A GLOBAL VIEW OF THE NEAR-INFRARED REFLECTANCE PROPERTIES OF RYUGU AS SEEN BY THE NIRS3 SPECTROMETER ON HAYABUSA2. R.E. Milliken[1], K. Kitazato[2], L. Riu[3], T. Iwata[3], M. Abe[3], M. Ohtake[3], S. Matsuura[4], T. Arai[5], Y. Nakauchi[3], T. Nakamura[6], M. Mastuoka[3], H. Senshu[7], N. Hirata[2], T. Hiroi[1], C. Pilorget[8], R. Brunetto[8], F. Poulet[8], J.-P. Bibring[8], D. Takir[9], D.L. Domingue[10], F. Vilas[10], M.A. Barucci[11], D. Perna[11,12], E. Palomba[13], A. Galiano[13], K. Tsumura[7], T. Osawa[14], M. Komatsu[15], A. Nakato[3], T. Arai[7], N. Takato[16], T. Matsunaga[17], Y. Takagi[18], K. Matsumoto[16], T. Kouyama[19], Y. Yokota[3], E. Tatsumi[20], N. Sakatani[3], Y. Yamamoto[3], T. Okada[3], S. Sugita[20], R. Honda[21], T. Motora[22], S. Kameda[23], H. Sawada[3], C. Honda[2], M. Yamada[7], H. Suzuki[24], K. Yoshioka[20], M. Hayakawa[3], K. Ogawa[25], Y. Cho[20], Y. Takei[3], T. Saiki[3], S. Nakazawa[3], S. Tanaka[3], M. Yoshikawa[3], S. Watanabe[3,22], Y. Tsuda[3]. [1]Brown University, Providence, RI, 02912, USA.[2]The University of Aizu, JP.[3]Institut of Space and Astronautical Science (ISAS/JAXA), JP. [4]Kwansi Gakuin University, JP.[5]Ashikaga Universty, JP.[6]Tohoku University, JP.[7]Chiba Institute of Technology, JP.[8]Institut d' Astrophysique Spatiale, FR.[9]Jacobs/NASA Johnson Space Center, USA.[10]Planetary Science Institute, USA.[11]LESIA, FR.[12]INAF, Osservatorio Astronomico di Roma, IT.[13]INAF, Istituto di Astrofisica e Planetologia Spaziali, IT.[14]Japan Atomic Energy Agency, JP.[15]SOKENDAI, JP.[16]National Astronomical Observatory of Japan, JP.[17]National Institute for Environmental Studies, JP.[18]Aichi Toho University, JP.[19]National Institute of Advanced Industrial Science and Technology, JP.[20]University of Tokyo, JP.[21]Kochi University, JP.[22]Nagoya University, JP.[23]Rikkyo University, JP.[24]Meiji University, JP.[25]Kobe University, JP. (Ralph_Milliken@brown.edu; kitazato@u-aizu.ac.jp)

Introduction: The Japanese Aerospace Exploration Agency (JAXA) Hayabusa2 spacecraft arrived at the target asteroid Ryugu in June 2018 and has been collecting a wealth of data since that time. Classified as a C-type asteroid, the hope is that Ryugu hosts primitive materials and possibly aqueous alteration phases (e.g., clay minerals, salts) and/or organic compounds, similar to what is observed in carbonaceous chondrite meteorites [1-3]. The Hayabusa2 payload includes the NIRS3 instrument, a point spectrometer with a 0.1° field of view that measures radiance over an effective wavelength range of ~.18 – 3.2 μm [4-5]. NIRS3 has successfully acquired many tens of thousands of spectra during the course of the mission at a range of altitudes and thus spot sizes (spatial footprints).

