Planetesimals: Early Differentiation And Consequences For Planets

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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

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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

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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

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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)

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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

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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

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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

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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

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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.

Keywords: Jupiter Trojans, Hildas, survey observation, size distribution

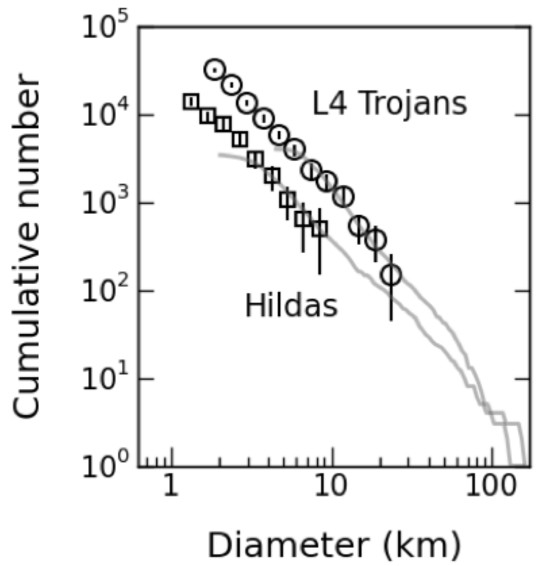

Figure 1. Cumulative size distributions of the L4 Jupiter Trojan (circles) and Hilda (squares) asteroids detected in our survey. Their cumulative numbers are scaled by those of the known objects shown as gray lines.

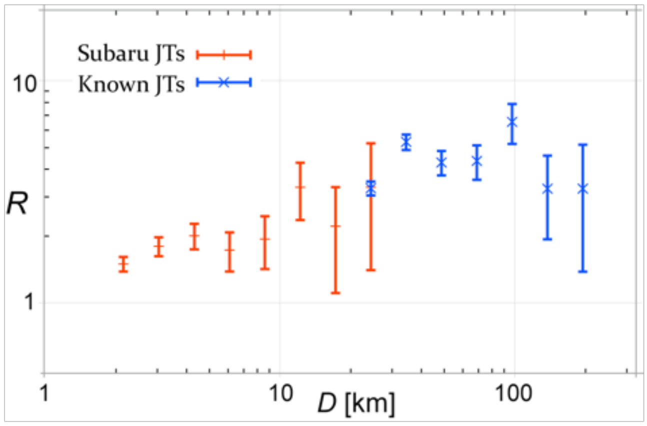

Figure 2. SFD of JTs on an R plot, this method can emphasize a shape of SFD. Blue: Known JTs with H < 12.3 mag (MPC). Red: JTs that we have detected through our own surveys. Note that the vertical axis is just relative to each other, and the unit is arbitrary.

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

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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.

Keywords: asteroids, hydrated minerals, near-infrared spectroscopy

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

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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.

Keywords: space weathring, solar wind, C-type asteroid

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

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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

On the possible detection of collisional environment from the crater shape distribution on iron bodies

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Iron bodies that are sources of iron meteorites are considered to be remnants of the cores of differentiated bodies formed early in the terrestrial planet region (Bottke et al., 2006). On the other hand, M type asteroids including asteroid 16 Phyche, which are candidates for the iron bodies, are located in the main asteroid belt. The surface temperature and the mutual collision velocity are different in the terrestrial planet region and the main asteroid belt. Therefore, if temperature and impact velocity influence the shape of craters on iron bodies, the collision environment and possibly the orbital evolution of the bodies could be constrained by the crater shape distribution on the surface.

We performed laboratory impact experiments and numerical simulations of metal projectiles and targets of SS400 steel, which has similar strength and brittle-ductile transition temperature to the iron meteorite (Ogawa et al., 2016, JpGU), and added data of Gibeon iron meteorite target (Ogawa et al., 2016, JSPS fall meeting) and rock projectiles. The experiments were conducted for targets of 150 K and room temperature with impact velocities ranging from 0.8 to 7 km/s. Formation of craters at impact velocity higher than 7 km/s or with an impactor 1 km in diameter on metal targets was simulated numerically using iSALE-2D code. The ANEOS equation of state of iron (Thomson, 1990), Johnson-Cook model (Johnson and Cook, 1983) as strength model were used. The parameters of the Johnson-Cook model for the iron meteorite were estimated based on the stress-strain curve of Henbury iron meteorite (Furnish et al., 1994), which is the same octahedrite meteorite as Gibeon iron meteorite. As a result, we confirmed that the numerical simulation reproduced experimental results.

Strength of Gibeon iron meteorite and SS400 increases by 150-200 MPa by cooling (Gordon, 1970; Furnish et al., 1994; Pennet et al., 1966; Sakino, 2015). Both crater depth and diameter became smaller as the strength increased due to cooling and the impact velocity decreased. However, the decreasing tendency appeared more remarkably in the depth than in the diameter. Consequently, the peak of frequency distribution of depth-to-diameter ratio of craters on the surface of iron bodies is expected to be smaller in the main asteroid belt than in the terrestrial planet region.

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Keywords: iron body, impact, crater

Dawn @ Ceres: Evidence for a Once Frozen Ocean World

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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

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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

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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.

Acknowledgments: This work has been supported by the NASA/Dawn mission under contract to UCLA and the Jet Propulsion Laboratory/Caltech

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Keywords: Geophysics , Vesta , Ceres

Current Understanding of the Evolution of Vesta

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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

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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 $theta^{\hat{}} = \tan(theta) / \tan(theta_r)$. Similarly we derive $theta^{\hat{}}$-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

Hayashi, K. and I. Sumita, Low-velocity impact cratering experiments in granular slopes, *Icarus* (submitted).

Keywords: Granular slopes, Impact processes, Asymmetric craters, Scaling relations, Asteroid Vesta

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

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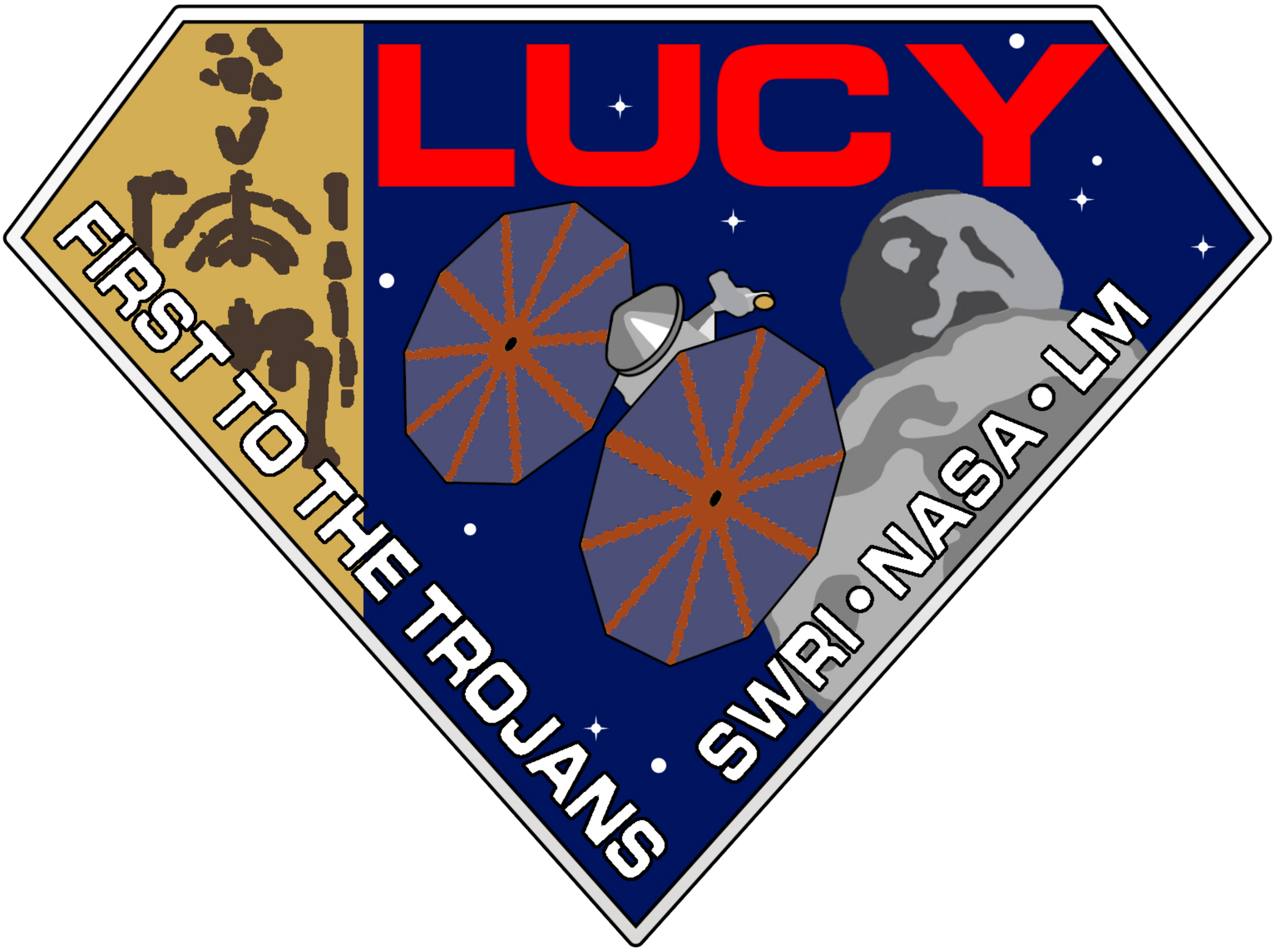
The Lucy mission is the first reconnaissance of the Jupiter Trojan asteroids - objects that hold vital clues to deciphering the history of the Solar System. Due to an unusual and fortuitous orbital configuration, Lucy, which has been selected as part of NASA's Discovery Program, will perform an exhaustive 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

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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).

Keywords: Itokawa, Return sample analysis, Hayabusa mission

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

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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 um with seven narrowband filters), a near-infrared spectrometer (NIRS, 0.8 - 2.1 um), 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.

