

[E] 口頭発表 | セッション記号 P (宇宙惑星科学) : P-PS 惑星科学

■ 2019年5月29日(水) 9:00 ~ 10:30 | 会 A01 東京ベイ幕張ホール

[P-PS03] Solar System Small Bodies: A New Frontier Arising Hayabusa 2, OSIRIS-REx and Other Projects

コンピーナ:石黒 正晃(ソウル大学物理天文学科)、中本 泰史(東京工業大学)、安部 正真(宇宙航空研究開発機構宇宙科学研究所)、Olivier S Barnouin(Johns Hopkins University Applied Physics Laboratory)、座長:Taishi Nakamoto(東京工業大学)

2018年6月、小惑星探査機「はやぶさ2」が約3年半の航海を経て、目的地リュウグウに到着した。また、別の小惑星探査機「OSIRIS-REx」も探査天体Bennuに間もなく到着しようとしている。これらの探査によって、太陽系小天体研究は、今まさに新しい局面を迎えようとしている。本セッションは、2012年から開催されてきたもので、これまでに実験、観測、探査、理論、さらにサンプル分析の観点から太陽系小天体の研究に関して議論を行ってきた。特に今回は、はやぶさ2とOSIRIS-RExの初期成果を中心に太陽系小天体に関する最新研究を持ち寄り、今後の展望を議論することを目的とする。はやぶさ2、OSIRIS-REx以外の研究成果発表も歓迎する。

9:00 ~ 9:15

[PPS03-19] The shape of Bennu: Implications for internal structure.

★Invited Papers

*Olivier S Barnouin¹、Micheal G. Daly²、Eric E Palmer³、Robert W Gaskell³、John R. Weirich³、Catherine L Johnson⁴、Manar Al Asad⁴、James H Roberts¹、Mark E. Perry¹、Hannah C.M. Sursorney⁴、R. Terik Daly¹、Edward B. Bierhaus⁵、Jeff A Seabrook²、Raymond C. Espiritu¹、A. Hari Nair¹、Lilian Nguyen¹、Gregory A Neumann⁶、Carolyn M Ernst¹、William V Boynton⁷、Micheal C. Nolan⁷、Coralie D. Adams⁹、Micheal C. Moreau⁶、Bashar Rizk⁷、Christian Drouet D'Aubigny⁷、Erica R. Jawin⁸、Kevin J Walsh¹⁰、Patrick Michel¹¹、Stephen R. Schwartz⁷、Ronald L. Ballouz⁷、Erwan M Mazarico⁶、Daniel J. Scheeres¹²、Jay W. McMahon¹²、W Bottke¹⁰、Seiji Sugita¹³、Naru Hirata¹⁴、Noayuki Hirata¹⁵、Sei-ichiro Watanabe¹⁶、Keara N. Burke⁷、Daniella N. DellaGuistina⁷、Carinna A. Bennet⁷、Dante Lauretta⁷ (1.Johns Hopkins University Applied Physics Laboratory、2.The Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada、3.Planetary Science Institute, Tucson, AZ, USA、4.Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada、5.Lockheed Martin Space Systems Company, Denver, CO, USA、6.NASA Goddard Space Flight Center, Greenbelt, MD, USA、7.Lunar Planetary Laboratory, University of Arizona, Tucson, AZ, USA、8.Smithsonian Institution National Museum of Natural History, Washington, DC, USA、9.KinetX Aerospace, Inc. Simi Valley, CA, USA、10.Southwest Research Institute, Boulder, CO, USA、11.Universit e C ote d'Azur, Observatoire de la C ote d'Azur, CNRS, Laboratoire Lagrange, Nice, France、12.Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO, USA、13.University of Tokyo, Tokyo, Japan、14.Aizu University, Aizu-Wakamatsu, Japan、15.Kobe University, Kobe, Japan、16.Nagoya University, Nagoya, Japan.)