High spatial resolution data were acquired during various descent operations, and together with the global spectral properties these data can be used to characterize the surface properties of Ryugu and make predictions of its composition, with particular attention to the role of hydrous phases. Such predictions will ultimately be tested when the collected samples are returned to and measured on Earth, providing a significant step forward in understanding how to relate spectroscopic properties of a C-type object to mineralogy and chemistry. This presentation will focus on results from data acquired as part of a 'global' mapping campaign, with particular focus on data acquired on July 11, 2018 (~40 m per spot) and July 19, 2018 (~20 m per spot) [5].

Data Analysis & Processing: NIRS3 measures all radiance from Ryugu over its operating wavelength range. When Ryugu is illuminated by the Sun its surface is warm enough that both reflected sunlight and thermally emitted radiation can contribute to the overall signal at the longer wavelengths (e.g., in the "3 μm" region that is sensitive to the presence of OH and H_2O). As such, in order to accurately retrieve surface reflectance values and to assess the presence or variations in OH/H_2O features, it is necessary to remove the thermally emitted contribution [5]. Raw data (DN values) are first converted to radiance values through multiplication by the radiometric calibration coefficient (RCC) value for each wavelength. The thermal radiance contribution is then estimated via fitting a Planck function to the measured radiance value at a wavelength that is close to, but outside of, the longer wavelength OH/H_2O region. Similar approaches have been successfully applied to near-IR reflectance data of the Moon [6]. The estimated thermal contribution is subtracted from the total radiance, and the residual radiance, believed to be reflected solar radiation, is then converted to I/F or reflectance by accounting for the Sun-Ryugu distance, solar flux, and viewing geometry.

The RCC was first derived based on pre-flight laboratory calibration measurements [4], but post-launch observations indicated an update to the RCC was necessary to retrieve accurate radiance values. Measurements of an onboard calibration lamp were used for this purpose, resulting in a revised RCC that has been used for the data discussed here [5].

Results: Reflectance spectra derived from NIRS3 measurements during the 'global' mapping campaign indicate that Ryugu is relatively spectrally homogenous at the ~20-40 m spatial scale. The surface of Ryugu is remarkably dark and exhibits an average albedo value of ~0.017±0.002 [5]. This is darker than other primitive objects visited by spacecraft, including the nucleus of comet 67P/Churyumov-Gerasimenko measured by the Rosetta spacecraft. Though it is relatively small, there is some albedo variation across the surface, with the equatorial region of Ryugu exhibiting an increase in albedo relative to adjacent terrains (Figure 1) [5].

In general, reflectance spectra of Ryugu are relatively flat with a slightly red (positive) spectral slope. The exact strength of this slope for wavelengths >2 μm is dependent on the accuracy of the thermal correction, and local geometry and physical properties can have strong links to surface temperature. Because of these complications and dependencies, small variations in spectral slope that appear to be correlated with physical/morphologic properties of Ryugu are being investigated in detail to determine if they are real surface spectral properties or within the uncertainty of the empirical thermal correction currently applied to the NIRS3 data.

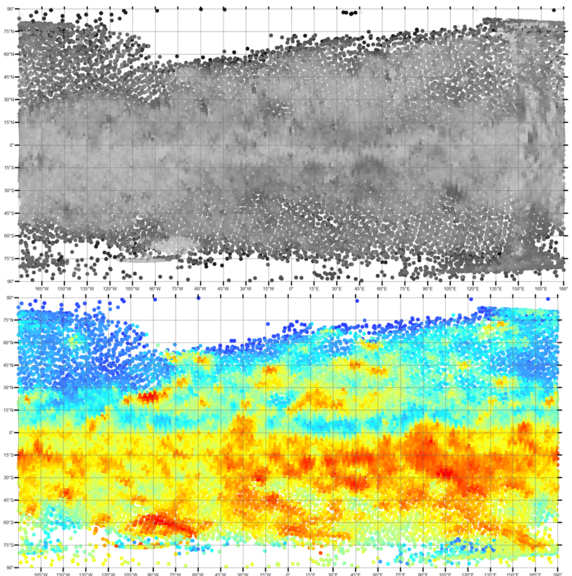

Figure 1. Top: Albedo map of Ryugu, showing minor variations with average albedo of ~0.017 and increase in albedo near equatorial ridge. Bottom: Temperature map derived from NIRS3 data, warmer colors indicate higher temperatures approaching ~375K. Data from July 11 & 19, 2018.