Keywords: Hayabusa, Asteroid, Itokawa

Estimation of Interior Density Distribution for Asteroid Itokawa

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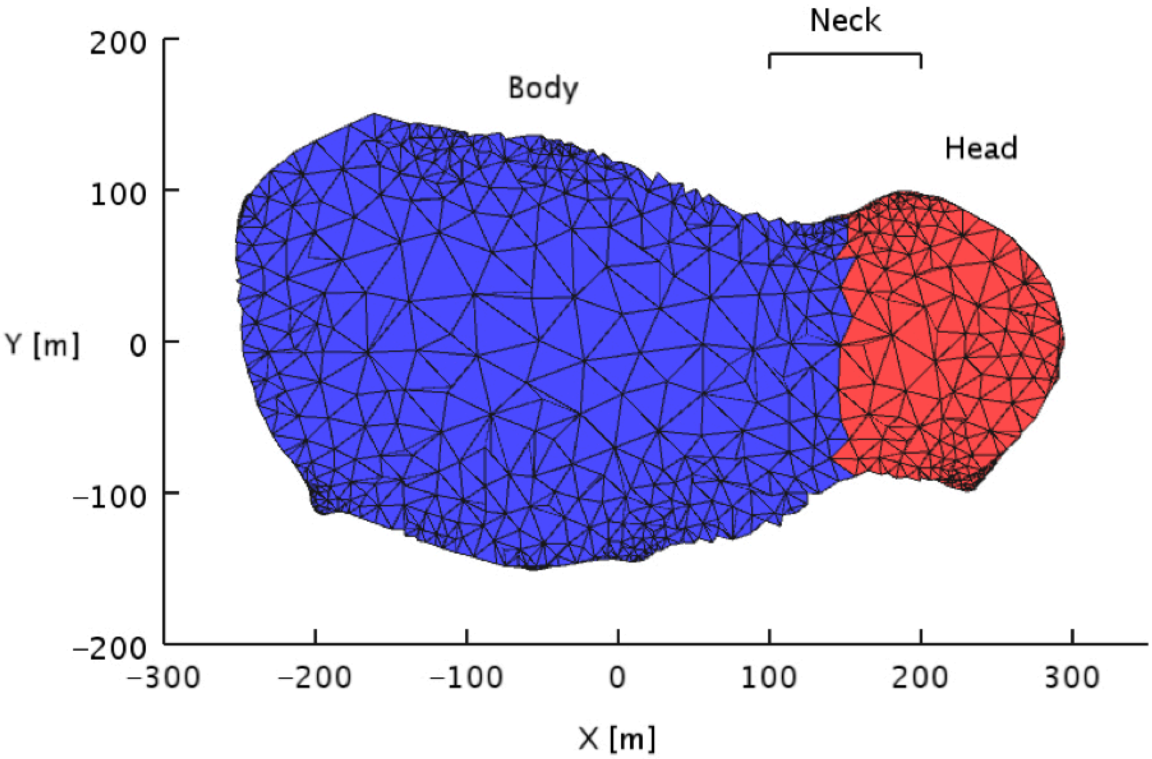
Itokawa is considered to be a rubble pile object based on high porosity of approximately 40 percent (Fujiwara, et al., 2006). However, internal structure and formation process of the sub-kilometer-sized rubble pile are still open questions. Interior density distribution of Itokawa gives us an important 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.

Keywords: Asteroid Itokawa, Gravity Field, Polyhedron Gravity Simulation, Density Inhomogeneity, Interior Structure


Neck
Body
Head
200
100
Y [m]
0
−100
−200
−300
−200
−100
0
100
200
300
X [m]

Space weathering of quasi-circular depressions on Itokawa and its orbital evolution

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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.

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Keywords: Asteroids, Hayabusa, Spectral analysis, Space weathering

OSIRIS-REx spacecraft current status and forward plans

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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].

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Keywords: asteroids, sample return missions, meteorite

Hayabusa2 and the formation of the Solar System

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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.

Keywords: C-type asteroid, Planetary exploration, Sample return

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

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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.

Keywords: Hayabusa2, SCI, impact crater, regolith science, DCAM

Hayabusa2 Multi-scale Asteroid Science

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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.

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

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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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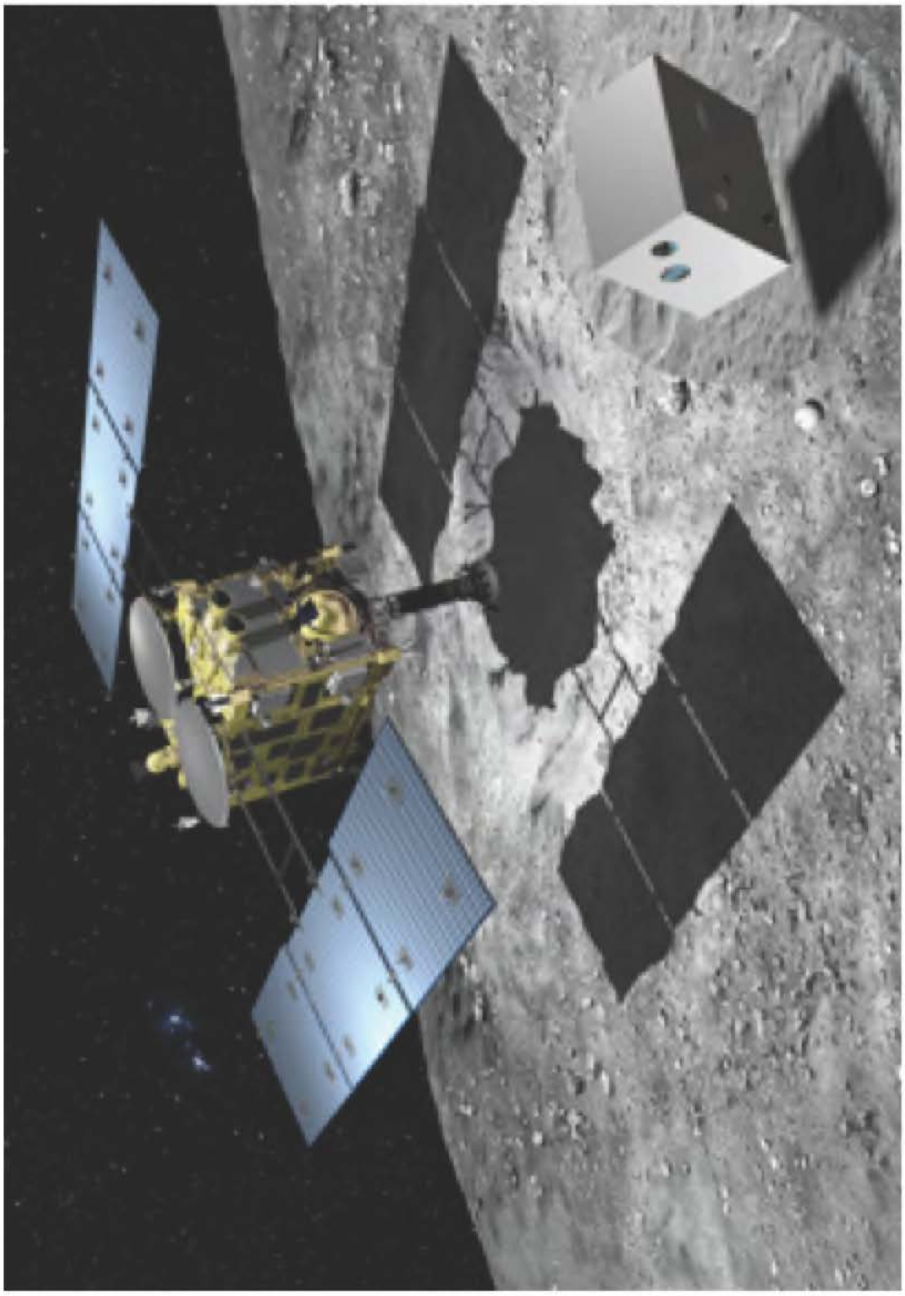
Keywords: Hayabusa, Mascot, Ruygu



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)

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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

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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.

Keywords: Phobos, Deimos, martian satellites , Mars, MMX

Science Experiments on a Jupiter Trojan Asteroid in the Solar Power Sail Mission

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

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About 40,000 metric tons per year of extraterrestrial materials enters the atmosphere and eventually reaches the ground. This extraterrestrial materials are derived either from cosmic dust background or from meteor showers. The former consists mostly of interplanetary dust and with minor interstellar dust. The latter are meteoroids generated from breakup of comets and asteroids. Parent bodies which are dynamically linked with major annual meteor showers have been identified. Meteoroid dusts are rare and important extraterrestrial matters of which origins are identified. Asteroid 3200 Phaethon is a parent body of the Geminids meteor shower, which is among the most active meteor showers. While most of the parent bodies of meteor showers are comets, cometary activity of Phaethon has only been reported near its perihelion at 0.14 AU. Phaethon is likely a comet to asteroid transitional body. Depletion of sodium, which is a moderately volatile element, and high dust density (about 2.9 g/cm^3), relative to other meteor showers are reported from spectroscopic study of the Geminids meteoroid. Because of its small perihelion distance, dehydration of the surface material by solar heating is expected, but some primitive, hydrous material may still reside in its interior. Phaethon is an ideal body to understand the origin of meteoroid dusts and thermal evolution of primitive bodies in the near-Earth orbit. Also, Phaethon is the largest body among potentially hazardous asteroids (PHAs), of which cross the Earth`s orbit. Thus, Phaethon is a critical mission target both in the context of science and planetary defense. Here, we presents a flyby mission to Phaethon and its related asteroids with DESTINY$^+$.

Keywords: Flyby, Meteor shower parent bodies, Interplanetary dust particles

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

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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

Distribution of ^{54}Cr Isotope Anomalies in Asteroid Belt

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Isotope Anomalies of ^{54}Cr in Various Meteorites: The degree of ^{54}Cr anomalies in various meteorites was shown to have a good correlation with the evaluated formation ages of their parent bodies [1], except for CAIs [2]. A possibility that the correlation is caused by an input of ^{54}Cr-rich grains ejected from a nearby supernova was proposed [1]. In the model, the input material was assumed to land on a certain ring of the solar nebula at the certain time. Then, the model may reproduce the increase of the ^{54}Cr content, but a spike of ^{54}Cr anomaly contained in CAIs cannot be reproduced by the model. Here, we look for the other process. Inside a molecular cloud core that would form a star and a protoplanetary disk system could be inhomogeneous [3]. This suggests that the isotope anomalies seen in meteorites today may be caused by the isotopic heterogeneity in the molecular cloud core.
In this study, a model that may reproduce the observed anomalies of 54Cr starting from the inhomogeneous molecular cloud core is examined.

Model: It is assumed that isotopically heterogeneous dust grains are inhomogeneously distributed in the initial molecular cloud core; especially, ^{54}Cr-rich grains are concentrated in the central part of the cloud core. Then, the concentration of ^{54}Cr-rich grains is calculated numerically as a function of the time and the place in the solar nebula. Model parameters are the initial angular velocity of the molecular cloud core omega, which determines the size of growing solar nebula, and the strength of the gas turbulence in the solar nebula alpha, which controls the radial flow of the gas and the diffusive motion of dust grains. The mass infall from the molecular cloud core lasts 0.4 Myr.

Results: A typical result is as follows. When omega = 3×10^{-15} s^{-1} and alpha = 10^{-4}, in the early phase (< 0.4 Myr), the concentration decreases as time because the infall of new dust grains from the cloud core dilutes the concentration of ^{54}Cr rich dust grains. Later (> 0.4 Myr), the concentration increases because of the diffusive motion in the nebula. These features are consistent with observations [1, 2].

Summary: We examined the possibility that an inhomogeneous molecular cloud core could generate the inhomogeneous and time dependent distribution of ^{54}Cr-rich dust grains in the asteroid belt. We found that indeed the mechanism may work. The isotope anomalies may be caused by the inhomogeneous initial molecular cloud and by the incomplete mixing of dust grains in the solar nebula.

