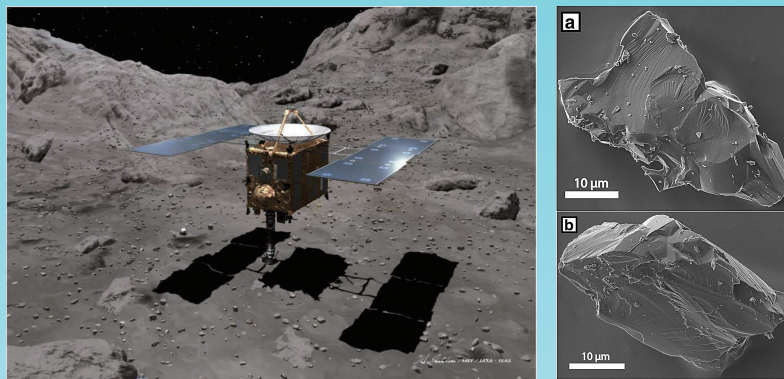


# Earth, Planets and Space

Science of solar system materials examined from Hayabusa and future missions (II)



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## PREFACE

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# Special issue “Science of solar system materials examined from Hayabusa and future missions (II)”

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Six years have passed since the first asteroid sample was returned from the S-type near-Earth asteroid 25143 Itokawa by the JAXA's Hayabusa mission in 2010 (Yada et al. 2014). Considerable progress has been made in the study of surface regolith materials and the understanding of planetary surface processes such as space weathering (Noguchi et al. 2011), the chronology of Itokawa and its dynamic evolution processes (Nagao et al. 2011; Park et al. 2015), and the thermal alteration undergone in parent bodies (Nakamura T et al. 2011). Discussions of new findings from the Hayabusa-returned samples and from a large collection of meteorites, micrometeorites, and interplanetary dust particles have continued, especially at the annual international Hayabusa symposia of solar system materials (Okada et al. 2015). Progress in sample return science has driven the next stage of exploration. Now, two new sample return missions to primitive, volatile-rich asteroids, JAXA's Hayabusa2 (Tsuda et al. 2013) and NASA's OSIRIS-REx (Lauretta et al. 2012), are en route to their target bodies, C-type 162173 Ryugu and B-type 101955 Bennu, respectively.

It is our great pleasure to present our second special issue of the journal *Earth, Planets and Space*, “Science of solar system materials examined from Hayabusa and future missions (II).” This special issue is based on discussions during the Hayabusa 2014 symposium, which featured new results from Hayabusa-returned samples and related studies, but was also open to any scientific results regarding primitive bodies and the early solar system, the results of laboratory experiments and ground-based

observations, and reports of new instruments and methods. We will begin with a brief introduction to the missions of the Hayabusa and its successor Hayabusa2. In addition, all six manuscripts published in this special issue are reviewed below.

Hayabusa (formerly MUSES-C) was an engineering mission organized by the Japan Aerospace Exploration Agency (JAXA) to demonstrate the technology to return samples from a near-Earth asteroid (Kawaguchi et al. 2003). It was launched in 2003, explored the S-type asteroid 25143 Itokawa in 2005, and returned surface samples from the asteroid to Earth in 2010. The four main technologies demonstrated in this mission during its round-trip to the asteroid were the ion engine used as the main thrusters, the optical navigation for approaching and landing on the asteroid, the sample collection on the asteroid under microgravity conditions, and the hypervelocity reentry of the sample capsule into the terrestrial atmosphere. These technical challenges were all successfully performed, and the asteroid samples were returned to Earth. This mission also has scientific significance for elucidating the origin and evolution of the early solar system based on exploration of a primitive solar system body. We found that the small S-type asteroid 25143 Itokawa was chondritic in composition and a low-density rubble pile in structure (e.g., Fujiwara et al. 2006). Most of its surface was rough and covered with boulders, but a small portion of its surface, where the samples were collected, was smooth and covered with pebbles (e.g., Yano et al. 2006). The returned samples have been curated in JAXA's Extraterrestrial Sample Curation Center, organized by the Astromaterials Science Research Group, Institute of Space and Astronautical Science, JAXA (Yada et al. 2014). About 700 grains have been cataloged thus

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far, with information from optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). Parts of the catalogued samples are available to researchers if their research proposals are accepted through a peer-review process. The results of primitive examinations of the Itokawa samples just after they were returned, as well as data from continued studies of these samples, have been reported in past special issues (e.g., Nakamura T et al. 2011; Nakamura E et al. 2012). A portion of these detailed studies was introduced in the previous EPS special issue “Science of solar system materials examined by Hayabusa and future missions.”

