Planetesimals: Early Differentiation And Consequences For Planets

*Linda T Elkins-Tanton[1], Ben Weiss[2]

1. Arizona State University, 2. Massachusetts Institute of Technology

L.T. Elkins-Tanton[1], B.P. Weiss[2]. [1]School of Earth and Space Exploration, Arizona State University, 781 Terrace Rd., Tempe AZ 85287, ltelkins@asu.edu, [2]MIT.

Planetesimals are small, rocky and icy planetary bodies that formed and evolved in the early solar system. Planetesimals play at least two important roles in planetary science. First, as the first generation of planetary objects, they served as the fundamental building blocks of planets. Intermediate in size between cm-sized pebbles and 1000-km-sized planetary embryos, they represent a critical and still enigmatic stage in planetary growth.

Because the formation of km-sized bodies is difficult to understand given the likelihood of erosive mutual collisions and rapid orbital evolution due to gas drag, solving this problem will provide fundamental constraints on the sizes of accreting bodies, the nature of turbulence in the nebula, and the intensity of nebular magnetic fields. Additionally, planetesimals, and their modern-day relics—asteroids, comets and Kuiper belt objects—are fascinating planetary worlds in their own right. They experienced a much broader range of thermal histories than planets; these diverse conditions produced a diversity igneous end states, from unmelted bodies, to partially melted bodies to fully molten and differentiated objects. Furthermore, their geologic evolution and internal structures were fundamentally sculpted by impacts and mutual collisions. In many ways, planetesimals are like the planets they became, but in other ways they are very unfamiliar places.

In 2017 Cambridge University press published an edited volume on planetesimals, summarizing the state of knowledge of this newly energized and rapidly-changing field [1]. Here we will present a review of research on planetesimals.

Iron meteorites demonstrate the existence of differentiated rocky planetesimals in the first 500,000 years after solids formed in the disk [2], and Vesta has differentiated into a metal core and silicate mantle (Raymond et al., this volume). Johansen et al. [3] suggest the icy asteroids formed between 2 to 4 My after calcium-aluminum-rich inclusions (CAIs). The breakthrough discovery of pebble accretion, which shows that pebble-sized objects accrete to form larger objects extremely efficiently through gravitational perturbation of their orbits, indicates that accretion timescale could have been as short as a few thousand years for 100 km objects [4]. This extremely short timescale supports the use of simple models that assume nearly instantaneous accretion relative to the timescale of ^{26}Al heating, although pebble accretion would have continued past the point of ^{26}Al activity, and coated the young planetesimals with unmelted rinds over ˜1 million years [3].

The meteorite collection and the asteroid belt differ in their ratios of primitive and differentiated metal and silicate fractions compared to models of differentiation, but all also differ in their ratios of metal and silicate in the completed planets Mercury, Venus, and Earth. However, the combined effects of fluid and magma mobilization and loss and impact erosion necessarily created a broad taxonomy of planetesimals, each of which would contribute a different share of volatiles, metals, and silicates to growing embryos and planets. Furthermore, we may not have samples from the material that formed the terrestrial planets, since most of our meteoritic material originated from the asteroid belt in relatively recent times.

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Keywords: rocky and icy planetary bodies , erosive mutual collisions , rapid orbital evolution, asteroids, comets and Kuiper belt objects, meteorite collection , pebble accretion

Dust growth and planetesimal formation near the snow line in protoplanetary disks

*奥住 聡[1]
*Satoshi Okuzumi[1]

1. 東京工業大学地球惑星科学系
1. Department of Earth and Planetary Sciences, Tokyo Institute of Technology

The growth of micron-sized dust particles into kilometer-sized planetesimals is the first step of planet formation in protoplanetary disks. The details of planetesimal formation are still poorly understood because a number of barriers have been identified that could hinder dust growth. In recent years, much attention has been paid to the roles of the snow line in dust growth. The snow line is the location where water ice sublimates and condenses, and recent models have shown that the sublimation, condensation, and other related processes like sintering greatly change the size distribution of icy dust particles near the snow line. In my talk, I will review how these processes could affect planetesimal formation near the snow line as well as the observational appearance of protoplanetary disks.

The high-inclination Trans-Neptunian Objects and the possible existence of Vertical TNO belt

*Hsing-Wen Lin[1]

1. Institute of Astronomy, National Central University

A new high-inclination, retrograde motion TNO, “Niku”, discovered by PS1 survey, and was soon linked with a supposed prograde Centaur, 2011 KT19. This unusual object can be stable for about 0.1Gyr with the 4 outer planets configuration of solar system. We compared 2011 KT19 “Niku” with the other five high-inclination objects, that have distant perihelion distances, and found that all of them have very similar longitudes of the ascending nodes (Ω). This result means the highly inclined, distant objects have common orbital plane, and moreover, the prograde and retrograde objects have opposite orbital axes. Our numerical integration shows that all of the six objects can not preserve the common ascending nodes in neither (1) the current 4 outer planets configuration, nor (2) current 4 outer planets plus the additional Planet Nine; after 1Myrs their ascending nodes will distribute randomly and lose the common orbital plane. Finally, we propose the possible existence of a new TNO, or Centaur belt oriented perpendicular to the ecliptic plane of our solar system. The future solar system object surveys, i.e. HSC and LSST, might be able to find more highly inclined, distant objects with a common orbital plane.

Keywords: Trans-Neptunian Objects, Centaur, Sky Survey

Clues on the origin of comets from Rosetta and Philae

*Bjorn Johan Ragnar Davidsson[1]

1. Jet Propulsion Laboratory, California Institute of Technology

The ESA Rosetta mission with US instrument participation successfully completed its two-year primary mission to comet 67P/Churyumov-Gerasimenko in Sep 2016. The Rosetta orbiter and the Philae lander made the most thorough documentation of the physical and chemical properties of a comet nucleus, gas and dust coma, and plasma environment thus far in the history of human spaceflight.

The evolving comet landscape revealed by the cameras, the composition of gas measured by mass spectrometers, the odd shapes and structures of dust aggregates documented by the atomic force microscope, and the interior structure probed by the bistatic radar are as mysterious as the Egyptian hieroglyphs that inspired the name of the spacecraft. Deciphering this ancient message that tells the story of the formation and evolution of the comet, and that provides insight to the Solar System environment in which comets are born and processed, is far from trivial.

I will provide an overview of the observations by Rosetta and Philae that are most relevant for reconstructing the origin of this comet nucleus. I will also sketch one formation scenario that has been proposed to explain the observed properties, that interprets the high porosity, low strength, structural and morphological properties, chemical composition, and apparent lack of aqueous alteration as signatures of an ancient mostly primordial nucleus that has not been substantially processed by heat and collisions since its birth at the dawn of the Solar System. Perceived problems with this interpretation are discussed and the significance of resolving these issues for understanding the early Solar System are described.

Keywords: Comets, Solar System origins, Rosetta

A Versatile Physicochemical Model for Small Solar System Bodies (SUISEI)

*Daniel C Boice[1]

1. Scientific Studies and Consulting

A suite of computational tools, named SUISEI, has been developed over the past decades and successfully applied to interpret observations of comets. A brief overview of SUISEI will be given; including ComChem, a global, multifluid gas dynamics simulation with detailed chemical kinetics of the cometary coma; coupled with ComDust, a model of comet dust evolution and interaction with gas; and ComNuc, a 3-D simulation of gas and heat flow within the comet nucleus porous subsurface layers. The combination of these tools have resulted in an improved knowledge of chemical species that form in cometary environments and their relationship to native molecules that exist in the nucleus ices by analyzing space- and ground-based observations and *in situ* measurements by instrumentation onboard spacecraft missions. This model is especially timely with the recent encounter of ESA’ s Rosetta spacecraft with Comet 67P/Churyumov-Gerasimenko which ended in September 2016. Applications of SUISEI will be made to comets and the near-Sun object, (3200) Phaethon.

Keywords: Comets, Reactive Gas Dynamics, Coma Chemistry, Cometary Dust, Comet 67P/Churyumov-Gerasimenko, (3200) Phaethon

Asteroid (16) Psyche: Visiting a Metal World

L.T. Elkins-Tanton[1], E. Asphaug[1], *James F Bell[1], D. Bercovici[2], B.G. Bills[3], R.P. Binzel[4], W.F. Bottke[5], G.M. Brown[3], J. Goldsten[6], R. Jaumann[7], I. Jun[3], D.J. Lawrence[6], P. Lord[9], S. Marchi[5], T. McCoy[8], D. Oh[3], R.S. Park[3], P.N. Peplowski[6], C.A. Polanskey[3], D. Potter[9], T.H. Prettyman[10], C.A. Raymond[3], C.T. Russell[11], S. Scott[9], H. Stone[3], K.G. Sukhatme[3], N.Z. Warner[3], B.P. Weiss[4], D.D. Wenkert[3], M. Wieczorek[12], D. Williams[1], M.T. Zuber[4]

1. Arizona State University, 2. Yale University, 3. Jet Propulsion Laboratory/California Institute of Technology, 4. Massachusetts Institute of Technology, 5. Southwest Research Institute, 6. Applied Physics Laboratory/Johns Hopkins University, 7. DLR/German Aerospace Center, 8. Smithsonian Institution, 9. Space Systems Loral, Inc., 10. Planetary Science Institute, 11. University of California, Los Angeles, 12. Observatoire de la Côte d'Azur

The Psyche mission has been selected as the 14th in the NASA Discovery program. This mission will investigate what is likely an exposed planetary metallic core, the asteroid (16) Psyche. Estimates of density range widely but cluster between 6,500 and 7,500 kg m^3 [1, 2, 3, 4]. Any density higher than 3,500 kg m^{-3} likely indicates metal: rocky main belt asteroids have average densities roughly one-third to one-half their parent rock density [5]. Orbiting in the outer main belt at ~3 AU, the asteroid (16) Psyche has an effective diameter of ~235 km [7], and is thought to be made almost entirely of Fe-Ni metal [8, 9].

Models show that among the accretionary collisions early in the solar system, some destructive “hit and run” impacts strip the silicate mantle from differentiated bodies [6]. This is the leading hypothesis for Psyche’s formation: it is a bare planetesimal core. If our observations indicate that it is not a core, Psyche may instead be highly reduced, primordial metal-rich materials that accreted closer to the Sun.

The mission has five objectives:
1) Determine whether Psyche is a core, or if it is unmelted material;
2) Determine the relative ages of regions of its surface;
3) Determine whether small metal bodies incorporate the same light elements as are expected in the Earth’s high-pressure core;
4) Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth’s core; and
5) Characterize Psyche’s topography and impact crater morphology.

We will meet these objectives by examining Psyche with three high heritage instruments and radio science:
(i) Two block-redundant multispectral imagers (MSL Mastcam heritage) with clear and seven color filters provide surface geology, composition, and topographic information. Lead: J.F. Bell, ASU, partnering with Malin Space Science Systems, Inc.;
(ii) A gamma-ray and neutron spectrometer (MESSENGER heritage) determines the elemental composition for key elements (e.g., Fe, Ni, Si, and K) as well as compositional heterogeneity across Psyche’s surface. Lead: D.J. Lawrence, APL;
(iii) Dual fluxgate magnetometers in a gradiometer configuration characterize the magnetic field. Investigation Lead: B.P. Weiss, MIT. Development Lead: C.T. Russell, UCLA; and
(iv) Radio science will map Psyche’s gravity field using the X-band telecomm system. Lead: M.T. Zuber, MIT.

The solar-electric propulsion chassis will be built by Space Systems Loral in Palo Alto, California [10], the mission will be led by ASU and JPL will be responsible for mission management, operations, and navigation.

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Keywords: Psyche, Metallic Asteroids, Space Missions

Main Belt Asteroids: A Melting Pot of Early Solar System Relicts

*Simone Marchi[1]

1. Southwest Research Institute

The Main Belt between Mars' and Jupiter's orbit hosts a myriad of asteroids, whose most massive members are the 500-km Vesta and 970-km Ceres. A classical view held that the current asteroid belt represents a tiny fraction (~0.1%) of a once-much-more massive population of planetesimals formed in-situ. Due to their being separated "at birth", asteroids were thought to have escaped major evolutionary processes typical of larger planets. As a consequence, asteroids have been largely regarded as primordial relicts of the early Solar System, thus spawning interest in their space exploration. Reconnaissance of first Main Belt asteroids by the Galileo and NEAR missions seemed to support this view.

Meanwhile, with the advent of advanced numerical modeling, it has become increasingly clear that not all asteroids are primordial, and those smaller than about ~100 km in diameter are thought to be collisionally generated fragments of larger siblings.

In recent years, other new ideas have emerged. The overall orbital architecture of the Solar System implies large-scale mobility of the giant planets. In some of the extreme scenarios, the primordial Main Belt is dismantled and reassembled by a migrating Jupiter within the first million of years of formation. Later dynamical instabilities would also add radial mobility resulting in vigorous mixing in the Main Belt region. In these modern views, the Main Belt acts as a melting pot, collecting objects scattered from the four corners of the Solar System: from the terrestrial planet region to the outer trans-neptunian disk.

The exploration of these relatively accessible small worlds, thus, provides us with an unparalleled means to study the broader issues of Solar System formation, such as the formation location and internal evolution of planetesimals. The Dawn mission at Vesta and Ceres has paved the way for these in-depth investigations, but also showed that the study of these fundamental issues is complicated by billions of years of collisional evolution.

The great challenge for future missions, such as Lucy and Psyche, lies in being able to tease out primordial and evolutionary processes in order to reach a deeper understanding of our Solar System formation.