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Keywords: Isotopic Anomaly, Solar Nebula

Effect of carbon grain destruction on chemical structure in protoplanetary disks

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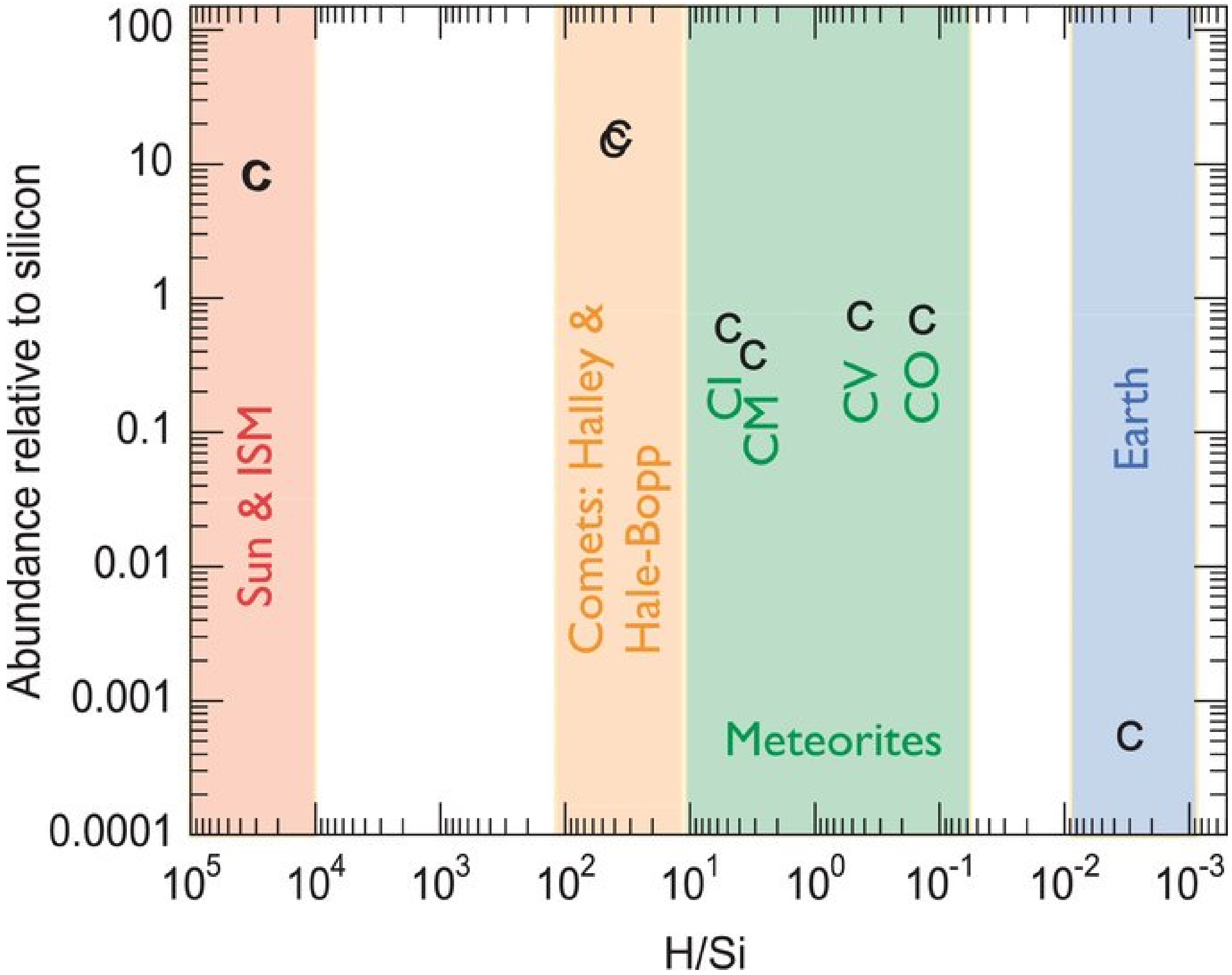
The bulk composition of Earth is dramatically carbon poor compared to that of the interstellar medium, and this tendency extends to the asteroid belt. There is a gradient in the amounts of condensed carbon relative to silicate.

Based on Lee et al. (2010), we calculate the molecular abundances in the protoplanetary disk using chemical reaction network, taking into account of carbon grain destruction in the inner disk. In this study, we consider two kinds of gas-phase abundances of carbon as initial condition. First, the normal abundance of Taurus molecular cloud, where oxygen abundance is larger than carbon abundance, is assumed. Second, we considered that all the carbon in the grain are sputtered into gas-phase, and thus the abundance of carbon is larger than that of oxygen. We compared the molecular abundances at different distance from the central star and find the differences between two initial conditions. Furthermore, we calculate the fraction of carbon in/on grains at different radii of the disk in order to understand the gradient of condensed carbon in our solar system.

Keywords: protoplanetary disk, chemical network, carbon depletion


Abundance relative to silicon
100
10
1
0.1
0.01
0.001
0.0001
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
H/Si
Sun & ISM
Comets: Halley &
Hale-Bopp
CI
CM
CV
CO
Meteorites
Earth
C

Understanding Molecular Oxygen in Cometary Atmospheres

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The Rosetta spacecraft discovered molecular oxygen during its orbiting of comet 67P Churyumov-Gerasimenko [Bieler et al., Nature 526, 678-681 (2015)]. Based on previous ground-based cometary observations, this was an unexpected finding, as was the significant amount of O_2 detected. The average value of $[O_2]/[H_2O]$ reported by Rosetta was 0.038, with a range of 0.01-0.10. Previous cometary ground-based measurements have relied on optical measurements, whereas the Rosetta study utilized mass spectroscopy.

We have initiated a research program to investigate optical spectra from various comets for evidence of molecular oxygen. Such emission from comets has not been reported previously, but there are compelling reasons for its presence in light of the Rosetta results. In contrast to the situation with molecular oxygen, the presence of atomic oxygen in cometary atmospheres is well established, with both $O(^1D)$ and $O(^1S)$ known emitters that give rise to the green and red emission lines. Nevertheless, it it is generally assumed that their source is photodissociation of CO_2, H_2O, and other oxygen-bearing species. Based on the most recent results by the Rosetta mission, photodissociation of O_2 itself becomes a viable source of $O(^1D)$, which is produced over a large spectral region, 130 to 175 nm.

This type of information has profound consequences for the understanding of cometary formation and the evolution of our solar system. This research also impacts future studies of extrasolar planets. Optical techniques will be the only means for studying *in situ* exoplanet atmospheres, at least in the short term, and thus it is critical to resolve the present conundrum.

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Keywords: comets, cometary atmospheres, oxygen airglow

Kilometer-sized trans-Neptunian objects revealed by OASES

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Organized Autotelescopes for Serendipitous Event Survey (OASES) is an optical observation project that aims to detect and investigate stellar occultation events by kilometer-sized trans-Neptunian objects (TNOs). The abundance and the size distribution of the kilometer-sized TNOs is thought to provide fundamental knowledge of the accretion processes from the early stages of the outer solar system. However, they are extremely faint and are impossible to detect directly even with 8-m˜10-m aperture telescopes. Instead of the direct detection, a monitoring observation of stellar occultation events is one of the possible ways to estimate the abundance and the size distributions of the kilometer-sized TNOs. Since stellar occultations by the TNOs are very rare (lower event rate than 10^{-2} events per year per star) and short duration (shorter than one second) events, a lot of stars must be monitored simultaneously with a sampling cadence much higher than general optical observation instruments. We thus developed multiple low-cost observation systems for wide-field and high-speed photometry. The observation system consists of commercial off-the-shelf 0.28 m aperture f/1.58 optics providing a 2.3 ×1.8 square-degree field of view and a commercial CMOS camera obtaining full-frame imaging with a frame rate greater than 10 Hz. This project currently exploits two observation systems, which are installed in Miyako island, Okinawa, Japan. Owing to the recent improving CMOS technology of high-speed imaging and low readout noise, the observation system is capable of monitoring ˜2000 stars at the Galactic plane simultaneously with V-band magnitudes down to ˜13.0, providing ˜20% photometric precisions in light curves with a sampling cadence of 15.4 Hz. The OASES two observation systems are therefore executing coordinated monitoring observations of a dense stellar field in order to detect the occultations by the kilometer-sized TNOs for the first time.

Keywords: trans-Neptunian objects, Kuiper Belt , remote sensing by telescopes

Lyman α imagings of comet 67P/Churyumov-Gerasimenko by the PROCYON/LAICA

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Water production rate of a comet is one of the fundamental parameters to understand not only the cometary activity when a comet approaches the Sun within 2.5 AU but also the formation processes of molecules that were incorporated into comets formed in the early Solar System.
Comet 67P/Churyumov-Gerasimenko (hereafter 67P/C-G) is a Jupiter-family comet with an orbital period of ~6.5 years. Because the comet during the apparition in 2015 was a target of ESA's Rosetta mission, comet 67P/C-G was the most interesting comet. By the Rosetta spacecraft along with Philae lander, various kinds of observations of the comet were carried out from close to the surface of the nucleus for more than two years including its perihelion passage on 2015 August 13. However, observation of the entire coma was difficult by the Rosetta spacecraft because the spacecraft was located in the cometary coma. An estimated water production rate strongly depends on physical models of the coma, notably depend on the asymmetry of the coma and nucleus of the comet.
To derive an absolute water production rate of the comet, wide-field imaging observations of the hydrogen Lyman α emission in comet 67P/C-G were carried out by the Lyman Alpha Imaging CAmera (LAICA) on board the 50 kg-class micro spacecraft, the PROCYON on UT 2015 September 7.40, 12.37, and 13.17. Our observational dates correspond to 25, 30, 31 days after the perihelion passage of the comet. We derived the water production rates of the comet from Lyman α fluxes of the comet by using a two-dimensional axi-symmetric Direct Simulation Monte-Carlo (DSMC) model of atomic hydrogen coma. Derived water production rates, $(1.46 \pm 0.47)\times 10^{28}$, $(1.24 \pm 0.40)\times 10^{28}$, and $(1.30 \pm 0.42)\times 10^{28}$ moleules s-1 on September 7.40, 12.37, 13.17, respectively, are comparable to the water production rates estimated from *in situ* measurements by the Rosetta instruments based on the coma model of the comet. We discuss about and secular change of water production rate, and also suggest an importance of observations with small satellites.

Keywords: Comet, 67P/Churyumov-Gerasimenko, PROCYON micro spacecraft for deep space exploration, LAICA telescope

THE ROLE OF ELECTRON DYNAMICS IN THE SOLAR WIND INTERACTION WITH COMET 67P/CHURYUMOV-GERASIMENKO AT 3 AU

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ESA’s Rosetta orbiter spacecraft escorted comet 67P/Churyumov-Gerasimenko for almost two years, carrying 21 scientific instruments. Five of those were dedicated to plasma measurements. The mission revealed for the first time, and in unprecedented detail, the fascinating evolution of the former Kuiper Belt object as it races along its 6.45yr elliptical orbit around the Sun [1]. Using a self-consistent 3-D fully kinetic electromagnetic particle-in-cell approach [2-3], we focus on the global cometary environment and, in particular, on the collisionless electron-kinetic interaction. We include cometary ions and electrons produced by the ionization of the outgassing cometary atmosphere in addition to the solar wind ion and electron plasma flow. We approximate mass-loading of the cold cometary ion and electron populations using a 1/r relation with distance to the comet with a total neutral production rate of $Q = 10^{26}\ s^{-1}$ [4-5]. Our simulation results disentangle for the first time the kinetic ion and electron dynamics of the solar wind interaction with a weakly outgassing comet. The simulated global structure of the solar wind - comet interaction confirms the results reported in hybrid simulations of the induced cometary magnetosphere [6-8]. We show that cometary and solar wind electrons neutralize the solar wind protons and cometary ions, respectively, in the region of influence around the comet, representing to first order a four-fluid behavior [9]. Analyzing ion and electron energy distribution functions, and comparing with plasma measurements from ESA's Rosetta mission to comet 67P/Churyumov-Gerasimenko, we conclude that a detailed kinetic treatment of the electron dynamics is critical to fully capture the complex physics of mass-loading plasmas [10].