Hayabusa2, the second asteroid sample return mission by JAXA, was launched in 2014 and is now on its way to the asteroid 162173 Ryugu. The target asteroid is classified as C-type, a volatile-rich carbonaceous type. The technology of Hayabusa2 is based on that of the first Hayabusa mission, but its science experiments are more specified to C-type asteroid and reinforced with the instruments (Tachibana et al. 2014). The remote sensing instruments are designed to focus on investigating the degree of hydration of minerals by measuring 3- $\mu\text{m}$  band absorption features and on physical state of the surface, such as the thermo-physical properties of the asteroid based on thermal infrared imaging (Okada and Iwata 2014). The spacecraft has a scientific lander called MASCOT (Micro-Asteroid Surface Scout) to conduct observations in situ on the surface of the asteroid (Ho et al. 2016). In the Hayabusa2 mission, scientific measurements will be conducted at a global scale with remote sensing, a local scale with the surface lander, and a micro-scale through analysis of returned samples. In addition, an impact experiment will be conducted using a small carry-on impactor; the excavated fresh, unweathered materials will be observed via remote sensing, and those materials will be returned to Earth.

A great deal of new results from the Hayabusa-returned samples has been presented at the annual Hayabusa symposia. In this special issue, another new finding from microscopic analysis has been provided by Dobrică and Ogliore (2016). This highlighted paper reports new microstructures on micron-scale particles. These researchers investigated the surface textures and chemical compositions of two small particles (RB-DQ04-0062 and RB-DQ04-0091) returned from the surface of the asteroid Itokawa by Hayabusa. Using high-resolution images from scanning electron, helium ion, and scanning transmission electron microscopy, they identified splash melts, surface blistering, and numerous small adhering particles on the Itokawa samples. They extracted seven focused ion beam sections from both of these Itokawa particles, targeting one splash melt and ten adhering particles, to investigate their composition and provenance

and the role of micrometeoroid impacts on Itokawa's surface. Based on the structure, mineralogy, and interface between the adhering particles and host grains, lithic fragments and particles deposited by impact were identified. These particles have morphologies and compositions consistent with impact-generated deposits, such as impact-generated silica glass, and one was a Ni-free, metallic Fe-rich, and S-rich assemblage that was likely generated by vapor recondensation during a micrometeoroid impact. This study shows that even though the regolith of the asteroid Itokawa is young (Nagao et al. 2011; Noguchi et al. 2011), it has been altered by micrometeoroid impacts.

Volatile-rich carbonaceous meteorites are increasingly attracting the interest of researchers to determine the implications of the properties of these meteorites to future missions such as Hayabusa2 and OSIRIS-REx. King et al. (2015) performed laboratory experiments to constrain the thermal alteration processes of volatile-rich asteroids. CI and CI-like carbonaceous chondrites provide a record of aqueous alteration in the early solar system, but those of the latter type seem to have experienced a late-stage period of thermal metamorphism. To constrain the nature and extent of the aqueous and thermal alteration, the bulk mineralogy and abundance of  $\text{H}_2\text{O}$  in CI chondrites (Ivuna and Orgueil) and CI-like chondrites (Y-82162 and Y-980115) were investigated using thermo-gravimetric analysis as well as near- and mid-infrared spectroscopy. Both CI chondrites analyzed showed significant loss of mass ( $\sim 30$  wt%) and similar patterns of mass loss upon heating to  $1000^\circ\text{C}$  due to dehydration and dehydroxylation of abundant phyllosilicates and Fe-(oxy)hydroxides, as well as the decomposition of Fe sulfides, carbonates, and organics. Infrared spectra of both CI chondrites have prominent 3- $\mu\text{m}$  features because of bound  $\text{OH}^-/\text{H}_2\text{O}$  in phyllosilicates and Fe-(oxy)hydroxides and only minor 11- $\mu\text{m}$  features from anhydrous silicates. These results indicate complete aqueous alteration and nearly the same degree of hydration experienced in both CI meteorites. In contrast, both of the CI-like chondrites show lower mass loss and contain less than a half the  $\text{H}_2\text{O}$  of the CI chondrites, and the 3- $\mu\text{m}$  feature is nearly absent from spectra, whereas the 11- $\mu\text{m}$  feature is intense. These CI-like chondrites experienced thermal metamorphism at temperatures  $>500^\circ\text{C}$ , which initially caused dehydration and dehydroxylation of phyllosilicates. Concerning future sample return missions, King et al. (2015) also note that the surfaces of many C-type asteroids have likely been heated through impact metamorphism and/or solar radiation and that thermally altered carbonaceous chondrites may therefore be good analogues for the samples that will be returned by the Hayabusa2 and OSIRIS-REx missions.

