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Hayabusa2: Scientific importance of samples returned from C-type near-Earth asteroid (162173) 1999 JU_3

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Hayabusa2 is an asteroid exploration mission to return surface samples of a near-Earth C-type asteroid (162173) 1999 JU_3. Because asteroids are the evolved remnants of planetesimals that were the building blocks of planets, detailed observation by a spacecraft and analysis of the returned samples will provide direct evidence regarding planet formation and the dynamic evolution of the solar system. Moreover, C-type asteroids are expected to preserve the most pristine materials in the solar system, a mixture of minerals, ice, and organic matter that interact with each other. Space missions are the only way to obtain such pristine materials with geologic context and without terrestrial contamination.

Hayabusa2 will launch off in 2014, arrive at 1999 JU_3 in mid-2018, and fully investigate and sample the asteroid at three different locations during its 18-month stay. The concept and design of the Hayabusa2 sampler are basically the same as that on-board Hayabusa, and impact sampling with a 5-g Ta bullet will be made at three locations of the asteroid. The sample container has three separate chambers inside to store samples obtained at different locations separately.

The spacecraft will return to Earth with samples in December 2020. Returned samples will be investigated by state-of-the-art analytical techniques in 2020 to understand the evolutionary history of the solar system from 4.56 Gyr ago to the present by combining results from laboratory examinations of the returned samples with remote-sensing datasets and comparing all results of observations of meteorites, interplanetary dust particles, and future returned samples.

Keywords: returned sample, C-type asteroid, planetesimal, early solar system, organic matter

Introduction

Sample return missions have provided extraordinary advances in our understanding of the origin and evolution of the solar system. In the following, we summarize the important findings from sample return missions successfully completed so far.

Lunar rocks returned by Apollo missions (1969–1972) provoked the hypothesis of a magma ocean in the early history of the moon (e.g., Wood *et al.*, 1970; Smith *et al.*, 1970), which is now a commonly accepted scenario for the early evolution of terrestrial planets and other sufficiently large rocky bodies. Likewise, the lunar crater chronology, based on a well-known correlation between the number density of craters and radiometric ages of lunar terrains, has been applied to other inner solar system bodies (e.g., Hartmann, 1970).

Particles obtained from the comet 81P/Wild2 in the Stardust mission (since 1999) showed that the comet is a mixture of materials formed in "hot" and "cold" environments. Most of the particles show oxygen isotopic compositions similar to the solar system composition, and some particles were fragments of Ca- and Al-rich inclusions (CAIs) and chondrules (e.g., Brownlee *et al.*, 2006; McKeegan *et al.*, 2006; Nakamura *et al.*, 2008), suggest-

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Fig. 1. Photographs of the Hayabusa2 spacecraft.

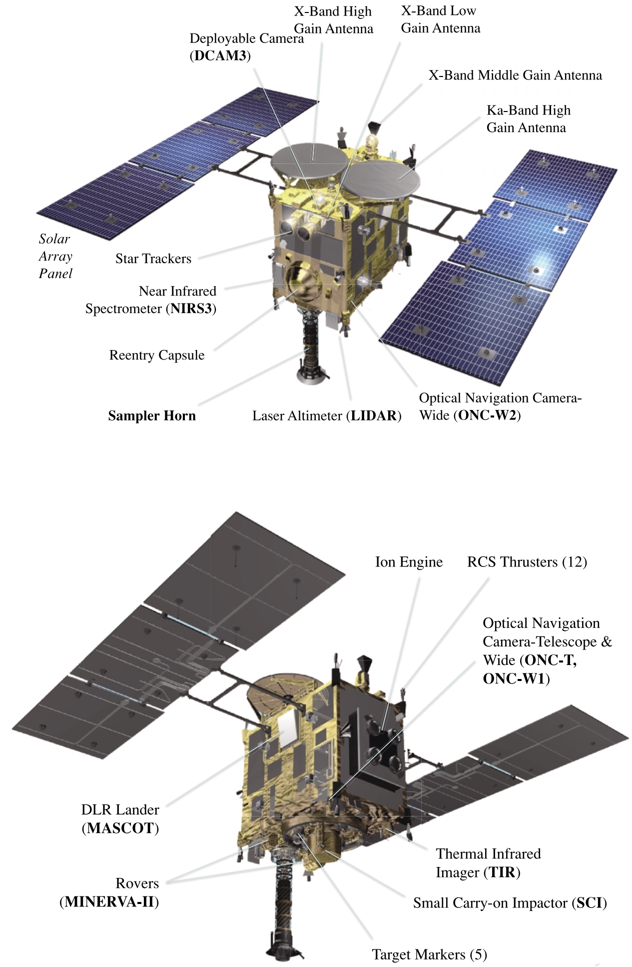

Fig. 2. Illustrations of the Hayabusa2 spacecraft with instrument names.

ing that they once experienced high temperatures, most likely in the inner region of the early solar system. The presence of sulfides formed by aqueous alteration processes (Berger *et al*., 2011) indicates either aqueous activity on comet Wild 2 or delivery of inner solar-system sulfides to the comet-forming region before comet formation. Organic materials recovered from the Stardust samples were enriched in nitrogen and had more fragile molecular structures compared to those of carbonaceous chondrites, suggesting that they had not been heavily processed and remained frozen in the comet (Sandford *et al*., 2006; Cody *et al*., 2008). These new findings have stimulated discussion on material circulation in the proto-solar disk (e.g., Ciesla, 2007). It is also noteworthy that Westphal *et al*. (2014) recently reported seven contemporary interstellar grains captured by the Stardust Interstellar Dust Collector, which are the first returned interstellar dust particles.

Solar-wind particles, captured by the GENESIS spacecraft (2001–2004) (Burnett *et al*., 2011; Burnett, 2013), provided new interesting information on the oxygen isotopic composition of the Sun (McKeegan *et al*., 2011). The oxygen isotopic composition of the Sun is close to that of CAIs, which is the oldest refractory rocky components with ^{16}O-enriched isotopic compositions (e.g., MacPherson, 2014), but is different from most of inner solar system bodies, including the Earth.

The Hayabusa spacecraft (2003–2010) made a return-trip to the near-Earth S-type asteroid (25143) Itokawa (e.g., Fujiwara *et al*., 2006). The first asteroidal returned samples directly linked S-type asteroids and ordinary chondrites, which are the most common meteorites recovered on the Earth (Nakamura *et al*., 2011; Ebihara *et al*., 2011; Yurimoto *et al*., 2011). The particles also showed that the asteroid was originally larger than 20 km in diameter, its interior was heated up to 800°C, and the asteroid was destroyed and re-accreted to form the present rubble pile asteroid form of Itokawa (Nakamura *et al*., 2011). Striking features of the Itokawa particles were records of various asteroidal surface processes, such as solar wind irradiation and micro-meteoroid impact (Tsuchiyama *et al*., 2011; Noguchi *et al*., 2011; Nagao *et al*., 2011; Nakamura *et al*., 2012). These records suggest that the interior of Itokawa had already been thermally inactive, but active surface processes such as space-weathering, re-surfacing and particle escape presently occur. Moreover, thermal fatigue of surface dust due to sunlight (Delbo *et al*., 2014) may also contribute to regolith formation.