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Keywords: Comets, Rosetta, 67P/Churyumov-Gerasimenko, particle-in-cell simulations, Electron dynamics

Polarimetric Study of (331471) 1984 QY1, a Potential Dormant Comet Candidate

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Identification between asteroids and comets are fundamental to know the spatial distribution of small bodies in the solar system, and yet, it is challenging to find dormant comets in the list of known asteroids because their appearances are indistinguishable from asteroids. Here we provide a unique research to discriminate asteroids and dormant comets via 'polarimetry'. We thus conducted a polarimetric observation of (331471) 1984 QY1 (hereafter QY1) using the Multi-Spectral Imager (MSI) on the 1.6-m Pirka Telescope from UT 2016 May 25 to June 24. The object has been regarded as a dormant comet candidate in terms of the dynamical property (i.e. the Tisserand parameter with respect to Jupiter T_J = 2.68, the probability of Jupiter-comet origin P_{JFC} = 96 %; Bottke et al. 2002). We investigated the phase angle dependence of polarization degree of QY1, and found that it shows the polarization degree P_{max} = 7.4 +/- 0.2 % around the phase angle α = 100 degree. The polarimetric property is similar to those of S-type asteroids rather than cometary nuclei. In this presentation, we introduce our observation and discuss about the possible origin of QY1 based on our observation together with the dynamical properties.

Keywords: asteroid, polarimetry, potential dormant comet

Meteor shower Forecast - Orbital Calculation of Cometary Dust Trails

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Meteor is a plasma emission that occurs when interplanetary dust called meteoroid enters the Earth's atmosphere. Meteoroids are thought to originate from asteroids and comets.mm-sized meteoroids ejected by a comet generate a meteoroid stream called dust trails, and when they intersect with the Earth’s orbit they can create meteor showers. Every time a comet returns to the sun, a large amount of dust is released with gas and a new dust trails is formed. Furthermore the orbit of the dust trails changes complicatedly due to gravity perturbations by planets, dwarf planets, moon. We can predict the appearance of meteor shower by calculating the orbit of dust and considering the intersection condition with the earth orbit. Meteor shower forecast can provide the date and time when dust trails encounter with the Earth’s orbit. We performed orbital calculations of dust trails formed by comet 109P/Swift-Tuttle, the parent body of Perseid meteor shower. In this study, the maximum of the 2016 Perseids is successfully predicted by our 1D orbital calculation and 2D orbital calculation model which are comparable to optical observational result. 1D orbital calculation supposes that dusts are emitted when comet is in perihelion (2D orbital calculation: perihelion and surroundings). Our new 4D orbital calculation model is also discussed. This calculation supposes that dusts are emitted from the comet in three axial directions. Three axial directions are progress direction of comet, radial direction and perpendicular to the orbital plane (1D and 2D orbital calculation consider only progress direction of comet). And, ejection velocity of dust in 2D orbital calculation and 4D orbital calculation was compared. We found that there was a difference in ejection velocity.

Keywords: comets, meteor shower, dust trails

4-D dust trail calculations of 1998 Bootid outburst and 1972 Giacobinid absence

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June Bootid out bursted in 1998, but its mechanism has not been known well. We made the first 4-D dust trail calculation for the meteor shower and revealed that several duat trails yielded in the 19th century close encounterd to the earth to show the meteors. The minimum velocity ejected from 7P/Pons-Winnecke is 10 m/s, and the peak time and the arc of the activity can be explained clearly. Also, the 4-D duat trail calculation revealed the mechanism of 1972 Giacobinid. Giacobinid was expected to show the activity in 1972 but almost no activity. This is because that the minimum ejection velocity from the parent comet was 60m/s which is over the sublimation velocity of H_2O.

Keywords: Bootid, Giacobinid, dust trail theory

Conceptual Study of Small Active Seismic Exploration Package on Moons and Small Bodies

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Seismic exploration is a powerful tool to probe inner structure of planetary bodies. Developing a seismic observation package that is compatible with small to middle size spacecraft will open a new window to investigate deep interior of planetary bodies including asteroids and small satellites such as Phobos. We have been designing and developing a seismic observation package with 3 axes seismometers, active seismic source and anchoring system. This was originally designed for Japanese Martian Moons eXploration (MMX) Mission. We were not selected for the nominal payload but the selection process of optional instruments is still ongoing. Here we will present the basic concept of our seismic observation package and describe each subsystem. The seismic observation package consists of 3 components, a seismometer, an active seismic source, and an anchoring mechanism. The seismometer is based on a short period sensor that was designed for Japanese Lunar A mission. In addition to the previous design, we are developing a new feedback for higher sensitivity at lower frequencies. Current sensitivity of the SP seismometer decrease below 1 Hz but with new feedback, the sensitivity stays high down to 0.1 Hz. The active seismic source is designed so that we can control the generated waveform. This is a well-developed method in terrestrial seismology known as ACROSS (Accurately Controlled Routinely Operated Signal System). By controlling the waveform of the seismic source we can search for the reflected signal through cross correlation method. The anchoring mechanism will be necessary especially on low gravity condition. One of the major problems in planetary seismic observation is the coupling between the instruments and the ground. This will be an important issue especially for active seismic source. We will describe results of our conceptual study of the seismic observation package and discuss the possibilities of future space missions.

Keywords: Small bodies, Planetary Exploration, Seismology

Orbit and Size Distribution of Faint Meteors by MU Radar and Highsensitive Cameras

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Solar system small bodies ranging between 10-15 and 1015g are continuously colliding with the Earth. Majority of them are so called meteoroids or IDPs (Interplanetary Dust Particles) whose diameters are estimated between 10 and several 100 μm. It is indicated by ground-based optical and radar observations or in-situ measurements that a daily mass influx of meteoroids is ranging from 100 to 300 tones. However, it is still a matter of determining size distributions of influx meteoroids and finding parent bodies of them, while parent bodies of major meteor showers have been identified as comets or dormant comets. Their physical and chemical aspects such as orbits, composition and structure are also poorly known. The influx rate of interplanetary dusts onto the Earth's surface is essential for the human space activities. Thus, it is also very important to investigate influx rate, orbits and mechanical strength of meteoroids.

High power large aperture (HPLA) radar observations have enabled to provide information on individual meteoroids' orbits, their influx and ablation processes in the upper atmosphere. The meteor head echo observation has been carried out using the middle and upper atmosphere radar (MU radar) of Kyoto University at Shigaraki (34.9N, 136.1S), which is large atmospheric VHF radar with 46.5 MHz frequency, 1 MW output transmission power and 8330 m2 aperture array antenna. We have revolutionary achieved to determine the most precise orbits of approximately 180,000 meteoroids observed between 2009 and 2016. In order to investigate the size distribution of these meteoroids, simultaneous observations using MU radar and high-sensitive optical observations, about 9th limiting magnitude, were achieved to obtain the relationship between Radar Cross Section (RCS) and visual magnitude that can provide the size of meteoroids.

This paper describes size distributions and orbital parameters of faint meteors observed by MU radar and a high-sentive camera (limiting magnitude~9th).

Keywords: Meteors, Meteoroids, Dusts, Asteroids, Comets

Oxidation processes of I-type spherules during atmospheric entry

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Oxygen isotope fractionation of atmospheric O_2 ($\delta^{18}O$ ~ 23.5‰) from ocean water (0‰) [1] is explained by photosynthesis and respiration of terrestrial biomes (Dole-Morita effect; [2-3]). One can expect that temporal variation of terrestrial biomass has been reflected in temporal $\delta^{18}O$ variation of atmospheric O_2, which may be recorded in iron-oxide rich cosmic spherules (I-type CSs) that were originally extraterrestrial FeNi metal and oxidized in the upper atmosphere upon entry. In this study, we analyzed oxygen isotope ratios of I-type CSs using ion microprobe in order to understand oxidation processes of I-type CSs.
Samples in this study are Antarctic I-type CSs and 3 iron-oxide spherules (MRs) artificially produced by melting of metallic iron powder. 9 CSs that show none or low Cr contents and contain coarse magnetite/wustite grains were selected and analyzed for oxygen isotopes using IMS-7f at Tohoku University. The analytical conditions were similar to those in [4].
The polished surface of the samples consists of wustite and magnetite. 4 out of 9 CSs are extraterrestrial in origin, given the low Cr_2O_3 contents (<0.2wt%). The $\delta^{18}O$ and $\delta^{17}O$ values of CSs and MRs plot on the terrestrial fractionation line with a slope of 1/2, indicating that oxygen isotope ratios of CSs reflect terrestrial ones. Similarly to deep-sea CSs (400-600 μm in diameter) [5], the $\delta^{18}O$ values of ~40‰ from 4 CSs (~100 μm in diameter) are higher than that of atmospheric O_2, suggesting oxygen isotope fractionation due to evaporation during atmospheric entry heating. But unlike the previous study [5], there is no correlation between radii of CSs and $\delta^{18}O$, suggesting that oxygen isotope fractionation requires factors besides particle radius. The $\delta^{18}O$ values of MRs are low at from 1‰ to 17‰ and similar to those of iron meteorite fusion crust [6], which are explained by kinetic isotope effect. It is suggested that MRs did not experience significant isotopic mass fractionation via evaporation and/or affected by adsorbed H_2O (~0‰) on metallic iron powder.
We performed numerical simulations of oxygen isotope fractionation during atmospheric entry heating of a FeO spherule with $\delta^{18}O$ of 15‰ by changing entry velocity, entry angle and initial radius based on the data in [7]. It is suggested from the comparison between results of simulation and measured CS data that entry velocity and angle besides particle radius may be the key factor for degree of oxygen isotope fractionation due to evaporation during atmospheric entry. The similar $\delta^{18}O$ values and different sizes between CSs in this study and those in [5] may be explained by difference in entry velocity (14-18km/s vs. 12km/s).
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Keywords: cosmic spherules, oxygen isotope ratios, isotope fractionation

Visualization of Near-Infrared Spectral Data of Eros Using the Small Body Mapping Tool

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One of the primary drivers for many missions visiting asteroids is to advance our understanding of their composition beyond what can be (and is) already measured by telescopes. Without sample return or lander missions, this task relies primarily on resolved near-infrared spectroscopic measurements. Scientific analysis using spectral data collected by point spectrometers is not as straightforward as for imaging spectrometers, where the local spatial context is immediately available. In the case of Eros and other highly non-spherical bodies, this problem becomes even more severe when trying to locate spectra that cross a mapped feature that bends over an irregularly shaped surface. Thus, it is often the case that outside of the mission teams, few from the community at large delve into these data sets, as they lack the tools necessary to incorporate the spectral information into geological analyses of the asteroids. Ultimately, we seek to make such spectral datasets, which NASA has invested significant amounts of money to obtain, more widely accessible and user-friendly. The Small Body Mapping Tool (SBMT) is a Java-based, interactive, three-dimensional visualization tool written and developed at APL to map and analyze features on irregularly shaped solar system bodies. The SBMT can be used to locate and then “drape” spacecraft images, spectra, and laser altimetry around the shape model of such bodies. It provides a means for rapid identification of available data in a region of interest and allows features to be mapped directly onto the shape model. The program allows the free rotation of a shape model (including any overlain data) in all directions, so that the correlation and distribution of mapped features can be easily and globally observed.