Keywords: asteroids, space missions, Dawn mission

The connection between asteroids and meteorites

*Michael John TOPLIS[1], Harry Y. McSween[2]

1. Institut de Recherche en Astrophysique et Planétologie, University of Toulouse, France, 2. Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, USA

Meteorites and asteroids provide two complementary windows into the processes that shaped the earliest stages of planet building in the internal part of the solar system. The study of meteorites has the advantage that samples can be examined in great detail in the laboratory. Their mineralogy and textures can be described down to extremely small length-scales, while their elemental and isotopic compositions can be quantified with ever increasing accuracy. All of this information provides valuable constraints on the physical and chemical processes that were at work in the early solar system and the time-scales of those processes. However, the stochastic nature of the process that delivers meteorites to Earth has the consequence that the meteorite record is potentially an incomplete or biased sample of inner solar system material that escaped accretion into the terrestrial planets. Furthermore, in light of their small size, meteorites cannot offer a direct view of geological context, hampering insight into the large-scale geophysical evolution of their parent bodies.

The study of main-belt asteroids has the potential to remedy several of these issues. For example, the spectral diversity of such asteroids provides a relatively complete picture of different types of small bodies of the inner solar system and their spatial distribution between Mars and Jupiter, even if the compositional constraints are rudimentary compared to those provided by meteorites. At the very different length-scale of individual parent-bodies, asteroids also offer the opportunity to constrain geological history and internal evolution through mapping of their surface material. While Earth-based and space-based telescopes can provide first order constraints, exploiting this potential requires dedicated study at the smallest length scales possible, calling for dedicated space-based missions.

After several successful flyby missions (e.g. NEAR and Galileo missions), orbiting spacecraft are revolutionizing insight into the mineralogy and chemistry of asteroids. Such missions have the advantage that they can observe the complete surface of a given asteroid, can accumulate data over many months, and can even obtain samples that return to Earth. In this way, the gap between meteorites and asteroids is being bridged. For example, the Hayabusa mission to the small asteroid Itokawa found material similar to L-type ordinary chondrites, while the Dawn mission to the large asteroid Vesta has confirmed the link between this asteroid and the Howardite-Eucrite-Diogenite family of differentiated meteorites. Currently the Dawn mission is wrapping up its observation of the largest asteroid of the main-belt, Ceres, providing constraints on the internal structure and workings of ice-rich, poorly differentiated bodies with similarities to carbonaceous chondrites.

In this review we will showcase these more recent data, highlighting the similarities between asteroids and meteorites, but also pointing out why Ceres is probably not the parent body of any known class of carbonaceous chondrite. We will also mention the exciting missions to a range of new bodies including small carbonaceous and metallic asteroids that are launched or planned for the coming years.

Keywords: Asteroids, Meteorites, Dawn mission

Size Frequency Distributions of Jupiter Trojans, Hildas and Main Belt Asteroids

*吉田 二美[1]、寺居 剛[1]
*Fumi Yoshida[1], Tsuyoshi Terai[1]

1. 自然科学研究機構国立天文台
1. National Astronomical Observatory of Japan

Jupiter Trojans (JTs) share the orbit with Jupiter and make clusters around the L4 (leading) and L5 (trailing) Lagrangian points of Jupiter. They are an important population locating between the inner and outer regions of the Solar System. Two different models have been proposed on the origin of JTs: (1) Classical model; planetesimals were captured into the Trojan orbit during accumulation phase of Jupiter and (2) Capture model; during the migration phase of giant planets, outer small bodies were penetrated to the inner region and then captured into the Trojan orbit. The (2) model suggests that current JTs can share the origin with trans-neptunian objects (TNOs). Meanwhile, if the (1) is correct, the origin of the current JTs is independent, which is the planetesimal near Jupiter at early Solar System. Thus, determining the origin of JTs would be an important key for understanding dynamical/collisional evolutions at the early stage of the Solar System history.

We think that the size-frequency distribution (SFD) is a good probe to investigate such dynamical/collisional evolutions mentioned above. Many people have believed that the SFD of each of the small body groups contains signatures of the accretional and collisional evolutions depending on the origin, dynamical evolution, and body properties. Therefore the detailed study of the SFD (e.g. shape, knee, dip etc.) identifies the dynamical/collisional evolutions that each group has experienced in its proper history. It will enable us to identify the origin of each group, and specify a relation among the groups that have currently different characteristics at different locations in the solar system.

In this study, we examined the SFDs of the JTs and Hilda group by using the 8.2-m Subaru telescope equipped with the wide-field CCD camera: Hyper Suprime-Cam. We detected more than seven hundred of km-size JT/Hilda asteroids. Our survey is the deepest survey for JTs and Hildas so far. We noticed that the SFDs of JTs and Hildas in the size range obtained from our survey have almost the same shape (Figure 1). The best-fit power law slope of JT's SFD is b=1.84+/-0.05 in $N(>D)\propto D^{-b}$. Meanwhile that of Hilda's SFD is b=1.89+/-0.12. Since the size of our detected JTs and Hildas are small (D<10km), it is reasonable to regard as they are all collisional fragments. This fact that in the both of JT and Hilda groups the collisional fragments have similar collisional parameters may indicate that they have similar composition and internal structure. We compared the SFD of JTs (Figure 2) with that of the main belt asteroids (MBAs) and then confirmed that the SFD of inner MBAs and middle MBAs show the different SFD from JT's one. However, we notice that the SFD of outer MBAs show similar characteristic with JTs.

キーワード：木星トロヤ群、ヒルダ群、サーベイ観測、サイズ分布
Keywords: Jupiter Trojans, Hildas, survey observation, size distribution

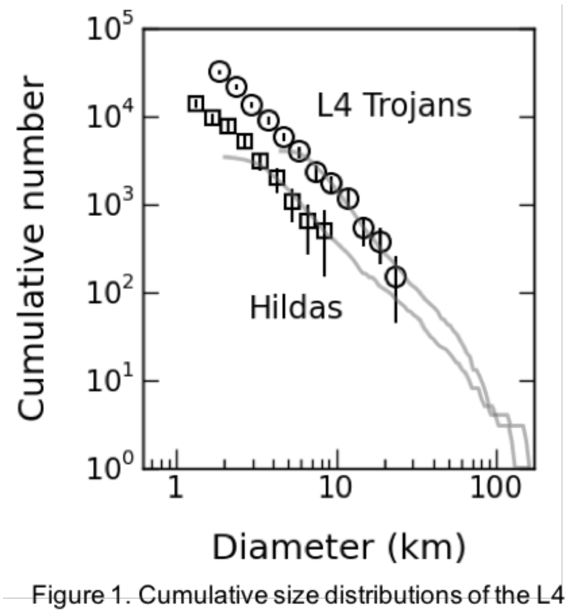

Figure 1. Cumulative size distributions of the L4 Jupiter Trojan (circles) and Hilda (squares) asteroids detected in our survey. Their cumulative numbers are scaled by those of the known objects shown as gray lines.

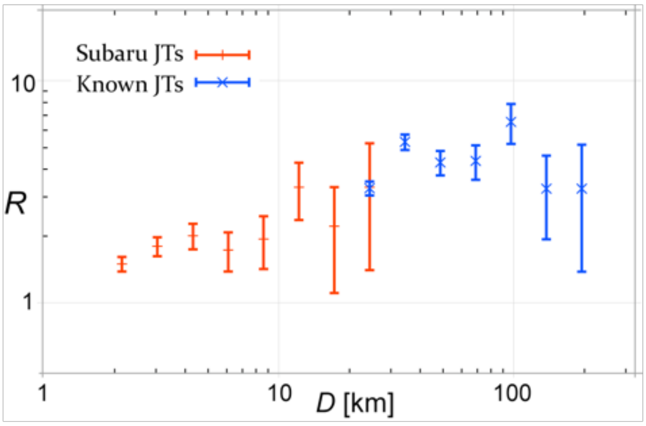

Figure 2. SFD of JTs on an R plot, this method can emphasize a shape of SFD. Blue: Known JTs with H < 12.3 mag (MPC). Red: JTs that we have detected through our own surveys. Note that the vertical axis is just relative to each other, and the unit is arbitrary.

Investigation of hydrated minerals on the main belt asteroids from the AKARI near-infrared spectroscopy

Investigation of hydrated minerals on the main belt asteroids from the AKARI near-infrared spectroscopy

*臼井 文彦[1]、長谷川 直[2]、大坪 貴文[3]
*Fumihiko Usui[1], Sunao Hasegawa[2], Takafumi Ootsubo[3]

1. 神戸大学、2. 宇宙航空研究開発機構、3. 東京大学
1. Kobe University, 2. Japan Aerospace Exploration Agency, 3. The University of Tokyo

The knowledge of hydrated minerals among asteroids is important for understanding a wide range of solar system formation, evolutionary processes, and thermal history. Formation of hydrated minerals occurs in environments where anhydrous rock and water are together. Since the hydrated mineral stably exists above the sublimation temperature of ice, it becomes an important marker indicating the presence of water, which does not reset by temperature change after formation. In order to explore the existence of water in the present solar system, it is necessary to investigate the presence of hydrous minerals and water ice on various asteroids. Water ice and hydrated minerals show absorption features in the observed spectrum, especially in the 3-micron band. However, since observed spectrum with a ground-based telescope in 2.5-2.85 micron is strongly affected by telluric absorptions, it is desirable to use space-borne telescopes to perform accurate observations for the identification of mineral species.

The Japanese infrared astronomical satellite AKARI, launched in 2006, had the capability of spectroscopy in targeted observation mode. Low-resolution spectroscopic observations were performed using the near-infrared channel (2.5-5 micron) of the Infrared Camera (IRC) on board AKARI, which provide valuable data because of its high sensitivity and unique wavelength coverage. We carried out a spectroscopic survey of asteroids with the IRC. In the warm mission period of AKARI (called Phase 3), 147 pointed observations for 66 asteroids were performed in the grism mode of 2.5-5 micron band.

The observed objects comprise 23 C-types, 17 S-types, 22 X-types, 3 D-types, and 1 V-type. From these observations, most C-type asteroids (17/23) were found to show a clear absorption feature related to hydrated minerals at a peak wavelength of around 2.7 micron. On the other hand, no S-types (17) have any clear absorption in this wavelength region. Some X-types (3/22) and D-types (1/3) have absorption feature like C-types.

In this talk, we present the results of the near-infrared asteroid spectroscopic survey with AKARI, and discuss the distribution of hydrated and/or hydroxylated minerals on asteroids in the main belt region.

キーワード：asteroids、hydrated minerals、near-infrared spectroscopy
Keywords: asteroids, hydrated minerals, near-infrared spectroscopy

Estimation of the reflectance spectra of C-type asteroids affected by solar wind proton irradiation

*仲内 悠祐[1]、安部 正真[2,1]、松本 徹[2]、北里 宏平[3]、土山 明[4]、鈴木 耕拓[5]、中田 吉則[5]
*Yusuke Nakauchi[1], Masanao Abe[2,1], Toru Matsumoto[2], Kohei Kitazato[3], Akira Tsuchiyama[4], Kohtaku Suzuki[5], Yoshinori Nakata[5]

1. 総合研究大学院大学物理科学研究科、2. 宇宙航空研究開発機構、3. 会津大学、4. 京都大学、5. 若狭湾エネルギー研究センター
1. SOKENDAI [The Graduate University for Advanced Studies], 2. The Japan Aerospace Exploration Agency, 3. University of Aizu, 4. Kyoto University, 5. The Wakasawan Energy Research Center

Asteroids and meteorites are thought to retain information on the early solar system. In particular, planetesimals similar to C-type asteroids and/or parent bodies of carbonaceous chondrites may have carried water and organics to the earth. However, meteorites do not retain direct evidence for which parent body they come from. Nevertheless, reflectance spectra suggest that carbonaceous chondrites may be from C-type asteroids.

The surface of airless bodies, however, exhibit spectra affected by space weathering effect. Recent studies suggest that the influence of solar wind implantation cannot be ignored in near earth airless bodies [Ichimura et al., 2012]. The absorption strength around 3 μm of reflectance spectra of silicate minerals which mainly contained in carbonaceous chondrites was changed by hydrogen irradiation [Nakauchi et al., 2014]. This change strongly suggests that hydroxyl group and/or H_2O were formed by hydrogen implantation.

In this study, based on the previous our study, the spectral change by hydrogen implantation on the C-type asteroids is estimated by spectral mixing model. Only the reflectance spectra of olivine, antigorite and saponite were taken into consideration of hydrogen implantation and other reflectance spectra of minerals and carbonaceous chondrite were obtained from the RELAB database.

After hydrogen irradiation, the absorption strengths of reflectance spectra estimated by mixing model showed different changes depend on carbonaceous chondrite groups. In CI and CM chondrites, the absorption strength at 2.77 μm changed strongly. On the other hand, the weathered spectra of CR and CV chondrites showed weaker change from 2.8 μm. These differences were suggested to be useful for meteorite type estimation.

When we estimate carbonaceous chondrite types using reflectance spectra on C-type asteroids, then, the space weathering effect of solar wind protons must be considered.