9:15 ~ 9:30

[PPS03-20] Global Geology of Bennu from NASA's OSIRIS-REx Space Mission

★Invited Papers

*Erica R Jawin¹、Kevin J Walsh²、Tim McCoy¹、Harold C Connolly³、Dante S Lauretta⁴、Ron L Ballouz⁴、Olivier S Barnouin⁵、C Beddingfield⁶、Carina A Bennett⁴、Edward B Bierhaus⁷、Keara N Burke⁴、Ben Clark⁸、Michael G Daly⁹、Marco Delbo¹⁰、Daniella DellaGiustina⁴、Jason P Dworkin¹¹、Christine Hartzell¹²、John Marshall⁶、Patrick Michel¹⁰、Jamie L. Molaro¹³、Mike Nolan⁴、Maurizio Pajola¹⁴、Mark Perry⁵、Bashar Rizk⁴、Scott Sandford¹⁵、Dan J Scheeres¹⁶、Stephen R Schwartz⁴、David Trang¹⁷ (1.Smithsonian National Institute, Washington, DC, USA、2.Southwest Research Institute, Boulder, CO, USA、3.Dept. of Geology, Rowan University, Glassboro, NJ, USA、4.Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA、5.The Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA、6.SETI Institute, Mountain View, CA, USA、7.Lockheed Martin Space Systems Company, USA、8.Space Science Institute, Boulder CO, USA、9.York University, Canada、10.Laboratoire Lagrange, Universit e C ote d'Azur, Observatoire de la C ote d'Azur, CNRS, Laboratoire Lagrange, Nice, France、11.NASA Goddard Space Flight Center, Greenbelt, MD, USA、12.Department of

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9:30 ~ 9:45

[PPS03-21] Modeling surface mobility mechanisms on a top-shaped near-Earth asteroid

★Invited Papers

*Ronald Ballouz¹、Nicola Baresi²、Olivier S Barnouin³、Carina A Bennet¹、Edward B Bierhaus⁴、Keara N Burke¹、Harold C Connolly⁵、Sarah T Crites²、Daniella DellaGiustitna¹、Erica Jawin⁶、Dante S Lauretta¹、Patrick Michel⁷、Derek C Richardson⁸、Dan J Scheeres⁹、Stephen Schwartz¹、Seiji Sugita¹⁰、Eri Tatsumi¹⁰、Florian Thuillet⁷、Kevin Walsh¹¹ (1.Lunar and Planetary Lab, University of Arizona, Tucson, AZ, USA、2.Institute of Space and Astronautical Science, Sagami-hara, Japan、3.The Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, USA、4.Lockheed Martin, Boulder, CO, USA、5.Department of Geology, Rowan University, Glassboro, NJ, USA、6.Smithsonian National Museum of Natural History, Washington, DC, USA、7.UCA-OCA-CNRS, Lagrange Laboratory, Nice, France、8.Dept. of Astronomy, University of Maryland, College Park, MD, USA、9.Dept. of Aerospace Engineering Sciences, University of Colorado, Boulder, CO, USA、10.University of Tokyo, Tokyo, Japan、11.Southwest Research Institute, Boulder, CO, USA)

9:45 ~ 10:00

[PPS03-22] Visualization and Analysis of Solar System Small Bodies with NASA's Solar System Treks Project

*Brian Hamilton Day¹、Emily Law² (1.NASA Solar System Exploration Research Virtual Institute, NASA Ames Research Center、2.NASA Jet Propulsion Laboratory, California Institute of Technology)

10:00 ~ 10:15

[PPS03-23] Density Distribution within Small Solar System Bodies Based on Smooth Terrain Shape: Asteroid 25143 Itokawa and Comet 67P/Churyumov-Gerasimenko

*金丸 仁明¹、佐々木 晶¹、Mark Wieczorek² (1.大阪大学、2.コートダジュール天文台)

10:15 ~ 10:30

[PPS03-24] 彗星探査計画CAESARに向けた非晶質珪酸塩の低温水質変成実験

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The shape of Bennu: Implications for internal structure.

