USING THERMAL INFRARED SPECTRA OF METEORITES TO INVESTIGATE ASTEROID COMPOSITION AND EVOLUTION H. C. Bates[1,2], K. L. Donaldson Hanna[2,3], A. J. King[4], N. E. Bowles[2], L. F. Lim[5], J. P. Emery[6] and S. S. Russell[1], [1]Natural History Museum, London, UK, (h.bates@nhm.ac.uk), [2]University of Oxford, Oxford, UK, [3]University of Central Florida, Orlando, FL, USA, [4]The Open University, Milton Keynes, UK, [5]Goddard Space Flight Centre, Greenbelt, MD, USA, [6]Northern Arizona University, Flagstaff, AZ, USA.

Introduction: The thermal infrared spectral range (TIR; ~5 – 50 µm) contains a number of diagnostic features of rock forming minerals, and is becoming an increasingly important tool for understanding the mineralogy and alteration history of asteroids. The Spitzer Space Telescope Infrared Spectrograph (IRS; [1]) and the Akari Infrared Astronomy satellite [2] have both observed asteroids in the TIR range, and the James Webb Space Telescope (JWST; [3]) will be able to observe asteroids in the TIR with greater sensitivity [4]. The OSIRIS-REx spacecraft is characterizing asteroid Bennu using the OSIRIS-REx Thermal Emission Spectrometer (OTES, ~5.5-50 µm; [5]), and the upcoming Lucy mission to the Jupiter Trojan asteroids will carry a similar instrument, the Lucy Thermal Emission Spectrometer (L'TES). Additionally, the Hayabusa2 Mobile Asteroid Scout (MASCOT) had a radiometer (MARA; [6]), with a series of channels covering some of the TIR range, to investigate Ryugu's surface.

Interpreting these remotely sensed spectra requires measurements of appropriate meteorite analogues across the same wavelength ranges. Complications can arise in these comparisons as spectral signatures in the TIR range are affected by a number of factors, including porosity, particle size, and environmental conditions [7, 8]. Nevertheless, first order comparisons between laboratory and remote measurements can be used to identify potential meteorite analogues for further investigation. Here we use TIR emissivity spectra of aqueously and thermally altered CM and CY chondrites to show how MARA observations could interpret the complex history of materials on Ryugu's surface. We also demonstrate the similarity of the TIR emissivity spectra of the CY meteorites with Jupiter Trojan asteroid and comet spectra.

MARA observations of Ryugu: Analysis of the near-IR spectra of Ryugu has suggested a surface composed of thermally metamorphosed CM or CY chondrite-like material [9, 10]. One way to investigate this relationship is to look at data from MARA, which whilst measuring the surface temperature of Ryugu, also collected emissivity measurements in selected wavelength channels: 5-7, 8-9.5, 9.5-11.5 and 13.5-15.5 µm [6].

Figure 1 shows the emissivity spectra of some unheated and dehydrated CM and CY [10] chondrites collected under simulated asteroid environment (SAE) conditions [e.g. 8], re-sampled to the MARA spectral channels. The SAE conditions were achieved by collecting spectra in an environment chamber where atmospheric gases were removed (pressure < 10^{-4} mbar), the interior was cooled to <-150 ^{o}C, and samples were heated from above and below until the maximum brightness temperature was ~75 ^{o}C [8]. For re-sampling, each calibrated emissivity was multiplied by the transmission of each filter [6], and then averaged across the wavelength range of each filter. Measurements were collected on powders with particle sizes <35 µm, therefore these observations will help interpret measurements of Ryugu in areas spectrally dominated by fines.

The spectra show little difference between unheated CM (LON 94101), moderately dehydrated CM (EET 96029) and intensely heated CY material (Y 86720 and B 7904). However, the intensely heated CM (PCA 02012) looks distinct in the first filter, where its spectra shows a lower emissivity. Based on the radiometric performance quoted in Grott et al. [11], MARA observations should be able to discriminate this difference in emissivity.

PCA 02012 is composed of ~20 vol% primary, Fo# 100-90 olivine, and ~30 vol% secondary, more Fe-rich olivine (Fo#60-70). Its lower emissivity in the 5.5-7 µm region is consistent with previous measurements of Mg-rich olivine [12] suggesting MARA spectra may be able to identify regions of Mg-rich olivine and pro-

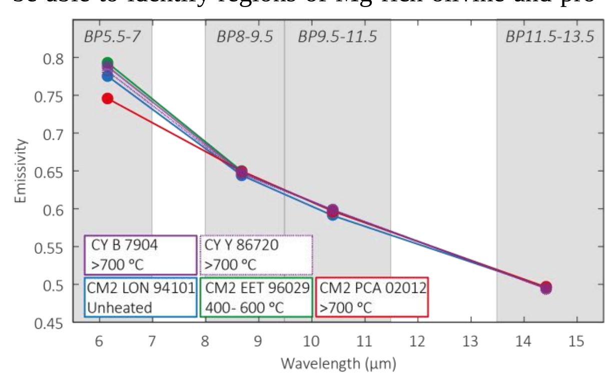


Figure 1: The TIR emissivity spectra of CM2 LON 94101, moderately heated CM EET 96029, intensely heated CM PCA 02012, and intensely heated CYs Y 86720 and B 7904. Meteorite spectra have been resampled using the MARA filter parameters, in order to see what different surface compositions on Ryugu would look like when observed with the MARA instrument.