Following Hayabusa's successful return, the Japanese Aerospace Exploration Agency (JAXA) plans another asteroid mission called Hayabusa2 to return surface samples of a carbonaceous-type (C-type) near-Earth asteroid, (162173) 1999 JU_3. Because asteroids are the evolved remnants of planetesimals, the building blocks of plan-

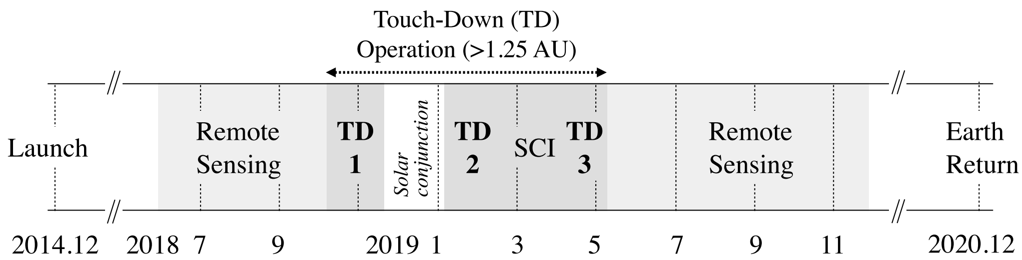

Fig. 3. Mission timeline with an asteroid proximity operation scenario example.

ets, detailed on-site observation by spacecraft and analysis of returned samples will provide direct evidence of planetesimal formation and the dynamical evolution of the solar system. Moreover, similar to comets, C-type asteroids are expected to be remnants of the most pristine materials in the solar system, now found as a mixture of minerals, ice, and organic matter. Space missions are the only way to obtain such pristine minerals, organics, and volatiles with geologic context and without terrestrial contamination.

In this paper, we describe and outline the scientific rationale of the Hayabusa2 mission, especially focusing on the importance of returned samples and their analysis.

HAYABUSA2

The basic design of the Hayabusa2 spacecraft (Figs. 1 and 2) is almost the same as Hayabusa, but many improvements and adoption of new technology were made based on the lessons learned from Hayabusa. The Hayabusa2 spacecraft use ion engines for propulsion, much like the engines of Hayabusa, but with increased durability and thrust force (Tsuda *et al*., 2013a). The spacecraft has two high-gain antennas for X-band (8 GHz) and Ka-band (32 GHz), which is used for data transfer from on-board scientific instruments at a rate four-times faster than with X-band. Because Hayabusa had problems with the reaction wheels (2 out of 3 reaction wheels were broken), Hayabusa2 has four redundant reaction wheels. Five target markers (TM) that are used as landmarks for touchdown are provided for the three touchdown operations. Touchdown with several-meter precision can be made with three TMs.

The spacecraft will launch off on November 30, 2014 from the Tanegashima Space Center, reach 1999 JU_3 in mid-2018, and fully investigate and sample the asteroid during its 18-month stay. The spacecraft will depart the asteroid in late 2019 and return to Earth with samples in December 2020 (Fig. 3).

Target asteroid 1999 JU_3

The target asteroid 1999 JU_3 is a C-type near-Earth asteroid (Fig. 4) that the Hayabusa2 spacecraft can reach with its ion-engine system among currently known near-Earth objects (Yoshikawa *et al*., 2012; Tsuda *et al*., 2013a). Compared to the best-characterized B-type near-Earth asteroid Bennu, a target object for the OSIRIS-REx sample-return mission (2016–2023; Lauretta *et al*., 2014), the dynamical, morphological, and thermal properties of 1999 JU_3 have not been well characterized. However its size, rotation period, and the Sun-Earth-asteroid geometry during the mission phase, where the solar panel and antennas can face towards the Sun and Earth simultaneously, are suitable for the sample return mission in 2014–2020 (Table 1; Binzel *et al*., 2001; Hasegawa *et al*., 2008; Kawakami *et al*., 2010; Müller *et al*., 2011; Kim *et al*., 2013).

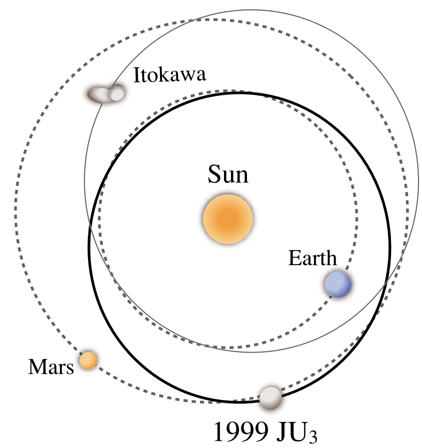

Fig. 4. Orbit of 1999 JU_3. The orbits of Earth, Mars and Itokawa are also shown for comparison.

Ground-based spectroscopic observations have confirmed that the asteroid is a C-type asteroid with a low albedo of ~0.06–0.07 (Vilas, 2008, 2012; Abe *et al*., 2008; Hasegawa *et al*., 2008; Campins *et al*., 2009; Müller *et al*., 2011; Moskovitz *et al*., 2012; Sugita *et al*., 2012; Lazzaro *et al*., 2013; Pinilla-Alonso *et al*., 2013). A possible 0.7-μm absorption feature obtained in July 2007 by Vilas (2008) is common for CM-type chondrites and is

Table 1. Properties of (162173) 1999 JU_3

Rotation period	7.625 ± 0.003 h	Kim *et al.* (2013)
Diameter	0.92 ± 0.12 km	Hasegawa *et al.* (2008)
	0.87 ± 0.03 km	Müller *et al.* (2011)
Aspect ratio	1.3:1.1:1.0	Kawakami *et al.* (2010)
Geometric albedo	0.063 +0.02/–0.015	Hasegawa *et al.* (2008)
	0.070 ± 0.006	Müller *et al.* (2011)
Magnitude (H)	18.82 ± 0.021	Kawakami *et al.* (2010)
	18.69 ± 0.07	Kim *et al.* (2013)
Slope parameter (G)	-0.110 ± 0.007	Kawakami *et al.* (2010)
	-0.09 ± 0.03	Kim *et al.* (2013)
Slope vector	$(\lambda, \beta) = (331° \pm 10°, 20° \pm 10°)$	Kawakami *et al.* (2010)
	$(\lambda, \beta) = (73°, -62°)$	Müller *et al.* (2011)
Thermal inertia	200–600 J m^{-2} $s^{-0.5}$ K^{-1}	Müller *et al.* (2011)
Perihelion/Aphelion	0.85/1.4 AU	
Spectral type	Cg	Binzel *et al.* (2001)

attributed to electron transfer between ferrous and ferric iron in hydrous silicates. However, this 0.7-μm feature was not observed in September 2007 (Vilas, 2008) and has never been confirmed by other observations. Sugita *et al.* (2013) suggested that the 0.7-μm feature observed in July 2007 is likely to be real and raised a possibility that, if the spin axis of 1999 JU_3 is tilted, the equatorial regions were observed in 2007, whereas only the pole was observed in 2012. If this is the case, hydrated phases may be present locally in the equatorial region of the asteroid.