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Introduction: We used data collected by the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft since November 1, 2018 to develop a global digital terrain model (DTM) of Bennu. The DTM is developed from images collected by the OSIRIS-REx Camera Suite using stereophotoclinometry (SPC). We validated the DTM independently using limb data and by the identification of keypoints between actual images and synthetic images rendered from the DTM. The results are also compared to an independent model derived from range measurements collected by the OSIRIS-REx Laser Altimeter (OLA). While developing the global model, we also refine the pole orientation and rotational state of the asteroid. The characteristics of the resulting global digital terrain model provide constraints on the factors responsible for the origin and evolution of Bennu's shape and surface.

Digital Terrain Model Construction from Imaging: About 1500 OCAMS images with ground sample distance ranging from 30 to 200 m were used to develop the global DTM of Bennu. We used distant limb data of Bennu to construct an initial DTM of Bennu. Then a combination of geometric stereo data and surface lighting conditions (or photoclinometry) modeled small patches (or maplets) of terrain across the asteroid. Geometric stereo typically defines the location of the center of each maplet, while the surface tilts across the maplet are estimated by best fitting the brightness variations of images that contain some portion of the maplet. These maplets are then combined to build a global model. The model increases in detail, accuracy, and precision as higher-resolution images and images with different viewing conditions are incorporated.

Digital Terrain Model Construction from Laser Altimetry: We collated several six-hour linear scans obtained by OLA during orbit around Bennu to make an independent shape model of Bennu at a resolution equivalent to the one derived from imaging. This DTM is improved relative to the SPC-derived model because OLA better resolves the heights, and extent of 1 to 3m boulders across the surface of the asteroid.

Bennu' s Geomorphological and Structural Properties: The evaluation of the both models shows that the average size of the asteroid is 490.06 ± 0.16 m.

The model shows the presence of several features:

- An equatorial ridge that is muted, and is diamond-shaped when viewed from the pole;
- Topographic north-south ridges that extend in some instances from pole to pole. The ridges influence the distribution of boulders, which are frequently concentrated between the ridges;
- Large craters that influence some of the attributes of the shape, primarily along the equator;
- A few large protruding boulders >40 m in diameter and >10 m high, mostly in the southern hemisphere;
- Grooves, scarps, and troughs that in some instances extend several 10s to 100s of meters, with depths ranging from 2–10 m.

Conclusion: The initial shape characteristics suggest that Bennu has some interior stiffness. Considering past modeling efforts investigating deformation due to spin-up, the lack of a circular equatorial ridge with a pronounced bulge, and the presence of high standing north-south ridges indicate that in spite of an abundance of evidence for material moving towards the equator, Bennu has interior structure that resists deformation.

Keywords: (101955) Bennu, Asteroids, OSIRIS-REx mission

Global Geology of Bennu from NASA's OSIRIS-REx Space Mission

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NASA's OSIRIS-REx sample return mission has been observing the near-Earth Asteroid (101955) Bennu since December 2018 and will be collecting a sample of the surface in the summer of 2020, to be returned to Earth in 2023. Preliminary and ongoing observations have yielded much information about Bennu's formation, evolution, and ongoing geologic activity. Here we report on the global geology of Bennu based on analyses of images combined with shape, mass, and slope measurements. Initial results suggest that Bennu is a rubble-pile asteroid, formed from a parent body that was collisionally disrupted and reaccumulated. The asteroid has a "top" shape which is spherical with an equatorial bulge, similar to other near-Earth asteroids including Ryugu as observed by the Hayabusa2 sample return space mission. Candidate impact craters have been observed at a range of diameters between ~10-150 m across the surface of Bennu, leading to a crater retention age of 100 million to 1 billion years. An apparent concentration of large crater candidates at low latitudes suggest that the equatorial ridge is stratigraphically old, and may have formed early in Bennu's history or been inherited from the reaccumulation event which created the asteroid. Several linear features have been identified on Bennu, the largest of which are topographic highs that extend longitudinally from the northern polar regions to the equator. Boulders are concentrated between several of these linear ridges, as well as in the interior of large candidate craters. Boulders on Bennu appear to be geologically diverse. Boulder sizes range from < 3 m to ~95 m in diameter with large variations in geometric albedo, morphology, degree of burial, and state of degradation. Fractured boulders have been identified with various numbers, orientations, and widths of fractures. Distinct clasts within several boulders indicate they may be breccias, while piles of boulders may represent disaggregated polymict or brecciated boulders. Current imaging resolution cannot resolve centimeter-sized particles, so direct detections of regolith or other sub-cm sized particles have not been made. However, several small candidate craters (< 20 m diameter) have a significant lack of boulders relative to the surrounding terrain, and additional datasets suggest the presence of a component of fine-grained particles. Improved image resolution will aid in the identification of regolith deposits on Bennu.

