

Quantitative analysis of spectral evolution of craters, boulders, and regolith on Ryugu and Bennu

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Spectral evolution of C-complex asteroids [1] needs to be identified to understand the implications for parent-body materials from telescopic observations. Spectroscopy of near-Earth C-complex asteroids Ryugu and Bennu provide data to identify the predominant weathering effects on the respective asteroids, which could be potentially extrapolated to main belt C-complex bodies. For instance, the spectral change of craters with increasing size showed a darkening/reddening effect for Ryugu [2, 3], whereas brightening/bluing was derived for Bennu [4]. In this study, we quantify the spectral evolution tracks of craters, boulders, and regolith to further constrain the weathering effects on Ryugu and Bennu.

Evidence of boulder breakdown on the surfaces of Ryugu and Bennu [5, 6] suggests a shorter lifetime for smaller boulders. Thus, a size-dependent spectral trend among boulders may reflect their spectral/physical evolution. For regolith, dependence on geopotential height should represent spectral evolution since regolith can migrate in the direction of local downslopes [7]. Moreover, for all geologic features, spectral evolution could be further deduced from latitude-dependent trends [8, 9]. To quantify the trends, we established spectral catalogues of craters and boulders on Ryugu based on images acquired by the Optical Navigation Camera [10]. For Bennu, we analyzed the catalogue based on images acquired by the mid-field multispectral imager MapCam [11] established in [4].

The trends we find from spectral analysis of both craters and regolith showed darkening/reddening on Ryugu and brightening/bluing on Bennu. Their significance was confirmed by t-tests with p-value <.01. The spectral evolution of these asteroids exhibits diverging tracks in spectral feature space. The rates of spectral change were estimated by combining the size-dependency of craters and their model ages with spectral measurements [12]. The weathering rate ($/\log_{10}$ time; time range $\sim 10^3$ – 10^7 yr) of albedo was quantified to be $-2.9(5) \times 10^{-4}$ for Ryugu and $+3.5(6) \times 10^{-4}$ for Bennu. As for the 480-to-850 nm spectral slope, the weathering rate ($/\mu\text{m}/\log_{10}$ time; time range $\sim 10^3$ – 10^7 yr) was $+0.006(2)$ for Ryugu and $-0.009(2)$ for Bennu. The observed bluing rate on Bennu is smaller than that estimated from main-belt asteroids [13] by an order of magnitude. These rates provide observational constraints for weathering experiments of returned samples. Also, comparison of the magnitude of the maturation between craters and regolith shows that weathering heterogeneity on the surface is produced mainly by surface migrations on Ryugu, and crater formations on Bennu.

However, boulder color trends show significant darkening/reddening for both asteroids. Although size-dependent trends of boulders may be due to the difference in material properties, the consistency with latitude-dependent trends supports the association with weathering processes. The possible difference in spectral evolution of boulders compared with that of regolith is consistent with the presence of fine particles, which may be produced by thermal disaggregation of boulder surfaces [3, 14]. Possible spectral alteration of boulders by the presence/absence of fines could be tested with reflectance measurements of returned samples.

[1] Lantz et al., 2018, *Icarus*, 302, 10-17. [2] Sugita et al, 2019, *Science*, 364(6437), eaaw0422. [3] Morota et al., 2020, *Science*, 368(6491), 654-659, aaz6306. [4] DellaGiustina et al., 2020, *Science*, 370(6517), eabc3660. [5] Molaro et al., 2020, *Nat. Commun.*, 11(1), 2913. [6] Ballouz et al., 2020, *Nature*, 587(7833), 205-209. [7] Jawin et al., 2020, *JGR: Planets*, 125(9). [8] Hemingway et al., 2015, *Icarus*, 261, 66-79. [9] Sen et al., 2021, LPSC, #2548. [10] Kameda et al., 2017, *SSR*, 208(1), 17-3. [11] Rizk et al., 2018, *SSR*, 214(1), 26. [12] Takaki et al., submitted to *Icarus*. [13] Nesvorný et al., 2005, *Icarus*, 173(1), 132-152. [14] Johnson & Fanale, 1973, *J. Geophys. Res.* 78, 8507-8518.

キーワード：宇宙風化、小惑星

Keywords: Space weathering, Asteroids