Asteroid 1999 JU_3 is likely to have originated from the inner asteroid belt, but it remains unclear whether or not it was derived from the known low-albedo families with low-inclination (<8°) in the inner asteroid belt (2.15–2.5 AU), such as Clarissa, Erigone, Polana, Sulamitis, Eulalia, and New Polana (Walsh *et al.*, 2013; Campins *et al.*, 2013).

Scientific goals and on-board instruments

The target asteroid 1999 JU_3 is expected to be closely related to carbonaceous chondrites, one of the chemical clans of primitive meteorites. In contrast to other chemical clans of chondrites, many carbonaceous chondrites were not severely heated in their parent bodies, which is not the case for most of ordinary chondrites and Itokawa particles. A large fraction of carbonaceous chondrites contains larger amounts of hydrous minerals that formed in the presence of water and carbon as organic compounds than other chondrites (e.g., Weisberg *et al.*, 2006; Brearley, 2006).

Because the chondrite parent bodies that formed in the early solar system were not extensively heated and did not melt, most likely due to their small sizes, they recorded complex chemical and physical processes during the early evolution of the solar system. Therefore, the study of primitive small bodies is not only of critical importance for the understanding the origin and early evolution of the solar system, but also of importance as a starting point of subsequent planetary formation.

Because C-type asteroids are highly likely to record the early history of the solar system to planet formation, including the subsequent supply of volatiles to the terrestrial planets, the main scientific goals of the Hayabusa2 mission are investigations of: (I) the origin and evolution of the solar system and (II) the formation process and structure of the asteroid. These scientific goals are further subdivided into: (1) evolution from a planetesimal to a near-Earth asteroid (i.e., thermal processes in a planetesimal in the early solar system, heating and space-weathering on the surface of near-Earth asteroid at its current orbit); (2) potential destruction and accumulation of a rubble-pile body that formed from a larger aqueously altered parent planetesimal (i.e., planetesimal formation and impact processes throughout the solar system history); (3) diversification of organic materials through interactions with minerals and water in a planetesimal (i.e., origin and evolution of volatile components in the early solar system and final state of organic matter and water prior to their delivery to the rocky planets); and (4) chemical heterogeneity in the early solar system (i.e., mixing of

Table 2. Scientific instruments on-board Hayabusa2

Laser altimeter	LIDAR
Multi-band telescopic camera	ONC-T
Wide-angle cameras	ONC-W1, ONC-W2
Near-infrared spectrometer	NIRS3
Thermal infrared imager	TIR
Small carry-on impactor	SCI
Sampler	SMP

high-temperature and low-temperature components during dynamical evolution of the proto-solar disk).

To fulfill these scientific objectives, a tight linkage between on-site geologic observations (km to mm scale) and analysis of returned samples (atomic scale) is crucial. The scientific instruments on board the spacecraft are a laser altimeter (LIDAR), a multi-band telescopic camera (ONC-T), wide-angle cameras (ONC-W1 and -W2), a near-infrared spectrometer (NIRS3), a thermal infrared imager (TIR), a small carry-on impactor (SCI), a deployable camera (DCAM3), and a sampler (SMP) (Fig. 2; Table 2). Below we briefly introduce on-board scientific instruments except for the sampler, which will be shown later in more detail.

LIDAR, which has been developed based on that on-board the Hayabusa spacecraft, measures altitudes of the spacecraft from the surface of the asteroid (30 m–25 km) by measuring the time of flight of a laser pulse and is used for the navigation of the spacecraft (Namiki *et al.*, 2013). It is also used for scientific purposes to determine the shape, the gravity field, the surface roughness and albedo of the asteroid and to detect a possible presence of levitating dust (Lee, 1996; Colwell *et al.*, 2005), which could be the source of Itokawa particles obtained by the Hayabusa spacecraft.

ONC-T, -W1, and -W2 are optical navigator cameras used for spacecraft navigation and scientific imaging observations (Sugita *et al.*, 2013). A telescopic camera (ONC-T) with multiband filters within a far-UV to near-infrared wavelength range (390 ± 20, 480 ± 15, 550 ± 15, 700 ± 15, 860 ± 20, 950 ± 30, and 589.5 ± 5 nm) is used for global imaging and spectroscopic observation with a spatial resolution of 2 m/pixel at an altitude of 20 km from the asteroid (Field of view (FOV): $5.7° \times 5.7°$; 1024×1024 pixel). The spectroscopic observation with ONC-T will aim to map an absorption feature around 0.7 μm as an indicator for the presence of hydrous silicates, the degree of UV absorption as an index of dehydration of hydrous phases, and the albedo at 0.55 μm as a potential indicator for the abundance of insoluble organic materials, all of which will be crucial information for sampling-site selection. ONC-W1 (FOV: $65.2° \times 65.2°$; 1024×1024 pixel) will be used for detailed imaging of the sampling site during touchdown operation with the highest spatial resolution of 1 mm/pixel, except for at altitudes between 50–5 m from the surface in the descent phase where it will be exclusively used for navigation. ONC-W1 is capable of imaging a sampling point at a height of ~3 m from the surface with a spatial resolution of ~3 mm/pixel. ONC-W2 is on the side of the spacecraft for spacecraft navigation with a slant view (FOV: $65.2° \times 65.2°$; 1024×1024 pixel).

NIRS3, a near-infrared spectrometer, will spectroscopically observe at wavelengths of 1.8 to 3.2 μm and a spectral resolution of 18 nm to detect specific molecular absorption bands on the asteroid, particularly focusing on the 3-μm absorption feature of hydrated silicates (Iwata *et al.*, 2013). The instrument is designed based on the NIRS on-board the Hayabusa spacecraft, which was used for spectroscopic observation in the 1–2 μm band. The global spectroscopic mapping will be made by attitude scanning of the spacecraft with a footprint of ~40 m per spectrum at an altitude of 20 km (FOV: $0.1° \times 0.1°$), which will also provide critical information for sampling site selection. The footprint for the low-altitude observation at 1 km is ~2 m/spectrum.

TIR is a thermal-infrared imager, developed based on a long-wavelength infrared camera on Akatsuki (Venus Climate Orbiter) (Fukuhara *et al.*, 2011), for thermal emission mapping of the asteroid in the wavelength range of 8–12 μm (FOV: $16° \times 12°$; 328×248 pixel) (Okada *et al.*, 2013, 2014). TIR investigates thermo-physical properties of the asteroid and constrains the timing of the touchdown operation because the spacecraft has a temperature limit for landing. In the current worst-case thermal model of the asteroid surface, the touchdown operation can be done only when the asteroid is at the solar distance of 1.25 AU or farther (Fig. 3), but the TIR observation may relax this solar-distance restriction.

Thermal inertia of the asteroid is closely related to the surface particle size, and thus TIR will also contribute to the assessment of sampling site candidates. The spatial resolution is ~20 m, ~1 m, and ~10 cm at altitudes of 20 km, 1 km, and 100 m, respectively.