Keywords: OSIRIS-REx, Bennu, Asteroid, Geology

Modeling surface mobility mechanisms on a top-shaped near-Earth asteroid

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The advent of near-Earth asteroid (NEA) encounters with spacecraft has provided a view of planetary surfaces evolving on the smallest objects yet explored. The arrival of OSIRIS-REx and Hayabusa2 at their target asteroids (101955) Bennu, with average diameter (d) = 0.49 km, and (162173) Ryugu (d = 0.90 km), revealed cratered top-shaped worlds with signs of surface mobility [1, 2]. Compared to larger planetary bodies, Bennu and Ryugu's small sizes and gravities challenge the conventional understanding of surface modification mechanisms, such as the redistribution of boulders on the surface or the erasure of craters.

On the larger NEA (433) Eros (d = 16.8 km), boulders were spatially correlated with impact craters, which degrade through impact-induced seismic shaking [3]. However, our poor understanding of rubble-pile interiors [4], combined with processes that operate more efficiently on smaller NEAs (such as thermal re-radiation torques, i.e., the YORP effect [5]), introduces new complexities to understanding surface mobility on Bennu and Ryugu.

Here, we first present evidence of a dynamic surface on Bennu and Ryugu. Then, we present an analysis of the dynamical processes that may dominate the surface modification of small top-shaped NEAs. We model the redistribution of material on the surface due to different input energy sources: i) impact-induced seismic shaking, ii) YORP spin-up, iii) impact cratering, and iv) planetary encounters. We use a combination of techniques that allows us to approach the problem at multiple length and time scales. The first step models the global effect of the energy sources using analytical techniques. In the second step, we model the fine grain scale interactions in a microgravity environment in short timescales using a particle dynamics code [6,7]. Finally, we propagate the accumulated effect of the fine-scale interactions by integrating individual surface modifications over the typical timescale of each individual process. The results are used to assess which of the above listed mechanisms are the most effective at transforming small NEA surfaces.

References:

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2. Sugita et al. 2019, Science, Accepted.

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4. Scheeres, D.J. et al. (2015) in *Asteroids IV* (eds. Michel, DeMeo, & Bottke), pp. 745–766.
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Acknowledgements:

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Keywords: Near Earth Asteroids, OSIRIS-REx, Hayabusa2

Visualization and Analysis of Solar System Small Bodies with NASA's Solar System Treks Project

