HIGH POROSITY NATURE OF THE TOP-SHAPE C-TYPE ASTEROID 162173 RYUGU AS OBSERVED BY HAYABUSA2.

S. Watanabe[1,2], M. Hirabayashi[3], N. Hirata[4], N. Hirata[5], R. Noguchi[2], Y. Shimaki[2], H. Ikeda[6], E. Tatsumi[7], M. Yoshikawa[2], S. Kikuchi[2], H. Yabuta[8], T. Nakamura[9], S. Tachibana[7,2], Y. Ishihara[2†], T. Morota[1], K. Kitazato[4], N. Sakatani[2], K. Matsumoto[10,11], K. Wada[12], H. Senshu[12], C. Honda[4], T. Michikami[13], H. Takeuchi[2], T. Kouyama[14], R. Honda[15], S. Kameda[16], T. Fuse[17], H. Miyamoto[7], G. Komatsu[18,12], S. Sugita[7], T. Okada[2], N. Namiki[10,11], M. Arakawa[5], M. Ishiguro[19], M. Abe[2], R. Gaskell[20], E. Palmer[20], O. S. Barnouin[21], P. Michel[22], A. S. French[23], J. W. McMahon[23], D. J. Scheeres[23], P. A. Abell[24], Y. Yamamoto[2], S. Tanaka[2], K. Shirai[2], M. Matsuoka,[2] M. Yamada,[12] Y. Yokota,[2] H. Suzuki,[25] K. Yoshioka,[7] Y. Cho,[7] S. Tanaka,[5] N. Nishikawa[5], T. Sugiyama[4], H. Kikuchi[7], R. Hemmi[7], T. Yamaguchi[2††], N. Ogawa[2], G. Ono[6], Y. Mimasu[2], K. Yoshikawa[6], T. Takahashi[2], Y. Takei[2], A. Fujii[2], C. Hirose[6], T. Iwata[2,11], M. Hayakawa[2], S. Hosoda[2], O. Mori[2], H. Sawada[2], T. Shimada[2], S. Soldini[2], H. Yano[2], R. Tsukizaki[2], M. Ozaki[2,11], Y. Iijima[2‡], K. Ogawa[5], M. Fujimoto[2], T.-M. Ho[26], A. Moussi[27], R. Jaumann[28], J.-P. Bibring[29], C. Krause[30], F. Terui[2], T. Saiki[2], S. Nakazawa[2], Y. Tsuda[2], [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, Auburn, AL 36849, USA, [4]University of Aizu, Aizu-Wakamatsu 965-8580, Japan, [5]Kobe University, Kobe 657-8501, Japan, [6]Research and Development Directorate, JAXA, Sagamihara 252-5210, Japan, [7]University of Tokyo, Tokyo 113-0033, Japan, [8]Hiroshima University, Higashi-Hiroshima 739-8526, Japan, [9]Tohoku University, Sendai 980-8578, Japan, [10]National Astronomical Observatory of Japan, Mitaka 181-8588, Japan, [11]SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193, Japan, [12]Chiba Institute of Technology, Narashino 275-0016, Japan, [13]Kindai University, Higashi-Hiroshima 739-2116, Japan, [14]National Institute of Advanced Industrial Science and Technology, Tokyo 135-0064 Japan, [15]Kochi University, Kochi 780-8520, Japan, [16]Rikkyo University, Tokyo 171-8501, Japan, [17]National Institute of Information and Communications Technology, Kashima 314-8501, Japan, [18]Università d'Annunzio, 65127 Pescara, Italy, [19]Seoul National University, Seoul 08826, Korea, [20]Planetary Science Institute, Tucson, AZ 85710, USA, [21]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, [22]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, 06304 Nice, France, [23]University of Colorado, Boulder, CO 80309, USA, [24]NASA Johnson Space Center, Houston, TX 77058, USA, [25]Meiji University, Kawasaki 214-8571, Japan, [26]DLR (German Aerospace Center), Institute of Space Systems, 28359 Bremen, Germany. [27]CNES (Centre National d'Etudes Spatiales), 31401 Toulouse, France, [28]DLR, Institute of Planetary Research, 12489 Berlin-Adlershof, Germany, [29]Institute d'Astrophysique Spatiale, 91405 Orsay, France, [30]DLR, Microgravity User Support Center, 51147 Cologne, Germany. [†]Current affiliation: National Institute for Environmental Studies, Tsukuba 305-8506, Japan, [††]Current affiliation: Mitsubishi Electric Corporation, Kamakura 247-8520, Japan, [‡]Deceased.