SCI, a small carry-on impactor, is the instrument for an asteroidal-scale micro-gravity impact experiment. A copper disk with a diameter of 265 mm, deformed into a semi-spherical shell by explosion, will hit the surface of the asteroid at the impact velocity of ~2 km/s (Saiki *et al.*, 2013; Arakawa *et al.*, 2013). The expected maximum size of the artificial crater is ~10 m in diameter for the non-cohesive sand surface. Since the spacecraft will move behind the asteroid after the release of SCI to escape from explosive debris, a wide-angle deployable camera (DCAM3), designed based on the detached camera on-board IKAROS (solar power sail demonstrator; Tsuda *et al.*, 2013b), will also be released with SCI for observation of the operation. DCAM3 consists of DCAM3-A and DCAM3-D, in which image data are transferred by analogue- and degital communication systems, respectively. In particular, DCAM3-D has an optical system with a field-of-view of 74° × 74° and a CMOS image sensor of 2000 × 2000 pixel that are enough to observe both SCI before explosion and the impact ejecta at a distance of 1 km. The images taken by DCAM3 will be transferred to the spacecraft in real time. The size and shape of the artificial crater and impact ejecta will be investigated by ONC-T, NIRS3, and TIR. The impact ejecta will be a target for sampling of subsurface materials that potentially have suffered little sunlight heating and space weathering if there is no significant regolith gardening.

The spacecraft will bring a lander MASCOT, which has been developed by DLR (Deutsches Zentrum für Luft- und Raumfahrt), in cooperation with CNES (Le Centre National d'Etudes Spatiales) and JAXA (Ziach *et al.*, 2013; Jaumann *et al.*, 2014). MASCOT has a multi-band wide-angle camera (CAM) with maximum spatial resolution of 0.14 mm/pixel, a six-band thermal radiometer (MARA), a three-axis fluxgate magnetometer (MAG), and a hyperspectral microscope (MicrOmega). MicrOmega obtains images of a ~2 mm area with a spatial resolution of ~20 μm/pixel with a pixel spectrum of 0.9 to 3.5 μm, which covers the characteristic absorption features of anhydrous silicates (olivine and pyroxene), phyllosilicates (O-H bond at ~3 μm), and organic matter (C-H bond at 3.4 μm). MASCOT is planned to be deployed to the location near the first touchdown point. MASCOT can work for two asteroidal days (~15 hours) with a primary battery and will hop at least once for observation at a different surface location.

Three small rovers (~1 kg each), MINERVA-IIs (MINERVA-II-1A, -1B and -2), will also be on-board. MINERVA-II-1A and -1B are developed based on MINERVA from the Hayabusa mission (Yoshimitsu *et al.*, 2003, 2004), and a Japanese university consortium developed MINERVA-II-2 (Tohoku Univ., Tokyo Denki Univ., Osaka Univ., Yamagata Univ., and Tokyo Univ. Science). The location and timing of their deployments have not yet been determined, but MINERVA's will make technological tests for surface mobility under a microgravity condition with possible scientific payloads of a camera and thermometer.

Scientific Basis of Analysis of Returned Samples

Scientific rationale for sample-return from a primitive carbonaceous asteroid

Primitive chondrites have been extensively investigated to study the origin and early evolution of the solar system. A group of carbonaceous chondrites, the CI (Ivuna-type) chondrites, has chemical compositions closely resembling the composition of the Sun, and has been used to determine the solar composition of trace elements, which cannot be precisely estimated from the spectroscopic observation of the Sun alone. The early solar system chronology has been built based on the ages of components in primitive chondrites and the oldest solid components (CAIs); 4567.3 ± 0.30 Myr (e.g., Connelly *et al.*, 2012) has been considered to be the age of the solar system. The extensive study on extraterrestrial organic materials has started after the fall of the Murchison carbonaceous chondrite (CM) in 1969 (e.g., Cronin and Pizzarello, 1986, 1997; Cronin and Chang, 1993; Schmitt-Kopplin *et al.*, 2010), from which the first extraterrestrial amino acids were extracted. Analysis of extraterrestrial organic materials recovered on Earth has made huge contributions to our understanding of the origin and evolution of organic matter during the solar system and planetary formation (e.g., Botta and Bada, 2002; Sephton, 2002; Pizzarello *et al.*, 2006; Gilmour, 2014), and one may raise a question: Do we need sample return missions from C-type asteroids?

The answer is *yes* because of the following reasons: (1) Extraterrestrial samples recovered on the Earth are always subject to the threat of contamination with water and organic matter. (2) There may be a sampling bias for carbonaceous chondrites (2.5% among all the meteorites; Grady, 2000); they might be broken up during atmospheric entry because they are much more fragile than ordinary chondrites, the most common meteorites on the Earth (63% among all the meteorites; Grady, 2000). (3) Geologic information has been erased from extraterrestrial materials recovered on the Earth.

With detailed geologic observation of asteroids and analysis of returned samples without any terrestrial contamination, we can distinguish asteroidal processes from processes in the solar nebula and understand the evolution of the early solar system more clearly.

Galactic chemical evolution and Sun's parent molecular cloud chemistry

The parental molecular cloud of the solar system formed after the 9-Gyr galactic evolution by assembling various elements formed in ancestor stars in the forms of gas and dust. One of the cores of the molecular cloud began to collapse 4.6 billion years ago to form the infant Sun with a surrounding proto-planetary disk.

Ancient stardust that formed in stellar envelopes of evolved stars has been preserved as pre-solar grains with anomalous isotopic compositions. Various presolar grains such as silicates, oxides, carbides, graphite, and diamond have been found in primitive meteorites and interplanetary dust particles. Their isotopic compositions reflect nucleosynthesis in individual stars and galactic chemical evolution (e.g., Zinner, 2014). Moreover, circumstellar dust formation processes, as well as the processes in the interstellar medium, are recorded in their lattice structures and morphology (e.g., Takigawa *et al.*, 2014). As mentioned above, contrary to expectations, cometary particles obtained from the Stardust mission do not contain significant amounts of presolar grains. The Wild 2 particles contain presolar grains at most at the level of primitive interplanetary dust particles (Floss *et al.*, 2013), implying effective transport of hot inner disk materials to the outer cold disk or the destruction of the primitive outer solar system materials (Brownlee *et al.*, 2006). Hence, the abundance of presolar grains in samples returned by the Hayabusa2 spacecraft will also be an interesting target to understand how material mixing occurred in the early solar system (Table 3).

Organic materials enriched in heavy isotopes (D and ^{15}N) have been found in carbonaceous chondrites, micrometeorites, and interplanetary dust particles (Botta and Bada, 2002; Sephton, 2002; Pizzarello *et al.*, 2006; Busemann *et al.*, 2006, 2009; Duprat *et al.*, 2010; Davidson *et al.*, 2012; Gilmour, 2014 and references therein). The Tagish Lake meteorite, an ungrouped carbonaceous chondrite, has a unique reflectance spectrum resembling D-type asteroids that are abundant in the outer asteroid belt and are expected to contain organic materials and ice (e.g., Brown *et al.*, 2000). Tagish Lake contains a high concentration of organic materials, and the deuterium enrichment of its bulk insoluble organic material (IOM) and the number of extremely D-enriched hot spots decreases with parent body alteration (Herd *et al.*, 2011). This indicates that the D- and ^{15}N-enrichments are pre-accretional signatures of organic materials. The enrichments of heavy isotopes have been attributed to chemical reactions at low temperatures (~10 K) in the Sun's parent molecular cloud (e.g., Sandford *et al.*, 2001).

