VISIBLE MULTI-BAND SPECTRA AND SPECULAR REFLECTIVITY OF RYUGU RETURNED SAMPLES.

K. Yumoto[1], Y. Cho[1], Y. Yabe[1], S. Mori[1], A. Ogura[1], A. Miyazaki[2], T. Yada[2], K. Hatakeda[2], K. Yogata[2], M. Abe[2], T. Okada[2], M. Nishimura[2], T. Usui[2], and S. Sugita[1], [1]Univ. of Tokyo (yumoto@eps.s.u-tokyo.ac.jp), [2]ISAS/JAXA.

Introduction: The Optical Navigation Camera (ONC) onboard the Hayabusa2 spacecraft mapped the visible spectra of Ryugu in sub-meter spatial scale [1]. Spectral variations among craters and boulders suggest that the spectral slopes in the visible wavelengths may correlate with exposure age [2] and heating temperatures [3]. Analyses of mineralogy and isotopic compositions of the returned samples are underway to place further constraints on the evolutional history of Ryugu. However, the visible reflectance spectra of the returned samples have not been fully characterized yet. The triage of the returned sample spectra is needed and should be compared with remote sensing data by ONC to place the results of sample analyses in the geologic context at global scales. Also, the spectral measurements of returned sample in microscopic scales provide ground-truth data for interpreting the spectra of C-complex asteroids in the main belt observed by ground-based and spaceborne telescopes.

In this study, we measured the multi-band reflectance spectra of Ryugu samples by using a multispectral stereo-camera system in the JAXA curation facility [4, 5]. Spectral mapping of samples in both rooms A and C, corresponding respectively to samples acquired by the first and second touchdowns, were performed at ~10 µm/pix resolution; referred to as "bulk sample spectra". In addition, the spectra of 69 relatively large (1–7 mm) sample particles were measured individually.

Statistical analyses of the spectra were performed and compared with the Ryugu global spectra [1] to evaluate the representativeness of the samples. Moreover, initial microscopic observations of the samples revealed a large reflectance variegation on the surface [5]. Such image morphology was also compared with remote sensing observations to investigate how the difference in spatial scales affects the observed spectral distribution.

Results:

Visible Multiband spectra. The spectra of returned samples were flat compared to typical CM/CI chondrites from UV to near infrared wavelengths (Fig. 1). The weak UV absorption, the obscure absorption feature at 0.7 um, and the slightly reddish spectral slope indicate that the spectra of Ryugu samples are consistent with C/Cb-type asteroids [6]. The measured spectra of the returned samples are consistent with observations by ONC-T [1, 7] except for the extent of UV absorption, of which bias may have been caused from the regional heterogeneity on the Ryugu surface and/or disturbance of surface condition by the sampling process.

The spectral variation among the particles spans a wide range (Fig. 2): some particles have a blue spectral slope comparable to those of B-type asteroids. The range of the variation in the visible-to-near infrared spectral slope is larger by a factor of 1.5 compared to that of the global variation observed at 2 m scale. This implies that materials with different spectral slope in the visible to near infrared are well mixed on Ryugu and thus, the ensemble of the returned particles well represents the global heterogeneity.

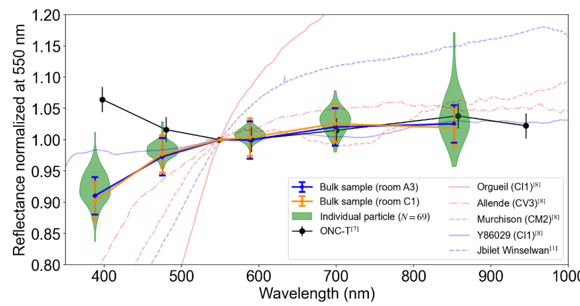

Fig. 1 Normalized reflectance spectra of Ryugu samples. Spectral distribution among particles is shown in kernel density plots. The spectra are compared with remote sensing data [7] and meteorites [1, 8]. Error bars show the measurement errors.

The reflectance of the returned particles was higher than those of bulk samples and remote-sensing observations by 30–70% (Fig. 2). The main reason for this bias is the shadows casted by mm-sized particles, which occupy ~20% of the observed area (Fig. 3). This implies that the reflectance of asteroids is affected by the roughness and/or particle size as well.

In addition, significantly high inter-particle and intra-particle reflectance variation (Fig. 2, 3) were observed. This is due to the presence of super-bright spots/facets in sub-mm scales. Such bright areas have a reflectance 10 times higher than the average and are ubiquitous on the surface of returned particles (Fig. 3). The intensity and position of these bright areas are known to change with respect to the direction of illumination [9]. Also, the photometric function of Ryugu [7] shows that such high reflectance cannot be explained by diffuse reflectivity. These observations suggest that the apparent bright areas observed on the returned samples are produced by specular-like reflective properties. We interpret that the variation of facet angles of each particle creates the bright areas seen in Fig. 3 and the variation of their areal fraction among particles create the wide distribution in Fig. 2.