キーワード：宇宙風化作用、太陽風、C型小惑星
Keywords: space weathring, solar wind, C-type asteroid

Thermal Modeling of Comet-Like Asteroids from Infrared Observations with AKARI

*Yoonsoo Park Bach[1], MASATERU ISHIGURO[1], Fumihiko Usui[2]

1. Dept of Physics and Astronomy, Seoul National University, 2. Center for Planetary Science, Graduate School of Science, Kobe University

Since thermal inertia is considered as a direct measure of the bodies’ surface characteristics and even particle size distrubution, it is of great importance to many scientists. From recent studies on small bodies, it has been suggested that their thermal inertias decrease with their sizes and spin rates. These relationships, however, are constructed only for asteroids and not for comet-like objects. AKARI satellite of JAXA successfully made spectroscopic observations for two of those comet-like targets, 107P/ (4015) Wilson-Harrington, which once showed cometary activity, and P/2006 HR30 (Siding Spring), which is a bare cometary nucleus. We investigated the physical characteristics of the targets using simple thermo-physical model and found geometric albedo of 0.040-0.060 (size of 3.6-4.4 km) and 0.035-0.050 (size of 23-27 km), respectively. For (4015) Wilson-Harrington, the thermal inertia is preferably less than 250 J m-2 K-1 s-0.5. It is also found that the pole orientation of P/2006 HR30 would exist near the ecliptic plane (the latitude between -40 and +70 deg). The best-fit thermal inertia can vary within certain degree depending on model assumptions. On the other hand, the geometric albedos, i.e., diameters, are confined to very narrow range for both targets as described above, and the values coincide well with previous studies ((4015) Wilson-Harrington) or an expectation for a cometary nucleus (P/2006 HR30). We discuss about the implications of the findings and future directions of thermal modeling of comet-like objects in the presentation.

Keywords: thermal modeling, asteroids

鉄質天体のクレーター形状分布からの衝突環境の検出について
On the possible detection of collisional environment from the crater shape distribution on iron bodies

小川 諒[1]、*中村 昭子[1]、長谷川 直[2]
Ryo Ogawa[1], *Akiko Nakamura[1], Sunao Hasegawa[2]

1. 神戸大学大学院理学研究科地球惑星科学専攻、2. 宇宙航空研究開発機構
1. Graduate School of Science, Kobe University, 2. Japan Aerospace Exploration Agency

鉄隕石の供給源である鉄質天体は、地球型惑星領域で早期に形成された分化天体のコアの名残であると考えられる(Bottke et al., 2006)。一方、鉄質天体の候補とされる16PhycheをはじめとするM型小惑星の多くは小惑星帯に存在する。地球型惑星領域と小惑星帯では、天体表面温度や衝突速度が異なる。それゆえ、温度や衝突速度がクレーター形状に影響をするのであれば、鉄質天体が経てきた軌道進化をクレーター形状分布から制約できる可能性がある。

我々は、金属弾丸と鉄隕石模擬物質としての炭素鋼SS400標的の衝突実験及び衝突シミュレーションを行ってきたが(小川他, 2016, JpGU)、標的にGibeon鉄隕石を(小川他, 2016, JSPS fall meeting)、弾丸に岩石を用いた実験とそのシミュレーションを追加した。実験は、地球型惑星領域相当の室温と小惑星帯相当の150 Kの標的に対し、衝突速度0.8ー7 km/sで行った。7 km/s以上の高速度衝突については衝撃物理コードであるiSALEー2Dを用いシミュレーションを行った。Gibeon鉄隕石の状態方程式は鉄のANEOS(Thompson, 1990)、強度モデルにはJohnson-Cook モデル(Johnson and Cook, 1983)を用いた。Johnson-Cook モデルのパラメータについてはGibeon鉄隕石と同じオクタヘドライト隕石であるHenbury鉄隕石の応力ー歪曲線(Furnish et al., 1994)から推定した。その結果、数値シミュレーションは実験結果を再現することを確かめた。

Gibeon鉄隕石とSS400は冷却することで強度は150-200 MPaほど増加する(Gordon, 1970 ; Furnish et al., 1994; Pennet et al., 1966; Sakino, 2015)。クレーター深さと直径は、冷却による強度増加や衝突速度の低下によりともに小さくなった。しかし、減少傾向は直径よりも深さで顕著に現れる。以上により、鉄質天体表面に形成されるクレーターの深さ直径比の頻度分布のピークは、地球型惑星領域よりも小惑星帯では小さくなると推定された。

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キーワード：鉄質天体、衝突、クレーター
Keywords: iron body, impact, crater

Dawn @ Ceres: Evidence for a Once Frozen Ocean World

*Christopher T Russell[1], Carol A Raymond[2], Julie C. Castillo-Rogez[2], Andreas Nathues[3], Maria Cristina DeSanctis[4], Tom H. Prettyman[5], Harry Y. McSween[6], Ralf Jaumann[7], Carle M. Pieters[8], Michael J. Toplis[9], Debra Buczkowski[10], David A. Williams[11], Harald Hiesinger[12], Ryan S. Park[2], Jian-Yang Li[5], Eleonora Ammannito[1], Dawn Team

1. University of California, Los Angeles, 2. Jet Propulsion Laboratory, NASA, 3. Max Planck Institute for Solar System Research, 4. Istituto di Astrofisica e Planetologia Spaziali, 5. Planetary Science Institute, 6. University of Kentucky, 7. German Aerospace Center, 8. Brown University, 9. Institut de Recherche en Astrophysique et Planétologie, 10. John Hopkins University Applied Physics Laboratory, 11. Arizona State University, 12. Muenster University

Before Dawn arrived, estimates of Ceres’ mass and size showed that the density of Ceres was intermediate between water and silicate rock. This suggested that Ceres contained a significant amount of water in its interior, either free or bound in hydrates or clathrates. The precision gravity and topography data obtained by Dawn revealed that the crust was much stronger than water-ice but less dense than silicate, suggesting that the crust was an intimate mixture of rock, ice, and hydrates about 50 km thick. This crust had preserved recent “small” craters, but ancient large basins were subdued or absent. Dawn’s camera revealed that the small very bright areas, now known as Cerealia and Vinalia Faculae, are mostly composed of sodium carbonate, probably created inside Ceres in a hydrothermal system. These observations are consistent with the present surface of Ceres being the product of an ancient ocean that first froze and was then eroded by meteor impact. Ceres once was and probably still is an active water world, as suggested by Ahuna mons, a geological feature believed to be of cryovolcanic origin. Ceres has water on its surface in the form of small ice patches, and it has a transient water atmosphere formed when strong fluxes of solar energetic protons strike the surface and liberate water molecules. This water world is further revealed by evidence for a global ice/water table that approaches the surface at high latitudes. Ceres awaits further landed and orbital exploration. Its low gravitational field, relative proximity to the Sun and benign radiation environment make Ceres an appropriate, accessible candidate in our exploration of ocean worlds.

Keywords: Ceres, Vesta, Dawn

The Geomorphology of Ceres

*Debra L. Buczkowski[1], Britney E. Schmidt[2], David A. Williams[3], Scott C. Mest[4], Jennifer E. C. Scully[5], Anton I Ermakov[6], Frank Preusker[7], Paul Schenk[8], Katharina A. Otto[7], Harald Hiesinger[9], David O'Brien[4], Simone Marchi[10], Hanna Sizemore[4], Kynan Hughson[11], Heather T. Chilton[2], Michael Bland[12], Shane Byrne[13], Norbert Schorghofer[14], Thomas Platz[15], Ralf Jaumann[7], Thomas Roatsch[7], Mark V. Sykes[4], Andreas Nathues[15], M. Cristina De Sanctis[16], Carol A. Raymond[5], Christopher T Russell[11]

1. Johns Hopkins University Applied Physics Laboratory, 2. Georgia Institute of Technology, 3. Arizona State University, 4. Planetary Science Institute, 5. NASA Jet Propulsion Laboratory, 6. Massachusetts Institute of Technology, 7. German Aerospace Center (DLR), 8. Lunar and Planetary Institute, 9. Westfälische Wilhelms-Universität Münster, 10. Southwest Research Institute, 11. University of California, Los Angeles, 12. United States Geological Survey, 13. Lunar and Planetary Laboratory, 14. University of Hawaii at Manoa, 15. Max Planck Institute for Solar System Research, 16. Istituto di Astrofisica e Planetologia Spaziale INAF

We assess the geology of Ceres at the global scale, to identify geomorphic and structural features, and to determine the geologic processes that have affected it globally. Geomorphic features identified include: impact craters, linear structures, domical features and lobate flows. Kilometer-scale linear structures—grooves, pit crater chains, fractures and troughs—cross much of Ceres, and include both those associated with impact craters and those that do not appear to have any correlation to an impact event. Domical features fall into two broad classes: large domes which are 10s to 100s km in diameter with heights 1-5 km; and small mounds <10 km in diameter exhibiting sub-kilometer relief. A range of lobate flows are observed across the surface of Ceres, and differences in their morphology suggest that multiple emplacement processes might be operative. However, Ceres is dominated by craters, including numerous polygonal craters and several floor-fractured craters (FFCs).

Geomorphic analysis of the Ceres FFC fracture patterns show that they are similar to lunar FFCs. FFCs on the Moon are hypothesized by Jozwiak et al. [2015] to be a product of intrusions of magmatic material below the craters uplifting their floors. We have cataloged the Ceres FFCs according to the classification scheme designed for the Moon. Class 1 Ceres FFCs have both radial and concentric fractures at the crater center, and concentric fractures near the crater wall. In the magmatic model these craters represent fully mature magmatic intrusions, with initial doming of the crater center due to laccolith formation resulting in the crater center fractures, while continuing outward uplift of the remaining crater floor results in concentric fracturing adjacent to the crater wall. Other large (>50 km) Ceres FFCs which have only linear or radial fractures at the center of the crater are also classified as Class 1 FFCs, but likely represent a less mature magmatic intrusion, with doming of the crater floor but no tabular uplift. Smaller craters on Ceres are more consistent with Type 4 lunar FFCs. The three Class 4 sub-classes all have a v-shaped moat separating the wall scarp from the crater interior, but different interior morphologies: Class 4a, with both radial and concentric fractures; Class 4b, having a distinct ridge on the interior side of its v-shaped moat and subtle fracturing; Class 4c, with a moat and a hummocky interior, but no obvious fracturing. A depth vs. diameter analysis shows that, like lunar FFCs, the Ceres FFCs are anomalously shallow. We also observe the d/D trend for the Class 1 FFCs is shallower than that for the Class 4 FFCs. This is consistent with the magmatic intrusion models, which suggest that the increased fracturing of Class 1 FFCs is due to increased uplift.

This three-dimensional characterization of the surface is used to determine if the geomorphology of Ceres is consistent with models of the dwarf planet predicting an icy crust and/or mantle. The lack of a large inventory of relaxed craters, the presence of ancient surface fractures, and extensive sub-surface fracturing (as demonstrated by the widespread distribution of polygonal craters), suggests that the crust is too strong to be dominated by ice. However, certain geomorphic features suggest that there may be at least some ice in the Ceres crust, and significant ice in its mantle. A latitudinal trend in the global distribution of lobate flows suggests that the differences in morphology might be explained by variations in ice content and temperature at the near-surface. Ahuna Mons and the other large domes appear to be cryovolcanic in nature, and the FFCs are hypothesized to be formed due to cryomagmatic intrusions under their floors. However, none of the impact craters that host large domes have fractured floors. This anti-correlation suggests that there may be a difference in crustal properties between where the FFCs and the volcanic features form.

Keywords: Ceres, geomorphology, floor-fractured craters, cryomagma

Interiors of Vesta and Ceres as constrained by the Dawn mission

*Anton Ermakov[1], Ryan S Park[1], Roger R Fu[2], Julie C Castillo-Rogez[1], Maria T Zuber[3], Carol A Raymond[1], Christopher T Russell[4]

1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA, 2. Lamont-Doherty Earth Observatory, Earth Institute, Columbia University, Palisades, NY, 10964, USA, 3. Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA, 4. University of California Los Angeles, IGPP/EPSS, Los Angeles, CA, 90095, USA

Introduction: Protoplanets Vesta and Ceres are the two most massive bodies in the asteroid belt. The planetary formation process had frozen for these bodies just before the run-away accretion, as they could not accrete enough mass. Gravity and topography data provide insight into internal structure of these bodies, which gives important clues to understanding the planetary formation process.

Data: Pre-Dawn shape models of Vesta [1] revealed substantial deviations from hydrostaticity, whereas for Ceres observed shape was consistent with a hydrostatic ellipsoid of revolution [2,3]. Images from the Framing Camera of the Dawn spacecraft have been used to construct shape models of Vesta and Ceres independently using stereophotogrammetry [3] and stereophotoclinometry [4] techniques, while the gravity field of these bodies has been determined via radio-tracking to a spherical harmonic degree $n=18$ and $n=16$, respectively [5,6].

Discussion: We find that Vesta was once hot and hydrostatic [7] and is no longer either. It was despun by two giant collisions [8,9] that produced the two largest basins on the asteroid's surface –Rheasilvia and Veneneia. These two basins in the southern hemisphere represent the largest deviation of Vesta from a hydrostatic equilibrium shape. On the other hand, the northern hemisphere is well approximated by an ellipsoid and represents the fossil shape of Vesta prior to the giant impacts [8,9]. Based on the gravity-topography admittance analysis, Vesta's topography is not compensated. The two most characteristic features in the Bouguer anomaly map are the region of highest topography –Vestalia Terra –with the strongest positive anomaly and the central peak of Rheasilvia, which is also associated with a positive anomaly which likely represents the deeper and denser layers excavated by the Rheasilvia impact. It is possible that the porosity variations control a substantial fraction of the remaining gravity signals. Unlike Vesta, Ceres possesses plenty of gravity anomalies that can be associated with geomorphologic units. Gravity/topography admittance analysis reveals that Ceres' topography is isostatically compensated [10]. We combine the gravity/topography data and finite element modeling to constrain Ceres' rheology and density structure. We find that Ceres' crust is light and mechanically strong with the volumetric water ice content <30%. Ceres has experienced limited viscous relaxation as evidenced by the deviation of its topographic power spectrum from the power law at low degrees [10,11].