Chan et al. (2016) developed a novel method using gas chromatography, combustion, and isotope ratio mass spectrometry to determine compound-specific nitrogen isotope compositions with an achiral column, which was previously shown to offer high precision for nitrogen isotopic analysis. They applied this method to determine the amino acid contents and stable nitrogen isotopic compositions of individual amino acids from thermally metamorphosed (above 500 °C) Antarctic carbonaceous chondrites, specifically the Ivuna-like (CI-like) meteorite Y-980115 and the Ornans-like (CO3.5) meteorite ALHA77003. In ALHA77003, almost no amino acids were detected because of its extensive history of thermal alteration. In Y-980115, amino acids were identified, and the  $\delta^{15}\text{N}$  values of selected amino acids are clearly extraterrestrial. Y-980115 has experienced an extended period of aqueous alteration, as indicated by the presence of hydrous mineral phases. This meteorite has also been exposed to at least one short-lived period of thermal metamorphism post-hydration. Chan et al. (2016) also suggest that these carbonaceous chondrite samples are good analogues for the target asteroid of the Hayabusa2 mission, Ryugu, which is a C-type asteroid likely composed of heterogeneous materials including both hydrated and dehydrated minerals.

In Hayabusa, Hayabusa2, OSIRIS-REx, and other missions, infrared spectroscopy helps us investigate surface mineralogy, the degree of hydration of silicates, and the existence of organics. Many databases have been constructed based on laboratory experiments to calibrate and interpret the observational results. However, in many cases, these experiments have been conducted under conditions too simplified to apply findings to real observations. Maturilli et al. (2016a) have developed and organized the Planetary Emissivity Laboratory (PEL) of the German Aerospace Center (DLR) and have demonstrated in laboratory experiments the dependence of laboratory-measured emissivity spectra on the emergence angle. Most of the previous work has been based on reflectance measurements in the visible to near-infrared spectral region, on emissivity measurements of flat, solid surfaces, and on measurements from the nadir direction, which are not directly applicable to the analysis of remote sensing data. Small bodies such as the asteroid Itokawa (the target of the Hayabusa mission) have very irregular surfaces, which is likely also the case for the asteroids Ryugu and Bennu, the targets of the Hayabusa2 and the OSIRIS-REx missions, respectively. The spectra from such rough surfaces are difficult to compare with previously reported laboratory spectra. Maturilli et al. (2016a) set up a series of spectral measurements to investigate this problem in the 1- to 16- $\mu\text{m}$  spectral range and measured the emissivity of two asteroid analogue materials

(meteorite Millbillillie and a synthetic enstatite) and slabs of serpentinite and basalt in a vacuum and under purged air, at a surface temperature of 100 °C, for emergence angles from 0° to 60°. Complementary reflectance measurements of the four samples were collected. For all samples measured, they found that emissivity and reflectance both show the same trend: Significant variations from values obtained at the nadir (0° emergence angle) appear only for emergence angles  $\geq 40^\circ$ .

Maturilli et al. (2016b) also constructed a new big database of emissivity and reflectance spectra that characterize asteroid analogues measured under vacuum conditions. A number of missions, such as NEAR-Shoemaker, Hayabusa, Rosetta, Hayabusa2, and OSIRIS-REx, have targeted small bodies in the solar system. Despite the rich collection of reflectance and emissivity spectral libraries available for asteroid analogues, these data are mainly based on measurements in air for a spectral range covering the visible to the mid-infrared spectrum from 0.4 to 25  $\mu\text{m}$ . To characterize minerals, rocks and meteorites suitable to serve as surface analogues for asteroids and cometary nuclei in general, spectroscopic measurements are needed for a wider spectral range and under vacuum conditions. To fill this gap, these authors acquired spectral measurements over a large spectral range (1–100  $\mu\text{m}$ ) for several meteorites and other analogues at the PEL of DLR in Berlin. These data provide more direct and suitable analogues for emissivity and reflectance measurements of asteroid and cometary surfaces.

At the annual Hayabusa symposia, instrumentation and methodology are essential topics for answering unresolved questions. Remote X-ray spectroscopy is one of the main instrumental techniques used in missions to terrestrial bodies. Hong and Romaine (2016) have developed sophisticated new X-ray optics that will be applied in remote planetary X-ray imaging spectrometry. The compositions of diverse planetary bodies are of fundamental interest to planetary science; they provide clues about the formation and evolutionary history of target bodies and the solar system. The masses and volumes of instruments used in focusing X-ray optics have been too large for resource-limited in situ missions; therefore, near-target X-ray observations of planetary bodies have been limited to those of simple collimator-type X-ray instruments. However, Hong and Romaine (2016) have now introduced the new Miniature lightweight Wolter-I focusing X-ray Optics (MiXO), which uses metal-ceramic hybrid X-ray mirrors based on electroformed nickel replication and plasma thermal spray processes. MiXO enables compact, powerful imaging by X-ray telescopes suitable for future planetary missions, especially for observing relatively small planetary bodies such as



asteroids and comet nuclei. These researchers have also presented several example configurations of MiXO telescopes and have demonstrated their performance relative to an alternative approach, micropore optics, which is being employed for the first planetary focusing X-ray telescope, the Mercury Imaging X-ray Spectrometer-T onboard *BepiColombo*. X-ray imaging spectroscopy using MiXO will open a wide area for new discoveries in planetary science and will greatly enhance our understanding of the natures and origins of diverse planetary bodies.