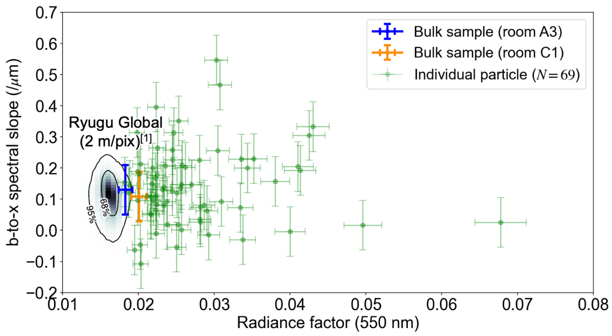

Fig. 2 Radiance factor at v band (550 nm) and b (480 nm)-to-x (850 nm) spectral slope of each particle. The grey contour in the lower left of the figure shows the global spectral variation observed by ONC-T at 2 m/pix resolution [1]. Error bars show the measurement errors.

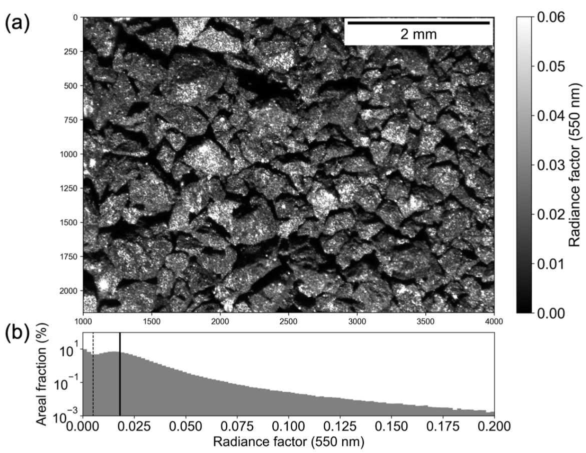

Fig. 3 (a) Radiance factor map of returned samples in room A. (b) Frequency histogram of radiance factor in (a). The dashed and solid lines show the threshold for shadow regions (~0.005) and the mean value (0.018).

Specular reflectivity. The hypothesis that the ubiquitous bright areas in the Ryugu returned samples are produced by specular reflectivity is tested by comparing the reflectance with photometric angles (Fig. 4). Our results show that the apparent bright facets seen in Fig. 4a are indeed observed from a direction close to that of specular reflection (Fig. 4b) and supports our hypothesis. Bright areas with various reflectance are present on the surface (Fig. 3b). Such observations imply a large conic angle of specular reflection (i.e., spread reflection) potentially caused by the corrugated surface property of the returned sample in scales comparable to the light wavelength (~1 μm).

The spectra of the specular reflections show a relatively redder slope throughout the UV to near infrared wavelengths. This trend was compared with spectra of sub-mm to mm-scale bright inclusions observed by an imager onboard the lander (MASCAM) [10]. Our results show that most of the bright inclusions categorized to have a "red" spectrum in [10] may be explained by specular reflections. However, the spectral slope of "blue" inclusions in [10] cannot be explained by specular reflections and their presence supports a compositional difference (e.g., carbonate-rich spots [9]).

Contributions from specular reflection have not been well considered for interpretation of asteroid reflectance. This is because the macroscopic photometric behavior could be sufficiently explained by diffuse reflections [1, 7] and the contribution is estimated to be <2% even for M-type asteroids [11]. However, our results show a steep increase in the areal fraction of specular reflections with decreasing spatial scale. The presence of specular reflections significantly affects the average reflectance as high as ≳20% (estimated from Fig. 3 after excluding bright areas with twice the average reflectance).

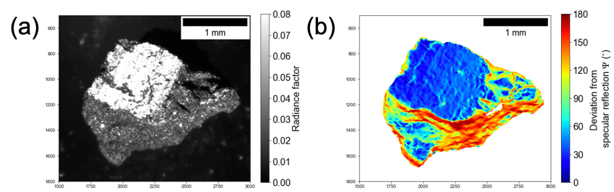

Fig. 4 (a) Reflectance map of a returned particle (ID: A0038). (b) The angle between the direction of specular reflection and the emission angle of observation.

Conclusion: Our results show that the spectra of returned samples are consistent with those observed by remote sensing in the visible to near infrared wavelengths. The large spectral variation among particles supports the representativeness of the returned samples. Our spectral measurement in microscopic scales revealed that the reflectance of Ryugu is highly affected by presence of micro shadows and specular reflectivity. Thus, factors affecting the contributions from shadows and specular reflectivity (e.g., composition and roughness) can be partly responsible for the reflectance variations of main belt asteroids.

References: [1] Sugita et al., 2019, *Science*, *364*(6437). [2] Morota et al., 2020, *Science*, *368*(6491), 654-659. [3] Sugimoto et al., 2021, *Icarus*, 114591. [4] Cho et al., submitted to *PSS*. [5] Yada et al., 2021, *Nat. Astron.*, [https://doi.org/10.1038/s41550-021-01550-6]. [6] Bus & Binzel, 2002, *Icarus*, *158*(1). [7] Tatsumi et al., 2020, A&A. [8] Pieters, 1983, *JGR, 88*, 9534–9544. [9] Pilorget et al., 2021, *Nat. Astron.*, [https://doi.org/10.1038/s41550-021-01549-z]. [10] Schröder et al., 2021, *PSJ*, *2*(2), 58. [11] Hiroi, 1993, *Icarus*, *102*(1).