We will present the results of our work on the NEAR/Near-Infrared Spectrograph (NIS) data, including improvements to the calibration made by using the geometric information provided by the SBMT and improvements to the SBMT itself to allow spectral visualization, manipulation, and analysis of these data in a spatial context.

Keywords: IR Spectroscopy, Asteroid, Mapping, Eros

Numerical simulation on the albedo of rough surfaces

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The bond albedo, or energy reflectance, is one of the most important physical parameters because it decides the thermal evolution of the surface. However the bond albedo could change with the roughness of the surface. Although the Hapke's parameter is often introduced to represent the effect of roughness on the phase function, the parameter is not straightforward.

We developed a new numerical model to simulate the image of a rough surface and by using the model calculated the bond albedo of the rough surface.
According to our model, even for the case with Lambertian polygons the bulk bond albedo depends not only on the roughness of the surface but also on the solar incident angle, because of heterogeneous distribution of irradiated area. In this presentation we will propose a new equation to calculate the bond albedo of a rough surface.

Keywords: albedo, rough surface, thermal evolution

Capability of Photoscan, a commercial implementation of the Structure from Motion technique, for Asteroid Shape Reconstruction

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Shape model reconstruction of asteroids from images take is important to control the spacecraft safely and scientific analysis of the asteroid exploration missions including Hayabusa2. Mori (2014) evaluated the capability of Bundler (Snavely, 2006), an implementation of structure from motion, in the asteroid shape reconstruction from images of explorer missions. However, Bundler has problems on robustness and stable processing. Agisoft Photoscan, a commercial implementation of structure from motion, is a possible alternate of Bundler. Photoscan is widely used in the geoscience research field. We evaluate the capability of Photoscan for asteroid shape reconstruction in Hayabusa2. We used image sets chosen from the asteroid Itokawa data set taken by Hayabusa as input images and the Itokawa's shape model reconstructed by Gaskell (2006) as the reference model. They are the same as those used by Mori (2014). We also follow his work on the evaluation scheme. Through our test, Photoscan successes to reconstruct the Itokawa’ s shape even from a dataset with a limited number of images, with which Bundler failed. Photoscan results also show stable accuracies in such cases. Robustness and stability of Photoscan are superior to those of Bundler. We conclude that Photoscan has enough capability for asteroid shape reconstruction.

Keywords: asteroid, shape reconstruction, Structure from Motion, Hayabusa2

Color and albedo on the Ceres surface from Dawn Framing Camera images

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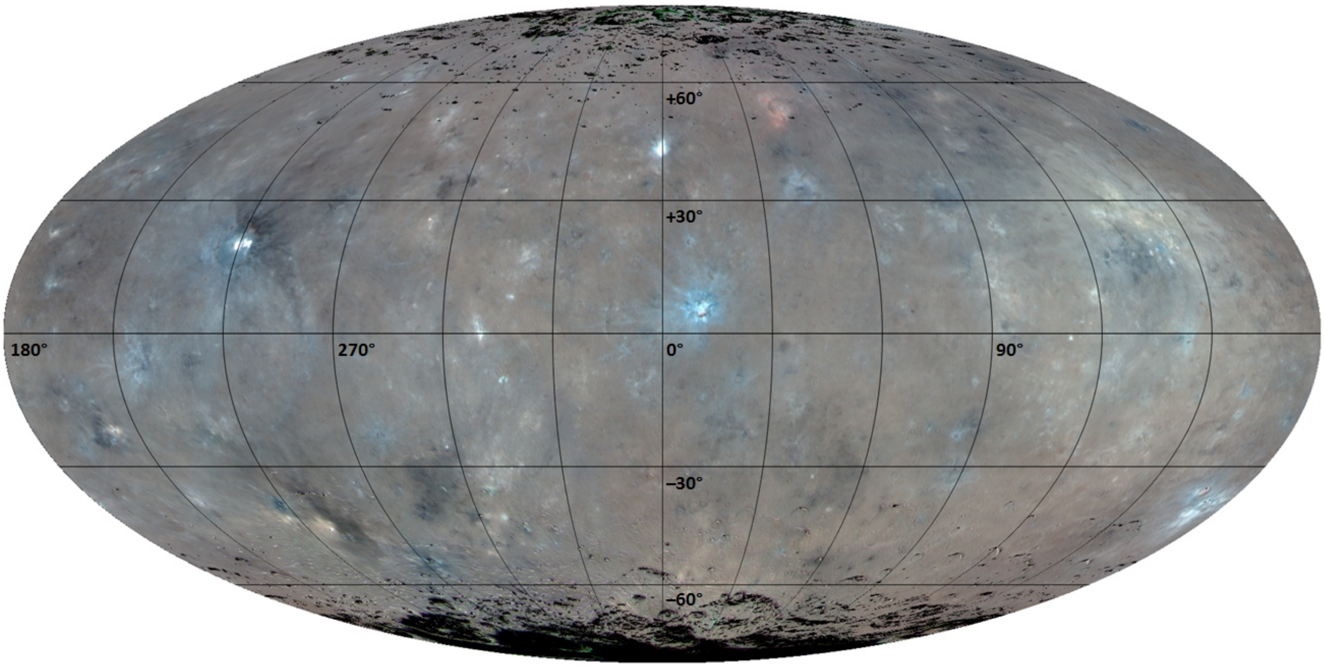
We present a global spectrophotometric characterization of the surface of dwarf planet Ceres using Dawn Framing Camera images. We employed a global photometric model to assemble photometrically corrected images acquired on approach to Ceres into global maps of albedo and color. An accumulating body of evidence suggests water ice is abundant below the Ceres surface. Water ice is not stable on the surface, yet has been directly detected in Oxo crater (Combe et al. 2016). Water may even exist in liquid form in the interior. Carbonates identified in the very bright and young Cerealia Facula in Occator crater suggest (past) hydrothermal activity (De Sanctis et al. 2016). We search for spectrophotometric evidence for water ice and hydrothermal activity in the visible wavelength range. Even though colors on Ceres are generally subdued, this small world is surprisingly colorful. The dominant color variation over the surface is represented by "blue" and "red" material, which have a negative and positive spectral visible slope, respectively. Blue terrain is widespread and often distributed in and around fresh craters. A clear correlation between blue color and youth exists (Schmedemann et al. 2016). One of the bluest, and possibly youngest, craters is Haulani, which may show evidence for cryovolcanic flows (Krohn et al. 2016). The blue color may be associated with dehydrated phyllosilicates (Schröder et al. 2017), although alternative explanations have been proposed (Stephan et al. 2017). On the other hand, red terrain is found in only a few locations, usually in small patches. The prime examples are found inside Occator crater and around Ernutet crater (Nathues et al. 2016, Schröder et al. 2017). The reddest terrain in Occator is found in the youngest parts of Cerealia Facula, and may be associated with hydrothermal activity. The origin of the red terrain near Ernutet has not yet been established. Our color and albedo maps allow us to identify sites of interest that we study in more detail using color images acquired at higher resolution.

Keywords: Ceres, surface, spectrophotometry


+60°
+30°
180°
270°
0°
90°
–30°
–60°

Surficial mineralogy of dwarf planet Ceres

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The Dawn spacecraft has been acquiring data on dwarf planet Ceres since January 2015 (1). The VIR spectrometer (0.25-5.0 μm) acquired data at different altitudes providing information on the composition of the surface of Ceres at resolutions ranging from few kilometers to about one hundred meters (2).
The average spectrum of Ceres acquired by VIR is well represented by a mixture of dark minerals, Mg-phyllosilicates, ammoniated clays, and Mg- carbonates (3). This result confirms and extends previous studies based on ground based spectra. Mg- phyllosilicates have been associated with the 2.72 μm absorption band precluded from telescopic measurements owing to the atmospheric absorptions. The ammoniated clays have been identified through the presence of an absorption feature centered at 3.06 μm as already suggested by (4) while the 3.9 μm absorption feature is indicative of the presence of carbonates as previously concluded by (5). Maps of the surface at about 1 km/px show that the components identified in the average spectrum are present all across the surface with variations in their relative abundance (6). Some localized areas however have peculiar spectral characteristics. One example is the spectrum of the bright faculae within Occator crater that is most consistent with a large amount of Na-carbonates and possibly ammonium salts (7). In addition, water ice has been detected on the surface (8) and organic rich regions have been identified in some localized areas across the surface (9). The retrieved composition indicates a pervasive aqueous alteration and at least localized hydrothermal activity of the surface of Ceres. In addition, the co-existence of ammonia-bearing hydrated minerals, water ice, carbonates, and organic material indicates a complex chemical environment that could allow the formation of prebiotic molecules making Ceres a primary target for exobiological studies.

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Keywords: Ceres, Dawn, VIS-IR spectroscopy, small bodies, asteroids, mineralogy

DETERMINING THE EFFECT OF INTERSTITIAL NEAR-SURFACE GROUND ICE ON THE MOBILITY OF LAYERED EJECTA DEPOSITS ON CERES

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During the Survey, High Altitude Mapping Orbit, and Low Altitude Mapping Orbit phases of the primary mission Dawn's Framing Camera observed a multitude of globally distributed lobate deposits. These flows were broadly interpreted as either similar to ice-cored/ice-cemented flows (Type 1 flows) on Earth and Mars, long run-out terrestrial or martian landslides (Type 2 flows), or highly mobile fluidized ejecta-like deposits (Type 3 flows) (Schmidt et al., 2016; Buczckowski et al., 2016; Schmidt et al., *Accepted*). The Type 3 flows are morphologically similar to fluidized/layered ejecta found on Mars and Ganymede (Mouginis-Mark, 1979; Boyce et al., 2010). The main structural difference between these putative cerean fluidized ejecta flows and their martian/ganymedean counterparts is that the latter tend to form full aprons around the entire circumference of their parent crater, while the former generally only occur around a fraction of the circumference (usually < 180º) of their parent crater.

Though there exists no consensus on the mode of fluidization for these ejecta deposits on Mars or Ganymede a large number of authors have interpreted the martian variety to be related to the presence of volatiles (particularly water ice) within the regolith target materials (such as Mouginis-Mark, 1979; Carr et al., 1977; Woronow, 1981, Weiss & Head, 2014). We address the hypothesis that the occurrence, morphology, and mobility of Type 3 cerean flows are a result of impact into, and emplacement on, a ground ice rich near-surface layer and that variations in the upper structure of Ceres and/or quantity of ground ice alters the mobility of fluidized ejecta in otherwise similar craters. We do this by cataloguing the global distribution of these flows and making comparisons to elemental abundance and mineralogical data, gathered by Dawn's Gamma Ray and Neutron Detector and Visible and Infrared Spectrometer respectively. We also quantify the ejecta mobility as a function of crater diameter and latitude. We define ejecta mobility (EM) as the ratio of the radius of the ejecta blanket versus the radius of the parent crater, and compare measured EM values of Cerean flows with various well studied martian analogs. We also measure drop-height-to-runout-length ratios (H/L) and compare them to planetary and experimental analogs of known composition.

We further asses the effect of ground ice as a lubricating agent in the production of these features by comparing the EM values for all Type 3 Cerean flows to a kinematic sliding model similar to the one developed by Weiss et al. (2014) to model the ejecta mobility for impacts into a variety of ground ice rich substrates of differing volatile content on Mars. This model should provide constraints on the relative importance of the effective coefficient of friction of the substrate beneath these flows, as well an independent estimate of the water ice content in the near surface.

