IRRADIATION-ENERGY DEPENDENCE ON THE SPECTRAL CHANGES OF HYDROUS C-TYPE ASTEROIDS BASED ON 4KEV AND 20KEV HE EXPOSURE EXPERIMENTS OF MURCHISON CM CHONDRITE.

T. Nakamura[1], C. Lantz[2], Y. Nakauchi[3], K. Amano[1], R. Brurnetto[2], M. Matsumoto[1], S. Kobayashi[1], M. Matsuoka[3], T. Noguchi[4], T. Matsumoto[4], M. E. Zolensky[5], [1]Division of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan (email: tomoki.nakamura.a8@tohoku.ac.jp), [2]Université Paris-Saclay, CNRS, Institut d'Astrophysique Spatiale, 91405, Orsay, France, [3]JAXA/ISAS, Sagamihara, 252-5210, Japan, [4]Faculty of Arts and Science, Kyushu University, Fukuoka 819-0395, Japan, [5]NASA/JSC, Houston, TX 77058, USA.

Introduction: C-type asteroid 162173 Ryugu was observed by remote sensing apparatus onboard Hayabusa2 spacecraft and found to be very dark object whose reflectance is (1.60 ± 0.15) % at 0.55 μm [1, 2] and showed a small 2.7 μm absorption band indicative of phyllosilicates [3]. The optical navigation camera detected color variations of Ryugu's surface in the wavelength range from 0.4 to 0.95 μm: Bluer spectra are observed at both poles and on the equatorial ridge, both of which are topographic highs and thus may be fresh material exposed by gradual erosion [2]. On the other hand, many locations at middle-latitude areas exhibit redder and darker colors [2]. Similar color variations are also detected in the near-infrared wavelength range [4]. These observations suggest that a surface-correlated process is responsible for the color variation, most probably from blue to red, but the mechanism for the change is not yet identified. Space weathering is one possible mechanism responsible for the color variation, but the spectral changes of C-type asteroids from space weathering are far from being fully understood.

Past experimental studies using hydrous carbonaceous chondrites such as Murchison and Tagish Lake show that He exposure (simulating solar wind irradiation) changes spectra to bluer and brighter [5, 6]. Recently our He exposure experiments indicate that spectral changes depend on physical properties such as porosity of exposed material [7]. In this study, we performed further He exposure experiments using Murchison CM chondrite in order to understand energy dependence on the spectral changes. We found that He energy is a critical parameter, as well as physical properties of the samples, that affects spectral changes of space weathering of hydrated C-type asteroids.

Sample and experiments: A 2-cm sized chip with a flat surface with roughness made by a #400 polishing disk was prepared from Murchison CM chondrite. It was cut to two 1-cm sized fragments and therefore the two fragments have a flat surface with exactly the same roughness. One fragment was irradiated by 20 keV He at a dose rate of $\sim 10^{13}$ ions/(sec cm^2) at CSNSM-IAS Orsay, France, until the total dose reached 1, 3, and 6 $x10^{16}$ ions/cm^2. The other fragment was irradiated by 4-keV He at the same dose rate of $\sim 10^{13}$ ions/(sec cm^2) at ISAS/JAXA, Japan with the same total dose (1, 3, and 6 $x10^{16}$ ions/cm^2). In summary, we performed 4 keV and 20 keV He exposure experiments on Murchison. The conditions of the two experiments are the same including physical properties (porosity and roughness) and irradiation properties (dose rates and total doses) and only difference is He energy.

Reflectance spectra of the same portions of the 20 keV sample were measured before and after exposure in the wavelength range from 0.45 to 11.5 μm in France. The spectra of the same area of unexposed and exposed area of the 4keV sample was also measured at wavelengths from 0.3 to 2.6 μm at ISAS/JAXA. The spectra of the unexposed and 4 keV exposed sample (only after 6 $x10^{16}$ ions/cm^{2}exposure) were measured from 0.4 to 15 μm at Tohoku Univ. TEM observations will be performed on FIB thin sections made from both 4 keV and 20 keV-exposed samples.

Results and discussion: Murchison shows small spectral changes by 20 keV He exposure (Fig. 1A): it becomes redder and darker only slightly after exposure of $1x10^{16}$ ions/cm^2, but becomes brighter and bluer with increasing total dose of He exposure up to $6x10^{16}$ ions/cm^2. The reflectance at 450 nm shows a slight increase from 5.6% (the unexposed sample) to 5.9% (the exposed sample at $6x10^{16}$ ions/cm^2). On the other hand, the Murchison sample exposed to 4 keV He shows larger spectral changes to the opposite direction compared with the 20 keV sample. It becomes redder and darker with increasing total dose of He exposure up to $6x10^{16}$ ions/cm^2 (Fig. 1B). The reflectance at 450 nm shows an apparent decrease from 6.8% (the unexposed sample) to 5.0% (the exposed sample at $6x10^{16}$ ions/cm^2). Our results clearly indicate that the spectra are completely different between 4 keV and 20 keV exposed Murchison samples with the total doses up to $6x10^{16}$ ions/cm^2, therefore suggesting that there is a large energy dependence on the spectral changes of hydrated C-type asteroids by space weathering attributable to solar-wind exposure.