All manuscripts in this special issue are fruitful and constructive for the ongoing discussion of the origin and evolution of the early solar system, and for the prospects of future volatile-rich carbonaceous-type asteroid missions such as Hayabusa2 and OSIRIS-REx, which will soon reach their destinations and commence observations, and then return abundant samples to Earth. Furthermore, these activities provide motivation for new missions to yet unvisited types of primitive bodies, which has led to NASA's selection of the Psyche mission for rendezvous with a metallic core (Elkins-Tanton et al. 2016) and the Lucy mission for multiple flybys of Trojan asteroids (Levison et al. 2016), and will hopefully lead to landing on a Trojan asteroid in a future mission (Okada et al. 2017).

#### Authors' contributions

TO is the lead guest editor of this special issue. RPB, HCC, TY, KO serve as the guest editors of this special issue. All authors read and approved the final manuscript.

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#### References

- Chan QHS, Chikaraishi Y, Takano Y, Ogawa NO, Ohkouchi N (2016) Amino acid compositions in heated carbonaceous chondrites and their compound-specific nitrogen isotopic ratios. *Earth Planets Space* 68:7. doi:10.1186/s40623-016-0382-8
- Dobrică E, Oglione RC (2016) Adhering grains and surface features on two Itokawa particles. *Earth Planets Space* 68:21. doi:10.1186/s40623-016-0391-7
- Elkins-Tanton LT, Asphaug E, Bell J, Bercovic D, Billis BG, Binzel RP, Bottke WF, Goldsten J, Jaumann R, Jun I, Lawrence DJ, Marchi S, Oh D, Park R, Peplowski PN, Polansky CA, Prettyman TH, Raymond CA, Russel CT, Weiss BP, Wenkert DD, Wiczorek M, Zuber MT (2016) Asteroid (16) psyche: the science of visiting a metal world. *Lunar Planet Sci Conf* 47:#1631
- Fujiwara A, Kawaguchi J, Yeomans DK, Abe M, Mukai T, Okada T, Saito J, Yano H, Yoshikawa M, Scheeres DJ, Barnouin-Jha O, Cheng AF, Demura H, Gaskell RW, Hirata N, Ikeda H, Kominato T, Miyamoto H, Nakamura AM, Nakamura R, Sasaki S, Uesugi K (2006) The rubble-pile asteroid Itokawa as observed by Hayabusa. *Science* 312:1330–1334
- Ho TM, Baturkin V, Grimm C, Grundmann JT, Hobbie C, Ksenik E, Lange C, Sasaki K, Schlotterer M, Talapina M, Termantasombat N, Wejmo E, Witte L, Wrasmann M, Wuebbels G, Roessler J, Ziach C, Findlay R, Biele J, Krause C, Ulamec S, Lange M, Mierheim O, Lichtenheldt R, Maier M, Reill J, Sedlmayr HJ, Bousquet P, Bellion A, Bompis O, Cenac-Morthe C, Deleuze M, Fredon S, Jurado E, Canalias E, Jaumann R, Bibring JP, Glassmeier KH, Hercik D, Grott M, Celotti L, Cordero F, Hendrikse J, Okada T (2016) MASCOT: the mobile asteroid surface scout onboard the Hayabusa2 mission. *Space Sci Rev*. doi:10.1007/s11214-016-0251-6
- Hong J, Romaine S (2016) Miniature lightweight X-ray optics (MiXO) for surface elemental composition mapping of asteroids and comets. *Earth Planets Space* 68:35. doi:10.1186/s40623-016-0409-1
- Kawaguchi J, Uesugi K, Fujiwara A (2003) The MUSES-C mission for the sample and return—its technology development status and readiness. *Acta Astronaut* 52:117–123
- King AJ, Solomon JR, Schofield PF, Russell SS (2015) Characterising the CI and CI-like carbonaceous chondrites using thermogravimetric analysis and infrared spectroscopy. *Earth Planets Space* 67:198. doi:10.1186/s40623-015-0370-4
- Lauretta DS, The OSIRIS-REx Team (2012) An overview of the OSIRIS-REx asteroid sample return mission. *Lunar Planet Sci Conf* 43:#2491
- Levison HF, Team Lucy Science (2016) Lucy: surveying the diversity of the Trojan asteroids, the fossils of planet formation. *Lunar Planet Sci Conf* 47:2061
- Maturilli A, Helbert J, Ferrari S, D'Amore M (2016a) On the effect of emergence angle on emissivity spectra: application to small bodies. *Earth Planets Space* 68:84. doi:10.1186/s40623-016-0464-7
- Maturilli A, Helbert J, Ferrari S, Davidsson B, D'Amore M (2016b) Characterization of asteroid analogues by means of emission and reflectance spectroscopy in the 1- to 100-μm spectral range. *Earth Planets Space* 68:113. doi:10.1186/s40623-016-0489-y
- Nagao K, Okazaki R, Nakamura T, Miura YN, Osawa T, Bajo K, Matsuda S, Ebihara M, Ireland TR, Kitajima F, Naraoka H, Noguchi T, Tsuchiyama A, Yurimoto H, Zolensky ME, Uesugi M, Shirai K, Abe M, Yada T, Ishibashi Y, Fujimura A, Mukai T, Ueno M, Okada T, Yoshikawa M, Kawaguchi J (2011) Irradiation history of Itokawa regolith material deduced from noble gases in the Hayabusa samples. *Science* 333:1128–1131
- Nakamura T, Noguchi T, Tanaka M, Zolensky ME, Kimura M, Tsuchiyama A, Nakato A, Ogami T, Ishida H, Uesugi M, Yada T, Shirai S, Fujimura A, Okazaki R, Sandford SA, Ishibashi Y, Abe M, Okada T, Ueno M, Mukai T, Yoshikawa M, Kawaguchi J (2011) Itokawa dust particles: a direct link between S-type asteroids and ordinary chondrites. *Science* 333:1113–1116
- Nakamura E, Makishima A, Moriguti T, Kobayashi K, Tanaka R, Kunihiro T, Tujimori T, Sakaguchi C, Kitagawa H, Ota T, Yachi Y, Yada T, Abe M, Fujimura A, Ueno M, Mukai T, Yoshikawa M, Kawaguchi J (2012) Space environment of and asteroid preserved on micrograins returned by the Hayabusa spacecraft. *Proc Natl Acad Sci*. doi:10.1073/pnas.1116236109
- Noguchi T, Nakamura T, Kimura M, Zolensky ME, Tanaka M, Hashimoto T, Konno M, Nakato A, Ogami T, Fujimura A, Abe M, Yada T, Mukai T, Ueno M, Okada T, Shirai K, Ishibashi Y, Okazaki R (2011) Incipient space weathering observed on the surface of Itokawa dust particles. *Science* 333:1121–1125
- Okada T, Iwata T (2014) Near infrared spectroscopy and thermal infrared imagery on Hayabusa2: hydrated and physical state of C-class asteroid 1999JU3. In: Ip WH (ed) New results in observations and space exploration of asteroids, Proc. Intl. CJMT-1 workshop on asteroidal science, Macao, Oct 16–17, 2012, pp 97–112
- Okada T, Zolensky ME, Ireland TR, Yada T (2015) The earth, planets and space special issue: "science of solar system materials examined from Hayabusa and future missions". *Earth Planets Space* 67:116. doi:10.1186/s40623-015-0235-x
- Okada T, Iwata T, Matsumoto J, Bibring JP, Ulamec S, Jaumann R, Nakamura R, Yano H, Kebukawa Y, Aoki J, Kawai Y, Terada K, Toyoda M, Ito M, Yabuta K, Yurimoto H, Saito Y, Yokota S, Okamoto C, Matsuura S, Tsumura K, Yonetoku D, Mihara T, Matsuoka A, Nomura R, Hirai T, Grand N, Cottin H, Thirkell L, Briois C, Saiki T, Kato H, Mori O, Kawaguchi J (2017) Science and exploration of a Jupiter Trojan asteroid in the Solar Power Sail mission. *Lunar Planet Sci Conf* 48:#1828