Conclusions: The divergent geodynamic evolutions of Vesta and Ceres may be attributed to three main factors: size, location and time of accretion. The latter two factors determine the properties of the accreted material and subsequently affect the type of heat transfer. Being smaller, Vesta cooled more quickly than Ceres and developed an elastic lithosphere before acquiring most of its topography. Ceres, on the other hand, had a longer cooling time and has not developed an appreciable lithosphere at a 4.5 Gy timescale. Consequently, Ceres is an order of magnitude closer to hydrostatic equilibrium than Vesta and its topography is isostatically compensated. Additionally, having accreted further out in the asteroid belt Ceres accreted and subsequently retained more volatiles, unlike mostly silica-dominated Vesta. This compositional difference affects the rate viscous relaxation of topography making Ceres’ near surface viscosities several orders of magnitude lower than those of Vesta. Inferred low mantle density for Ceres implies strong hydration, which favors accretion with a lower ^{26}Al abundance and/or efficient early heat transfer due to hydrothermal circulation.

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Keywords: Geophysics , Vesta , Ceres

Current Understanding of the Evolution of Vesta

*Carle M Pieters[1], C. T. Russell[2], C. A. Raymond[3], E. Ammannito[2,4], J.-Ph Combe[5], M. C. De Sanctis[4], H. Hiesinger[6], R. Jaumann[7], T. B. McCord[5], H. Y. McSween[8], A. Nathues[9], T. H. Prettyman[10]

1. Brown University, 2. UCLA, 3. JPL/CalTech, 4. INAF, 5. BearFight, 6. Muenster Univ., 7. DLR, 8. Univ. Tennessee, 9. Max Plank Inst., 10. PSI

The Dawn spacecraft left asteroid 4-Vesta in September 2012 after spending more than a year accumulating orbital measurements of the only remaining intact planetary embryo that formed and differentiated during the first few 10s of My of Solar System evolution. Diverse data from Dawn’s three principal instruments [Framing Camera (FC), Visible and InfraRed imaging spectrometer (VIR), and Gamma Ray and Neutron Detector (GRaND)] have been calibrated and are available through the PDS for analysis. Although initial results have been reported for this ~525 km massive asteroid, important new insights will continue to emerge as these valuable data are integrated and analyzed in more detail. We highlight some of the important results, surprises, and issues that merit further investigation. Before Dawn’s arrival, telescopic measurements of Vesta revealed that the Howardite-Eucrite-Diogenite (HED) class of basaltic achondrite meteorites are most likely derived from Vesta or the family of similar nearby small bodies that might be the result of a major impact in the past. The highest resolution images from HST suggested the presence a gigantic crater near the south pole of Vesta that could mark such an impact and might (if recent) account for Vesta’s apparently unweathered surface.

As global data were acquired by Dawn’s instruments at increasing higher resolution, not only did the FC images allow the major ~500 km basin at the south pole (Rheasilvia) to be characterized in exquisite detail, but they also revealed a second large basin (Veneneia) and both basins were shown to be relatively old (1-3 Gy) based on different models of crater statistics. The spectroscopic data from VIR identified and mapped diagnostic absorptions of minerals in a spatial context and confirmed that the mineral composition of Vesta is dominated by pyroxene with the same bulk composition as the howardite meteorites (a mixture of eucrites and diogenites). This was substantiated with elemental data from GRaND, confirming Vesta’s early melting and differentiation. Geophysical data imply the presence of a dense ~110 km core. Nevertheless, distinct spatial variations are found to occur in regular patterns across the surface. The giant Rheasilvia basin at the south pole exposed abundant Mg-rich pyroxene (diogenites), but no evidence of olivine, a mineral commonly associated with mantle lithology and expected to have been revealed by such a deep excavation. In contrast, only a few small olivine-bearing areas have been identified in the northern hemisphere.

A significant surprise was to find concentrations of H (from GRaND) and OH (from VIR) which are correlated with large surface areas of relatively low albedo. The pattern is not associated with temperature or latitude variations (as on the Moon), but instead indicates the spatially coherent presence of a minor foreign component of OH-bearing species such as carbonaceous chondrite (CC) regionally embedded within the regolith. The presence of foreign CC components is also consistent with inclusions found in howardite breccias. Similarly, the special form of regolith space weathering observed on Vesta does not follow the formation of lunar-like nanophase opaques on regolith grains, but instead involves minor mixing of the regolith with a small amount of a neutral darkening agent such as CC micrometeorites. On a local scale, the presence of concentrated volatiles is suggested by mysterious clusters of unusual pits that are found in a few major craters, the morphology of which implies a rapid release of volatiles.

Altogether, Vesta has indeed revealed itself to be a fascinating planetary embryo that has survived from the dawn of solar system evolution. It also informs us that surfaces of large asteroids can contain a notable

foreign component. We are fortunate to have the diverse HED samples to constrain the early evolution of this planetary embryo and the Dawn data to constrain Vesta’s complex evolution to the present.

Keywords: Vesta, Dawn mission, Planetary embryo

Low-velocity impact cratering experiments in granular slopes and a comparison with Vestan craters

林 康介[1]、*隅田 育郎[1]
Kosuke Hayashi[1], *Ikuro Sumita[1]

1. 金沢大学大学院 自然科学研究科
1. Graduate School of Natural Science and Technology, Kanazawa University

Low-velocity impact cratering experiments are conducted in sloped granular targets to study the effect of the slope angle *theta* on the crater shape and its scales. We use two types of granular matters, sand and glass beads, former of which has a larger friction coefficient mu_s = tan($theta_r$), where $theta_r$ is the angle of repose. Experiments show that as *theta* increases, the crater becomes shallower and elongated in the direction of the slope. Furthermore, the crater floor steepens in the upslope side and a thick rim forms in the downslope side, thus forming an asymmetric profile. High-speed images show that these features are results of ejecta being dispersed farther towards the downslope side and the subsequent avalanche which buries much of the crater floor. Such asymmetric ejecta dispersal can be explained by combining the Z-model and a ballistic model. Using the topographic maps of the craters, we classify crater shape regimes I-III, which transition with increasing *theta* : a full-rim crater (I), a broken-rim crater (II), and a depression (III). The critical *theta* for the regime transitions are larger for sand compared to glass beads, but collapse to close values when we use a normalized slope $theta^{\wedge}$ = tan(*theta*) / tan($theta_r$). Similarly we derive $theta^{\wedge}$-dependences of the scaled crater depth, length, width and their ratios which collapse the results for different targets and impact energies. We compare the crater profiles formed in our experiments with deep craters on asteroid Vesta and find that some of the scaled profiles nearly overlap and many have similar depth / length ratios. This suggests that these Vestan craters may also have formed in the gravity regime and that the formation process can be approximated by a granular flow with a similar effective friction coefficient.

Reference

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キーワード：粉粒体斜面、衝突過程、非対称なクレーター、スケーリング則、小惑星ベスタ
Keywords: Granular slopes, Impact processes, Asymmetric craters, Scaling relations, Asteroid Vesta

Lucy: Surveying the Diversity of the Trojan Asteroids: The Fossils of Planet Formation

*Harold F Levison[1]

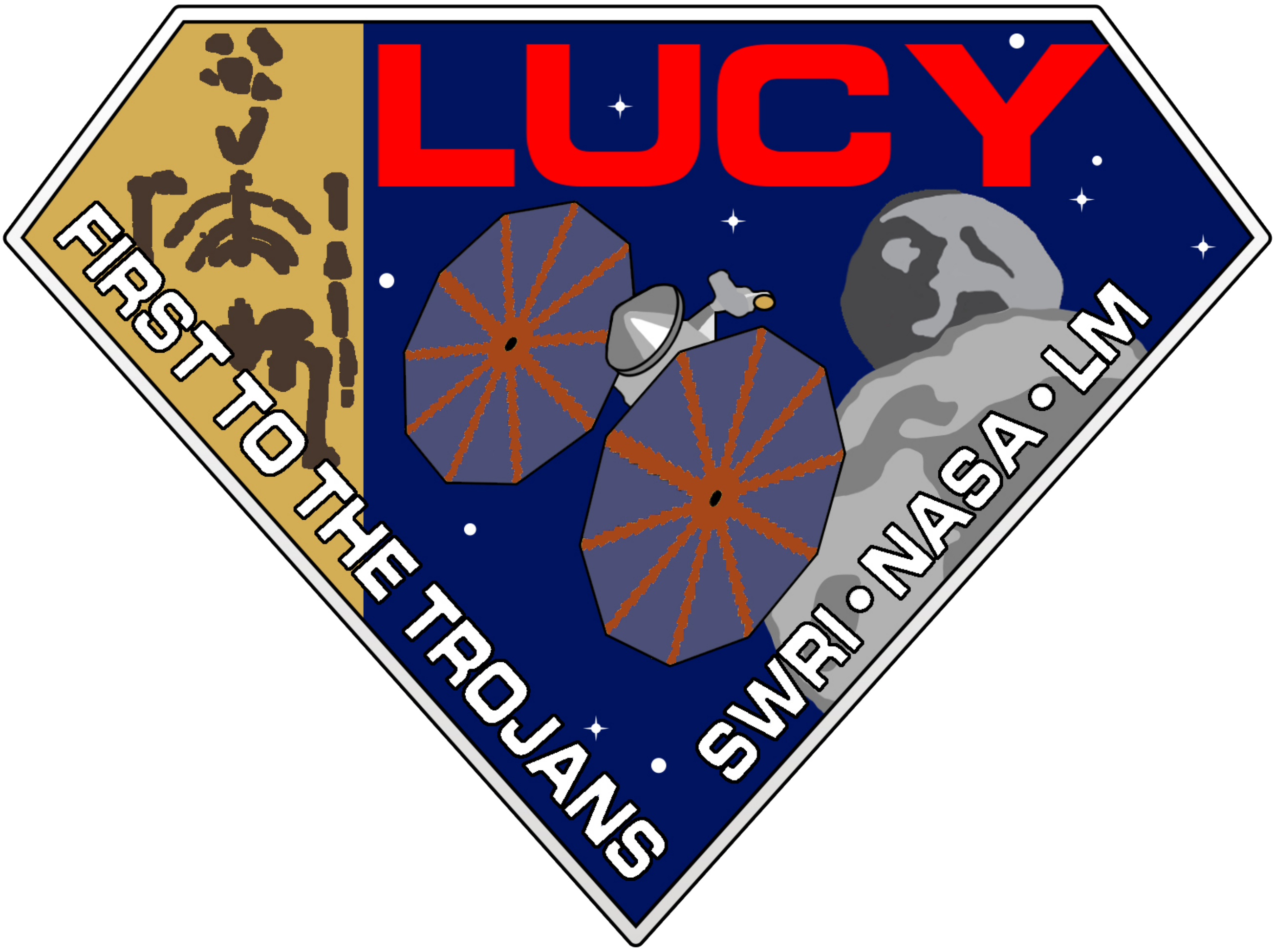
1. Southwest Research Institute

The Lucy mission is the first reconnaissance of the Jupiter Trojan asteroids - objects that hold vital clues to deciphering the history of the Solar System. Due to an unusual and fortuitous orbital configuration, Lucy, which has been selected as part of NASA's Discovery Program, will perform an exhaustive landmark investigation that visits six of these primitive asteroids, covering both the L4 and L5 swarms, all the known taxonomic types, the largest remnant of a catastrophic collision, and a nearly equal mass binary. More specifically, Lucy will visit: Eurybates (L4, C-type), Polymele (L4, P-type), Leucus (L4, D-type), Orus (L4, D-type) and the Patroclus-Menoetius binary (L5, P-types). It will launch in 2021 and will have encounters from 2025-2033.

Lucy will use a suite of high-heritage remote sensing instruments to map the geology, surface color and composition, thermal and other physical properties of its targets at close range. More specifically, Lucy's primary science objectives are: i) Surface composition: Lucy will map the color, composition and regolith properties of the surface and determine the distribution of minerals, ices and organics species; ii) Surface geology: Lucy will map albedo, shape, crater spatial and size distributions, determine the nature of crustal structure and layering, and determine the relative ages of surface units; iii) Interior and bulk properties: Lucy will determine the masses and densities, and study subsurface composition via crater windows, fractures, ejecta blankets, and exposed bedding; iv) Satellite and ring search: Lucy will determine the number, size-frequency distribution and location of km-scale satellites and dense rings.

Owing to their unique location near Jupiter and the critical role they play in revealing and constraining models of the formation and evolution of the Solar System, Trojans have been a high priority for space missions for over a decade. By studying these important bodies, Lucy, like the human fossil for which it is named, will revolutionize the understanding of our origins.