Background: On 27 June 2018 Hayabusa2 Spacecraft arrived at the Home Position (HP) ~20 km above the sub-Earth point of near-Earth C-type asteroid Ryugu. After two months observation of a telescopic optical camera (ONC-T) we constructed global shape models of Ryugu [1, 2]. In order to evaluate the consistency of shape models we used two independent methods; the stereophotoclinometry (SPC) technique [3] and the Structure-from-Motion (SfM) technique [4]. While the SPC-based model (Fig. 1) reproduces well the global shape and topographic features on the surface, the SfM-based model [1] shows better representation of topological features at steep slopes like large boulders. Except for boulders the two models are in good agreement with each other.

Low Bulk Density: Physical parameters of Ryugu were obtained from the initial Hayabusa2 observations [1]. Here we will summarize the data related to bulk density of Ryugu. The total volume obtained from the SPC-based shape model is 0.377±0.005 km^3. Gravity measurement in August 2018 revealed that the asteroid's mass is $(4.50\pm0.06) \times 10^{11}$ kg. The bulk density is thus derived as 1.19 ± 0.03 g cm^{-3}.

The density is significantly smaller than bulk densities (1.6 to 2.4 g cm^{-3}) measured for "hydrated" C-type asteroids having the 0.7-μm absorption (Ch- and Cgh-type) [5]. However, it remains within the 0.8–1.5 g cm^{-3} range measured for BCG-types (B-, C-, Cb-, and Cg-type), which might be related to unheated icy asteroids [5]. Based on VNIR spectra obtained by ONC-T and a NIR spectrometer (NIRS3) Ryugu was confirmed to be Cb-type [2, 6]. Thus, low bulk density of Ryugu is consistent with the spectral type.

High Porosity: NIRS3 observations indicate that hydrated minerals are widely spread on the surface of Ryugu [6]. The presence of water ice, which would be plausible for the low bulk densities of main-belt C-complex asteroids, is unlikely for near-Earth asteroid Ryugu because the radiative equilibrium temperature (~250 K) is higher than the ice sublimation temperature (~230 K) at its central pressure of ~8 Pa and the thermal diffusion time of Ryugu is estimated to be much shorter than the typical dynamical lifetime of near-Earth asteroids (~10^7 yr) [1]. Note that the parent body of Ryugu located in the Main Belt might have water ice and low density of Ryugu could be ascribed to loss of volatile components without subsequent compaction.

The total porosity of Ryugu is derived if we assume the grain density of the asteroid. If we adopt the grain densities of CM carbonaceous chondrites (CCs), the derived total porosity is 57% to 63%. If we adopt those of Orgueil CI CC, the predicted total porosity is 50 to 52%.

The estimated total porosity is even higher than that of rubble-pile asteroid Itokawa (44 ± 4%) [8, 9], indicating that asteroid Ryugu is also a rubble pile. This is consistent with a theory arguing that all Solar System bodies with diameter of ~1 km should be rubble piles [10] and might have formed from reaccumulation of fragments generated by catastrophic disruption events of ~100-km sized parent bodies [11].

Top Shape: Hayabusa2 reveals that Ryugu is a top-shape asteroid; a prominent elevated ridge around the equator. The average surface tilt angle in both side of equatorial ridge is 34 ± 4° relative to its spin axis (Fig. 1). Ryugu is the first top-shape asteroid to be directly observed up close by a spacecraft.

