Reflectance spectrum of Ryugu grains and their acid-extracted residues in the UV–VIS range

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Introduction: Reflectance spectrum in the ultraviolet to visible (UV–VIS) range is among the most frequently used wavelength range for observations of main-belt C-complex asteroids. Furthermore, distinctive spectral differences (e.g., spectral slope, absorption at UV) have been reported among C-complex asteroids [1]. However, their interpretation is not necessarily straightforward. This is because the UV–VIS spectrum is controlled by various physical (e.g., grain size) and/or chemical (e.g., mineralogy) state of the reflector. Thus, it is difficult to translate the UV–VIS spectral properties into physically and mineralogically well-defined constraint(s) on asteroid materials.

Studies on the UV–VIS spectra of samples returned from asteroid Ryugu may help us resolve this problem. This is because the physical/chemical state of the returned samples have been studied in detail and pre-processing of the samples allows us to control the sample state (e.g., extraction of certain minerals by acid treatments). Remote sensing by the Optical Navigation Camera (ONC) onboard Hayabusa2 revealed a dark/flat and homogeneous UV–VIS spectrum on the surface of Ryugu [2]. The dark/flat nature of the spectrum was confirmed by initial description of the returned samples [3, 4]. However, grain-to-grain spectral variation was substantially higher than those observed by remote sensing [5]. The variation in reflectance has been attributed to specular reflections caused by micro-scale facets, which were not resolved by remote sensing [5]. Such a result suggests that the texture of grains and abundance of opaque minerals with high reflectivity in the UV–VIS range can highly affect the reflectance of C-complex asteroids. However, the specific (sets of) minerals and/or organic matter that affect the spectra of returned samples have not been identified yet.

In this study, we compared the UV-VIS spectra of intact Ryugu grains with those of acid-extracted residues to evaluate how insoluble organic matter (IOM) contribute to Ryugu's dark and flat spectrum.

Samples and methods: We measured the UV–VIS spectra of returned samples with and without acid treatments that dissolve specific minerals: intact (i.e., un-extracted) grains, HCl-extracted residues, and HCl/HF-extracted residues. All samples were allocated to and processed by the Hayabusa2 IOM team. We measured 50 intact grains from aggregate samples A0106, A0108, and C0109 and 35 grains in the HCl-extracted residues from A0108. Minerals, such as carbonates, sulfides, and magnetite are removed by HCl extraction, and the residue mainly comprises of phyllosilicates and IOM. We also measured 19 grains in the HCl/HF-extracted residues from C0002 and C0107. HCl/HF extraction only leaves IOM within the residue. The sizes of all grains ranged from ~10 µm to 200 µm except for one ~1 mm intact grain from A0108.

The UV–VIS spectra were measured by a high-resolution multi-band spectrometer developed at the University of Tokyo. The spatial resolution is ~2 µm at 550 nm with a 300 µm × 300 µm field of view. The spectrometer is equipped with 25 narrow (10 nm width) band-pass filters from 230 to 1000 nm. Energy of the light power was reduced (30 µW at 550 nm) to avoid sample alteration. A standard diffuse reflector with 99% reflectance (Spectralon/Labsphere) was used for radiometric calibration.

Results and Discussion: The reflectance image of the largest grain measured in this study is shown in Fig. 1. Areas with high reflectance in Fig. 1 are specular reflections. Such specular reflections were also observed in acid-extracted residues. These photometric effects were not corrected in our analysis but reflectance from the entire grain (within the dashed curve in Fig. 1) were integrated to obtain the average reflectance for each grain. The spectrum of a typical grain for each of the three mineralogic composition type is shown in Fig. 2. These spectra show that mineralogy have a significant effect on the 1) reflectance, 2) UV absorption feature, and 3) VIS spectral slope as follows.

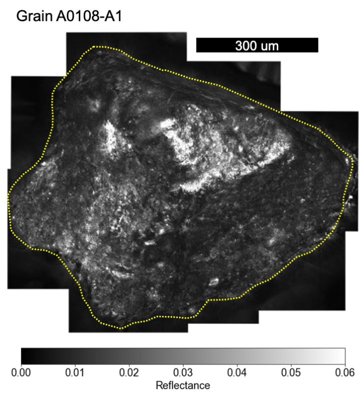

Fig 1 Reflectance image of the largest grain (from A0108) measured in this study. The dashed curve shows the rim of the grain.

1. *Reflectance*: Though reflectance has large grain-to-grain variation, Fig. 2 shows that phyllosilicate + IOM residues (i.e., HCl-extracted residues) have a significantly darker reflectance. Such correlation of reflectance with mineralogy provides insights into the reason for the dark nature of carbonaceous materials. Our result implies that the mixing state of phyllosilicates with IOMs may be important in effectively darkening the carbonaceous material. However,

reflectance of acid-extracted residues can be affected by physical and/or chemical alteration caused by the extraction process. Characterization of such alteration is needed to verify the implication of our result.