- Park J, Turrin BD, Herzog GF, Lindsay FN, Delaney JS, Swisher CC, Uesugi M, Karouji Y, Yada T, Abe M, Okada T, Ishibashi Y (2015)  $^{40}\text{Ar}/^{39}\text{Ar}$  age of material returned from asteroid 25143 Itokawa. *Meteorit Planet Sci*. doi:[10.1111/maps.12564](https://doi.org/10.1111/maps.12564)
- Tachibana S, Abe M, Arakawa M, Fujimoto M, Iijima Y, Ishiguro M, Kitazato K, Kobayashi N, Namiki N, Okada T, Okazaki R, Sawada H, Sugita S, Takano Y, Tanaka S, Watanabe S (2014) Hayabusa2: scientific importance of samples returned from C-type near-earth asteroid (162173) 1999JU<sub>3</sub>. *Geochem J* 48:571–587. doi:[10.2343/geochemj.2.0350](https://doi.org/10.2343/geochemj.2.0350)
- Tsuda Y, Yoshikawa M, Abe M, Minamino H, Nakazawa S (2013) System design of the Hayabusa2—asteroid sample return mission to 1999 JU<sub>3</sub>. *Acta Astronaut* 91:356–362. doi:[10.1016/j.actaastro.2013.06.028](https://doi.org/10.1016/j.actaastro.2013.06.028)
- Yada T, Fujimura A, Abe M, Nakamura T, Noguchi T, Okazaki R, Nagao K, Ishibashi Y, Shirai K, Zolensky ME, Sandford S, Okada T, Uesugi M, Karouji Y, Ogawa M, Yakame S, Ueno M, Mukai T, Yoshikawa M, Kawaguchi J (2014) Hayabusa returned sample curation in the planetary material sample curation facility of JAXA. *Meteorit Planet Sci* 49:135–153
- Yano H, Kubota T, Miyamoto H, Okada T, Scheeres D, Takagi Y, Yoshida K, Abe M, Abe S, Barnouin-Jha O, Fujiwara A, Hasegawa S, Hashimoto T, Ishiguro M, Kato M, Kawaguchi J, Mukai T, Saito J, Sasaki S, Yoshikawa M (2006) Touchdown of the Hayabusa spacecraft at the Muses Sea on Itokawa. *Science* 312:1350–1353