Organic materials found in returned samples from the comet Wild 2 are enriched in N and O compared with IOM found in carbonaceous chondrites (Cody *et al.*, 2008), suggesting that N- and O-rich organic materials are the most primitive organic materials in the solar system.

The survey of such primitive organic materials in returned samples and their characterization will be of significant importance (Table 3), but various alteration processes in asteroids may have overprinted the primitive signatures. The Hayabusa2 spacecraft will sample surface rocks at multiple locations with multi-scale geological information, and the alteration effect on the parent asteroid and both pre- and post-accretional evolution of organic matter will possibly be investigated in detail, as in the case of IOM in Tagish Lake (Herd *et al.*, 2011).

The abundances of pre-solar grains and D- and ^{15}N-rich primitive organic materials will also be a scientific target of analysis of the returned samples, as an index of

Table 3. Examples of scientific objectives of analysis of returned samples

Galaxy/Molecular Cloud	Protoplanetary Disk	Planetesimal	Main-Belt Asteroid	Near Earth Asteroid
Presolar Grains	**CAIs, Chondrules, and Metal**	**Aqueous Alteration Thermal and Shock Metamorphism**	**Shock Metamorphism**	**Space Weathering**
Nucleosynthesis	High temperature processes	Conditions and timing	Conditions and timing	Ages, Regolith dynamics, Space environments, SW, Surface activity, Orbital evolution
Galactic chemical evolution	Constraint on the timing of parent body formation			
Molecular Cloud Organics	**Disk Organics**	**Diversity of Organics**	**Galactic Cosmic Rays**	**Thermal Metamorphism**
Low temperature processes	Fischer-Tropsch type reactions	Mineral-Organics association	Exposure history	Heating by sunlight
Enrichment of heavy isotopes (D, ^{15}N)		L-enantiomer excess of amino acids		
			Bulk Density	
			Internal structure	
Spatial Variation/Heterogeneity of Returned Samples				
Planetesimal formation processes, Disk evolution				
Parent body size, Parent body processes				
Comparison with Meteorites, IDPs, and OSIRIS-REx Samples				
Uniqueness and commonness				

parent-body thermal and/or aqueous alteration because their abundances decrease with degrees of parent body processes (Table 3).

Pre-accretional chemical evolution and planetesimal formation in the proto-solar disk

Chondrites are more or less chemically similar to the Sun except for the light and extremely volatile elements (H, C, N, and noble gases), but they show chemical diversity in terms of redox state, abundances of refractory, volatile and siderophile elements, and oxygen isotopic composition (e.g., Weisberg *et al*., 2006). This chemical diversity of chondrites has been attributed to elemental and oxygen-isotopic fractionation processes in the early solar system prior to planetesimal formation and should have been preserved in the proto-solar nebula, even if the transport of inner disk materials to the outer disk occurred as recorded in Wild 2 cometary particles (e.g., Ciesla, 2007). It will thus be important to investigate chemical diversity within 1999 JU_3 with on-site remote sensing and analysis of returned samples from multiple locations in order to constrain material mixing within the proto-solar disk and the potential feeding zone of the asteroid (Table 3).

Characteristic constituents within chondrites are high-temperature components formed in the proto-solar disk, such as CAIs and chondrules (e.g., Lauretta *et al*., 2006; Connolly *et al*., 2006; Apai *et al*., 2010 and references therein). The abundance of CAIs and the size, chemical composition, and redox state of chondrules differ among the chemical groups of chondrites, so the properties of high-temperature components can also be used for classification of returned samples. Their absolute and relative ages determined by U–Pb and ^{26}Al–^{26}Mg systems have been intensively studied to constrain the evolution of the early solar system (e.g., Bouvier and Wadhwa, 2010; Connelly *et al*., 2012; Kita *et al*., 2013). The formation ages of high-temperature components in samples from 1999 JU_3 will make contribution to early solar system material evolution and will constrain the formation age of the planetesimal as well.

It has not yet been clarified how organic materials formed at low temperatures were altered in the proto-solar disk, whether or not organic matter formed newly in the disk prior to planetesimal formation, and how the total concentrations of organic matter in chondrites were determined (e.g., Pizzarello *et al*., 2006). These issues should be solved by understanding the evolution of organic matter in proto-planetary disks in future studies. The samples from 1999 JU_3 would give the best opportunity to tackle the problem because the samples will be returned with detailed geological information on asteroidal processes but without significant terrestrial contamination of organic matter.

Planetesimal processes: Properties of the parent planetesimal and final evolutional stage of volatiles

Ground-based observation has shown that 1999 JU_3 may have partly experienced aqueous alteration (Vilas, 2008). Because 1999 JU_3 is a ~1-km-sized asteroid, aqueous alteration should have occurred inside a parent planetesimal of 1999 JU_3, which must have been larger than the present size of the asteroid. If this is the case, 1999 JU_3 is likely to be a rubble-pile body formed after the destruction of the parent planetesimal, and sampling at different surface locations would correspond to the collection of samples evolved at different depths of the parent asteroid. The combination of analyses of returned samples from multiple surface locations and multi-scale remote-sensing observations with ONC-T and NIRS3 is thus expected to provide us the first opportunity to study aqueous alteration processes at an asteroidal scale. If carbonates are found in the samples, they may record the timing of aqueous alteration (Fujiya *et al*., 2012) and would be a target for ^{53}Mn–^{53}Cr dating. If a large amount of carbonates are present (several μmoles as CO_2), clumped-isotope thermometry could be applied to estimate the alteration temperature (Guo and Eiler, 2007). A systematic study of the degree and variety of aqueous alteration and its age will invoke discussion on the timing of planetesimal formation and the size and structure of the planetesimal.

Thermal metamorphism in the parent planetesimal, if any, will also be investigated. The degree of thermal metamorphism, recorded in the mineralogy and petrology of the returned samples, such as degree of crystallization of chondrule mesostases, chemical compositions of olivine and pyroxene, release temperatures of noble gases and so on, with the age information may provide constraints on the maximum temperature, duration, onset of metamorphism, and timing of planetesimal formation, as intensively discussed for Itokawa particles (Nakamura *et al*., 2011).

Diversification of organic matter in the C-type asteroid is one of the most important scientific themes of analysis of returned samples. It has been known that the relative abundance of the amino acid isovaline is correlated with the abundance of phyllosilicates, products of asteroidal aqueous alteration (Pizzarello *et al*., 2003). Moreover, excess of the L-enantiomer of isovaline in carbonaceous chondrites has been known to positively correlate with the degree of aqueous alteration (Glavin and Dworkin, 2009). A systematic study of variations in the mineralogy, petrology, and soluble and insoluble organic matter content in distinct fragments of the Tagish Lake meteorite also showed that parent-body aqueous alteration played an important role in the diversification of organic matter (Herd *et al*., 2011): The abundance of D- and ^{15}N-rich organic matter and the bulk H/C and D/

H ratios decreases with the degree of alteration, while some molecules of prebiotic importance such as α-amino acids and light acetic acid formed due to water-mediated reactions during alteration. The bulk D/H ratio, total abundances of light elements, and insoluble and soluble organic materials in samples obtained at different locations with geological contexts will be systematically studied as done for the Tagish Lake fragments to understand the final evolutionary stage of organic matter in early, small planetesimals prior to potential accretion to larger bodies.