Initial results from the global classification campaign suggests that Type 3 cerean flows preferentially occur at low- to mid-latitudes, which could be indicative of preferential creation or preservation at these locations. Measured H/L for these flows plot systematically lower than comparable length landslides on other terrestrial bodies. This reinforces their interpretation as propelled phenomena rather than gravitationally induced mass wasting. Since Ceres lacks any meaningful atmosphere, the morphological differences between Type 3 cerean flows and layered ejecta on Mars should be able to help quantify the role of interstitial gases and fluid drag in the creation of these features.

Keywords: Dawn, Ceres, Ground Ice, Fluidized Ejecta

Simulated Imaging Experiment for Landing Site Selection by Hayabusa2

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The Hayabusa2 spacecraft was launched in 2014 and is expected to arrive at the asteroid Ryugu, which belongs to the C-type asteroids in 2018. One of the objectives of the Hayabusa2 mission is to return with primordial samples from Ryugu. By using reflectance spectroscopy from the ground, Vilas (2008) detected the 700 nm-band absorption of Ryugu, indicating the presence of hydrated minerals. The *Hayabusa2* spacecraft performs multi-band spectrum observation using a telescopic optical navigation camera (ONC-T) with seven bandpass filters, and specifies the point at which the 700 nm absorption feature exists for the landing site selection. Thus, it is important to confirm the detectability of the absorption of 700 nm from multi-band spectral observation. Multi-band spectral imaging was performed using the ONC-T flight model on the carbonaceous chondrites having the similar reflectance spectrum as that of the C-type asteroid (Kameda et al., 2015). The ONC-T is equipped with a wheel containing seven bandpass filters that is rotated to perform multi-band spectrum observation. When the filter wheel is rotated to change the bandpass filters, the field of view of the ONC-T at the Ryugu surface drifts owing to asteroid spin; however, previous research that showed the detectability of the absorption of 700 nm did not simulate the drift of the field of view of each band.
In this study, this effect is confirmed by using a camera that simulates ONC-T.
An experimental system is used in which the x-axis stage is placed beneath the sample holder to simulate the drift of the field of view whereby the camera has the similar CCD and bandpass filters as that of the ONC-T. Multi-band spectral imaging was performed on these carbonaceous chondrites in which the x-axis stage moves with each change the bandpass filter.
Moreover, the amount of drift in the field of view varies depending on the altitudes from the Ryugu surface, which in this study are assumed as 20 km (HP) and 5 km, respectively. Therefore, we measure the reflectance spectra and depth of 700 nm absorption feature in the case of 30 m spatial resolution, which is specified as the region at which hydrated minerals are present.

Keywords: Hayabusa2, Multi-band spectral imaging

Detectability Performance of Thermal Infrared Imager TIR on Hayabusa2

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The thermal infrared imager TIR [1] onboard the JAXA’ s second asteroid explorer Hayabusa2 is a thermal camera based on two-dimensional uncooled micro-bolometer array, inherited from the Longwave Infrared Camera (LIR) on Akatsuki (formerly PLANET-C) Venus climate orbiter [2]. TIR is to observe the thermal emission from the target body, C-type near-Earth asteroid 162173 Ryugu (formerly 1999JU_3) to investigate its surface thermo-physical properties that are strongly related to representative grain size and porosity. Such information enables us to understand its formation process and surface evolution processes. The data from TIR will be used to select the landing sites for sample collection and for the surface lander and rovers both from scientific and technical viewpoints. Typical grain size derived from the thermal inertia map determined by TIR data is scientifically essential to select the suitable sites for collection by the sampling device and for the analysis of returned samples. Typical boulder abundance and predicted thermal environments are technically essential for safety and hazard-free landing operations.
TIR has been checked in flight by observations of the deep sky as backgrounds, and of the Earth and the Moon as known targets during the Earth swing-by operation campaign. The first and longest distance observation of the Earth and the Moon was carried out on 14 October 2015, at about 2 x 10^7 km from the Earth. There were opportunities that TIR observed the Earth and the moon 7 times before and 18 times after the Earth Swing-by on 3 December 2015. During that period, the distance changed by two orders of magnitude, and the distance dependency of TIR response is now derived for the thermal brightness of the Earth and the Moon. The dependency is inversely proportional to the square of distance, for the diameter of the Moon corresponding to 0.2 to 6 pixels of TIR images. From this trend, the detection limit (> 10 DN for the target body) is at about 1.5 x 10^8 km for the Moon [3].
This result indicates the possible detection of unknown asteroids closely passing by the Hayabusa2 spacecraft. For the 100 m sized asteroid of C-type (its geometric albedo ~ 0.05), the detection limit (> 10 DN) is estimated about 2 x 10^3 km from the spacecraft. During April to June in 2017, Hayabusa2 will be around the L5 point of the sun-earth Lagrange point, gravitationally meta-stable point, so that unknown small bodies may be detected if they pass within such a distance. Before arrival at asteroid Ryugu which is of rounded shape and with diameter of 0.88 km, it will be detected at 1.5 x 10^4 km distance. Ryugu will be investigated during the approach phase and its light-curve of brightness temperature will be investigated before arrival. Around Ryugu, TIR is estimated to detect small moons encircling Ryugu at Home Position (20 km from the target asteroid) if they have diameter larger than 1 m, and their orbits are traced by continual imags taken with TIR.

Acknowledgments

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Keywords: asteroid exploration, Hayabusa2, Thermo-physical property, thermal infrared imager, thermal inertia

Geometric and Radiometric Calibration of the Thermal Infrared Imager onboard the Hayabusa2 Spacecraft by the Earth Observation

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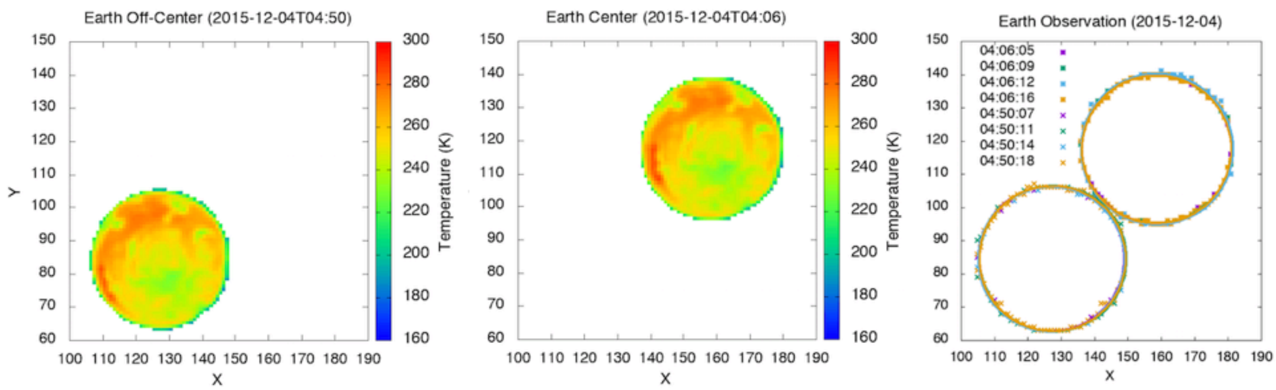
The TIR is an infrared thermal imager onboard the Hayabusa2 spacecraft, which will perform thermography of C-type asteroid 162173 Ryugu through in situ observations during the rendezvous phase in 2018 and 2019. The Hayabusa2 spacecraft carried out an Earth swing-by on December 3, 2015, and the TIR observed the Earth and the Moon for its performance checks. The detector of the TIR is an uncooled microbolometer array (320A, NEC Inc.), and the optical system has a germanium triplet lens. The observation wavelength is an integrated wavelength range of 8 to 12 micrometers. The field of view is 16 x 12 degrees, and the number of image pixels is 328 x 248 (Okada et al., 2016). The performance of the TIR was evaluated in the pre-launch test, and the conversion table from the detected radiation intensity to a brightness temperature was constructed for every pixel. The focal length was evaluated by using a large aperture collimator, as well as the image distortion and the ratio of pixel aperture. Otherwise, the performance check is necessary after launch because the observed temperature depends on surrounding changes, such as radiation and heat flow from the spacecraft and the TIR itself in space. The detector alignment correction and the observed temperature evaluation were performed by the Earth and the Moon observations in the Earth swing-by phase. The alignment was corrected to determine the Earth center position within a sub-pixel accuracy for the observed image pixel by fitting to the observed limb positions using the ellipse function for the flatness shape (6356.75 km / 6378.14 km) calculated by SPICE kernels (NAIF/NASA). The observed temperature evaluation was performed to compare the Earth sea data regarded as a blackbody with observed data with the Earth observation satellites, such as MODIS onboard Aqua and Terra. In this study, the results of the calibrations by the Earth and the Moon observations for the performance checks of the TIR are introduced.

Keywords: Hayabusa2, Thermal Infrared Imager, Earth, Calibration



HEAT: Image and database browser for the thermal imager on Hayabusa2

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Hayabusa2 is a sample return mission to asteroid 162173 Ryugu, which will arrive at the asteroid in 2018. The Thermal Infrared Imager (TIR) on Hayabusa2 performs thermal observations of the asteroid to select sites for a safe touchdown and sample return, and to know the origin and thermal history of the asteroid. Procedures of nominal TIR data analysis are as follows; (1) Metadata of TIR image is collected. (2) Local time of a center of the raw image is solved as a specified longitudinal zone on the shape model. (3) the temporal profile of surface temperature is tagged with individual TIR images and the local time. (4) Thermal inertia of the local site is estimated from the profile. (5) Thermal model based on the thermal inertia is established on the shape model. This report introduces an efficient tool for the TIR to resolve the issues as mentioned above. The developed software includes functions of the calibration database and the visualizing browser, called HEAT: Hayabusa2 Exploration Assistant for the TIR. The HEAT has three specific use: visualization, calibration, and analysis.

Keywords: Hayabusa2, TIR, HEAT, Calibration, Software, Database

Database of observed areas and its visualizer in HARMONICS, Hayabusa/Hayabusa2

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We report a visualization tool HARMONICS (HAyabusa Remote MONItoring and Commanding System) for planning observations and scientific analysis in both Hayabusa and Hayabusa2 missions. This software visualizes positions and attitudes of spacecraft, and FOVs (Field Of View) of scientific instruments. The database of observation history and coverages is established for HARMONICS. Newly additional functions are projection of footprints of scientific instruments and observed images to irregular shape model and the conversion of file format from fits file to jpg, png.

Keywords: HARMONICS, Software, Visualization, Hayabusa2, Exploration, SPICE

Multi-band image analysis of Itokawa and optical properties analysis of Hayabusa2/ONC-T

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Hayabusa2 is planned to bring samples from Ryugu back to the earth. Choosing sampling sites on Ryugu is very important. Sampling fresh materials not affected by space weathering very much is important for obtaining information on early evolution of the Solar System, because space weathering may overwrite record from the long past. In order to understand where on small asteroid we can find fresh materials, we analyzed the data taken by AMICA/Hayabusa. In addition, we analyzed optical characteristic, especially the point spread function (PSF), of the multi-band visible camera (ONC-T) of Hayabusa2 in order to carry out the same spectral analysis of space weathering.

Specifically, we analyzed the following two things.

1. Based on the data taken by Hayabusa, we estimated space weathering on the surface of Itokawa and searched for geometric parameters (HAY-A-AMICA-3-AMICAGEOM-V1.0) that exhibit good correlation with space weathering.