# Adhering grains and surface features on two Itokawa particles

E. Dobrică\* and R. C. Ogliore

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## Abstract

We investigated the surface texture and chemical compositions of two ~40- $\mu\text{m}$  particles returned from the surface regolith of asteroid Itokawa (RB-DQ04-0062 and RB-DQ04-0091) by the Japan Aerospace Exploration Agency's Hayabusa mission. We identified splash melts, surface blistering, and many small adhering particles. Seven focused ion beam sections were extracted from both Itokawa particles, targeting one splash melt and ten adhering particles to investigate their composition and provenance and the role of micrometeoroid impacts on Itokawa's surface. Based on the particle's structure, mineralogy, and interface between the adhering particle and host grain, we identified lithic fragments and particles deposited by impact. These have morphologies and compositions consistent with impact-generated deposits: two have morphologies and compositions that are consistent with impact-generated silica glass, and one was a Ni-free, metallic Fe, and S-rich assemblage that was likely generated by vapor recondensation during a micrometeoroid impact. This study shows that, even though its regolith is young, micrometeoroid impacts have altered the regolith of asteroid Itokawa.

**Keywords:** Asteroid, Micrometeoroid, Regolith, Space weathering

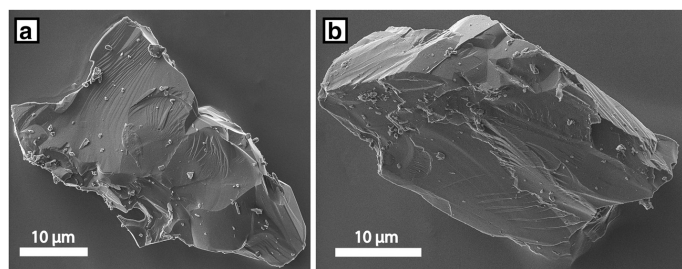


Figure 1

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# Miniature lightweight X-ray optics (MiXO) for surface elemental composition mapping of asteroids and comets

Jaesub Hong\*, Suzanne Romaine and The MiXO team

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## Abstract

The compositions of diverse planetary bodies are of fundamental interest to planetary science, providing clues to the formation and evolutionary history of the target bodies and the solar system as a whole. Utilizing the X-ray fluorescence unique to each atomic element, X-ray imaging spectroscopy is a powerful diagnostic tool of the chemical and mineralogical compositions of diverse planetary bodies. Until now the mass and volume of focusing X-ray optics have been too large for resource-limited in situ missions, so near-target X-ray observations of planetary bodies have been limited to simple collimator-type X-ray instruments. We introduce a new Miniature lightweight Wolter-I focusing X-ray Optics (MiXO) using metal-ceramic hybrid X-ray mirrors based on electroformed nickel replication and plasma thermal spray processes. MiXO can enable compact, powerful imaging X-ray telescopes suitable for future planetary missions. We illustrate the need for focusing X-ray optics in observing relatively small planetary bodies such as asteroids and comet nuclei. We present a few example configurations of MiXO telescopes and demonstrate their superior performance in comparison to an alternative approach, micro-pore optics, which is being employed for the first planetary focusing X-ray telescope, the Mercury Imaging X-ray Spectrometer-T onboard *BepiColumbo*. X-ray imaging spectroscopy using MiXO will open a large new discovery space in planetary science and will greatly enhance our understanding of the nature and origin of diverse planetary bodies.

