August, 2009 to July, 2010. The final report of the group indicates that a spacecraft should land on lunar surface in around 2015 to promote lunar exploration using advanced robot technology in 2020. Despite of this result, the SELENE-2 is delayed and still remains as the Phase-A study. Presently, the earliest launch date is 2018 when we successfully proceed to Phase-B within the fiscal year 2013.

One of our meager but important progresses are that technological development of candidate instruments, especially, we have developed seismometry system and camera system, both of which were considered to be main scientific instruments for geophysical and geological instruments. As for the seismometry system, we have almost successfully performed interface tests which were done by international collaboration. Development of a sensor of the visible to near infrared camera system, on the other hand, also conducted good performance under the suitable temperature condition on board the rover.

We are preparing for the upcoming review board to proceed to phase-B study. In order to achieve it, we are under investigation to make high reliable system, and realistic scenario of the mission profile assuming some appropriate landing sites which have been selected among the Japanese lunar scientists. Further technical development is also to be aggressively continued for reducing risks.

Keywords: Moon, Lunar exploration, SELENE-2
Recent status of SELENE-2/VLBI instrument

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We proposed a VLBI (very long baseline interferometry) radio source mission for the Moon lander SELENE-2. The purpose of our mission is to improve the lunar gravity field and to estimate the lunar interior structure. Differential VLBI observations between an orbiter and a lander are carried out to determine the position of the orbiter and the lander in addition to the conventional 2-way Doppler observation (Fig.1). VLBI measures a difference in an arrival time of a signal transmitted from a radio source to two ground stations. This measurement gives plane-of-sky position information of the radio source in contrast to 2-way Doppler measurement that gives line-of-sight position information. The combination of VLBI with Doppler is effective for precise position determination of the spacecraft.

This presentation shows the recent status of the VLBI radio source mission of SELENE-2.

1. A simulation study of the lunar gravity field estimation is carried out. The result shows that a potential Love number k2 accuracy better than 1 % can be achieved by 3 months of the VLBI mission duration provided that arc length is 14 days and that historical tracking data including SELENE are combined with.

2. The sensitivity of the geophysical parameters, in particular that of k2, the moment inertia of the Moon, and the seismic travel time, for the lunar deep interior structure is evaluated. A preliminary result shows that a density and a radius of the lunar core can be estimated within the error of 10 %.

3. We have conceptual design for an antenna that will be used on the lunar surface. A simulation evaluates the electric characters of the antenna, which are the gain, the beam pattern, and its temperature characteristics.

4. In order to decrease the power consumption of the VLBI radio source, the observation method and the manner of the operation are reconsidered.

Keywords: selene-2, vlbi, moon, internal structure
波形の類似性を考慮した大規模月地震データの可視化システムの実装
An implementation of a visualization system for large scale moonquake data considering waveform similarity

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1969-1977 の 7 年半の間、NASA のアポロミッションで月面に設置された地震計での連続観測により膨大な量の月地震データが取得された。これまでの月地震データの解析より、月深部およそ 700-1200km で起こる深発月震は同一の震源から周期的に発生する事が明らかにされており、(e.g., Lammlein, 1977) 特に、同一震源から発生する深発月震間では高い波形の類似性が見られている。(e.g., Nakamura,2003) この波形の類似性は震源を分類し、かつ月地震の発生原因を究明する上での重要な情報となるので、現在に至るまで、人手による月地震の分類が進んでおり、特に長周期地評計で観測されたデータの多くについては月地震の種類及び震源のラベル付けがされている。(Nakamura et al., 2008)

しかし、膨大なサイズの月地震データ全てを人手によって分類することは困難である。コンピュータを用いて月地震の分類を行う場合、適正な正解データが存在せず、データ自体も非常にノイズが大きいという特性を持っているため、相関関係などの分類手法を直接適用しても全ての月震データに対して必ずしも有益な結果を得る事は限らない。

そこで、本研究では、月地震データの分類を促進するため、波形の類似性を考慮した月地震データを可視化するための Web システムの実装を目指す。本システムでは、まず Self-Organizing Map (SOM) を用い、月地震データを 2 次元空間上へマッピングする事で波形の類似性の観点から可視化を行う。また、処理のバックエンドに Hadoop を用いることで、膨大な量のデータに対する SOM の処理に応答する。SOM は、ある設定した特徴量に注目して機械的に波形を分類するので、様々な物理条件を反映させた分類結果を提示することが期待できる。Web インターフェースを通じて、SOM の結果及び月地観データを提示することにより、多くの研究者がその評価結果を参照し、解析研究に反映させる事が可能となる。本発表では、これまで実施した SOM による月地震分類の結果と Web インターフェースの開発状況についての報告を行う。

キーワード: 月地震, 可視化, 自己組織化マップ, Hadoop
Keywords: Moonquake, Visualization, Self-Organizing Map, Hadoop
月レーザ測距用ホロー型逆反射板の材料選定及び重量・熱変形計算
Development of the retro-reflector on the moon for the future lunar laser ranging

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月レーザ測距の精度は主に地上局や大気遅延モデルの改良によって最近 25年ほどの間にほぼ 1桁向上した。残存する誤差（〜2cm）も单一素子型の逆反射板を新たに設計することで原理的に解消され、月の回転変動や潮汐変形の決定精度向上が期待される。
現在、アポロ11号の逆反射板を凌ぐ反射効率を持つ口径 20cmの单一素子逆反射板の開発を進めているが、ブリズムでの制作は均質性や重量から困難であり、3枚の板材を組み合わせるホロー（ミラー）型素子を目指している。材質は、(1) 熱膨張率と熱収縮率の比、(2) 強度、等から、珪素（Si）またはクリアセラム-EX（OHARA）が有力であり、製作法は3枚の板材をオプティカルコンタクトで接着する手法が有力である。発表では力学的/熱的物性に加え、口径（D）や板材の厚み（t）を考慮する材質選定とその検討結果、逆反射板の月面環境下における重力及び熱変形計算結果を示し今後の開発方針を議論する。