2. *UV absorption feature*: Fig. 2 shows that though spectra of intact grains are flat throughout the UV–VIS range, spectra of acid-extracted residues show a broad UV absorption centered at ~300 nm. The absorption shape of IOM in Ryugu samples, which is characterized by steepening of the spectral slope from VIS to UV, is consistent with those in Murchison meteorites [6]. Meteoritic studies show that such UV absorption may be caused by abundance of C-H bonds in organics [7] or deficit of magnetite [8]. Since acid extraction removes magnetite and increases the concentration of IOM in the residues, our result is consistent with both hypotheses.
3. *VIS slope*: Fig. 2 shows that IOMs exhibit a redder slope in the VIS range. Such trend is consistent with measurements of IOMs in carbonaceous meteorites [6, 9].

These correlation of the spectra with demineralization can be clearly observed in Fig. 3; residues have deeper UV absorption and IOMs have redder VIS slope. This result suggests that variations in UV absorption and spectral slope observed among C-complex asteroids [1] may represent difference in relative abundance of organics to other acid-soluble minerals.

Conclusion: We measured the UV–VIS spectra of Ryugu returned samples and their acid-extracted residues to evaluate how IOM contributes to the dark and flat spectra of Ryugu. Our results show that a variation of constituting minerals/organics, especially demineralization of opaque minerals with higher reflectivity and increase in concentration of IOM, has a significant effect on the reflectance, UV absorption feature, and VIS slope of Ryugu returned samples. This result implies that spectral variation in the UV–VIS range observed among C-complex asteroids may represent chemical variation such as abundance of organics and other acid-soluble minerals.

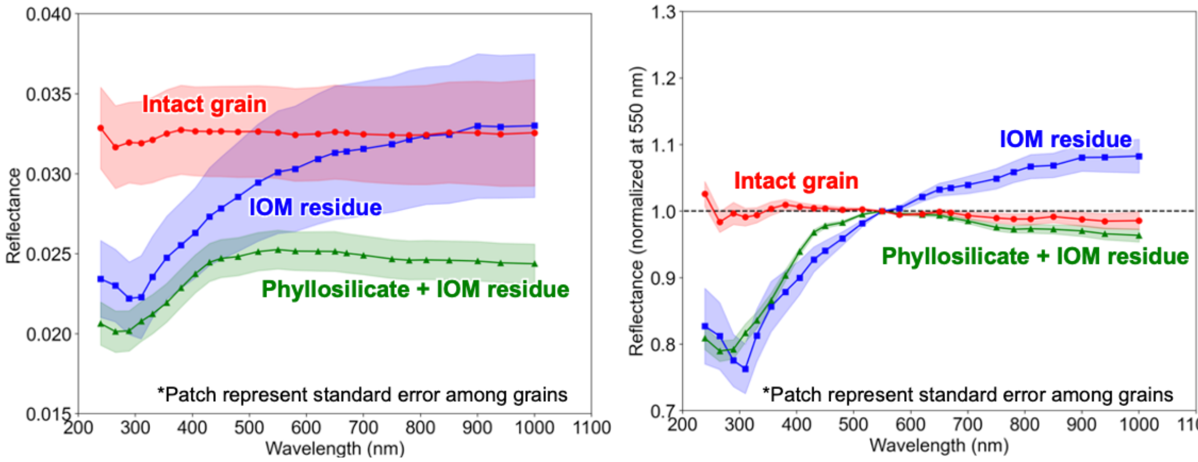

Fig 2 ***(Left)*** **Average reflectance spectrum for each of the mineralogic composition.** ***(Right)*** **Reflectance spectrum after normalization at 550 nm. The patch represents the standard error observed among grains.**

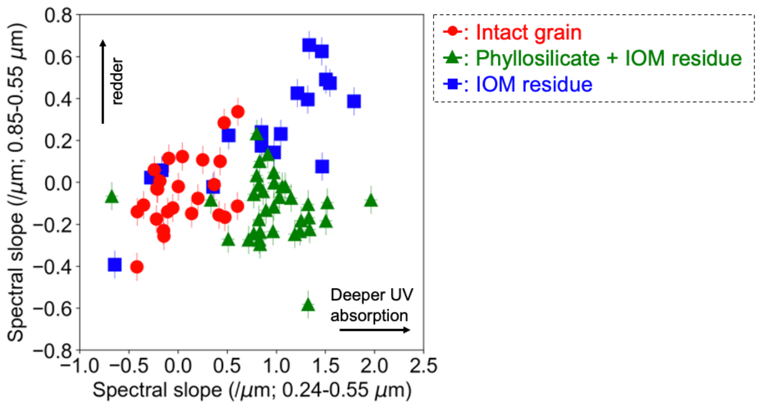

Fig 3 Correlation plot between UV and VIS spectral slope. Each plot shows the spectrum for each grain measured in this study.

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