2. In preparation of such data analysis using Hayabusa2 data, we investigated PSF characteristics of Hayabusa2/ONC-T.

First, we conducted image correction for Hayabusa images. We calculated the ratio of light intensity of p-band (860nm) image to b-band (430nm) image (P/B). The ratio represents the degree of space weathering because space weathering caused reddening. We investigated the correlation between the ratio and slope and between the ratio and gravity in order to find out physical characteristics of places unaffected by space weathering.

This analysis was carried out on Sagamihara and MUSES-C. Sagamihara and MUSES-C are smooth areas covered by regolith where safe sampling is possible. We found that the P/B of Sagamihara is larger than that of MUSES -C. That is, MUSES -C is fresher than Sagamihara, although the topographic slope of both areas is small. Furthermore, the surface gravity on Sagamihara is larger than that on MUSES-C. Then, we measured P/B ratio along four lines in both Sagamihara and MUSES-C. For each line, correlation coefficient between ratio P/B and slope and between ratio P/B and gravity was calculated. We found the calculation results indicate that correlation coefficient between P/B and topographic slope is low (˜ -0.40) and that between ratio P/B and gravity is high (˜0.85). This means that the distribution of space weathering correlates more strongly with gravity than topographic slope. This result suggests that areas with weaker surface gravity would retain regolith particles for longer period of time on Itokawa. Thus, in exploration of small bodies, we should carry out sampling where gravity is weak in order to sample fresh substance relatively unaffected by space weathering.

Second, we analyzed the PSF of Hayabusa2/ONC-T. In our analysis, we approximated PSF as summation of Gaussian functions following Ishiguro (2014). We derived PSF by calculating coefficients of Gaussian function. We made unblurred images by applying edge detection to images for calibration. We reproduced the blurred images by convolving estimated unblurred images with PSF. This procedure was repeated with changing coefficients one by one. We obtained optimum coefficients to make residuals smallest.

First, we calculated PSF correction coefficients of Hayabusa and tried to reproduce the PSF calculated by previous work (Ishiguro 2014). Results indicate that the error between our PSF and the PSF by Ishiguro 2014 was 9.8%. Although this difference in coefficients is not very small, both coefficient sets can remove PSF-derived halos around the asteroid disk very well. The intensity of halo residuals turned out to be only 0.2 - 0.8% of the intensity of the light sources. Then we calculated the PSF correction coefficients of ONC-T/Hayabusa2 by the same procedure. Finally, we correct images taken by Hayabusa2 by using the PSF we calculated. The residuals were less than 1% in all bands, indicating that the same-quality of image analysis as Hayabusa will be possible for Hayabusa2.

Novel method for analyzing ejecta curtain growth of impact crater formed on regolith layer: Implication for impact phenomena made by Hayabusa-2 Small carry-on impactor

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Impact cratering is recognized as an universal phenomenon in the formation and evolution process of the Solar System. The scaling laws for impact cratering are necessary in order to study the evolution of planetary surfaces caused by the impacts of small bodies. By using the scaling laws, we can apply experimental results of cm-sized craters formed in the laboratory to km-sized craters formed on the planetary bodies (e.g., Housen et al., 1983). However, it is necessary to study the gravity effect on the crater formation process. Then, Hayabusa-2 equips a Small Carry-on Impactor (SCI) to launch a copper projectile on the asteroid Ryugu (Saiki et al., 2016). We will observe the crater formation process and the ejecta curtain with a Deployable Camera 3 Digital (DCAM3-D) (Ishibashi et al., 2016, Ogawa et al., 2016). One of the scientific purposes of the ejecta curtain observation by DCAM3-D is to determine the scaling law for the ejecta velocity distribution on Ryugu (Arakawa et al., 2016,. However, it is difficult to deduce the relationships between the ejection velocity and the ejection distance from the successive images of the ejecta curtain. Thus, we are studying to construct the scaling law of the ejecta velocity distribution (Tsujido et al., 2015, Matsue, JPGU 2017), and more, we advocated a new simple theory predicting the ejecta curtain geometry called "Ejecta Curtain Growth (ECG) analysis method" (Arakawa et al., 2016). We can estimate the ejection velocity of the ejecta particle at each initial position using simple equations of ballistic motion, then we obtain an ejecta velocity distribution. Then, we compared the result of the ejecta particle tracking velocimetry (PTV) method with that of ECG analysis method on the quartz sand target (Matsue, JPGU 2017). Finally, we applied the ECG analysis method to the real scale SCI experiments conducted on the ground (Wada et al., 2014) and succeeded to obtain the ejecta velocity scaling law.

Keywords: Ejecta curtain, Hayabusa-2 SCI, Ejecta velocity distribution

MASCOT –a Mobile Lander on-board Hayabusa2 Spacecraft - Operations and Status after Launch

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MASCOT (‘Mobile Asteroid Surface Scout’) is a 10 kg mobile surface science package on board JAXA’s Hayabusa2 spacecraft, currently on its way to the near-Earth asteroid (162173) Ryugu. MASCOT has been developed by the German Aerospace Center (DLR) in cooperation with the Centre National d’Etudes Spatiales (CNES). The concept of MASCOT is to perform in-situ measurements on the asteroid’s surface and to support the Hayabusa2 mission in the sampling site selection. MASCOT is equipped with 4 scientific instruments, a wide angle camera, a hyperspectral IR microscope, a radiometer and a magnetometer. MASCOT is powered by a primary battery which shall enable MASCOT to investigate the asteroid surface for up to 2 asteroid days. An internal mobility mechanism shall relocate MASCOT on the asteroid surface to investigate different landing sites in detail.

MASCOT will be separated at a low altitude above the asteroid surface and its science activities will already start during the descent phase. After touching the asteroid surface MASCOT will bounce across the asteroid surface till it comes to rest. After autonomous self-rightening the scientific surface operations will start. Hayabusa2 will hover above the asteroid surface near the sub-solar point. MASCOT will also operate autonomously without visibility to its mother spacecraft during the asteroid night-time. The MASCOT system and its operational concept are designed to enable an optimum science return within its lifetime, which is driven by the capacity of the battery.

After an intensive development, integration and test campaign MASCOT is now on its way to its target Ryugu. Hayabusa2 launch took place on December 3rd, 2014 from Tanegashima Space Center, Japan. The target asteroid will be reached in summer 2018. Several In-Flight activities like health check and calibration of the scientific instruments have been performed on MASCOT during the past 2.5 years of the 4 years cruise phase. In cooperation with the Hayabusa2 team the MASCOT team is presently planning and testing the on-asteroid phase. First tests of an on-asteroid baseline scenario were performed with a functional-representative MASCOT Ground Reference Model. For environmental tests a MASCOT flight spare model is available.

The presentation will provide an overview of the MASCOT system and its planned operation concept on the asteroid as well an update of MASCOT status and its first operations in cruise.

Keywords: Hayabusa2, MASCOT, (162173 Ryugu)

Present status of curation of the Hayabusa-returned samples and development of the Hayabusa2 curation facility

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The Hayabusa-returned samples are only the regolith samples returned from surface of an asteroid at present on the Earth since its return in 2010 [1]. Their preliminary examination revealed that they were comparable to equilibrated LL chondrites in mineralogy, petrology and chemical and oxygen isotopic compositions [2-4]. The Astromaterial Science Research Group (ASRG) of JAXA has continued their initial descriptions using FE-SEM/EDS without exposing to air, stored them in highly purified N_2 environment and distributed them to the world-wide researchers, as the international announcement of opportunity (AO) for their researches [5]. So far more than 700 of particles have been described by FE-SEM/EDS, and more than 80% of them are Itokawa origin. And more than 160 of them have been distributed during the four times of the international AO. The latest international AO was performed in 2016 and six proposals have been selected for sample allocation. The fifth international AO will start soon in this year.
The Hayabusa2 is heading toward near-Earth C-type asteroid Ryugu, previously named 1999JU3, to reach there in 2018 and try to touchdown onto its surface for sample recovery [6]. It will return the captured samples to the Earth in 2020. The ASRG is now preparing for the curation facility to receive the recovered samples under the supervision of the Hayabusa2 project, the steering committee of the ASRG, and the advisory committee for specifications of the Hayabusa2 curation facility. One cleanroom will be newly constructed next to the one where clean chambers for the Hayabusa returned samples is situated. In the cleanroom, new clean chambers for the curation of Hayabusa2-returned samples have been developed. Because the target body Ryugu is C-type asteroid, which is thought to be related to carbonaceous chondrites, some fraction of samples will be obtained in vacuum condition to avoid terrestrial N_2 contamination to volatile and organic materials in them. After taking some fractions in vacuo, rest of the samples will be processed in highly purified N_2 condition as well as the Hayabusa-returned samples. One of the chamber is for handling mm-size samples, which has different shape from that of μm-size samples. The construction of the new cleanroom will start in this year and all the clean chambers will be set in the middle of 2018. After the establishment of them, their functional checks and then rehearsal for receiving returned samples will be performed until the Hayabusa2 sample return in 2020.
References: [1] Abe et al. (2011) Abstract #1638. 42nd LPSC. [2] Nakamura et al. (2011) Science 333: 1113. [3] Ebihara et al. (2011) Science 333: 1119. [4] Yurimoto et al. (2011) Science 333: 1116. [5] Yada et al. (2014) Meteoritics Planet. Sci. 49: 135. [6] Yoshikawa M. et al. (2015) Abstract id.2254481. IAU General Assembly, Meeting #29.

Keywords: asteroid, sample return, curation, Hayabusa, Hayabusa2

The sample return from the Jupitar Trojan D/P type asteroid.

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Analyses of returned samples from Moon (e.g., New views of the MOON, 2006), asteroid (e.g., Nakamura et al., 2011) and comet (e.g., Brownlee et al., 2006) were essential to understand their origin and nature as well as increasing our knowledge about the Solar System. The most recent returned sample was from the S-type asteroid Itokawa by Hayabusa mission in 2010. The results by series of analyses provided new insights for the connection to meteorite researches, space weathering processes, small asteroidal body formation in the Solar System (e.g., Nakamura et al., 2011; Yurimoto et al., 2011). JAXA Hayabusa 2 and NASA Osiris-REx are both current sample return missions from the organic-rich asteroids, Ryugu (C-type) and Bennu (B-type), respectively (Tachibana et al., 2014; Lauretta et al., 2014). Both missions have complementary scientific goals that are to understand the Solar System evolution in the point of view of organics, water and associated minerals. We, therefore, are working on the possibility of the sample return from Trojan asteroid that is expected to contain primordial chemical information at the very beginning of Solar System formation.
D/P-type Jupiter Trojan asteroids likely consist of dominant of organics (carbonaceous materials) and anhydrous silicates (hydrated silicates cannot be excluded), possibly with water (ice) in its interiors (Guilbert- Lepoutre, 2014). Beside in-situ HRMS analysis of isotopic ratios, elements and molecules in surface and subsurface samples on the Trojan asteroid, analysis of returned samples containing non-volatile materials (organics and minerals) as well as water (ice) will open a new insight of the detailed scientific objectives for the Solar System evolution. Since, in-situ analysis is limited in terms of sample preparations, lack of relationship among components, and mineralogical/petrological contexts, the state-of-the-art microanalysis techniques on the Earth will provide these additional information such as isotopic ratios of individual component (organics and associated minerals), trace amount of gaseous spiecies (e.g., Noble gases, CO, CO2, NH3, CH4 gasses in the ice), and organic compounds that are hard to be detected under the current in-situ HRMS system (e.g., amino acids).
The details of the sample return capsule are not yet fixed but a cryo-system is highly encouraged. Thus, we will receive “extraterrestrial ice (water)” that has a pristine water at the Solar System which contains the information of nebular gas, formation of ice, reservoir of volatiles (water and organics), and the origin of the Earth’s water.
In this talk, we will present the possibility of sample return from the Trojan asteroid by the Solar Power Sail mission.