Keywords: Trojan Asteroids, mission


LUCY
FIRST TO THE TROJANS
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Hayabusa mission: A current summary of return sample analysis

*中村 智樹[1]、野口 高明[2]
*Tomoki Nakamura[1], Takaaki Noguchi[2]

1. 東北大学大学院理学研究科地学専攻、2. 九州大学 基幹教育院
1. Department of Earth and Planetary Materials Sciences, Faculty of Science, Tohoku University, 2. Faculty of Arts and Science, Kyushu University

Itokawa dust particles provide a first opportunity for scientists to analyze return samples from asteroid (Yada et al. 2014, Uesugi et al. 2014). Regardless of small size of the particles, a clear picture that describes formation and evolution of a rubble pile asteroid is obtained from a variety of evidence found from the particles. Here we summarize history of Itokawa from past to present. (1) Formation of Itokawa parent body: Itokawa parent asteroid formed in the early solar system as a S-type asteroid of LL-chondrite composition with a radius of 20km or larger, most likely 2.2Myr after CAIs, the oldest solar system material (Nakamura et al. 2011; 2014, Yurimoto et al. 2011, Ebihara et al. 2011; 2015, Tsuchiyama et al. 2011; 2013; 2014, Mikouchi et al. 2014, Nakashima et al. 2014, Wakita et al. 2014, Takeda et al. 2015). Absolute age of the parent-body formation remains to be clarified. (2) Internal heating: Decay heat of short-lived radionuclides such as 26Al raised the temperature of Itokawa parent asteroid up to 800˜900 °C at approximately 5 Myr after CAIs and cooled down slowly (Nakamura et al. 2011, Tanaka et al. 2014, Wakita et al. 2014), which probably developed an onion shell asteroid. The heating made parent-body interior to LL5 and 6 material (Nakamura et al. 2011, Nakashima et al. 2014). (3) Impact break-up: A catastrophic impact occurred, possibly at 1.3 ±0.3 Ga ago (40Ar/39Ar age from Park et al. 2015), and broke the parent asteroid into smaller pieces. Re-accumulation of some pieces would have formed a smaller rubble-pile asteroid (Nakamura et al. 2011), but the size of the first rubble pile asteroid is uncertain. The impact effects are observed in many Itokawa dust particles (Nakamura et al. 2012), but most of evidence indicates small-scale impacts (Matsumoto et al. 2016). For instance, diagnostic shock indicators such as planar fractures and 001 screw dislocations of olivine occur only in a small zone on one concave side of the dust particle (Langenhorst et al. 2014). (4) Formation of current Itokawa: Current-size Itokawa formed recently. Short noble gas (He and Ne) cosmic exposure age of 1.5Ma (Meier et al. 2014) and 8Ma at most (Nagao et al. 2011) indicates that current Itokawa surface is young, which is consistent with the absence of cosmogenic B (Fujiya et al. 2016). Young exposure age was discussed in terms of YORP effect (Connolly et al. 2015). (5) Space weathering: Itokawa surface experienced space weathering for a short period of time. Space-weathered surface of a particle consists of a thin layer of FeS-rich vapor or sputtered deposition, and thick layers of partially amorphous material with abundant Fe-rich nanoparticles formed mainly by solar wind irradiation (Noguchi et al., 2011; 2014a, Keller and Berger, 2014, Thompson et al., 2014). Considering short cosmic exposure ages, incipient space weathering effects appears to have been dominated by solar-wind irradiation. The degree of weathering is variable between particles (Bonal et al. 2015). (6) Accretion of dust particles from other asteroids and comets: Small dust and meteoroids are expected to come from other asteroids and comets and accreted on the Itokawa surface. These outer small bodies are rich in organics and therefore organic-bearing particles are expected to be found from Itokawa dust particles. However, so far, no extraterrestrial organics were detected from soluble organic compounds (Naraoka et al. 2014), IR spectra (Kitajima et al. 2015), H, C, and N isotope signatures (Ito et al. 2014), and Carbon-XANES spectra (Yabuta et al. 2014). Neither carbonaceous matter nor hydrated minerals were detected through Raman analysis (Bonal et al. 2015). Halite, possibly indigenous and came from hydrous asteroids, was detected (Noguchi et al. 2014b).

キーワード：イトカワ、リターンサンプル解析、はやぶさミッション
Keywords: Itokawa, Return sample analysis, Hayabusa mission

A Review of Remote Sensing Observations of the Near-Earth Asteroid (25143) Itokawa

A Review of Remote Sensing Observations of the Near-Earth Asteroid (25143) Itokawa

*石黒 正晃[1]、Lee Mingyeong[1]、Jin Sunho[1]
*MASATERU ISHIGURO[1], Mingyeong Lee[1], Sunho Jin[1]

1. ソウル大学物理天文学科
1. Department of Physics and Astronomy, Seoul National University

The Hayabusa spacecraft carried out detailed scientific observations of its mission target asteroid, (25143) Itokawa, using the onboard devices: a telescopic imaging camera (AMICA, at 0.38 - 1.01 mm with seven narrowband filters), a near-infrared spectrometer (NIRS, 0.8 - 2.1 mm), an x-ray fluorescence spectrometer (XRS), and a laser altimeter (LIDAR), revealing its shape, mass, and surface topography and mineralogical properties. From the low bulk density (1.9±0.1 g/cm^3), high porosity (40 %), boulder-rich appearance, and irregular shape, it is considered that Itokawa has a rubble-pile structure. We learned that Itokawa has a large variety of albedo, color, and spectral shape, which can be explained by space weathering on the S-type asteroid. At the conference, we review these findings by the remote-sensing devices. In addition, we introduce our resent research activity at Seoul National University using AMICA data archive, which includes an updated data reduction process, studies of back-scattering properties and spatial variation of the optical spectra using all AMICA filters.

キーワード：Hayabusa、Asteroid、Itokawa
Keywords: Hayabusa, Asteroid, Itokawa

小惑星イトカワにおける内部密度分布の推測
Estimation of Interior Density Distribution for Asteroid Itokawa

*金丸 仁明[1]、佐々木 晶[1]
*Masanori Kanamaru[1], Sho Sasaki[1]

1. 大阪大学
1. Osaka University

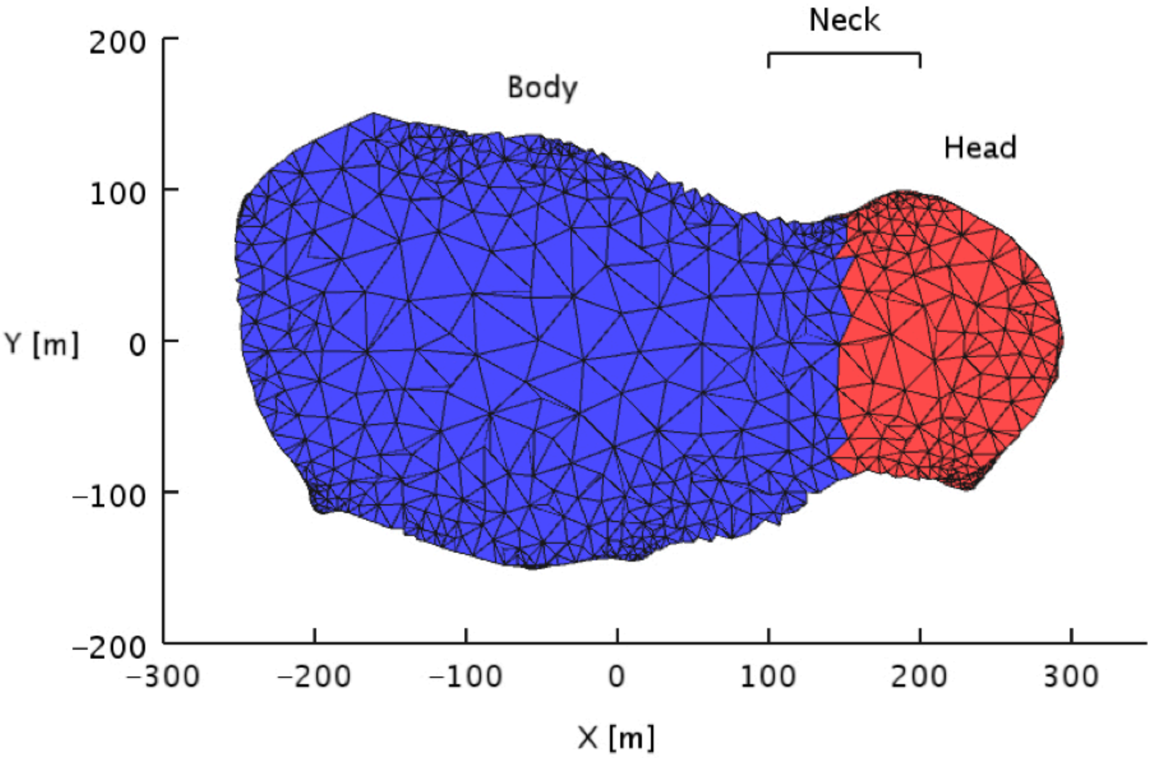
Itokawa is considered to be a rubble pile object based on high porosity of approximately 40 percent (Fujiwara, et al., 2006). However, internal structure and formation process of the sub-kilometer-sized rubble pile are still open questions. Interior density distribution of Itokawa gives us an important clue to understand the formation process. It is possible that Itokawa has interior structure derived from processes of collisional breakup and reconfiguration.

Light curve observation and thermophysical simulation for Itokawa suggested the center-of-mass (COM) is displaced from the center-of-figure (COF) by approximately 21m (Lowry, et al., 2014). Such a great offset between the COM and COF can be explained by a significant difference of bulk density between two lobes, "head" and "body". The COM offset is important evidence of density inhomogeneity within the asteroid. The goal of this study is to make a determination on the density distribution of Itokawa from a different view point, focusing on the shape and the gravity field.

We remodeled a conventional gravity simulation of a constant-density polyhedron (Werner and Scheeres, 1997) so as to represent density inhomogeneity within a 3D shape model of Itokawa. We verified an interior density map, where the head part of Itokawa has a higher density value than the remaining body part. We calculated the gravity potential all over the surface of Itokawa and obtained potential variance as an index of density distribution estimation. We searched for a minimum value of potential variance assigning different density values to the head and body part. The minimum of potential variance was recognized as an estimation solution of density distribution. Our estimation is based on the assumption that the surface terrain of the asteroid comes close to the equi-potential surface over sufficient time due to erosion and resurfacing processes (Richardson and Bowling. 2014).

This study implied new evidence of internal density inhomogeneity of asteroid Itokawa. Potential variance through the global surface was minimized where the head density was approximately 2,750 kg/m^3. The head part of such a high density corresponds to a density value of 1,870 kg/m^3 in the remaining body part and a COM offset by 16 m toward the head of Itokawa. If both the head and body of Itokawa consist of LL-chondrites whose bulk density is 3,190 kg/m^3, it is found that Itokawa has porosity widely ranging from approximately 14% to 41% between two lobes. It is possible for the head of Itokawa to have a more coherent and monolithic structure in comparison with the other regions. It is possible that the head part of Itokawa is composed of large fragments derived from a parent body.

キーワード：小惑星イトカワ、重力場、多面体重力場シミュレーション、密度不均質、内部構造
Keywords: Asteroid Itokawa, Gravity Field, Polyhedron Gravity Simulation, Density Inhomogeneity, Interior Structure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イトカワの円形窪地地形の宇宙風化と軌道変化
Space weathering of quasi-circular depressions on Itokawa and its orbital evolution

*巽 瑛理[1]、杉田 精司[1]
*ERI TATSUMI[1], Seiji Sugita[1]

1. 東京大学大学院地球惑星科学専攻
1. The University of Tokyo, Department of Earth and Planetary Science

Introduction: The orbital evolution of asteroids is important for understanding both the current distribution of asteroids and the mass flux to terrestrial planets. Near-Earth objects, such as Itokawa, Ryugu and Bennu, are estimated to have come from the asteroid main belt, through changing their orbits by the Yarkovsky effect to resonances with Jupiter where asteroids are scattered and removed from the main belt to such as near-Earth orbit. Spacecraft explorations to asteroids have obtained detailed morphologies and spectral properties of near-Earth asteroids. In particular, observations by AMICA (Asteroid Multi-band Imaging Camera) onboard the spacecraft Hayabusa revealed that the asteroid Itokawa exhibit of heterogeneous reddening and darkening, strongly suggesting space weathered on this asteroid [1]. The different degree of space weathering is likely to reflect different lengths of exposure time to space. Thus, the time scale of surface modification processes on asteroids could be estimated from the degree of space weathering. In this study, we analyze the degree of space weathering for quasi-circular depressions on Itokawa, which may be impact origin [2]. Finally, we discuss the residence times of Itokawa both in the main belt and the near-Earth orbit.

Method: Previous work on the principal component analysis of spectra obtained by AMICA suggested that, the first principal component (PC1) of Itokawa is possibly the trend of space weathering [3]. Thus, we used PC1 score to assess the degree of space weathering on Itokawa. Using high-resolution images taken from lower altitudes than the home position, we generated space weathering maps of Itokawa. After the PC1 score of each circular depression is derived, the PC1 scores are converted into relative exposure time based on the laser irradiation experiments on Olivine and LL chondrites [4,5]. The exposure time might indicate the lower limit of each circular depression.

Results and Discussions: The highly space weathered quasi-circular depressions mostly have fresh rims compared to their old floors, while the moderately weathered ones usually have the rims weathered similarly as the floors. This suggests that the rims gradually collapsed and moved towards the floors of depressions. This observation supports the crater modification process by seismic shaking by small impacts on asteroids [6]. Furthermore, we found that the age distribution of large quasi-circular depressions (>100 m) is not uniform, while that of small ones is relatively uniform. More specifically, all the depressions larger than 100 m turned out to be older than the average exposure time of Itokawa. This may reflect the change in the impact rate on Itokawa. For example, the impact energy flux in the main belt is ~50 times that in near-Earth orbits. In other words, the number of craters formed in a unit time is 50 times larger in the main belt than in the near-Earth orbit, if the impact energy dominates the crater size. The orbital change from the main belt to the current orbit may explain the lack of fresh and large circular depressions on Itokawa.
Our previous study suggests that the formation of large circular depressions on Itokawa might take 9.9-33 Myr in the main belt [7]. Other previous studies suggested the space weathering time scales on Itokawa,

such as <8 Myr [8] and ˜1.5 Myr [9] from CRE ages of the sample analyses and <10 Myr [3] and 2-8 Myr [10] from the spectral analyses. All of these estimates are based on the solar ion flux at the near-Earth orbit (˜1 AU). Although the space weathering rate in the inner main belt is approximately 4 times smaller than at the current orbit of Itokawa, the residence time in the main belt on the order of 10^7 yrs based on the number density of large craters might received enough space weathering effect as previous sample analyses and spectral analyses suggested. That is, the residence time of Itokawa in the near-Earth orbit is possibly very short (10^4-10^5 yr) as the number density of small and fresh craters suggests.

