Spectral evolution of Ryugu and Bennu inferred from variations in visible spectra of returned samples

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Introduction: Our understanding of the surface compositions of primitive asteroids relies heavily on visible to near-infrared (0.4–2.5 μm) spectra obtained through ground-based telescopes [1, 2]. Spectral variations among these asteroids correlate with their heliocentric distance, potentially reflecting heterogeneities in the protostellar disk at the time of planetesimal formation [3]. However, the spectra of primitive asteroids show almost no absorption features in the 0.4–2.5 μm range, with variations primarily in albedo and spectral slope. This absence of distinct absorption features complicates the connection between composition and spectral characteristics. Spectral measurements of carbonaceous chondrites indicate that both albedo and spectral slope are strongly influenced by physical properties of surface materials, such as porosity and grain size [4, 5]. Additionally, ion and laser irradiation experiments on carbonaceous chondrites demonstrate that albedo and spectral slope can evolve over time due to space weathering effects [6, 7]. Furthermore, the porosity and grain size of asteroid surface materials are altered through space weathering processes, including heating and impacts [8]. To address these complexities, it is essential to establish ground-truth knowledge on the influence of physical properties and various space weathering processes on albedo and spectral slope, using remote sensing observations and analyses of returned samples from Ryugu and Bennu.

Near-Earth carbonaceous asteroids Ryugu and Bennu share many characteristics, including low bulk density, low thermal inertia, dark albedo, and boulder-rich surfaces [9, 10, 11, 12]. Analyses of returned samples reveal that their mineral abundances and isotopic compositions are similar, though not identical, to those of CI carbonaceous chondrites [13, 14]. Despite these similarities, their spectral types differ, with Ryugu classified as Cb-type [15] and Bennu as B-type [12], representing the reddest and bluest spectral end members within the C-complex asteroids. Additionally, spectral analyses of craters of varying surface ages indicate that the spectra of Ryugu and Bennu have evolved in completely opposite directions due to space weathering—Ryugu has darkened and reddened, while Bennu has brightened and blued [15, 16, 17, 18]. A study by [18] suggests that the spectral difference between the two bodies resulted from the opposite spectral evolutions, though the reason for this diverging evolutions between two otherwise similar asteroids remains unclear. Returned samples allow further investigation by correlating spectral characteristics with microscopic properties, such as grain size and the chemical and morphological byproducts of space weathering (e.g., microcraters, nanophase iron particles).

In this study, we investigate the cause of the opposite spectral evolutions on Ryugu and Bennu by analyzing the correlation of spectra with surface age and grain size/porosity based on remote sensing observations and returned sample analyses.

Methods: We examined the relationship among spectra, surface age, and grain size/porosity by correlating the spectra of 322 craters on Ryugu and 1,560 craters on Bennu with their diameters, photometric functions, and thermal inertia. Crater diameters serve as a proxy for surface age, as smaller craters typically indicate younger surfaces due to their greater susceptibility to erasure by resurfacing effects [19]. Photometric functions for each crater were derived by extracting photometric data from all disk-resolved images of Ryugu and Bennu and fitting them using Hapke's bidirectional reflectance model [20]. The slope of the fitted phase function in the phase angle range of 5–10º was used as a proxy for grain size and porosity, as this range is known to represent the shadow-hiding opposition effect [21]. Thermal inertia values for each crater were obtained from previous studies [22, 23].

The visible spectra of over 400 Ryugu samples, including both aggregates and individual particles, were measured at the JAXA curation facility using a multi-band microscope. Similarly, the visible spectra of five Bennu aggregate samples allocated to JAXA [24] were measured with the same instrument. As an initial comparison with remote-sensing data, we investigated the dependence of spectral characteristics on grain size.

Results and discussion: We observe intercorrelations among crater spectra, diameters, photometric functions, and thermal inertia. On Ryugu, larger craters tend to have darker, redder spectra, lower thermal inertia, and steeper phase functions, while on Bennu, larger craters tend to exhibit brighter, bluer spectra, higher thermal inertia, and shallower phase functions. These findings suggest that not only have the spectra evolved in opposite directions between Ryugu and Bennu, but their surface materials have undergone contrasting changes in grain size/porosity—on Ryugu, surface materials have become finer or more porous, whereas on Bennu, they have become coarser or more compact. This contrast likely drove the opposite spectral evolutions observed on the two bodies. Consistent with this trend, aggregate samples from both Ryugu and Bennu demonstrate that finer ($\lesssim$200 μm) grains exhibit darker, redder spectra compared to coarser ($\gtrsim$1 mm) grains. These findings support the hypothesis that the spectral differences between Ryugu and Bennu are primarily attributed to differences in surface physical conditions rather than composition.

There are several factors that influence the evolution of grain size and porosity on asteroid surfaces, including the mechanical strength of surface materials. We suggest that differences in asteroid size may be a key factor in explaining the divergent spectral evolutions of Ryugu and Bennu. According to a model by [8], the evolution of sub-millimeter-sized fine grains is largely governed by the efficiency of electrostatic levitation. This model predicts that the maximum grain size that can be lifted by electrostatic forces is 32 μm on Ryugu and 60 μm on Bennu, given that Ryugu is twice the size of Bennu. Consequently, the model suggests that the surface coverage of grains in the 32–60 μm range should increase over time on Ryugu and decrease on Bennu, which may account for the opposite spectral evolutions observed on the two bodies.

The results of this study underscore the significant role that surface physical conditions play in shaping asteroid spectra, highlighting the need for detailed examination in future sample analyses. Among Bennu samples, we observe significant grain-by-grain spectral variability. We identified a few millimeter-sized grains that are as blue, or even bluer, than Bennu's surface among a majority of grains that are as red as Ryugu's surface. Investigating the abundance of fine particles and the microscopic textures of these blue-colored Bennu grains will be essential for understanding the origins of spectral variability among primitive asteroids.

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