Geological evolution of asteroids in the solar system

Planetesimal-scale thermal metamorphism and/or aqueous alteration would have ceased in the first 10 Myr after planetesimal formation if the heat source was the now-extinct short-lived radionuclide ^{26}Al. After the early-stage metamorphism, the major geologic event for asteroids during solar system history is impact, through which asteroids accumulate into larger bodies or break into pieces. If 1999 JU_3 is a C-type aqueously altered asteroid, it would have once been a larger body in which fluids circulated, and would have been destroyed and re-accumulated as a rubble-pile body. The timing of impact events could be determined by K–Ar dating of shock veins and/or Pb–Pb dating of phosphates, although the shock ages may not correspond to the timing of formation of the present 1999 JU_3. If 1999 JU_3 is a rubble-pile body and has a large accessible 100 m-sized boulder, the boulder may not have moved since the formation of the rubble pile body and the formation age of the asteroid could be determined from surface samples of the boulder. A galactic cosmic ray exposure age of such a boulder could correspond to the formation age of the rubble pile.

The bulk density of returned samples should be measured to determine the porosity of 1999 JU_3, of which volume and mass will be determined by the spacecraft. The strength of returned samples will also be an important parameter to understand the internal structure of the asteroid and its evolution. These pieces of information may place constraints on the orbital evolution and source of 1999 JU_3.

Orbital evolution and surface geological processes of a near-Earth asteroid

The target asteroid 1999 JU_3 is a near-Earth asteroid, of which the surface has been heated by sunlight and has endured space-weathering by solar wind more than at its original orbit in the inner asteroid belt.

Itokawa particles well preserve space-weathering and surface irradiation processes on their surfaces (e.g., Noguchi *et al.*, 2011, 2014; Nagao *et al.*, 2011; Busemann *et al.*, 2014), and thus the surface structures and chemical and isotopic compositions of the returned particles from 1999 JU_3 will be carefully investigated to understand space-weathering and surface irradiation on the surface of C-type asteroids for the first time. Thermal metamorphism at the surface of this near-Earth asteroid will also be studied because it may have once had a perihelion smaller than 1 AU (Michel and Delbo, 2010), combined with temperature data obtained by TIR and MASCOT, which could provide a constraint on the orbital evolution of 1999 JU_3 in the inner solar system (e.g., the maximum temperature and duration). Comparison between surface samples and sub-surface SCI ejecta samples will be important for this purpose.

The shape, size and friability of regolith particles will also provide an opportunity to study regolith formation processes due to thermal fatigue (Delbo *et al.*, 2014), micro-meteoroid impact (Tsuchiyama *et al.*, 2011; Nakamura *et al.*, 2012), tidal effect (Connolly *et al.*, 2014), and the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect, a torque caused by irradiation of sunlight onto and re-radiation from the surface of a small rotating irregular-shaped object (Connolly *et al.*, 2014).

The orbits of near-Earth asteroids are not stable, within a typical lifetime of ~10 Myr (e.g., Morbidelli *et al.*, 2002). The perihelion of 1999 JU_3 might have become smaller than 1 AU more than several Myr ago (Michel and Delbo, 2010), but the timing of its orbital evolution from the main belt to the near-Earth orbit is not well constrained. Returned samples may contain a record of orbital change in their abundances of solar-cosmic-ray (SCR) produced short-lived radionuclides with half-lives ($t_{1/2}$) of 0.1–10 Myr, such as ^{10}Be ($t_{1/2}$ = 1.51 Myr), ^{26}Al ($t_{1/2}$ = 0.72 Myr), ^{41}Ca ($t_{1/2}$ = 0.1 Myr), ^{53}Mn ($t_{1/2}$ = 3.7 Myr), and ^{81}Kr ($t_{1/2}$ = 0.23 Myr). The flux of solar cosmic rays to the surface of the asteroid, i.e., also the spallation rate, should have increased when the asteroid changed its orbit from the main belt to the near-Earth orbit. The abundances of SCR-synthesized short-lived radionuclides are determined by a balance between spallation and decay rates and their steady abundances are thus different between those at the main belt and at the near-Earth orbit. After the orbital change, the abundances of SCR-synthesized short-lived radionuclides such as ^{10}Be, ^{26}Al, and ^{41}Ca should start to shift to new steady-state abundances. The transition timescale to the new steady state depends on the half-life of each short-lived radionuclide and thus the abundances of various SLRs potentially record the timing of the orbital change.

Integration of multi-scale data from the atomic-scale to asteroidal-scale, and comparison with meteorites, interplanetary dust particles, and future returned samples

Detailed micro-scale information obtained from 1999 JU_3 samples should be tightly combined with on-site remote sensing data obtained at the asteroidal- to regional-scales. Integrated data sets from atomistic to asteroidal scales will be a key to reconstructing the entire history of 1999 JU_3.

Because of the limited opportunity of sample return missions from small bodies, it is vital to compare 1999 JU_3 samples with meteorites, interplanetary dust particles, and future returned samples in order to expand the knowledge obtained in the mission to all aspects of cosmochemistry. The B-type near-Earth asteroid Bennu, the target asteroid for the OSIRIS-REx mission (2016–2023), may also have originated from the inner main belt, most likely from the Eulalia or the "new" Polana asteroid families (Walsh *et al.*, 2013). The comparison of samples obtained in two missions is crucial for better understanding of the common and distinct characteristics of the two asteroids.

REQUIREMENTS FOR SAMPLING AND THE HAYABUSA2 SAMPLER

Required specification for sampler

Recent developments of analytical techniques have enabled us to analyze smaller amounts of the samples as in the case of Itokawa samples (Nakamura *et al.*, 2011; Yurimoto *et al.*, 2011; Ebihara *et al.*, 2011; Noguchi *et al.*, 2011; Tsuchiyama *et al.*, 2011; Nagao *et al.*, 2011; Nakamura *et al.*, 2012) and the required amount is expected to be further reduced by the 2020s. However, in order to obtain typical and/or average features of 1999 JU_3, at least 100 mg of surface samples, including several mm-sized particles, are required for analysis to attain the scientific goals listed in Table 3.

It is also important to obtain samples at multiple surface locations with different geological features and to preserve them separately in a sample container to understand the geological evolution of the asteroid. This leads to better understanding of the processes prior to planetesimal formation and of recent processes as a near-Earth object. Thermal effects during sampling should be minimal.

The Hayabusa sample catcher contained contaminants in the form of carbon-rich particles and inorganic particles (Uesugi *et al.*, 2014; Ito *et al.*, 2014; Yabuta *et al.*, 2014; Yada *et al.*, 2014). Contamination to the Hayabusa2 samples must be minimal and any possible contamination should be recognized in advance. Furthermore, it is necessary for the sample container to be handled more easily during the sample curation operation than the Hayabusa sample container to reduce the curation work and ensure fast initial analysis of the returned samples.

