MID-IR SPECTRUM OF RYUGU SAMPLE C0137 COMPARED TO IN-SITU DATA AND CARBONACEOUS CHONDRITES. M. Hamm[1,2], V. E. Hamilton[3], and C. A. Goodrich[4], [1]Freie Universität Berlin, Malteserstr. 74-100, 12249 Berlin, Germany, [2]Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany, (maximilian.hamm@dlr.de) [3]Southwest Research Institute, Boulder, CO 80302 USA, [4]Lunar and Planetary Institute, Houston, TX 77058 USA.

Introduction: The Near-Earth Asteroid (162173) Ryugu has been investigated by the JAXA Hayabusa2 mission [1]. Hayabusa2 successfully returned samples from two sites of Ryugu's surface to Earth in December 2020[2]. Part of this mission was the deployment of the MASCOT lander [3] which studied Ryugu's surface in detail. Ryugu is a rubble-pile asteroid covered in boulders and large pebbles [4-6]. Observations in the visible and near-infrared wavelength range indicate that Ryugu is as dark as any measured meteorite samples and that the closest match is thermally metamorphosed carbonaceous chondrites [6,7]. Although Hayabusa2 did not carry a dedicated thermal infrared spectrometer, the MARA instrument on the MASCOT lander observed a single boulder of the most common type on the surface of Ryugu through six channels with different filters, two broadband filters and four narrowband filters from 5.5-7 µm (B06), 8 – 9.5 µm (B08), 9.5 – 11.5 µm (B09), and 13.5 – 15.5 µm (B13)[8]. Here we compare the effective emissivity from MARA [9] with the infrared spectra of carbonaceous chondrite (CC) meteorite thin sections, remote-sensing spectra from Bennu, and the C0137 sample of Ryugu.

Methods: The reduction of MARA and OTES data plus laboratory thermal infrared spectra of polished meteorite sections are described by [10] and are unchanged for this analysis, including the Ryugu particle C0137.

Results: Based on the infrared flux observed by MARA, the emissivity of Ryugu in the four narrow bands (Fig. 1), is $\varepsilon_{B06} = 0.87^{+0.02}_{-0.01}$, $\varepsilon_{B08} = 0.98^{+0.01}_{-0.01}$, $\varepsilon_{B09} = 0.92^{+0.01}_{-0.01}$, $\varepsilon_{B13} = 0.95^{+0.02}_{-0.01}$. The MARA results are compared to Bennu and averaged spectra of meteorite thin sections and Ryugu particle C0137, which are resampled to the four MARA filters' instrument functions (black horizontal lines in Fig. 1). For systematic comparison, we plot the ratios of $\varepsilon_{B09}/\varepsilon_{B08}$ and $\varepsilon_{B13}/\varepsilon_{B08}$ against each other for non-normalized spectra in Fig. 2. Aqueously altered CC form a trend (green oval) that is largely distinct from unaltered and heated CC. The MARA result overlaps with CC petrologic types 1, 1/2, and 2 but not results for Bennu spectra from OSIRIS-REx [9,10]. The particle C0137 lies further away from the CI1 CCs.

Discussion: The difference in spectral parameters between particle C0137, remote sensing data, and meteorites could be attributable to several factors. First, we consider the difference between remote sensing and C0137 data and then we address the difference between C0137 and CC meteorites and the uniqueness of these band ratios.

Remote sensing vs. Ryugu sample spectra. The parameterization of the C0137 spectrum and the results obtained for MARA lie within the region of aqueously altered chondrites (Fig. 2) and the MARA values are consistent with CI chondrites, including uncertainties. However, even accounting for uncertainties, the C0137 point does not overlap the MARA point. The Bennu points lie outside any CC field, likely due to the exceedingly low contrast of these spectra, which have a maximum band depth of ~0.02 (emissivity).

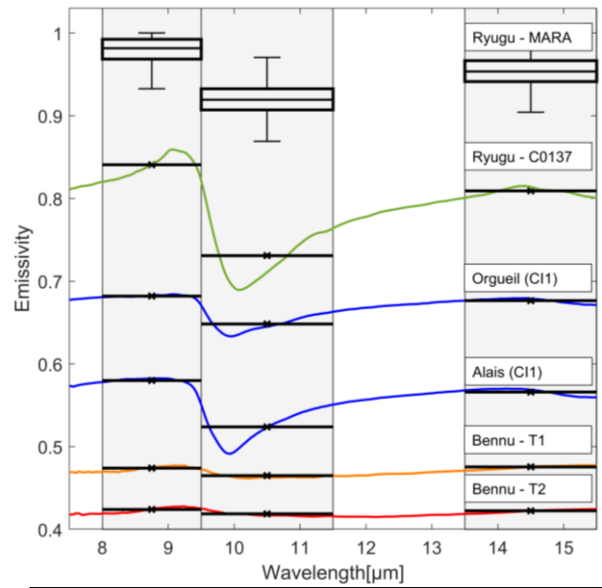

Figure 1: *Boxplot of Ryugu's emissivity estimated within the four narrowband channels of MARA, compared to MIR spectra of Ryugu samples, CI1 chondrites, and Bennu. The box boundaries are given by the 25th and 75th percentile, the center is given by the median, and the whiskers are defined by outliers of the estimated distribution.*