**Keywords:** X-ray fluorescence, Elemental abundance, X-ray imaging

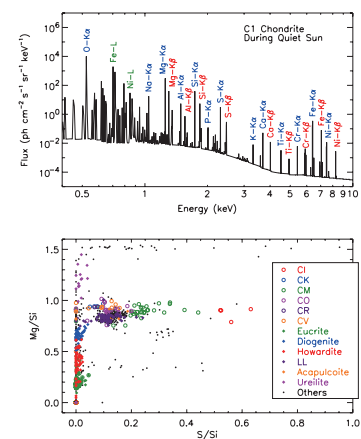


Figure 1

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# Characterising the CI and CI-like carbonaceous chondrites using thermogravimetric analysis and infrared spectroscopy

Ashley J. King\*, Jake R. Solomon, Paul F. Schofield and Sara S. Russell

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## Abstract

The CI and CI-like chondrites provide a record of aqueous alteration in the early solar system. However, the CI-like chondrites differ in having also experienced a late stage period of thermal metamorphism. In order to constrain the nature and extent of the aqueous and thermal alteration, we have investigated the bulk mineralogy and abundance of H<sub>2</sub>O in the CI and CI-like chondrites using thermogravimetric analysis and infrared spectroscopy.

The CI chondrites Ivuna and Orgueil show significant mass loss (28.5–31.8 wt.%) upon heating to 1000 °C due to dehydration and dehydroxylation of abundant phyllosilicates and Fe-(oxy)hydroxides and the decomposition of Fe-sulphides, carbonates and organics. Infrared spectra for Ivuna and Orgueil have a prominent 3-μm feature due to bound –OH/H<sub>2</sub>O in phyllosilicates and Fe-(oxy) hydroxides and only a minor 11-μm feature from anhydrous silicates. These characteristics are consistent with previous studies indicating that the CI chondrites underwent near-complete aqueous alteration.

Similarities in the total abundance of H<sub>2</sub>O and 3 μm/11 μm ratio suggest that there is no difference in the relative degree of hydration experienced by Ivuna and Orgueil.

In contrast, the CI-like chondrites Y-82162 and Y-980115 show lower mass loss (13.8–18.8 wt.%) and contain >50 % less H<sub>2</sub>O than the CI chondrites. The 3-μm feature is almost absent from spectra of Y-82162 and Y-980115 but the 11-μm feature is intense. The CI-like chondrites experienced thermal metamorphism at temperatures >500 °C that initially caused dehydration and dehydroxylation of phyllosilicates before partial recrystallization back into anhydrous silicates. The surfaces of many C-type asteroids were probably heated through impact metamorphism and/or solar radiation, so thermally altered carbonaceous chondrites are likely good analogues for samples that will be returned by the Hayabusa-2 and OSIRIS-REx missions.

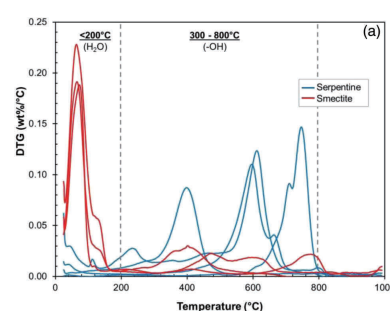


Figure 1

**Keywords:** Meteorites, Asteroids, Aqueous alteration, Dehydration, Hayabusa-2, OSIRIS-REx

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# Amino acid compositions in heated carbonaceous chondrites and their compound-specific nitrogen isotopic ratios

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## Abstract

A novel method has been developed for compound-specific nitrogen isotope compositions with an achiral column which was previously shown to offer high precision for nitrogen isotopic analysis. We applied the method to determine the amino acid contents and stable nitrogen isotopic compositions of individual amino acids from the thermally metamorphosed (above 500 °C) Antarctic carbonaceous chondrites Ivuna-like (CI)1 (or CI-like) Yamato (Y) 980115 and Ornans-like (CO)3.5 Allan Hills (ALH) A77003 with the use of gas chromatography/combustion/isotope ratio mass spectrometry. ALHA77003 was deprived of amino acids due to its extended thermal alteration history. Amino acids were unambiguously identified in Y-980115, and the  $\delta^{15}\text{N}$  values of selected amino acids (glycine +144.8 ‰;  $\alpha$ -alanine +121.2 ‰) are clearly extraterrestrial. Y-980115 has experienced an extended period of aqueous alteration as indicated by the presence of hydrous mineral phases. It has also been exposed to at least one post-hydration short-lived thermal metamorphism. Glycine and alanine were possibly produced shortly after the accretion event of the asteroid parent body during the course of an extensive aqueous alteration event and have abstained from the short-term post-aqueous alteration heating due to the heterogeneity of the parent body composition and porosity. These carbonaceous chondrite samples are good analogs that offer important insights into the target asteroid Ryugu of the Hayabusa-2 mission, which is a C-type asteroid likely composed of heterogeneous materials including hydrated and dehydrated minerals.