Hayabusa2 sampler

The concept and design of the Hayabusa2 sampler are also the same as the Hayabusa sampler with some modifications to satisfy the scientific requirements (Figs. 1 and 5). In order to collect a sufficient amount of samples compliant with both monolithic bedrock and regolith targets, a 5-g Ta projectile will be shot at 300 m/s at the timing of touchdown, and the ejecta will be transferred into a sample catcher through an extendable sampler horn and a conical horn under microgravity. The estimated amount of collected samples will exceed the required amount for sample analysis of 100 mg, details of which will be reported elsewhere. Three projectiles are prepared for sampling at three surface locations.

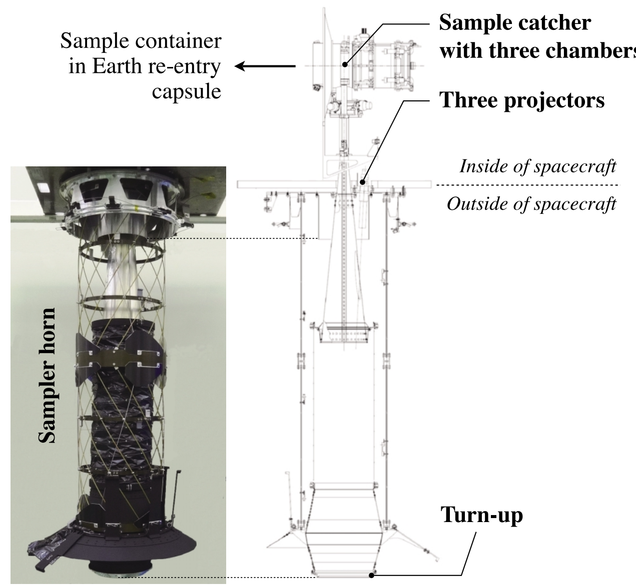

Fig. 5. Photograph of the Hayabusa2 sampler horn and schematic illustration of the Hayabusa2 sampler.

The sample catcher of Hayabusa2, located at the top-end of conical horn, has three chambers to store samples obtained at the three locations separately (Fig. 6). An inlet to the sample catcher is rotatable to select a chamber to store samples at each location. The size of the sample catcher is almost the same as that of the Hayabusa spacecraft with two chambers, and a total volume is ~45 cm^3. The new sample catcher has a design that is much easier to be taken apart during curation on the ground than that of the Hayabusa spacecraft.

After three sampling operations, the sample catcher is transferred into the sample container inside the Earth re-entry capsule and sealed. The container sealing method is an aluminum metal seal (Fig. 6) to avoid the terrestrial air contamination after the return to Earth return, which occurred with the Hayabusa container sealed with double fluorocarbon O-rings (Okazaki *et al.*, 2011). The new aluminum metal seal is designed to only allow a leak of 1 Pa of air for 100 hours at the atmospheric pressure. To avoid further potential contamination, volatile compo-

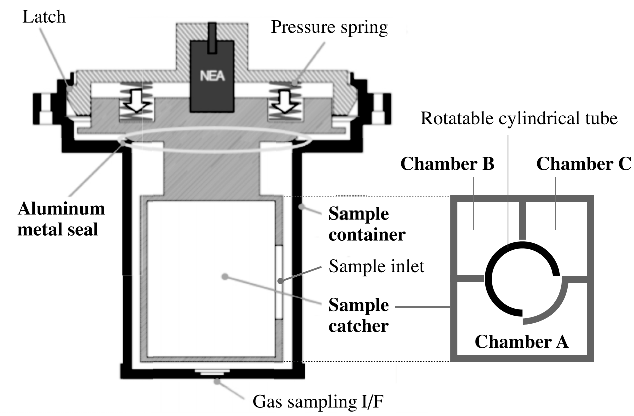

Fig. 6. Schematic illustration of the Hayabusa2 sample catcher and container.

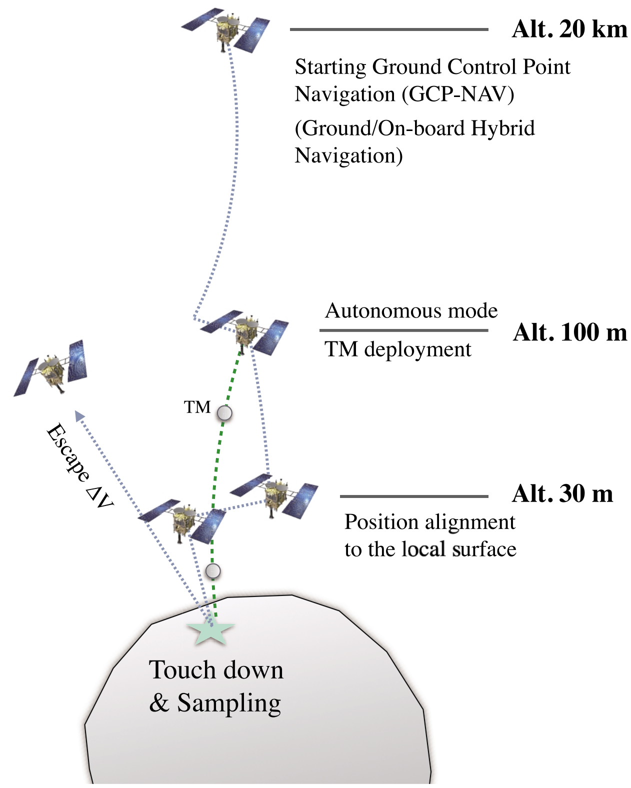

Fig. 7. Operation sequence for touchdown and sampling.

nents will be extracted prior to the opening of the container (Fig. 6). The container will be attached to a vacuum line and the bottom of the container, part of which is thinned and will be pierced with a needle to extract volatiles such as H_2O, noble gases, and organic gas species. The sample catcher and container are cleaned by a 38 kHz ultrasonic cleaning device sequentially in highly purified 2-propanol and methanol/dichloromethane to minimize terrestrial inorganic and organic contamination (Yada *et al*., 2014). Particles in construction sites of the sampler and the spacecraft are also sampled and analyzed as potential contaminants, and a sapphire glass witness plate is attached to the sample container to monitor the contamination throughout the mission.

A back-up sampling method is also prepared; the tip of the sampler horn is turned up like the teeth of a comb, and surface pebbles will be lifted up by the tip of the horn during touchdown (Fig. 5). The lifted pebbles will be transferred into the sample catcher by deceleration of the spacecraft. Particles larger than 100 μm can be stored in the sample catcher by deceleration with four 20-N chemical thrusters, even if the particles are positively charged at the surface of the asteroid (~5 V; Colwell *et al*., 2005) and are stuck to the sampler horn with electrostatic force.

Because the same sampler horn will be used for three touchdown operations, there is a possibility of mixing particles during the second and third sampling. Fine particles (<100 μm) may also be mixed within the sample catcher through a gap between the rotatable inlet and the chamber walls. These fine particles are thus regarded as representing a global feature of the asteroidal surface as discussed below.