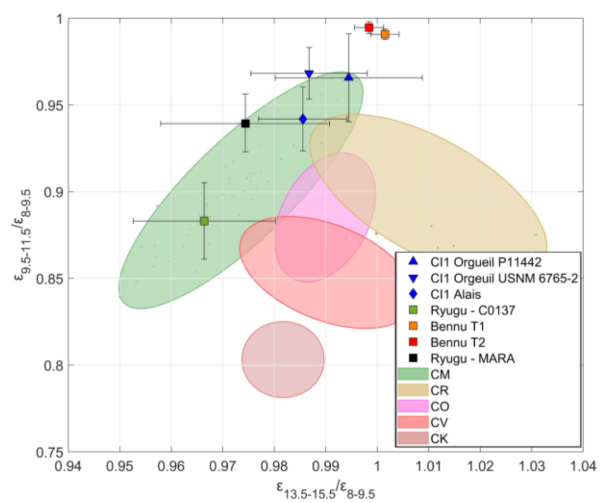

Figure 2: *Ratios of the averaged emissivity within the B09 and B13 bands, and the B08 band plotted against each other for various spectra of carbonaceous chondrite thin sections, Bennu, and Ryugu. Ovals illustrate the groups of Carbonaceous Chondrites*

The difference between MARA and C0137 might arise from a compositional or physical bias. Initial analysis of samples of Ryugu shows them to be remarkably like CI1 chondrites [11]. As such, compositional bias seems unlikely. Physical differences between the natural surface of Ryugu and the polished section of C0137 are much more likely to explain the difference. For example, a small amount of dust could cause the MARA spectrum to have reduced spectral contrast or a slightly different integrated emissivity (particularly from 9.5 – 11.5 µm). Furthermore, evidence of space weathering was found in grains of Ryugu samples [12], and roughness has been found to reduce spectral contrast of MIR spectra [13]. The container C samples of Ryugu are from the second sampling site in the vicinity of an artificial crater. They are more likely to contain sub-surface, less space weathered, materials [2]. Thermal infrared spectra of Bennu are interpreted as being consistent with a small amount of volume scattering from only ~5-10 µm of surface dust that is not sufficient to affect the derived thermal inertia data [10]. The Because spectral contrast can be diagnostic of the abundance of dark or opaque components, we have not normalized the spectra. Given that data shown here for all meteorites were measured on polished sections, surface roughness should not be a factor as it might be if the meteorites had been measured as powders.

Ryugu sample spectrum vs. CC meteorite spectra. The band ratios of the C0137 sample spectrum are not close to the CI1 meteorite values despite the clear spectral similarity of Ryugu samples to CI1 chondrites [14]. Both meteorite band ratio values are larger than the values for C0137. Possible reasons for this difference include meteorite representativeness and variability in the Ryugu specimens. CI1 meteorites are rare in our collections, at least in part due to their physical weakness. Because several of these meteorites have small masses, even fewer of them are available in sufficient quantity for spectral study. The three CI1 spectra included in our analysis (Alais and two Orgueil) may not be fully representative of CI1 spectral variability. Some CI1 meteorites have been poorly curated at times and are known to exhibit terrestrial weathering that might affect their spectral shape or spectral contrast. Our spectra of Orgueil and Alais exhibit notably lower total spectral contrast than meteorites recovered more recently but with overall similar spectral shapes, such as the C2-ung meteorites Tagish Lake and Tarda. Low spectral contrast will result in larger band ratio values for the same spectral band shape and position. If the lower contrast of the CI1 meteorites is a result of weathering, it is plausible that less weathered CI1 chondrites might plot closer to C0137 in Fig. 2. Finally, it is possible that if additional mid-IR spectra of Ryugu samples were plotted [14] they would exhibit a spread in values that might overlap CI1 chondrites and the MARA results.

Parameter uniqueness. The emissivity minimum around 10 µm of C0137 is similar to that of Orgueil whereas the minima of CM chondrites are located at increasingly longer wavelengths [15]. The MARA band ratios cannot distinguish between CM and CI chondrites, so this method seems to be limited primarily to distinguishing between aqueously altered CC and those that are not (in the absence of further analysis of the origin of the distribution of the CI/CM band ratio values). With the acquisition of more mid-IR spectra of Ryugu samples and possibly more CI1 meteorites, we can expect to get a better understanding of potential systematic differences between the surface of Ryugu's boulders and the returned samples.

Summary: We measured the mid-IR spectrum of Ryugu sample C0137, a sample from the second touchdown site close to an artificial crater, for comparison with MARA emissivities measured at Ryugu. Convolved to the MARA band passes, the C0137 spectrum is consistent with aqueously altered carbonaceous chondrites but differs beyond the uncertainties from the Ryugu asteroid surface spectrum and those of CI1 meteorites. The most likely reasons for these differences include sample preparation methods as compared to asteroid surface physical properties, and meteorite representativeness.

References: [1] Tsuda, Y. et al. (2013) *Acta Astronautica*, *91*, 356-362. [2] Yada, T. et al. (2021) *Nat. Astron.* https://doi.org/10.1038/s41550-021-01550-6. [3] Ho, T.-M. et al. (2021) *PSS, 200*, 105200. [4] Watanabe, S., et al. (2019) *Science*, *364*, eaav8032. [5] Jaumann, R., et al. (2019) *Science*, *365*, 817-820. [6] Sugita, S., et al. (2019) *Science*, *364*, aaw0422. [7] Kitazato, K., et al. (2021) *Nat. Astron.*, *5*, 246-250. [8] Grott, M., et al. (2019) *Nat Astron. 3*, 971–976. [9] Hamm, M., et al. (2022), Nat. Comm. 13, 364 [10] Hamilton, V. E., et al. (2021) *A&A 650*, A120. [11] Nakamura, E. et al. (2022) *Proc. Jpn. Acad., Ser. B, 98*. [12] Noguchi, T. et al., (2022) *Nat. Astron.*, https://doi.org/10.1038/s41550-022-01841-6 [13] Osterloo, M.M., *Icarus* 220 (2012) 404–426 [14] Nakamura, T. et al. (2022) *Science* https://doi.org/10.1126/science.abn8671. [15] Hanna, R. D. et al. (2020) *Icarus, 346*, 113760.