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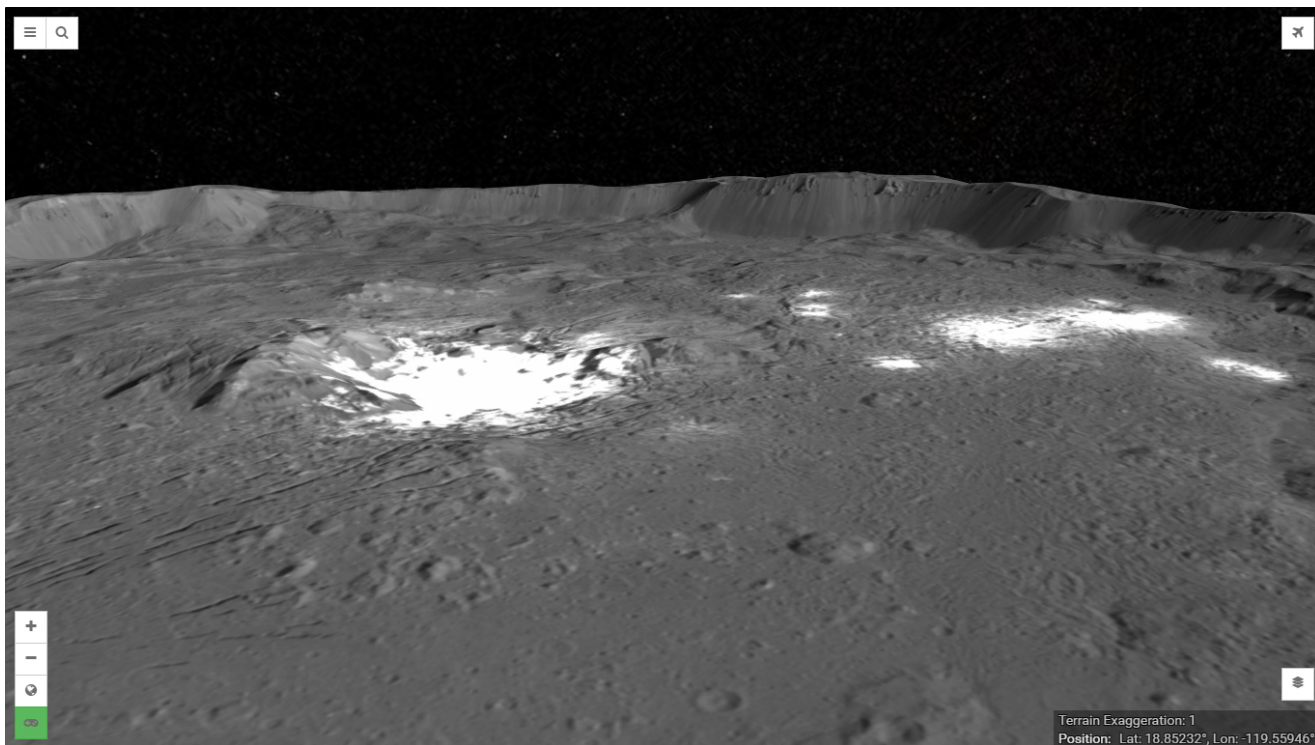
1. NASA Solar System Exploration Research Virtual Institute, NASA Ames Research Center, 2. NASA Jet Propulsion Laboratory, California Institute of Technology

In its investigations of Vesta and Ceres, NASA's Dawn mission has returned spectacular data detailing the surfaces of these two prominent small bodies in our Solar System's asteroid belt. In order to greatly facilitate dissemination, visualization, and analysis of this data, and public understanding of the mission, the Dawn mission has partnered with NASA's Solar System Treks Project (SSTP). SSTP has recently released an update to the Vesta Trek online portal (<https://trek.nasa.gov/vesta/>) and has released a new Ceres Trek portal (<https://trek.nasa.gov/ceres/>).

This presentation will showcase the use of the Ceres Trek and Vesta Trek portals and demonstrate how they can be used to visualize and analyze particularly interesting landforms such as the pitted terrain on Vesta and relic cryovolcanoes on Ceres. We will also demonstrate the new VR capability that has been added to the portals, allowing users to generate their own virtual reality flyovers for any user-defined paths along the bodies' surfaces. In addition to highlighting the portals for Ceres and Vesta, the presentation will preview additional portals being planned/developed for other small bodies. NASA and JAXA have requested the development of a portal for the asteroid Ryugu to facilitate dissemination, visualization, and analysis of data from Japan's Hayabusa2 mission, and a portal for Mars' moon Phobos in support of mission planning for Japan's MMX mission. We are also planning a portal for the asteroid Bennu with data from the OSIRIS-Rex mission.

All of these products are efforts in the NASA Solar System Treks Project (SSTP), available at <https://trek.nasa.gov>. NASA's Solar System Trek online portals provide web-based suites of interactive data visualization and analysis tools to enable mission planners, planetary scientists, students, and the general public to access mapped data products from past and current missions for a growing number of planetary bodies including the Moon, Mars, Vesta, etc. These portals are being used for site selection and analysis by NASA and a number of its international partners, supporting upcoming missions. In addition to demonstrating the capabilities of selected portals in this presentation, we will solicit input from the community for ideas for future enhancements to the portals.

