**AN OVERVIEW OF HAYABUSA2 MISSION AND ASTEROID 162173 RYUGU.** S. Watanabe[1,2], M. Hirabayashi[3], N. Hirata[4], N. Hirata[5], M. Yoshikawa[2], S. Tanaka[2], S. Sugita[6], K. Kitazato[4], T. Okada[2], N. Namiki[7], S. Tachibana[6,2], M. Arakawa[5], H. Ikeda[8], T. Morota[6,1], K. Sugiura[9,1], H. Kobayashi[1], T. Saiki[2], Y. Tsuda[2], and Hayabusa2 Joint Science Team[10], [1]Nagoya University, Nagoya 464-8601, Japan (seicoro@eps.nagoya-u.ac.jp), [2]Institute of Space and Astronautical Science, JAXA, Japan, [3]Auburn University, U.S.A., [4]University of Aizu, Japan, [5]Kobe University, Japan, [6]University of Tokyo, Japan, [7]National Astronomical Observatory of Japan, Japan, [8]Research and Development Directorate, JAXA, Japan, [9]Tokyo Institute of Technology, Japan, [10]Hayabusa2 Project

**Summary:** The Hayabusa2 mission reveals the nature of a carbonaceous asteroid through a combination of remote-sensing observations, in situ surface measurements by rovers and a lander, an active impact experiment, and analyses of samples returned to Earth.

**Introduction:** Asteroids are fossils of planetesimals, building blocks of planetary formation. In particular carbonaceous asteroids (or C-complex asteroids) are expected to have keys identifying the material mixing in the early Solar System and deciphering the origin of water and organic materials on Earth [1]. Before 2018, the only carbonaceous asteroid that spacecraft visited was (253) Mathilde; NEAR Shoemaker spacecraft flew by the ~50 km sized C-type asteroid in June 1997. More than 20 years later, the great leap has come; Hayabusa2 and OSIRIS-REx encountered (162173) Ryugu and (101955) Bennu in 2018 and try to return asteroid surface samples to Earth [2,3].

**Mission profile:** Hayabusa2 spacecraft arrived at C-type near-Earth asteroid Ryugu on June 27, 2018 [2]. The spacecraft did not enter into circum-asteroid orbit but hovered around the "Home Position", located at an altitude of ~20 km. The remote sensing instruments suite onboard Hayabusa2 are the Optical Navigation Camera-Telescopic (ONC-T) with seven narrowband filters, a Thermal Infrared Imager (TIR), a Near-Infrared Spectrometer (NIRS3), and a laser Light Detection and Ranging (LIDAR) system.

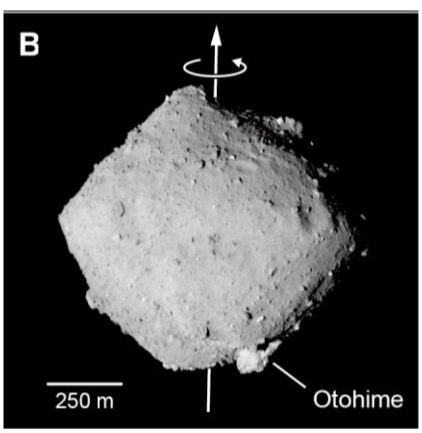


*Figure 1. ONC-T image of Ryugu taken from 20 km altitude on July 10, 2018. Hemisphere centered at 5°S, 11°E. White arrow represents the spin axis [2].*

Combined with the rotational motion of the asteroid, global surveys of Ryugu were conducted several times from ~20 km above the sub-Earth point (SEP), including global mapping from ONC-T (Fig. 1) and TIR, and scan mapping from NIRS3 and LIDAR. Descent observations covering the equatorial zone were performed from 3−7 km altitudes above SEP. Off-SEP observations of the polar regions were also conducted. Based on these observations, we constructed two types of the global shape models (using the Structure-from-Motion and SPC techniques) [2] and selected target sites for sampling touchdown and lander/rover deployments. .

On September 21, 2018, rovers MINERVAII-1A, B were landed in a northern midlatitude region on Ryugu [4] and sent rocky surface images (Fig. 2). On October 3, lander MASCOT landed in a southern midlatitude region and perform in situ measurements[5, 6]. One of the MASCam image shows a cauliflower-like rock consisting of a dark matrix with small, bright inclusions [5]. During multiple low-altitude (40−60 m) descent maneuvers for the rover/lander deployments and touchdown rehearsals, we conducted high-resolution (< 1 cm) observations of specific regions.

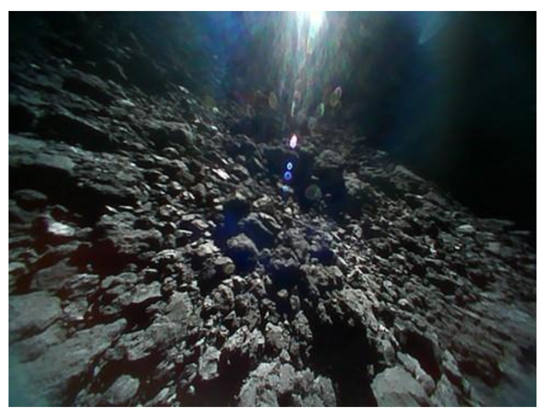

*Figure 2. Surface of Ryugu taken from a hopping rover MINERVAII-1B (Owl) on September 23. Credit: JAXA.*

On February 21, 2019, the Hayabusa2 spacecraft conducted its first touchdown on the equatorial ridge of Ryugu, shooting a projectile within a sampler horn and collecting surface materials. The operation of a Small Carry-on Impactor (SCI) was carried out on April 5, 2019, and an artificial impact crater with a diameter of >10 m was formed (Fig. 3) [7]. A Deployable Camera

3 (DCAM3) recorded live images of the evolving ejecta curtain generated by the SCI impact [7]. To obtain deposited subsurface materials ejected from the SCI crater, the second touchdown site was selected at ~20 m north of the center of the SCI crater. The second touchdown was conducted on the target site on July 11, 2019, collecting ejecta from the SCI crater (Fig. 4).