Derived surface slopes to the equipotential surface assuming the present shape and uniform interior demonstrate minimal variation with latitude if, at some epoch, Ryugu had a spin period of 3.5 hours (about half of the current value) [1]. This suggests that the top shape was formed by centrifugally induced structural failure during a rapid rotation era including the original reaccumuration stage that formed Ryugu [12]. When a spheroidal asteroid spins rapidly, a deformation process might be induced either on the surface or in the interior, depending on the internal structure. The high porosity nature of Ryugu as well as no significant offset between the centers of figure and gravity suggest that the internal tensile strength of the asteroid is uniform and low. This suggest that the deformation of interior structural failure would be preferable [13].

Discussion: The 2.72-μm absorption feature of Ryugu observed by NIRS3 is similar to those of heated/shocked CI/CM chondrites [6]. However, the fraction of these meteorites are relatively small whereas BCG types are abundant, so that another meteoritic counterpart of BCG types are expected. Pyroxene-rich interplanetary dust particles (IDPs) are considered to originate from BCG-types based on the mid-infrared spectroscopy [5, 2]. If high porosity BCG types are very fragile, they should be destroyed at the atmospheric entry, which is consistent with the scanty of BCG-originated meteorites. The presence of large boulders on Ryugu, however, may contradict the weakness of fragments of the asteroid. Thus, comparative studies of IDPs with Ryugu (and Bennu) based on the NIR spectra and sample analyses are the key to understand the origin and evolution of BCG-type asteroids.

References: [1] Watanabe S. et al. (2019) *Science*, under review, [2] Sugita S. et al. (2019) *Science*, under review, [3] Gaskell R. W. et al. (2008) *Meteoritics & Planet Sci.*, 43, 1049–1061. [4] Szeliski R. (2010) *Computer Vision: Algorithms and Applications* (Science & Business Media, Springer, New York), [5] Vernazza P. et al. (2015) *Astrophys. J.*, 806, 204, [6] Kitazato K. et al. (2019) *Science*, under review, [7] Macke R. J. et al. (2011) *Meteoritics & Planet Sci.*, 46, 1842–1862, [8] Fujiwara A. et al. (2006) *Science* 312, 1330–1334, [9] Tsuchiyama A. et al. (2011), *Science*, 333, 1125–1128, [10] Walsh K. J. (2018) *Ann. Rev. Astron. Astrophys.* 56, 593–624, [11] Michel P. et al. (2001) *Science*, 294, 1696–1700. [12] Michel P. et al. (2019), *LPS L*, Abstract [13] Hirabayashi T. et al. (2019) *LPS L*. Abstract.

Additional Information: The Hayabusa2 spacecraft was developed and built under the leadership of JAXA, with contributions from the German Aerospace Center (DLR) and the Centre National d'Études Spatiales (CNES). We thank NASA, DSN, and JPL for their supports for the execution of the Hayabusa2 mission. This study was supported by KAKENHI from the Japan Society for the Promotion of Science (JSPS) (Grant Nos. JP17H06459, JP17K05639, JP16H04059, JP17KK0097, JP26287108, JP16H04044), CNES, and the JSPS Core-to-Core program "International Network of Planetary Sciences".

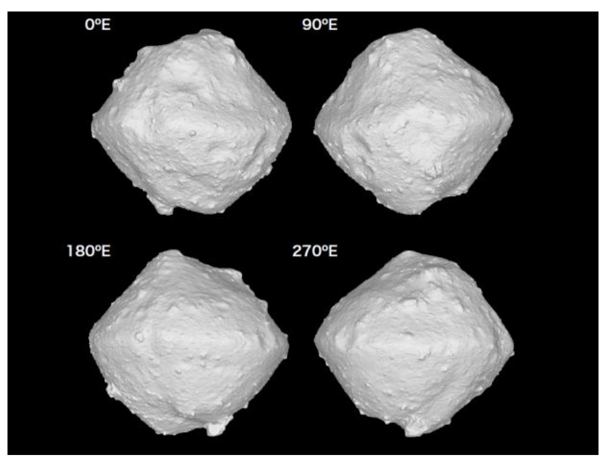

Figure 1. The SPC-based shape model (SPC20181204) viewed from 4 different directions (labeled central longitudes) of the equatorial plane of Ryugu. Generating a polygon model with 3,145,728 facets based on total 1,217 ONC-T images.