Keywords: Ceres, Vesta



Density Distribution within Small Solar System Bodies Based on Smooth Terrain Shape: Asteroid 25143 Itokawa and Comet 67P/Churyumov-Gerasimenko

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Small solar system bodies are the remnants of the early stage of the solar system formation. Shapes and interior structures of small bodies tell us about how they formed and evolved. Particularly, the interior density distribution of small bodies is an important clue for better understanding of planetesimal collisions and subsequent accumulation processes. However, we have much less information about their interiors than their surface properties, partly because it is difficult to measure the exterior gravity precisely in a small body mission. We have investigated a method to estimate density distribution within a small body based on combining spacecraft imagery and the simulated gravity field on the surface of the small body (Kanamaru and Sasaki, 2019; Kanamaru, Sasaki and Wieczorek, in prep.).

If a small body possesses loose regolith sufficiently, over geologic time, impact-induced seismic shaking or cometary activity may have triggered mass movement from a high standing region to a low standing region (Richardson and Bowling, 2014). Our inversion of density distribution assumes that a very flat region on a small body, which is covered with fine gravels and associated with the low standing area in gravitational potential, might approximate an equi-potential surface. Therefore, the inversion processes include (1) mapping a smooth terrain on a 3D shape model of the small body using the Small Body Mapping Tool, and (2) computing dynamic elevations above a reference potential surface given ununiform density distribution (as shown in the upper left panel in Figure). As a criteria for mapping the smooth terrain, we also used a surface roughness defined as the standard deviation of the dynamic elevations within a circle of a specific scale (upper right panel in Figure). The misfit between the smooth terrains and the equi-potential surface is characterized by the standard deviation of the surface elevations within the flat region. On the above assumption of the topographic erosion process, the minimum misfit gives a best fitting density. We applied this method to asteroid Itokawa and comet 67P/Churyumov-Gerasimenko to investigate whether each of their lobes has a different density from the other or not.