Our previous He exposure experiments on the same carbonaceous chondrite Y 980115 indicated that spectral changes are completely different depending on the physical properties of the C chondrite samples: compressed samples become bluer and brighter by He exposure compared with less compacted samples [8]. Taken together, our results of present and previous He exposure experiments suggest that space weathering of hydrated C-type asteroids is more complex than previously thought (e. g., [6]). High-energy He exposure to compressed samples (e. g., shock compacted CM chondrites like MET01072) changes spectra to bluer and brighter, while low-energy He exposure to less compacted samples (e. g., unshocked CM chondrites such as Murchison and Murray) changes spectra to redder and darker in the wavelength range of < 900 nm (Fig. 1B).

The mechanism of spectral reddening by 4 keV exposure and that of bluing by 20 keV exposure is not well understood. Comparison of nm-scale surface layer modifications between 4 keV and 20 keV samples by TEM observation is now underway.

Spectral changes of space-weathered surface of the hydrated C-type asteroid Ryugu can be interpret based on our results of He exposure experiments. Space weathering of Ryugu surface seems to have made spectra redder and darker [2], which is consistent with spectral changes observed in our low-energy He exposure on unshocked CM samples. Therefore, it is inferred that the dominant process occurring on Ryugu's surface is alteration by low-energy ion irradiation of less-compressed rock fragments.

On the other hand, although not ubiquitously, space weathering on compressed materials seems to have occurred on Ryugu surface. Rock fragments with smooth surfaces and platy morphology occur on Ryugu [8]. The shape of the fragments suggests that they are broken fragments of larger rocks with parallel fractures, along which they were separated into rock fragments with smooth surface and platy morphology. Such parallel fractures were found in shocked CM chondrite MET01072 ([9], see Fig. 2). The fractures formed perpendicular to the shock compaction axis, suggesting that they formed during pressure release by expansion of rocks induced by volatile evaporation [9].

It is inferred that the catastrophic impact that crushed the parent asteroid and made a rubble-pile of Ryugu produced many boulders with parallel fractures and later small impacts or thermal fatigue produced many rock fragments with smooth surfaces and platy morphology on Ryugu surface. If such platy fragments are really impacted and compressed hydrous carbonaceous chondrite-like material, then He exposure on compressed rocks occurred on Ryugu's surface, which resulted in less reddening of spectra.

References: [1] Watanabe S. et al. (2019) *Science* 364, 268. [2] Sugita S. et al. (2019) *Science* 364, 252. [3] Kitazato K. et al. (2019) *Science* 364, 272. [4] Riu L. et al. (2020) *LPSC LI abstract*, in this volume. [5] Lantz C. et al. (2017) *Icarus* 285, 43–57. [6] Lantz C et al. (2018) *Icarus* 302, 10–17. [7] Nakamura et al. (2019) *82nd annual meeting of the Meteoritical Society*, Abstract #6211. [8] Jaumann et al. (2019) *Science* 365, 817. [9] Nakamura et al. (2016) *Goldschmidt Conf.* abstract #2228.

Acknowledgment: This work has been funded by the CNES-France (Hayabusa2 mission) and by the French ANR project CLASSY (Grant ANR-17-CE31-0004-02).

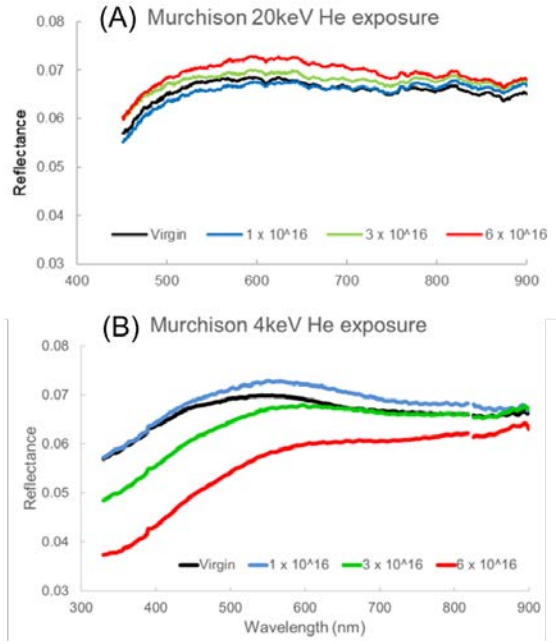

Fig. 1. Reflectance spectra of Murchison CM chondrite irradiated by 20 keV He (A) and 4 keV He (B) with total dose of 1, 3, and 6 x10^{16} ions/cm^2.

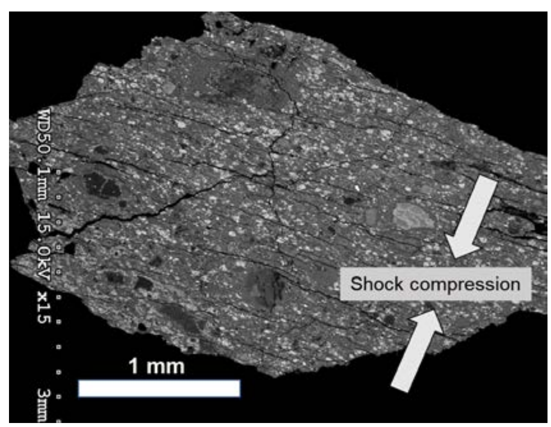

Fig. 2. Back-scattered electron image of MET01072 CM chondrite, showing high densities of parallel fractures in a direction perpendicular to the shock compression axis.