Keywords: Jupitar Trojan Asteroid, Sample Return

In-Situ Landing Analysis of a Jupiter Trojan Asteroid Using a High Resolution Mass Spectrometer in the Solar Power Sail Mission

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The Solar Power Sail (SPS) mission is one of candidates of the upcoming strategic middle-class space exploration to demonstrate the first outer Solar System journey of Japan. The mission concept includes in-situ analysis of the surface and subsurface (up to 1 m) materials of a Jupiter Trojan asteroid using high resolution mass spectrometry (HRMS). The current mission sequence proposes the launch in late 2020s, and rendezvous to a D or P type Trojan asteroid of ~20-30 km in diameter in 2030s.
The key questions for the Jupiter Trojan asteroid exploration are: (1) constraining planet formation/migration theories, (2) evolution and distribution of volatiles (water and organics) in the Solar System, (3) origin of Earth's water, and (4) surface processes of Jupiter Trojan asteroids.
We plan to analyze volatile materials on the Jupitar Trojan, for their isotopic and elemental compositions using a HRMS with a combination of pyrolysis ovens and gas chromatography (GC) columns. This HRMS system allows to measure H, N, C, O isotopic compositions and elemental compositions of molecules prepared by various pre-MS procedures including stepwise heating up to 600ºC, pyrolysis-GC, and high-temperature pyrolysis with catalyst in order to decompose the samples into simple gaseous molecules (e.g., H_2, CO, and N_2). The required mass resolution should be at least 30,000 for analyzing isotopic ratios (e.g., $H_2{}^{16}O$, $HD^{16}O$ and $H_2{}^{18}O$ for H and O isotopic measurements) for simple gaseous molecules. For elemental compositions of molecules/ions, mass accuracy of ~10 ppm is required to determine elemental compositions for molecules with *m/z* up to 300 (as well as compound specific isotopic compositions for smaller molecules). Our planned analytical sequences consist of three runs for both surface and subsurface samples. In addition, 'sniff mode' which simply introduces environmental gaseous molecules into a HRMS will be done by the system. The details of the analytical methods and apparatus are under developments.

Keywords: Jupiter Trojan Asteroid, Solar Power Sail , Mass spectrometry

Meteoroid Environment Measurement during the Interplanetary Cruising and in the Jupiter Trojan Region by the ALADDIN-2 Dust Detector onboard the Solar Power Sail

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The IKAROS-ALADDIN was the world’ s largest PVDF-based micrometeoroid detector and successfully observed the distribution of >10 micron-sized dust particles between the Earth and Venus orbits in 2010-11. For the Solar Power Sail to Jupiter Trojan asteroids, we have improved the sensor design and signal processing of the dust detector as ” ALADDIN-2” , based on lessons learned from the development and operation of its first generation.
We hereby report current status of these advancements and applications of the ALADDIN-2. At the IKAROS-ALADDIN sensors, stapler-type terminal connectors were employed in combination with stitching by Kevlar threads. For increasing the robustness of terminal connection over a decade of the Solar Power Sail (SPS) mission duration, grommet-type terminal with washer will be used at ALADDIN-2. For better mass estimation of impacting meteoroids, signal integration circuit is added to the ALADDIN-based electronics so that it sums up values of multiple peaks of an impact signal that are related to meteoroid mass and impact velocity. As for the SPS, the ALADDIN-2 sensors of about 4-5 m^2 will be mounted on the sail membrane, i.e., an order of magnitude larger than that of the IKAROS-ALADDIN, for effective detection rate of decreasing meteoroid flux against heliocentric distance. Also slow velocity impacts on the same detectors will be processed their impact signals by a newly dedicated electronics unit for better understanding the meteoroid environment nearby Jupiter TTrojan astetoids after the spacecraft rendezvous. Both hypervelocity and slow velocity impact calibration tests are currently in progress.

Keywords: Micrometeoroids, Hypervelocity Impacts, Circumsolar Dust Ring

Design of a telescopic camera and a multi-band wide-angle camera onboard the Mars Moons Exploration mission

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Design of a telescopic camera and a multi-band wide-angle camera onboard the Mars Moons Exploration mission

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The Japan Aerospace Exploration Agency (JAXA) is planning the Martian Moons Exploration (MMX) mission to reveal the origin of Phobos and Deimos which are satellites of Mars. This mission will observe the two satellites as well as Mars and return samples from Phobos. We designed a telescopic camera (TL) and a multi-band wide-angle camera (WAM), which are installed onboard the MMX spacecraft.
The objective of TL is to reveal the geographical features of Phobos. We must find a flat area for landing point and identify rocks and craters. We designed the telescopic camera with a spatial pixel resolution of 10 cm/pix at the surface of Phobos when the spacecraft is at an altitude of 20 km. This resolution is twenty times higher than that of the telephoto camera (ONC-T) onboard *Hayabusa2*. We also discuss the selection of the focus position and the effect of temperature on the performance of the camera.
The objective of WAM is to determine the distribution of the materials on the surface of Phobos. We cannot get multiband images with the wide-angle camera onboard *Hayabusa2* because it has only a monochrome sensor. Moreover, the ONC-T with seven band-pass filters placed on a wheel results in a fault that its field of view is shifted during wheel rotation when the spacecraft is descending. Therefore, we designed seven wide-angle cameras with narrow band filters to simultaneously take images at all wavelengths. The depth of field of WAM is 1m to infinity such that we can determine the distribution of materials during landing and orbiting around Phobos.
In this presentation, we illustrate the design of these cameras.

Keywords: MMX, Phobos, camera

Observation Plans for Hydrated Minerals and Carbonaceous Materials on Phobos and Deimos by Near-Infrared Hyperspectral Imager MacrOmega

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The Martian Moons Exploration (MMX) is a probe which will be launched by the Japanese launch vehicle H-III and will navigate the quasi satellite orbit of Phobos, and will make a fly-by of Deimos.
NIRS4/MacrOmega is an imaging spectrometer in the wavelength range of 0.9 to 3.6 micrometers which is one of the candidate instruments to be installed on the MMX spacecraft.
It is based on MicrOmega on the ExoMars Rover and Hayabusa2 MASCOT and modified as a hyper-spectral imager with spectroscopic function provided by an Acousto-Optic Tunable Filter (AOTF).
MMX aims to elucidate the evolution of our solar system by investigating the migration process of primitive materials in the early stage. NIRS4/MacrOmega will observe hydroxide or hydrated mineral absorptions on Phobos and Deimos in the wavelength of 2.7-3.2 micrometers. By analyzing the shape of the spectra, we will distinguish between water in hydrous silicate minerals, water molecules, and water ice particles. NIRS4/MacrOmega will also try to detect the absorption by organic matter in the wavelength range of 3.3-3.5 micrometers. These results will support efforts to answer the question of the origin of the Martian satellites, and identify whether they are satellites formed by a giant impact or asteroids captured by Mars.
NIRS4/MacrOmega will observe Phobos to survey the sampling site before sampling, to investigate the sampling site precisely at the touch-down mode, and to make global mapping. Global mapping of Phobos to select prior areas and landing sites will be performed on the quasi satellite orbit at 100 to 200 km in altitude. Precise mapping for candidate landing sites will be followed at about 20 km in altitude. We will also examine the high-resolution observation for selected areas at the orbit lower than 10 km, and precise observations toward blue and red region at the Mars-Phobos Lagrangian points 1 and 2. In the touch down phase, we will observe toward sampling site at full wavelength in the altitude of 20 km to 1 m. Observations for Deimos will be basically executed from the fly-by orbit, and they are examined to be made at the near circular orbit.

Keywords: MMX, Phobos, Deimos, near infrared, hydrated mineral

Elemental analysis using LIBS for Martian Moons Exploration (MMX)

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Phobos and Deimos are the two satellites of Mars. There are two major hypotheses for their origin: asteroid capture [Hunten, 1979] and a giant impact [Rosenblatt et al. 2016]. JAXA's Martian Moons Exploration (MMX) is planned to be a sample return mission from Phobos. One of the main goals of MMX is to determine the origin of the two Martian moons. To determine the origin of the moons, it is necessary for the returned sample to contain information on satellite formation. Therefore, we should identify the uniformity or nonuniformity of the distribution of surface material on Phobos. We can obtain the averaged elemental composition using a gamma-ray and neutron spectrometer (GNS) as the nominal instruments, but the distribution of the elemental composition cannot be obtained with a resolution of about 10 mm. We propose using laser-induced breakdown spectroscopy (LIBS) that can perform an elemental analysis with a spatial resolution of 1 mm at a distance of 1 m or more. Because the MMX operating time is limited to be about 1 hour, a LIBS instrument that can perform measurements in tens of seconds could be suitable onboard MMX.

Understanding the heterogeneity of the materials around the sampling site is important for providing the geological context of the returned sample. Thus, we conducted an experiment to demonstrate that we can determine whether the Phobos surface composition resembles that of Martian meteorites or that of a carbonaceous chondrite in a short time by LIBS. We used a small laser with an output of about 12 mJ/pulse and a wavelength of 1534 nm. For the data acquired with the spectrometer, the range of wavelengths from about 380 nm to 800 nm was used for analysis. The distances between the lens to converge the laser beam and the sample and between the condensing lens of the spectrometer and the sample were both 1.5 m. The effective diameter of the light collection optical system was 20 mm. The samples were placed in a vacuum chamber, which was evacuated to 10^{-3} Pa. We verified the feasibility of the LIBS measurement, including signal-to-noise ratio, under realistic conditions. The samples were Allende (a carbonaceous chondrite), NWA1068 (a Martian meteorite), and Zagami (a Martian meteorite). The samples were irradiated 150 times at each measurement point at a frequency of 10 Hz. The exposure time of the spectrometer was 1 s. We measured 16 points per a sample to obtain the bulk composition of the meteorites. The emission spectra of the major elements, Fe, Ca, Al, Mg, Si, and Ti, were detected in the average spectra of the 16 measurement points. By subtracting the spectra of the Martian meteorites from that of the carbonaceous chondrite, we found that the intensity of the emission lines of Fe and Mg, which are abundant in the Allende meteorite, exhibited positive values. In contrast, the intensity of the emission lines of Al and Ca, which are abundant in the NWA1068 and the Zagami meteorites, exhibited negative values. These results showed that LIBS is able to distinguish between asteroid-like and Martian-like materials.

Next, we evaluated whether LIBS was able to conduct this measurement within the MMX operating time on the surface. It was assumed that the focus adjustment and image acquisition takes 30 s and moving from one measurement point to another takes 20 s. The laser irradiation frequency was assumed to be 2 Hz to reduce electric power consumption. With these times, it required about 35 minutes to conduct the data acquisition as in our experiment (i.e., measuring 16 points with 150 laser irradiations per point). This indicates that LIBS is able to obtain sufficient data within the operating time of the lander. Thus, our results suggest that LIBS can reveal whether Phobos is similar to the asteroids or to Mars.

In this presentation, we will also report on the production of an engineering model and the results of experiments using it.

Keywords: LIBS, Martian Moons Exploration (MMX), in situ analysis