References: [1] Ishiguro et al., (2007), MAPS. [2] Hirata et al., (2009), Icarus. [3] Koga et al., (2014), LPSC. [4] Sasaki et al., (2001), Science. [5] Hiroi et al., (2006), Nature. [6] Richardson et al., (2004), Science. [7] Tatsumi and Sugita, (2017), LPSC. [8] Nagao et al., (2011), [9] Science. Meier et al., (2014), LPSC. [10] Bonal et al., (2015), Icarus.

キーワード：小惑星、はやぶさ、スペクトル解析、宇宙風化
Keywords: Asteroids, Hayabusa, Spectral analysis, Space weathering

OSIRIS-REx spacecraft current status and forward plans

*Scott Messenger[1], Dante S. Lauretta[2], Harold C. Connolly Jr.[3]

1. NASA Johnson Space Center, 2. Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, AZ, USA, 3. Dept. of Geology, Rowan University, Glassboro, NJ, USA

The NASA New Frontiers OSIRIS-REx spacecraft executed a flawless launch on September 8, 2016 to begin its 23-month journey to near-Earth asteroid (101955) Bennu [1]. The primary objective of the OSIRIS-REx mission is to collect and return to Earth a pristine sample of regolith from the asteroid surface. The sampling event will occur after a two-year period of remote sensing that will ensure a high probability of successful sampling of a region on the asteroid surface having high science value and within well-defined geological context. The OSIRIS-REx instrument payload includes three high-resolution cameras (OCAMS), a visible and near-infrared spectrometer (OVIRS), a thermal imaging spectrometer (OTES), an X-ray imaging spectrometer (REXIS), and a laser altimeter (OLA).

As the spacecraft follows its nominal outbound-cruise trajectory, the propulsion, power, communications, and science instruments have undergone basic functional tests, with no major issues. Outbound cruise science investigations include a search for Earth Trojan asteroids as the spacecraft approaches the Sun-Earth L4 Lagrangian point in February 2017. Additional instrument checkouts and calibrations will be carried out during the Earth gravity assist maneuver in September 2017. During the Earth-moon flyby, visual and spectral images will be acquired to validate instrument command sequences planned for Bennu remote sensing.

The asteroid Bennu remote sensing campaign will yield high resolution maps of the temperature and thermal inertia, distributions of major minerals and concentrations of organic matter across the asteroid surface. A high resolution 3d shape model including local surface slopes and a high-resolution gravity field will also be determined. Together, these data will be used to generate four separate maps that will be used to select the sampling site(s). The Safety map will identify hazardous and safe operational regions on the asteroid surface. The Deliverability map will quantify the accuracy with which the navigation team can deliver the spacecraft to and from specific sites on the asteroid surface. The Sampleability map quantifies the regolith properties, providing an estimation of how much material would be sampled at different points on the surface. The final Science Value map synthesizes the chemical, mineralogical, and geological, observations to identify the areas of the asteroid surface with the highest science value. Here, priority is given to organic, water-rich regions that have been minimally altered by surface processes.

Asteroid surface samples will be acquired with a touch-and-go sample acquisition system (TAGSAM) that uses high purity pressurized N_2 gas to mobilize regolith into a stainless steel canister. Although the mission requirement is to collect at least 60 g of material, tests of the TAGSAM routinely exceeded 300 g of simulant in micro-gravity tests. After acquiring the sample, the spacecraft will depart Bennu in 2021 to begin its return journey, with the sample return capsule landing at the Utah Test and Training Range on September 23, 2023.

The OSIRIS-REx science team will carry out a series of detailed chemical, mineralogical, isotopic, and spectral studies that will be used to determine the origin and history of Bennu and to relate high spatial resolution sample studies to the global geological context from remote sensing. The outline of the sample analysis plan is described in a companion abstract [2].

[1] Lauretta, D. S., et al. Meteoritics & Planetary Science 50.4 (2015): 834-849. [2] Connolly H. C. Jr. et al. (2017) JPGU abstract (this volume).

Keywords: asteroids, sample return missions, meteorite

はやぶさ２と太陽系形成
Hayabusa2 and the formation of the Solar System

*渡邊 誠一郎[1,2]、はやぶさ2 サイエンスチーム[2]
*Sei-ichiro WATANABE[1,2], Hayabusa2 Science Team[2]

1. 名古屋大学大学院環境学研究科地球環境科学専攻、2. 宇宙航空研究開発機構宇宙科学研究所
1. Division of Earth and Planetary Sciences, Graduate School of Science, Nagoya University, 2. JAXA/ISAS

Explorations of small solar system bodies bring us direct and unique information about the formation and evolution of the Solar system. Asteroids may preserve accretion processes of planetesimals or pebbles, a sequence of destructive events induced by the gas-driven migration of giant planets, and hydrothermal processes on the parent bodies. After successful small-body missions like *Rosetta* to comet 67P/Churyumov-Gerasimenko, *Dawn* to Vesta and Ceres, and *New Horizons* to Pluto, two spacecraft *Hayabusa2* and *OSIRIS-REx* are now traveling to dark primitive asteroids.The *Hayabusa2* spacecraft journeys to a C-type near-earth asteroid (162173) Ryugu (1999 JU3) to conduct detailed remote sensing observations and return samples from the surface. The Haybusa2 spacecraft developed by Japan Aerospace Exploration Agency (JAXA) was successfully launched on 3 Dec. 2014 by the H-IIA Launch Vehicle and performed an Earth swing-by on 3 Dec. 2015 to set it on a course toward its target. The spacecraft will reach Ryugu in the summer of 2018, observe the asteroid for 18 months, and sample surface materials from up to three different locations. The samples will be delivered to the Earth in Nov.-Dec. 2020.

Ground-based observations have obtained a variety of optical reflectance spectra for Ryugu. Some reported the 0.7 μm absorption feature and steep slope in the short wavelength region, suggesting hydrated minerals. Some others obtained very flat spectra. Such variety might reflect surface chemical inhomogeneity. Through deciphering memories recorded on the asteroid, Hayabusa2 will increase our knowledge of the material mixing and transfer processes in the early solar system, mineral-water-organic interactions on planetesimals, and dynamical processes such as impact [1].

Hayabusa2 carries a sampler and four onboard remote-sensing instruments: a multi-band optical imager (ONC-T), a laser altimeter (LIDAR), a near infrared spectrometer covering 3-μm absorption band (NIRS3), and a thermal infrared imager (TIR). It also has three small rovers of MINERVA-II and a small lander MASCOT (Mobile Asteroid Surface Scout) developed by DLR in cooperation with CNES. Further, Hayabusa2 has impact experiment devices, which consist of a small carry-on impactor (SCI) excavating underground materials and a deployable camera (DCAM3) to observe the ejecta curtain. The interdisciplinary research using the data from these onboard and lander’ s instruments and the analyses of returned samples is the key to the success of the mission.

[1] Tachibana et al. (2014) Geochem. J. 48, 571-587.

キーワード：C型小惑星、惑星探査、サンプルリターン
Keywords: C-type asteroid, Planetary exploration, Sample return

Small Carry-on Impactor Elucidates the Nature of Craters and the Evolution of Solar System

*和田 浩二[1]、はやぶさ2 SCI/DCAM チーム
*Koji Wada[1], Hayabusa2 SCI/DCAM team

1. 千葉工業大学惑星探査研究センター
1. Planetary Exploration Research Center, Chiba Institute of Technology

In this presentation, scientific challenges using Small Carry-on Impactor (SCI) in Hayabusa2 mission are introduced and discussed.

Hayabusa2 is now going to a C-type, Near-Earth Asteroid (NEA) 162173 Ryugu (Ryugu), bringing Small Carry-on Impactor (SCI). SCI will be exploded several tens of minutes after separated from Hayabusa2 at an altitude of ˜ 500 m above the surface of Ryugu and will shoot 2 kg copper projectile at an impact speed of 2 km/s toward the surface of Ryugu. As a consequence of this impact, an artificial impact crater will be formed on the surface of Ryugu and a large number of fragments and grains from the excavated crater will be ejected, forming an ejecta curtain.

The scientific objectives of SCI mission are mainly classified into two themes: one is to open a window accessing the interior of the asteroid for understanding the present physical/chemical condition of Ryugu, while the other is to conduct an impact experiment on a real asteroid surface in space. In terms of the former objective, excavating the asteroid surface will hopefully enable us to observe fresh materials affected by no or weak space weathering and thermal alteration. Observing the ejecta curtain in-situ and the finally formed crater also allow us to estimate physical property of Ryugu’s surface, contributing to the regolith science on small bodies. Furthermore, we hope to collect the asteroid sample excavated from depth of several 10 cm at around the crater. From a point of view of impact experiment in space, SCI impact is a precious opportunity to examine the effects of the projectile scale and the gravity on the scaling laws relevant to the crater cavity and the ejecta. Since this experiment is conducted on the real asteroid, the data will be anchor points for the science of impact cratering.

It should be noted that the moment of SCI impact and the growing ejecta curtain cannot be observed in-situ from the Hayabusa2 spacecraft itself because the spacecraft needs to escape far away, behind Ryugu, to avoid collisions of debris from SCI explosion. For in-situ observation, we have prepared a small, handy-sized camera that will be separated from the spacecraft in the middle way of escape, observing the SCI impact about 1 km away from the impact site. That camera is called Deployable Camera 3 (DCAM3). Images taken by DCAM3 will play a key role for understanding the cratering mechanism and the surface condition of Ryugu.

キーワード：はやぶさ２、小型搭載型衝突装置、衝突クレータ、レゴリス科学、分離カメラ
Keywords: Hayabusa2, SCI, impact crater, regolith science, DCAM

Hayabusa2 Multi-scale Asteroid Science

*薮田 ひかる[1]
*Hikaru Yabuta[1]

1. 広島大学大学院理学研究科地球惑星システム学専攻
1. Hiroshima University, Department of Earth and Planetary Systems Science

The Japanese C-type asteroid sample return mission, Hayabusa2, was launched on December 3, 2014. The spacecraft is scheduled to arrive at the asteroid 162173 Ryugu on July 2018. During its 18-month stay, remote-sensing observations will be carried out by the on-board instruments, Optical Navigation Camera (ONC), Near Infrared Spectrometer (NIRS3), Thermal Infrared Imager (TIR), and Light Detection and Ranging (LIDAR). Based on the data from global mapping of the asteroid surface at 20 km in altitude, the three landing sites for collecting the asteroid samples will be determined. Furthermore, MASCOT, the small rover which packages a wide angle camera, a radiometer, a magnetometer and an infrared microscope, will acquire thermal inertia and chemical heterogeneities in a scale of centimeters to micrometers. It is therefore very important that the scientists from remote sensing, MASCOT, and sample analyses are mingled for sharing the common picture of the multi-scale science and that a discussion body is formed for integrating the observation results from the Hayabusa2 mothership and MASCOT. For this purpose, the international working group of multi-scale asteroid science has been newly organized. One of the tasks in the multi-scale asteroid science group is to work out a landing site selection strategy. Based on the scientific goal of Hayabusa2, we have targeted the region where water and organic compounds are abundant as the most scientific valuable site, which corresponds to primitive carbonaceous chondrites. For the characterization of surface materials of the asteroid, we created flow strategies using the three spectral parameters; i) 0.7 μm absorption features in reflectance spectra derived from hydrous minerals (i.e., serpentine), ii) 0.39 and/or 0.55 μm reflectance that are derived from albedo and organic carbon contents, iii) 3 μm absorption features derived from hydrated minerals, which enables the determination up to other five meteorite groups.