Touchdown operation and possible sampling strategy

Touchdown operation for sampling (Fig. 7) will be made at the surface location without 50-cm sized or larger boulders and with the local surface angle of <30° for safety reasons. In the initial descent phase down to the altitude of 100 m, the horizontal position and velocity is controlled from the ground using surface images taken by ONC-T and ONC-W1 and the vertical velocity is controlled in the range of 0.1–1 m/s on board by LIDAR (Ground/onboard-based hybrid navigation; GCP-NAV). A target marker (TM) will be deployed at an altitude of 100 m and further descent will be in fully autonomous mode. The spacecraft tracks the TM that reflects light from an on-board flash lamp using ONC-W1. The laser range finder with four laser beams (LRF1) determines the surface orientation relative to the spacecraft below an altitude of 30 m and the spacecraft aligns its position to the local touchdown area. The final 5-m descent is a free fall, and the detection of the bending of the sampler horn determined by another laser range finder (LRF2) triggers the projectile shooting for sampling followed by the escape operation for ascent. Touchdown with a single TM will be made with an uncertainty of several tens of meters, while the uncertainty will be reduced down to several meters with three TMs.

The highest priority of the first touchdown point for sampling will be the location with absorption features at 0.7 and/or 3 μm (observed with ONC-T and NIRS3), which are related to the presence of hydrated minerals. The presence of hydrated minerals indicates that the materials did not experience severe thermal metamorphism that would have decomposed hydrated minerals, which will enable us to obtain samples that record both asteroidal aqueous alteration and events prior to asteroid formation. Moreover, since a close relation between hydrated minerals and organic matter has been found in carbonaceous chondrites (Pizzarello *et al.*, 2003; Glavin and Dworkin, 2009), the presence of organic matter is also expected.

The possible second touchdown point can be a location with little or no evidence of hydrated minerals to compare with the first touchdown samples. The 0.55-μm albedo, observed with ONC-T, may indicate an abundance of insoluble organic matter, and can thus be used for the selection of the second touchdown point. If no compositional variation is observed for the asteroid surface by remote sensing, sampling from bedrock can be made because it could have recorded the irradiation history of galactic cosmic rays since the formation of the asteroid. The SCI ejecta are planned to be the target of the third (final) touchdown, which will be the samples with minimal surface processes (sunlight heating and/or space-weathering). Three TMs will be used for touchdown onto the impact ejecta with an uncertainty of several meters.

Multi-scale observation of geological features of touchdown locations with on-board instruments and rovers is crucial because such observations are impossible to be obtained from extraterrestrial materials recovered on Earth. The touchdown locations will be observed in detail with ONC-W1. The highest spatial resolution for imaging the sampling point with ONC-W1 is ~3 mm/pixel, which is sufficient to recognize the circular track of the sampler horn (~14 cm in diameter) and to identify the artificial crater for sampling. The observation of the first touchdown area with MASCOT, if possible, would provide a link between spatial scales of sample analysis (mm-nm) and of on-site remote sensing (km-mm) because the wide angle camera (CAM) on MASCOT can image the surface with a spatial resolution of ~0.1 mm.

Samples to be curated and analyzed

The characteristics of the Hayabusa2 sample container leads to the classification of the returned samples into three categories: (i) mm-sized coarse grains separately stored in three chambers, (ii) <100 μm-sized fine particles that may be mixed in the sample container, and (iii) volatiles extracted from the container prior to opening. Coarse grains should represent the material properties at the different locations, and petrologic and mineralogical studies of them will provide important constraints on understanding the history of the asteroid and the solar system. The size, weight, and morphology of coarse particles will also be important to investigate geological surface processes. Moreover, the friability of particles is also an important physical parameter, not only for understanding asteroid surface processes, but also for investigation of particle fragmentation during atmospheric re-entry, opening of the parachute, and landing. Simulation experiments for sample fragmentation in the sample container will be performed in the near future.

Fine particles will provide insights into the global average surface features and geologic surface processes, such as space weathering and regolith formation. Volatile components will be the first extraterrestrial volatiles to be returned and will be an important analysis target to investigate the origin and evolution of organic matter and water in the solar system and the final evolutionary state of organics in asteroids.

The initial analysis of the returned samples will be conducted with a limited amount of samples and for a limited duration. To accomplish the scientific goals of the mission, the three categories of samples should be analyzed by multiple analysis teams focusing initially on non-destructive analysis of grains, then on elemental and isotopic analysis of grains, petrology, and mineralogy of coarse and fine particles, chemistry and isotopic compositions of volatiles, and chemistry of insoluble and soluble organic materials. It is also noted here that a team to integrate all the results and link them to the remote-sensing data is important, which can only be done for returned samples.

SUMMARY

Hayabusa2, an asteroid exploration mission to return surface samples of the C-type near-Earth asteroid 1999 JU_3, sets the following scientific objectives to reveal the solar system history from the beginning to the present: Understanding (1) Thermal evolution from planetesimal to near-Earth asteroid; (2) Destruction and accumulation of a rubble pile; (3) Diversification of organics through interactions with minerals and water on a planetesimal; and (4) Material circulation in the early solar system. The basic design of the spacecraft is the same as in the Hayabusa mission, but with many improvements and new technology. The on-board instruments necessary for the fulfillment of the scientific objectives are a laser altimeter (LIDAR), a multi-band camera (ONC-T), a near-infrared spectrometer (NIRS3), a thermal infrared imager (TIR) and wide-angle cameras (ONC-W1 and -W2). A lander MASCOT and small rovers (MINERVA's) will also provide geological information from the surface. A small impactor (SCI) will be aboard for an asteroid-scale impact experiment, which will create a crater of several meters in diameter.

The sampler, of which the concept and design are the same as the Hayabusa sampler, has three projectiles for impact sampling at three different locations. The samples at different locations will be separately stored in a sample container with three chambers. The sampling site selection will be made based on the presence/absence of hydrated phases and organic matter, the degree of space-weathering, and geological features with a priority of safety. One of the sampling sites could be near the artificial impact crater to sample impact ejecta that are likely to be sub-surface materials.

Hayabusa2 will be launched in November 2014, arrive at 1999 JU_3 in mid-2018, and fully investigate and sample the asteroid during its 18-month stay. The spacecraft will return to Earth with samples in December 2020. The returned samples will be categorized into coarse grains preserving regional information, fine grains representing the average surface features including space weathering, and volatile components released inside the sample catcher. These three categorized samples should be investigated by state-of-the-art laboratory instruments to understand the history of the solar system, especially focusing on (1) galactic chemical evolution and the Sun's parent molecular cloud chemistry, (2) pre-accretional chemical evolution and planetesimal formation in the proto-solar disk, (3) planetesimal processes, such as the final evolutionary stage of volatiles in small early solar system objects prior to possible accretion to planets, (4) geological evolution of asteroids in the solar system, and (5) orbital evolution and surface geological processes of a near-Earth asteroid. In the 2020s, we will have new analytical techniques to reveal the solar system history; fluorescence spectroscopy with muonic X-rays, for instance, may be a new, non-destructive method to identify the content and distribution of organic components in mm- to cm-sized pebbles (Terada *et al*., 2014).

Integration of multi-scale data from atomic-scale to asteroidal-scale and comparison with meteorites, interplanetary dust particles, and future returned samples are also critical to understand the evolutionary history of the asteroid and its unique and common characteristics.

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