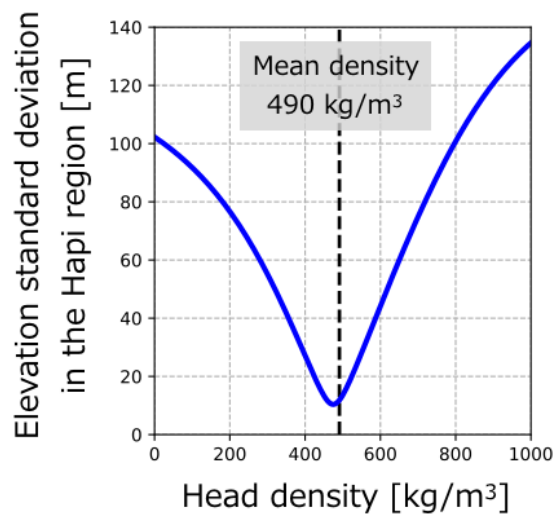
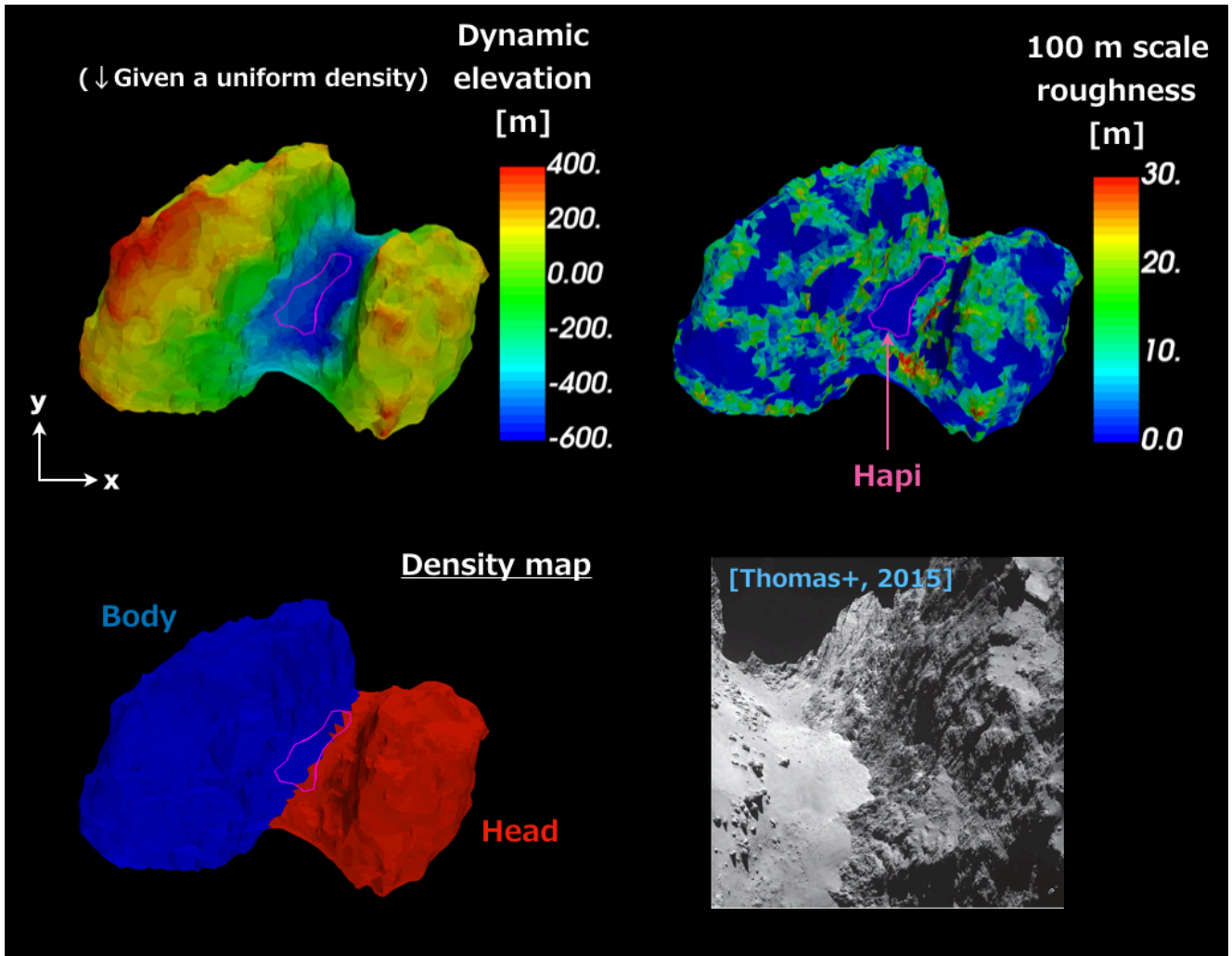
There exists three major smooth terrains on Itokawa, named MUSES-C Regio, Sagamihara Regio and Uchinoura Regio. Given different densities to the two lobes of Itokawa (the head and body), the misfit for the smooth terrains is minimized where the head of Itokawa has a higher density than the mean bulk density. Based on the consideration of the systematic errors that arise from the uncertainty of the shape model itself and the calculation error of the gravity field, the allowable range of the head density is estimated to be 2,450 (2,220-2,670) kg/m³ in contrast to the body density of 1,930 (1,976-1,879) kg/m³. Such a great contrast in density between the two lobes is consistent with the independent estimate of the center-of-mass/center-of-figure offset of Itokawa based on the YORP spin-up observation (Lowry et al., 2014).

The comet nucleus of 67P also has a smooth terrain called Hapi, which is likely to be covered with particles falling from other regions. In the density inversion for the two lobes of 67P, the head and body

(see the middle left panel in Figure), the best fitting density of the head is similar to the mean bulk density unlike the case of Itokawa (lower panel in Figure). This result indicates a global scaled homogeneity of 67P, which is consistent with the gravity measurement by Patzold et al. (2016). If the bi-lobed shape of the comet was formed by a sub-catastrophic disruption of its parent body and merger of two main fragments (Jutzi and Benz, 2017), it is possible for the two lobes to have the same density.