At a global scale, the surface materials of Ryugu do not exhibit spectral evidence for pyroxene. That is, there are no clear indications of absorptions in the ~2 µm region that would be indicative of Fe^{2+} in the M2 sites of pyroxene [7]. This is not uncommon for certain types of carbonaceous chondrites, particularly aqueously altered samples (type C1/C2) where primary silicates have been converted to secondary phases (e.g., clay minerals). However, the spectra of Ryugu also do not exhibit strong absorption features in the 3 µm region that might be expected for a volatile-rich body. Instead, all spectra of Ryugu exhibit a weak and narrow feature with a reflectance minimum at 2.72 µm. This feature is interpreted to indicate the presence of OH, likely attached to Mg cations based on its position. Though non-unique, this feature is consistent with the presence of Mg-serpentine, and the position of the absorption does not appear to vary across Ryugu's surface.

Although the OH feature is ubiquitous across Ryugu it is very weak, particularly compared with lab spectra of typical aqueously altered C chondrites [8]. The closest meteorite match based on existing spectral libraries is to thermally metamorphosed C chondrites and spectra of heated samples of Ivuna (Figure 2). This suggests that Ryugu may represent a primitive object that was thermally metamorphosed prior to disruption and reformation as a rubble pile. Alternatively, the weak OH feature may indicate destruction of hydrous phases at the optical surface by space weathering processes on what is otherwise a more aqueously altered object. A third alternative is that Ryugu did not experience significant aqueous alteration that would give rise to abundant hydrous phases, and the observed OH feature is indicative of low abundances of phyllosilicates and/or OH formed by solar wind implantation.

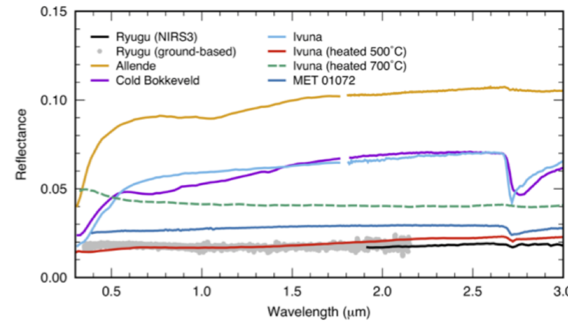

Figure 2. Modified Fig. 3 from [5] showing comparison between typical Ryugu spectrum as acquired by NIRS3 and laboratory spectra of various C chondrites including thermally metamorphosed sample Meteorite Hills 01072. Within existing spectral libraries of meteorite samples, C chondrites that have experienced thermal metamorphism or alteration provide the closest spectral match in the near-IR.

Conclusions: The surface of Ryugu is rather homogenous at the 20-40 m spatial scale. As summarized in [5], the major characteristics are that Ryugu is (1) extremely dark, (2) spectrally 'flat' with only a weak red slope, (3) exhibits spectral evidence for OH across its surface, (4) lacks clear spectral evidence for pyroxene at this scale, and (5) is most closely matched by lab reflectance spectra of thermally metamorphosed C chondrites.

The Hayabusa2 mission has successfully acquired multiple samples from the surface of Ryugu, and the safe return of these samples to Earth for detailed laboratory studies will allow us to test whether or not thermal metamorphism, space weathering, limited aqueous alteration or a combination of these processes best explains the spectral properties observed by NIRS3. Regardless of the origin of these features, it is clear that Ryugu is spectrally distinct from Bennu, and as such it provides a unique and distinct data point for improving our understanding of how to use near-IR reflectance data of C-type objects to infer their mineralogy, chemistry, and geological history.

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