キーワード：はやぶさ２、マルチスケール小惑星科学、宇宙探査における国際協力
Keywords: Hayabusa2, Multi-scale asteroid science, International cooperation in space explorations

A Mobile Asteroid Surface Scout (MASCOT) on board the Hayabusa 2 Mission to the near Earth asteroid (162173) Ryugu

*Ralf Jaumann[1,2], Jean Pierre Bibring[3], Karl Heinz Glaßmeier[4], Matthias Grott[1], Tra Mi Ho[5], Stefan Ulamec[6], Nicole Schmitz[1], Christian Krause[6], Uli Auster[4], David Hercik[4], Jens Biele[6], Alexander Koncz[1], Cedric Pilogret[3], Vincent Hamm[3], Hitoshi Kuninaka[7], Tatsu Okada[7], Makoto Yoshokawa[7], Seicoro Watanabe[8], Masaki Fuijmoto[7], Harald Michaelis[1], Tilman Spohn[1]

1. German Aerospace Center DLR Berlin, 2. Freie Univ. Berlin, Inst. of Geosciences, Berlin, Germany, 3. Univ. de Paris Sud-Orsay, IAS, Orsay, France, 4. Inst. of Geophysics, Univ. Braunschweig, Germany, 5. DLR, Inst. of Space Systems, Bremen, Germany, 6. DLR-MUSC, Linder Höhe, Cologne, Germany, 7. ISASJAXA, Yoshinodai, Chuo, Sagamihara, Kanagawa, Japan, 8. Dep. of Earth and Planetary Sciences, Nagoya Univ. Furo-cho Chikusa-ku, Nagoya, Japan

MASCOT is part of JAXA’ s Hayabusa 2 asteroid sample return mission that has been launched to asteroid (162173) Ryugu (1,2,3) on Dec 3rd, 2014. It is scheduled to arrive at Ryugu in 2018, and return samples to Earth in 2020. The German Aerospace Center (DLR) developed the lander MASCOT with contributions from CNES (France) (2,3). Ryugu has been classified as a Cg-type (4), believed to be a primitive, volatile-rich remnant from the early solar system. Its visible geometric albedo is 0.07, its diameter 0.87 km (5). The thermal inertia indicates thick dust with a cm-sized, gravel-dominated surface layer (5,6). Ryugu shows a retrograde rotation with a period of 7.63 h. Spectral observations indicate iron-bearing phyllosilicates (1) on parts of the surface, suggesting compositional heterogeneity. MASCOT will enable to in-situ map the asteroid’ s geomorphology, the intimate structure, texture and composition of the regolith (dust, soil and rocks), and its thermal, mechanical, and magnetic properties in order to provide ground truth for the orbiter remote measurements, support the selection of sampling sites, and provide context information for the returned samples (2,3). MASCOT comprises a payload of four scientific instruments: a camera, a radiometer, a magnetometer and a hyperspectral microscope (2,3,7,8). Characterizing the properties of asteroid regolith in-situ will deliver important ground truth for further understanding telescopic and orbital observations as well as samples of asteroids. MASCOT will descend and land on the asteroid and will change its position by hopping (3). This enables measurements during descent, at the touch-down positions, and during hopping. The first order scientific objectives for MASCOT are to investigate at least at one position: the geological context of the surface by descent imaging and far field in-situ imaging; the global magnetization by magnetic field measurements during descent and any local magnetization at the landing positions; the mineralogical composition and physical properties of the surface and near-surface material including minerals, organics and the detection of possible, near–surface ices; the surface thermal environment by measuring the asteroids surface temperature over the entire expected temperature range for a full day-night cycle; the regolith thermophysical properties by determining the surface emissivity and surface thermal inertia; the local morphology and in-situ structure and texture of the regolith including the rock size distribution and small-scale particle size distribution; the context of the observations performed by both, the instruments onboard the main spacecraft and the in situ measurements performed by MASCOT (‘cooperative observations’). Provide documentation and context of the samples and correlate the local context of the in situ analysis with the remotely sensed global data; the body constitution on local and/or global scales and constrain surface and possibly sub-surface physical properties; the context of the sample collected and returned by the main spacecraft by qualifying its generic value and processed/pristine state and thus support the laboratory analyses by indicating potential alteration during sampling, cruise, atmospheric

entry and impact phases.

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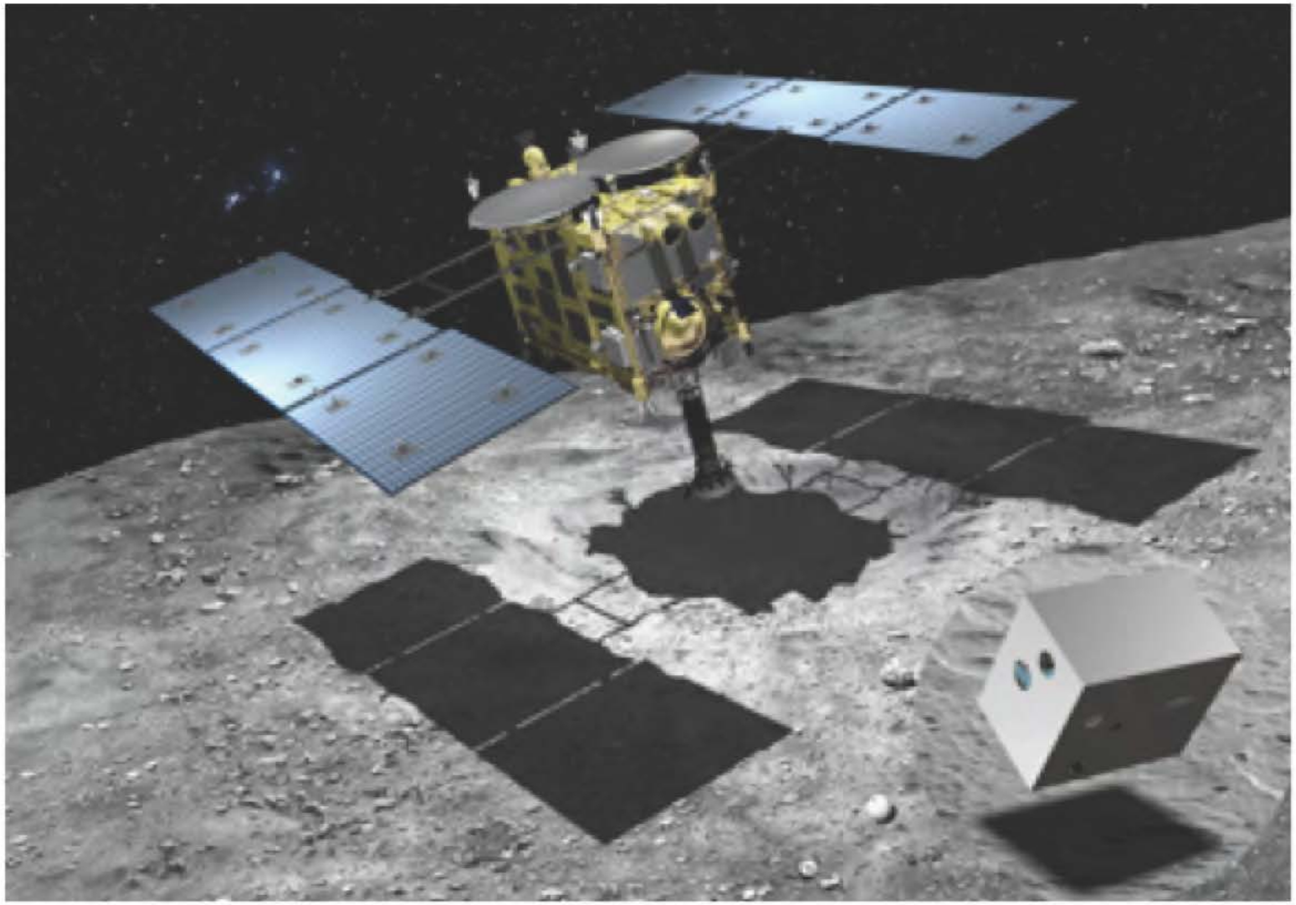
Keywords: Hayabusa, Mascot, Ruygu



Artist's conception of HY-2 during sampling, also showing MASCOT landed on the surface.
CREDIT:JAXA/Akihiro Ikeshita.

NASA’ s ASTEROID REDIRECT MISSION (ARM)

*Paul Abell[1], Daniel Mazanek[2], David Reeves[2], Paul Chodas[3], Michele Gates[4], Lindley Johnson[4], Ronald Ticker[4]

1. NASA Johnson Space Center, 2. NASA Langley Research Center, 3. Jet Propulsion Laboratory, 4. NASA Headquarters

Introduction: To achieve its long-term goal of sending humans to Mars, the National Aeronautics and Space Administration (NASA) plans to proceed in a series of incrementally more complex human spaceflight missions. The next logical step for human spaceflight is to gain flight experience in the vicinity of the Moon. These cis-lunar missions provide a “proving ground” for the testing of systems and operations while still accommodating an emergency return path to the Earth that would last only several days. Cis-lunar mission experience will be essential for more ambitious human missions beyond the Earth-Moon system, which will require weeks, months, or even years of transit time.

Mission Description and Objectives: NASA’ s Asteroid Redirect Mission (ARM) consists of two mission segments: 1) the Asteroid Redirect Robotic Mission (ARRM), a robotic mission to visit a large (greater than ~100 m diameter) near-Earth asteroid (NEA), collect a multi-ton boulder from its surface along with regolith samples, and return the asteroidal material to a stable orbit around the Moon; and 2) the Asteroid Redirect Crewed Mission (ARCM), in which astronauts will explore and investigate the boulder and return to Earth with samples. The ARRM is currently planned to launch at the end of 2021 and the ARCM is scheduled for late 2026. The Asteroid Redirect Mission is designed to address the need for flight experience via conducting integrated crewed and robotic vehicle mission operations in cis-lunar space and provide opportunities of for testing the systems, technologies, and capabilities that will be required for future human deep space missions. A principle objective of the ARM is the development of a high-power Solar Electric Propulsion (SEP) vehicle, and the demonstration that it can operate for many years in interplanetary space, which is critical for deep space exploration missions. A second prime objective of ARM is to conduct a human spaceflight mission involving in-space interaction with a natural object, in order to provide the systems and operational experience that will be required for eventual human exploration of Mars, including the Martian moons Phobos and Deimos. The ARCM provides a focus for the early flights of the Orion program, which will take place before the infrastructure for more ambitious flights will be available. Astronauts will participate in the scientific in-space investigation of nearly pristine asteroid material, at most only minimally altered by the capture process. The ARCM will provide the opportunity for human explorers to work in space with asteroid material, testing the extravehicular activities that would be performed and the tools that would be needed for later exploration and investigation of primitive body surfaces in deep space.

Target Asteroid Candidates: NASA has identified the NEA (341843) 2008 EV5 as the reference target for the ARRM, but is also carrying three other NEAs as potential options [(25143) Itokawa, (162173) Ryugu, and (101955) Bennu]. The final target selection for the ARRM will be made approximately a year before launch, but there is a strong recommendation from the scientific and resource utilization communities that the ARM target be volatile and organic rich. Three of the proposed candidates are carbonaceous NEAs. Specifically, the reference target, 2008 EV5 is a carbonaceous (C-type) asteroid that has been remotely characterized (via visual, infrared, and radar wavelengths), is believed to be hydrated, and provides significant return mass (boulders greater than 20 metric tons).

Conclusion: While NASA continues to use the International Space Station to prepare for deep space exploration, the ARM will enable our next steps on the journey to Mars. NASA’ s ARM is key to our deep space endeavors, providing important advancement of exploration capabilities and aiding the development of scientific operations for future robotic and human missions.

Keywords: Near-Earth Asteroids, Human Exploration, Sample Return, Cabonaceous Meteorites

Martian Moons eXploration (MMX): connecting small bodies with habitable planets

*倉本 圭[1]、川勝 康弘[2]、藤本 正樹[2]、玄田 英典[3]、今村 剛[4]、亀田 真吾[5]、松本 晃治[6]、宮本 英昭[4]、諸田 智克[7]、長岡 央[8]、中村 智樹[9]、小川 和律[10]、大嶽 久志[2]、尾崎 正伸[2]、佐々木 晶[11]、千秋 博紀[12]、橘 省吾[1]、寺田 直樹[9]、臼井 寛裕[3]、和田 浩二[12]、渡邊 誠一郎[7]、MMX study team
*Kiyoshi Kuramoto[1], Yasuhiro Kawakatsu[2], Masaki Fujimoto[2], Hidenori Genda[3], Takeshi Imamura[4], Shingo Kameda[5], Koji Matsumoto[6], Hideaki Miyamoto[4], Tomokatsu Morota[7], Hiroshi Nagaoka[8], Tomoki Nakamura[9], Kazunori Ogawa[10], Hisashi Otake[2], Masanobu Ozaki[2], Sho Sasaki[11], Hiroki Senshu[12], Shogo Tachibana[1], Naoki Terada[9], Tomohiro Usui[3], Koji Wada[12], Sei-ichiro Watanabe[7], MMX study team

1. 北海道大学、2. JAXA、3. 東京工業大学、4. 東京大学、5. 立教大学、6. 国立天文台、7. 名古屋大学、8. 早稲田大学、9. 東北大学、10. 神戸大学、11. 大阪大学、12. 千葉工業大学
1. Hokkaido Univ., 2. JAXA, 3. Tokyo Inst. Tech., 4. Univ. of Tokyo, 5. Rikkyo Univ., 6. NAOJ, 7. Nagoya Univ., 8. Waseda Univ., 9. Tohoku Univ., 10. Kobe Univ., 11. Osaka Univ., 12. Chiba Inst. Tech.

Martian Moons eXploration, MMX, is a mission under pre-phase A study in ISAS/JAXA to be launched in 2020s. The basic question that MMX is going to answer is how water was delivered to rocky planets and enabled to produce the habitability of rocky planets in the solar system. Planet formation theories suggest that delivery of water, organic compounds and other volatiles from outside the snow line entitles the rocky planet region to be habitable. Small bodies like comets and asteroids play the role of delivery capsules. Then, dynamics of small bodies around the snow line in the early solar system is important issue to be understood. Mars was at the gateway position to witness the process, which naturally leads us to explore two Martian moons, Phobos and Deimos, to answer to the basic question.

On the origin of Martian moons, there are two leading hypotheses, “Captured volatile-rich primordial asteroid” and “Giant impact”. Current observational facts such as orbital properties and surface reflectance spectra are individually supportive of either hypothesis but insufficient to judge which is true. MMX project aims to collect samples from a Martian moon to conclude this discussion through in-depth sample analyses in combination with close-up observations of the moons. Depending on the conclusion, we will further extract information and constraints on material distributions and transports at the outer edge of the early inner solar system as well as on planetary formations.

If the capture hypothesis is true, the Martian moons may serve as an anchor to estimate chemical properties of primitive asteroids and their original formation environments possibly near the Jovian orbit. The dynamics of transportation across the snow line to the circum-Martian orbits would also be constrained, which improves our understanding of building blocks and circum-planetary environments of Mars and the other terrestrial planets during accretion. Acquisition of constraints on the delivery of water and other volatile to Mars is particularly important because these are difficult to be deduced from observations of Mars alone that has experienced differentiation and volatile escape.