**Keywords:** Carbonaceous chondrites, Meteorites, Astrochemistry, Compound-specific isotopic analysis, Nitrogen isotopes, Amino acids, Organic materials, Meteoritic composition, Gas chromatography/combustion/isotope ratio mass spectrometry

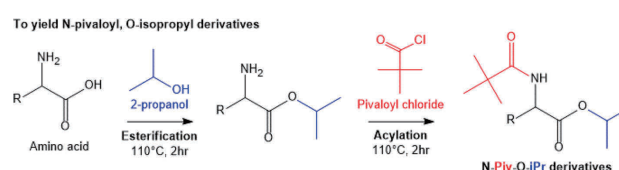


Figure 1

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# On the effect of emergence angle on emissivity spectra: application to small bodies

Alessandro Maturilli\*, Jörn Helbert, Sabrina Ferrari and Mario D'Amore

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## Abstract

Dependence of laboratory-measured emissivity spectra from the emergence angle is a subject that still needs a lot of investigations to be fully understood. Most of the previous work is based on reflectance measurements in the VIS–NIR spectral region and on emissivity measurements of flat, solid surfaces (mainly metals), which are not directly applicable to the analysis of remote sensing data. Small bodies in particular (c.f. asteroids Itokawa and 1999JU3, the respective targets of JAXA Hayabusa and Hayabusa 2 missions) have a very irregular surface; hence, the spectra from those rough surfaces are difficult to compare with laboratory spectra, where the observing geometry is always close to “nadir.” At the Planetary Emissivity Laboratory of the German Aerospace Center (DLR), we have set up a series of spectral measurements to investigate this problem in the 1- to 16- $\mu\text{m}$  spectral region. We measured the emissivity for two asteroid analogue materials (meteorite Millbillillie and a synthetic enstatite) in vacuum and under purged air, at surface temperature of 100 °C, for emergence angles of 0°, 5°, 10°, 20°, 30°, 40°, 50°, and 60°. Emissivity of a serpentinite slab, already used as calibration target for the MARA instrument on Hayabusa 2 MASCOT lander and for the thermal infrared imager spectrometer on Hayabusa 2 orbiter, was measured under the same conditions. Additionally, a second basalt slab was measured. Both slabs were not measured at 5° inclination. Complementary reflectance measurements of the four samples were taken. For all the samples measured, we found that for calibrated emissivity, significant variations from values obtained at nadir (0° emergence angle) appear only for emergence angles  $\geq 40^\circ$ . Reflectance measurements confirmed this finding, showing the same trend of variations.

**Keywords:** The Hayabusa 2 mission, Asteroid analogue materials, Emissivity measurements, Emergence angle, Infrared spectroscopy

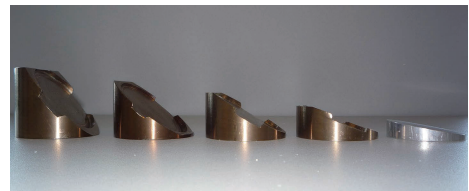


Figure 1

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# Characterization of asteroid analogues by means of emission and reflectance spectroscopy in the 1- to 100- $\mu\text{m}$ spectral range

Alessandro Maturilli\*, Jörn Helbert, Sabrina Ferrari, Björn Davidsson and Mario D'Amore

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## Abstract

The last decades have seen a large number of missions targeting small bodies in the solar system. NASA, ESA and JAXA sent missions to different solar system small bodies (SSSB), and the Japan mission Hayabusa returned samples from the surface of the S-type asteroid Itokawa. JAXA launched in 2014 a follow-up mission (Hayabusa2) to collect a sample from carbonaceous (C-type) asteroid 1999 JU3 asteroid and bring it back to Earth. The NASA's OSIRIS-REx mission will launch in September 2016 to explore the carbonaceous asteroid Bennu. Despite an already existing rich collection of reflectance and emissivity spectral libraries for asteroid analogues, those are mostly based on measurements in air for a spectral range covering the visible to the medium infrared (approximately, from 0.4 to 25  $\mu\text{m}$ ). To characterize minerals, rocks and meteorites suitable for being surface analogues for asteroids and SSSB in general, spectroscopic measurements are needed for a wider spectral range and in vacuum, conditions that more closely resemble those found on asteroid surfaces. To fill this gap we acquired spectral measurements over a large spectral range (1–100  $\mu\text{m}$ ) for several meteorites and other analogues at the Planetary Emissivity Laboratory of the German Aerospace Center in Berlin. Those data provide more direct analogues for asteroid surfaces and expand our existing database of emissivity and reflectance measurements.

**Keywords:** Asteroid analogue materials, Emissivity measurements, Reflectance measurements, Infrared spectroscopy

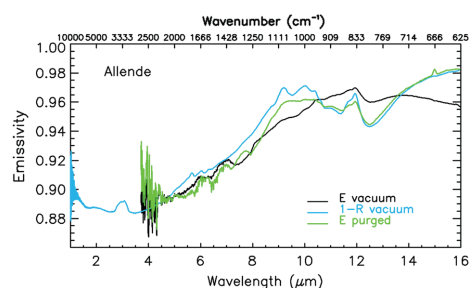


Figure 1

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