キーワード：月レーザ測距, 逆反射板, 単一素子, ホロー, クリアセラム EX, 単結晶シリコン
Keywords: Lunar Laser Ranging, Retroreflector, Single, Hollow, CCZ-EX, Single crystal silicon
 Developing a test model of Laser-Induced Breakdown Spectroscopy for mounting lunar and planetary rovers

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LIBS(Laser Induced Breakdown Spectroscopy:レーザー誘起絶縁破壊分光装置)はレーザーと分光器を用いて、岩石の元素組成をその場で測定することができる装置である。2012年の8月に火星に着陸して調査を行っているNASAの探査ローバー「Curiosity」にも搭載されており、実際に火星岩石の組成に関するデータも得られている。

LIBSは高エネルギーのパルスレーザーを測定対象に照射しプラズマ化させる。プラズマ化した原子は制動放射や再結合、脱励起によってエネルギーを失っていく、失われたエネルギーは光として放出される。発生した光を分光することによって波長元素ごとの輝線スペクトルが得られ、測定対象の組成を調べることが可能となる。

私たちはLIBSをローバーに搭載して試験を行うためにLIBS試作機を作製した。LIBS試作機はブレーキダウンに必要なエネルギー密度を得るためにレンズを使用し、レーザー光を集光させており、そして1.0m〜1.5m先にある測定物に対して自動で焦点調整を行っている。

私たちは2012年10月28日から11月3日にかけて伊豆大島でフィールド試験を行った。今回のフィールド試験では1m前後離れた岩石に自動で焦点を合わせ、YAGレーザーを照射し、プラズマ光を発生させることに成功した。さらにこの操作を無線通信により行った。一方で測定対象によって、自動焦点調整ができないことがあった。これは測定対象の反射率の違いによるCCDカメラが電子過飽和を起こしてしまうことが原因であった。このため、露光時間を自動で調整するプログラムを作成し、新たな自動焦点調整の手法を開発した。このプログラムによって露光時間を調整しながら集光点の位置を探すことが可能となった。

Keywords: elemental compositions, LIBS, Moon, Mars
Performance of a visible-InGaAs sensor onboard a lunar exploration camera

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Information of the lunar highland could help us to know the solidification of the lunar magma ocean and to estimate the internal structure of the Moon. We are now planning to develop a visible-SWIR macro camera with rock abrasion tool (RAT) which is required to establish a light-weighting for setting on a head of rover’s arm. The purpose of this camera is to observe the texture of polished rock surface (grain size, shape, species, and crystal configuration) to investigate the geologic history of the rock. The target crystal grain size is about 200 um in average diameter. We thus need a 500 x 500 pixel sensor to achieve 20 um/pixel spatial resolution with fields of view exceeding 100 mmphi. Spectra in the 0.8 ? 1.7 um region is important to analyze major mineral species found on the Moon. So, these requirements are achieved by a visible-InGaAs sensor which has sensitivity from visible to infrared wavelength. It is important to know the performance for using space exploration, especially, an environment at the lunar surface. We’ll report the details of the examinations about a dark current test of a visible-InGaAs sensor.

Keywords: visible-InGaAs sensor, dark current
Harleacala 40cm telescope used to observe sodium atoms emitted from the lunar surface using a Haleakala 40cm telescope

Kagitani et al., 2010, Planetary and Space Science, 58, 1660-1664, Variation in lunar sodium exosphere measured from lunar orbiter SELENE (Kaguya)
ライナーガンマ、リマシルサリスでの月磁気異常における表面下の磁化ソース
Subsurface magnetization source of Reiner Gamma and Rima Sirsalis magnetic anomalies on the Moon

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アポロ計画以降、磁力計と電子反射計の観測により月には磁気異常が複数存在することが知られている。しかしながら、これらの磁気異常の起源はまだ明らかになっていない。起源を推定するために、磁気異常ソースの磁化の情報を知ることは非常に重要である。本研究では、それらの形成過程に対する洞察を得るために2つの地域での月磁気異常をモデル化した。Reiner GammaとRima Sirsalisの磁気異常を対象とした。モデル化には低高度観測を行った期間でのLunar Prospectorの磁力計データを使用した。まず、磁気双極子による単純なモデルをついて、その結果に基づいて磁気異常を一様に磁化した月面に垂直な直方体モデルを構築した。結果として、2つの磁気異常地域について計5つの磁気異常ソースモデルが得られた。Reiner Gammaでの磁気異常では、直方体の位置と形状は高いアルベドを持つスワールの形態のような表面の特徴とよく一致することがわかった。このような一致は、表面での高いアルベドと磁気異常ソースとの間に相関があることを示唆している。Rima Sirsalisでの磁気異常では、2つの細長いソースはともに6 kmの深さに位置し、シルサリス渓谷に沿って延びている。この結果から、磁気異常ソースは表面下の渓谷と関係があるのかもしれない。本研究により表層や表面下での構造と磁気異常との相関を議論するために、磁気双極子よりも直方体のような有限の大きさを持った磁化したソースを考える方が有効であることが実証された。

キーワード: 月, 磁気異常, 直方体ソース, スワール, 渓谷
Keywords: moon, magnetic anomaly, prism source, swirl, rille