Recent numerical simulations of Martian moon accretion from giant impact ejecta suggest that the moons may be constituted from a mixture of nearly equal proportion of impactor and proto-Mars materials. Ejected materials may experience weak impact-induced heating, avoiding severe homogenization due to melting and vaporization before agglomeration. It would therefore be possible to estimate the material properties of impactor and proto-Mars, separately, from returned regolith samples if the giant impact hypothesis is true. This would provide unique constraints for the physico-chemical state of proto-Mars as well as for the material supply to Mars. These constraints are clues to understand the surface environment of Mars where chemical evolution toward life expectedly proceeded under the presence of liquid water.

キーワード：フォボス、ダイモス、火星衛星、火星、MMX
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Science Experiments on a Jupiter Trojan Asteroid in the Solar Power Sail Mission

*岡田 達明[1,2]、癸生川 陽子[3]、伊藤 元雄[4]、青木 順[5]、河井 洋輔[5]、寺田 健太郎[5]、豊田 岐聡[5]、薮田 ひかる[6]、圦本 尚義[1,7]、中村 良介[8]、矢野 創[1]、岡本 千里[9]、ビブリン ジャン＝ピエール[10]、ウラメッツ シュテファン[11]、ヨウマン ラルフ[11]、岩田 隆浩[1]、松本 純[1]、森 治[1]
*Tatsuaki Okada[1,2], Yoko Kebukawa[3], Motoo Ito[4], Jun Aoki[5], Yosuke Kawai[5], Kentaro Terada[5], Michisato Toyoda[5], Hikaru Yabuta[6], Hisayoshi Yurimoto[1,7], Ryosuke Nakamura[8], Hajime Yano[1], Chisato Okamoto[9], Jean-Pierre Bibring[10], Stephan Ulamec[11], Ralf Jaumann[11], Takahiro Iwata[1], Jun Matsumoto[1], Osamu Mori[1]

1. 宇宙航空研究開発機構宇宙科学研究所、2. 東京大学、3. 横浜国立大学、4. 海洋研究開発機構高知コア研究所、5. 大阪大学、6. 広島大学、7. 北海道大学、8. 産業技術総合研究所、9. 神戸大学、10. フランス宇宙物理学研究所、11. ドイツ航空宇宙センター
1. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 2. The University of Tokyo, 3. Yokohama National University, 4. Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, 5. Osaka University, 6. Hiroshima University, 7. Hikkaido University, 8. National Institute of Advanced Industrial Science and Technology, 9. Kobe University, 10. Institut d’Astrophysique Spatiale, Orsay, 11. German Aerospace Center

Introduction: A Jupiter Trojan asteroid mission is being studied using a hybrid propulsion system of a large area solar power sail (SPS) and an ion engine [1]. The asteroid will be investigated scientifically and for the landing site selection through remote sensing, followed by *in situ* observations on the asteroid with a lander. A sample-return is also studied as an option. LUCY [2] has been selected as the NASA’s next Discovery class mission which aims at understanding the diversity of Jupiter Trojans by multiple flybys, contrary to the SPS mission which will rendezvous and land on a Jupiter Trojan asteroid and conduct in-depth measurements. The SPS mission has been studied by the Japan-Europe joint team [3]. The key scientific objectives and the strawman payloads are introduced below.

SPS Mission Concept: The SPS is a candidate of the next medium class space science mission in Japan. This mission is based on the technology that generates electric power using a large-area (47m x 47m) thin-film solar panel to activate the ion engine even in the Jupiter orbit. The hybrid propulsion system enables us to visit and explore the outer solar system without using a radioisotope thermoelectric generator (RTG). The 1.3-ton spacecraft will carry a 100-kg class lander which has 20-kg mission payloads.

SPS Mission Design: The SPS will be launched in late 2020s, and it will take at least 11 years to rendezvous a Jupiter Trojan asteroid after the swing by the Earth and Jupiter. During the long-term cruise phase, scientific observations are planned such as the infrared astronomy under a dust-free condition, the very long baseline gamma ray interferometry, and the dust and magnetic field measurements. After arrival, the spacecraft will start observations and a lander will be deployed and descend to the asteroid. It will take ca. 30 years in total if the optional sample-return is conducted.

Science Experiments of a Trojan Asteroid: A classical static model of solar system evolution suggests that the Jupiter Trojans were formed around the Jupiter region and survive until now as the outer end members of asteroids. A dynamical model such as Nice model [4] indicates that they formed at the far end of the solar system and then transferred inward due to a dynamical migration of giant planets. The physical, mineralogical, organics and isotopic studies in regard to the heliocentric distance could solve their origin and evolution processes, so as the solar system formation. To achieve these goals, the measurements of surface materials with the lander are expected, as well as the characterization of the whole asteroid from the mothership [5]. The asteroid shape and geological features will be characterized by a telescopic imager. The surface mineralogy and the degree of hydration are mapped using a near- and thermal-infrared spectrometer. The landing site will be characterized by geological, mineralogical, and geophysical observations using a panoramic camera, an infrared hyperspectral imager, a magnetometer, and a thermal radiometer. The surface materials will be classified with a Raman spectroscopy, with a close-up imager monitoring the surface. Materials from surface and subsurface (~1m) will be collected with the sampling system. Those samples will be measured by a high resolution mass spectrometer (HRMS) with $m/\Delta m > 30{,}000$ to investigate isotopic ratios of D/H, $^{15}N/^{14}N$, and $^{18}O/^{16}O$, as well as molecules from organic matters (M = 30 to 1000). Parts of those collected samples will be also observed with a microscope.

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Keywords: solar power sail, Jupiter Trojan asteroid, D-type asteroid, organic matter, high resolution mass spectrometry

DESTINY$^+$ミッション：小型衛星による流星群母天体フライバイ

DESTINY$^+$ mission: Flyby to Meteor Shower Parent Bodies

*荒井 朋子[1]、小林 正規[1]、石橋 高[1]、亀田 真吾[3]、千秋 博紀[1]、和田 浩二[1]、渡部 潤一[2]、伊藤 孝士[2]、石黒 正晃[4]、大塚 勝仁[5]、浦川 聖太郎[6]、阿部 新助[7]、関口 朋彦[8]、木下 大輔[9]、吉川 真[10]、中村ﾒｯｾﾝｼﾞｬｰ 圭子[11]、薮田 ひかる[12]、佐々木 晶[13]、木村 宏[14]、中村 智樹[15]、中藤 亜衣子[16]、小松 睦美[20]、三河内 岳[18]、橘 省吾[21]、廣井 隆弘[17]、矢野 創[10]、佐藤 幹哉[24]、並木 則行[2]、Srama Ralph[22]、Kruger Harald[23]、山田 学[1]、船瀬 龍[18]、五十里 哲[18]、尾崎 直哉[18]、稲守 孝哉[19]、Sarli Bruno[10]、岩田 隆浩[10]、岡田 達明[10]、豊田 裕之[10]、西山 和孝[10]、川勝 康弘[10]

*Tomoko Arai[1], Masanori Kobayashi[1], Ko Ishibashi[1], Shingo Kameda[3], Hiroki Senshu[1], Koji Wada[1], Jun-ichi Watanabe[2], Takashi Ito[2], MASATERU ISHIGURO[4], Katsuhito Ohtsuka[5], Seitaro Urakawa[6], Shinsuke Abe[7], Tomohiko Sekiguchi[8], Daisuke Kinoshita[9], Makoto Yoshikawa[10], Keiko Nakamura-Messenger[11], Hikaru Yabuta[12], Sho Sasaki[13], Hiroshi Kimura[14], Tomoki Nakamura[15], Aiko Nakato[16], Mutsumi Komatsu[20], Takashi Mikouchi[18], Shogo Tachibana[21], Takahiro Hiroi[17], Hajime Yano[10], Mikiya Sato[24], Noriyuki Namiki[2], Ralph Srama[22], Harald Kruger[23], Manabu Yamada[1], Ryu Funase[18], Satoshi Ikari[18], Naoya Ozaki[18], Takaya Inamori[19], Bruno Sarli[10], Takahiro Iwata[10], Tatsuaki Okada[10], Hiroyuki Toyota[10], Kazutaka Nishiyama[10], Yasuhiro Kawakatsu[10]

1. 千葉工業大学惑星探査研究センター、2. 国立天文台、3. 立教大学、4. ソウル大学、5. 東京流星観測網、6. 日本スペースガード協会、7. 日本大学、8. 北海道教育大学、9. 台湾国立中央大学、10. 宇宙航空研究開発機構、11. NASA、12. 広島大学、13. 大阪大学、14. 神戸大学、15. 東北大学、16. 京都大学、17. ブラウン大学、18. 東京大学、19. 名古屋大学、20. 総合研究院大学、21. 北海道大学、22. University of Stuttgart、23. Max Planck Institute、24. かわさき宙と緑の科学館
1. Planetary Exploration Research Center, Chiba Institute of Technology, 2. National Astronomical Observatory of Japan, 3. Rikkyo University, 4. Seoul National University, 5. Tokyo Meteor Network, 6. Japan Spaceguard Association, 7. Nihon University, 8. Hokkaido University of Education, 9. Taiwan National Central University, 10. Japan Aerospace Exploration Agency, 11. National Aeronautics and Space Administration , 12. Hiroshima University, 13. Osaka University, 14. Kobe University, 15. Tohoku University, 16. Kyoto University, 17. Brown University, 18. The University of Tokyo, 19. Nagoya University, 20. The Graduate University for Advanced Studies, 21. Hokkaido University, 22. University of Stuttgart, 23. Max Planck Institute, 24. Kawasaki Municipal Science Museum

JAXAの次期小型科学衛星プロジェクトに提案中の深宇宙探査技術実証機DESTINY+ミッションでは，流星群母天体のフライバイ観測を目指しており、最優先探査標的天体はふたご座流星群母天体の小惑星Phaethonである。母船（DESTINY+本体）及び母船から放出される超小型機（PROCYON-mini）にそれぞれ可視近赤外カメラおよびダストアナライザを搭載し、惑星間ダスト、星間ダスト、ダストトレイル、Phaethon周辺ダストの物理化学特性のその場観測及びPhaethon表層の地形および表層物質の分光観測を行う。本稿では、本ミッションの科学的意義及び得られる科学的成果及び波及効果について述べる。

キーワード：フライバイ、流星群母天体、惑星間塵
Keywords: Flyby, Meteor shower parent bodies, Interplanetary dust particles

Panel Discussion on Missions to the Solar System’ s Small Bodies

*James L Green[1], Masaki Fujimoto[2]

1. NASA Headquarters, 2. JAXA ISAS

Our panel of experts will discuss how small bodies provide unique scientific opportunities to investigate the formation of the Solar System. They represent remnants of the building blocks of the planets and provide insight into the conditions of the earliest history of the Solar System and the factors that gave rise to the origin of life. Small bodies also experience a myriad of processes, providing numerous natural science laboratories to gain knowledge into the evolution of the Solar System. Indeed, research and exploration enabled by small bodies will help advance our knowledge of the Solar System’ s formation and evolution and about the early Solar System conditions necessary for the origin of life.
Missions to small bodies are clearly one of the major pillars of ISAS/JAXA space science program and indeed, the recent DISCOVERY selection result projects that two more of the kind will be added to the NASA Planetary Science Small Bodies Program. JAXA’ s Hayabusa 2 is expected to arrive to its target asteroid 162173 in July 2018. JAXA is also reviewing a new spacecraft mission to the Martian system; a sample return mission to Phobos called MMX (Martian Moons Explorer). First revealed in 9 June 2015, MMX's primary goal is to determine the origin of the Martian moons. Alongside collecting samples from Phobos, MMX will perform remote sensing of Deimos, and may also observe the atmosphere of Mars as well. As of January 2016, MMX was announced to be launched in fiscal year 2022. In addition, DESTINY+, a small scale technology demonstrator which will also conduct scientific observation of asteroid 3200 Phaethon is also being discussed.
Similarly, NASA also continues its exploration of small bodies. The Dawn spacecraft after orbiting Vesta for more than a year is now orbiting the largest asteroid, Ceres. In addition, the robotic asteroid rendezvous and sample return mission, OSIRIS-REx (Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer), was launched in September 2016. The first U.S. mission of its kind, OSIRIS-REx will approach the near-Near Earth Asteroid 1999 RQ36 (Bennu), in October of 2019. It will collect at least 60 g of pristine regolith/surface material and return it to Earth in September 2023. Finally, NASA announced two new Discovery class missions which will study small bodies.
Psyche is an orbiter mission that will explore the origin of planetary cores by studying the metallic asteroid 16 Psyche. This asteroid may be the exposed iron core of a protoplanet, likely the remnant of a violent collision with another object that stripped off the outer crust. This mission was just selected by NASA's Discovery Program.
The Lucy mission will tour six Jupiter Trojans. The mission is named after the iconic 'Lucy' hominin skeleton, because the study of Trojans could reveal the "fossils of planet formation": materials that clumped together in the early history of the Solar System to form planets and other bodies. The Australopithecus itself was named for a Beatles song, "Lucy in the Sky with Diamonds". On 4 January 2017, *Lucy* was chosen, along with the *Psyche* mission, as NASA's next Discovery class missions.
This is truly an exciting time for Small Bodies’ science and these are true missions of discovery that integrate into our investigations and understanding of how the Solar System formed and evolved. In this session we will look at results from active missions, status of the missions in progress to their target, and overview the newly announced missions.

Keywords: Small Bodies, NASA, JAXA, Missions