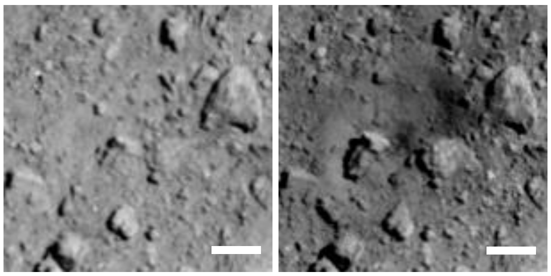

*Figure 3. ONC-T images of SCI aiming point area before (left) and after (right) the impact. Scale bars are 5 m. Credit： JAXA/U Tokyo/Kochi U/Rikkyo U/ Nagoya U/Chiba Inst of Tech./Meiji U/U Aizu/AIST.*

*Figure 4. Small monitoring camera CAM-H image of the sampler horn and soaring surface materials taken just after the second touchdown on Ryugu on July 11, 2019. Credit: JAXA/Kobe University.*

**Real face of Ryugu:** The physical parameters of Ryugu were determined from Haybusa2's observations [2]. Ryugu is a retrograde rotator (the obliquity is 171.6°) with a spin period of 7.63262 hours. In spite of the slow rotation rate, Ryugu has a spinning-top shape with an almost perfect circular equatorial ridge, suggesting rotation-induced deformation of Ryugu during a period of rapid rotation [2, 8]. The equatorial radius is $502 \pm 2$ m and polar-to-equatorial axis ratio is $0.872 \pm 0.007$. The mass estimated from gravity measurement operation is $(4.50 \pm 0.06) \times 10^{11}$ kg. The bulk density is derived to be $(1.19 \pm 0.02) \times 10^3$ kg m$^{-3}$, which falls within the range of bulk densities measured for BCG-types. The total porosity is >50% if the constituent grain density is similar to those of carbonaceous chondrites [2, 9]. The porosity is even higher than that of the rubble-pile asteroid Itokawa ($44 \pm 4\%$), the target S-type asteroid of Hayabusa mission [10], suggesting that Ryugu is also a rubble pile. Ryugu's high porosity could be ascribed to loss of volatile components.

NIRS3 observations indicate that OH-bearing minerals are ubiquitous on Ryugu [11]. The central wavelength (2.72 μm) and depth (10%) of Ryugu's 3-μm absorption band falls on the correlation line found from the spectral survey of asteroids in the 3-μm band using the infrared astronomical satellite Akari [12].

The spectral data obtained with ONC-T and NIRS3 indicated that Ryugu is a Cb-type asteroid with a low geometric albedo of $4.5 \pm 0.2\%$ at 0.55 μm [11, 13]. The regional variation in visible and NIR reflectance data is less than 15%. Coupled with the fact that the deficient of small craters on Ryugu [13], this suggests efficient mixing processes in the surface layer. However, there are few evidence of large-scale grain-size segregation, unlike Itokawa [10], suggesting lower degree of global surface activity. The only known exception may be fewer spatial densities of boulders in small ($D$ < 30 m) craters, indicating possible vertical grain-size segregation in the surface layer.

The SCI impact experiment establishes a scaling law connecting impact energy and the diameter of the generated crater on Ryugu, showing cohesive forces in the surface layer of Ryugu should be very weak [7]. For a cohesionless surface, the surface age of Ryugu is estimated to be $9 \times 10^6$ years based on collision frequency models for the main belt [13, 7]. The younger surface age is interpreted, not necessarily as the formation age of the rubble pile, but as the age of the top shape formation due to Ryugu's spin-up probably by the YORP effect. Comparative studies between Ryugu and Bennu would be key to understanding not only the origin and structure of top-shaped asteroids, but also the properties and evolution of carbonaceous asteroids.

**Acknowledgments:** This study was supported by JSPS "International Network of Planetary Sciences". S.W. thanks KAKENHI support from JSPS (grant JP17H06459 and JP19H01951). M.H. acknowledges NASA/SSW (NNH17ZDA001N /80NSSC19K0548).

**References:** [1] Alexander+ (2012) *Science,* 337, 721. [2] Watanabe+ (2019) *Science*, 364, 268. [3] Lauretta+ (2019) *Nature*, 568, 55. [4] Van wal+ (2019) 29th AAS/AIAA Space Flight Mech. Mtg, 19-243. [5] Jaumann+ (2019) *Science*, 365, 817. [6] Grott+ (2019) *Nature Astron.*, doi:10.1038/s41550-019-0832-x. [7] Arakawa+ (2019) submitted to *Science*. [8] Hirabayashi+ (2019) *ApJL*, 874, 1. [9] Macke+ (2011) *Meteorit. Planet. Sci.*, 46, 1842. [10] Fujiwara+ (2006) *Science*, 312, 1330. [11] Kitazato+ (2019) *Science*, 364, 272. [12] Usui+ (2018) *Pub. Astron. Soc. Japan*, 71, 1. [13] Sugita+ (2019) *Science*, 364, 252.