キーワード：太陽系小天体、小惑星25143イトカワ、チュリモフ・ゲラシメンコ彗星、内部密度分布構造、重力場

Keywords: Small solar system body, Asteroid 25143 Itokawa, Comet 67P/Churyumov-Gerasimenko, Interior density distribution, Gravity field



彗星探査計画CAESARに向けた非晶質珪酸塩の低温水質変成実験 Low temperature hydration experiments of cometary analog materials towards the Comet Astrobiology Exploration Sample Return (CAESAR) mission

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The Comet Astrobiology Exploration Sample Return (CAESAR) mission is a final candidate for selection as the fourth mission in NASA's New Frontiers Program. CAESAR aims to acquire and return to Earth for laboratory analysis a minimum of 80 g of surface material from the nucleus of comet 67P/Churyumov-Gerasimenko (67P) (Squyres et al. 2018). Near-infrared spectra of a short-period comet 67P taken by the spectrometer onboard Rosetta spacecraft also indicate the absence of phyllosilicates in this comet (Capaccioni et al. 2015). In order to return anhydrous samples from 67P, optimal conditions for sampling should be determined because cometary dust particles especially amorphous silicates are highly reactive. Hydration process of anhydrous crystalline silicates such as olivine is already well-characterized, whereas reaction of water vapor or ice with amorphous silicates and organic matters at temperatures below H₂O freezing points has been poorly understood. In this study, we performed incubation experiments of amorphous silicates and organic matters under low temperature conditions with ice or vapor of D₂O/NH₃.

Amorphous silicate nanoparticles with three different chemical compositions and textures (S1, S2, and S3), and commercial glycine and ribose powder were used in the experiments. S1 is composed of ~100 nm particles having MgSi₂O₅ composition prepared with sol-gel processing. S2 and S3 are condensates from high temperature gases. S2 is amorphous Mg₂SiO₄ nanoparticles of ~80 nm in size synthesized in a Radio Frequency plasma system (Koike et al. 2010). S3 is 30-100 nm sized amorphous silicate with Mg/Si ~ 0.93 embedded with metallic Fe-Ni particles condensed from a high temperature vapor of the CI chondritic ratios of Mg, Al, Ca, Fe, and Ni to Si in an induction thermal plasma system (Kim et al. 2017).

Two types of ice were used in the experiments to evaluate the effects of corrosive gases in 67P; (A) Pure D₂O ice (99.90% purity) and (B) Mixture D₂O ice with 0.3% H₂O and 0.15% NH₃. Experiments with different ices were performed in different vacuum containers placed in a cryogenic box. About 5 mg of three silicate and glycine samples were put in different open-top glass bottles (2 ml). Approximately 50 mg of chipped ice fragments were put in the glass bottles and directly contact with the silicate and glycine samples. Roughly ~500 mg of the same ice fragments were put in the vacuum containers as a vapor source. The temperature of the cryogenic box sets at -17 or -27°C. The samples were exposed with saturated vapor of ices for 10-120 days. As a comparison, exposure experiments of amorphous silicate samples (S1, S2, and S3) to H₂O vapor were also conducted at 25 and 50°C for 10 days.

The exposed silicate samples were analyzed with a powder X-ray diffraction (XRD, Rigaku SmartLab) and Fourier-transform infrared spectroscopy (FT-IR; JASCO MFT-680, Thermo Nicolet iS5). The recovery rate of glycine (i.e., molar ratio of recovered glycine over starting glycine) and ribose were obtained by liquid

chromatography tandem mass spectrometer (LC/MSMS; Shimadzu LCMS-8040).

No clear change of the XRD patterns and FT-IR spectra for S1, S2, and S3 was confirmed after the experiments for <120 days at -17 and -27°C. The recovery of glycine exposed to D₂O ice and NH₃-containing D₂O ice for 10 days was 108±8 mol% and 105±8 mol%, respectively. The recovery of ribose exposed to D₂O ice and NH₃-containing D₂O ice for 10 days was 108±12 mol% and 105±12 mol%, respectively. Because the ice sublimation timescale is very short at the experimental temperatures, the present results indicate that cometary silicates at <-20°C in comets are pristine even if they have high surface to volume ratio and amorphous structures as GEMS grains in anhydrous CP-IDPs.

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