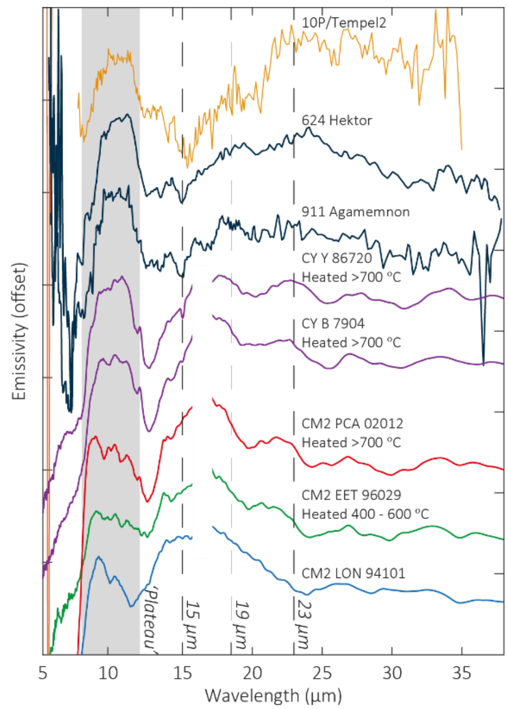
vide additional constraints on likely analogues for Ryugu's surface.

TIR spectra of Trojan asteroids and comets: Spectral similarities have been found between Jupiter Trojan asteroids and comet nuclei, notably asteroids and comets that are classified as D-type [13]. Spectra of both show a 10 µm emissivity 'plateau', (Fig. 2) as well as emissivity peaks near 19 and 23 µm, and emissivity minima near 15 µm [13, 14]. The similarity in the Trojan and comet nuclei spectra suggest similar surface compositions and physical properties, for example the under-dense 'fairy-castle' surface structure as a possible explanation for the plateau [14].

Figure 2 shows that the TIR spectra of aqueously and thermally altered CY chondrites (e.g., B 7904 and Y 86720 [10]), collected under ambient conditions [8], are similar to those of the Trojans and comet nuclei. The spectra of aqueously and thermally altered CM chondrites, also shown in Figure 2, do not provide a good spectral match. All measurements were collected in a chamber which is held at ambient pressure (~1000 mbar N_2) and temperature (~28 ^{o}C), whilst the sample is heated from below to 80 ^{o}C [8]. Samples were powdered to a particle size of <35 µm, which results in the transparency feature near 12.5 µm.

The CY chondrite spectra show a similar 'plateau' to the Trojan and comet nuclei spectra, as well as additional similar features near 15, 19 and 23 µm (Fig. 2). The peaks near 19 and 23 µm are caused by the fundamental bending vibrations associated with olivine. In the CY chondrites, these features are attributed to Fo#50-70 olivine [15], which recrystallized from a dehydrated phyllosilicate phase during heating to >700 ^{o}C [10]. This suggests that Fe-rich olivine may be present on the Trojans and comets. The plateau feature in the CY spectra is similarly caused by stretching vibrations of recrystallized olivine and dehydrated phyllosilicates. We see this plateau shape without the samples being in an under-dense environment, suggesting its presence in the Trojan spectra may be a result of mineralogy and not thermophysical properties. Vernazza et al. [16] suggested the surface composition of some D-type asteroids is similar to anhydrous interplanetary dust particles (IDPs). However, their similarity with the CY spectra might suggest an alternate mineralogy and therefore processing history for these asteroids. Morbidelli et al. [17] suggested that Trojan asteroids may have experienced heating during a period of orbital migration, giving a mechanism for thermal processing of these bodies. In order to fully explore the potential of this spectral relationship, measurements of the CY meteorites under the appropriate near-surface Trojan and comet conditions are needed.

Figure 2: The TIR emissivity spectra of comet 10P/Tempel2 [11], the Jupiter Trojan Asteroids 624 Hektor and 911 Agamemnon [12], the CY chondrites Y 86720 and B 7904, and CM chondrites LON 94101, EET 96029 and PCA 02012. Meteorite spectra are scaled by a factor of five for comparison. Features of interest are noted, and gaps in the data near 16.7 µm are due to a low transmission through the FTIR beam-splitter.



Conclusions: Here we demonstrate how TIR lab measurements of the appropriate analogues can help interpret remote observations. We show what MARA observations of Ryugu might look like if the surface has some dehydrated CM or CY-like material, and we also demonstrate the similarities between Jupiter Trojans and comet nuclei and CY spectra. This spectral similarity could help constrain some of the mineralogy and processing histories of small bodies in the outer solar system.

References: [1] Houck J. et al. (2004) *Astrophysical Journal Supp, 154,* 18-24. [2] Murakami H. et al. (2007) *PASJ, 59,* S369-S376. [3] Gardner J. P. et al. (2006) *Space Science Reviews, 123,* 485-606. [4] Rivkin A. (2016) *PASP, 128.* [5] Christensen P. et al. (2018) *Space Science Reviews, 214* [6] Grott M. et al. (2017) *Space Science Reviews, 208,* 413-431. [7] Salisbury J. et al. (1991) *Icarus, 92,* 280-297. [8] Donaldson Hanna K. L. et al. (2019) *Icarus, 319,* 701-723. [9] Kitazato K. et al. (2019) *Science, 364,* 272-275. [10] King A. J. et al. (2019) *Geochemistry, 79, 125531.* [11] Grott M. et al. (2013) *44th LPSC,* Abstract #597 [12] Bates et al. (2019) *MAPS in press.* [13] Kelley M. et al. (2017) *Icarus, 284,* 344-358. [14] Emery J. et al. (2006) *Icarus, 182,* 496-512. [15] Lane M. et al. (2011) *JGR, 116.* [16] Vernazza P. et al. (2015) *Astrophys. Journal, 806.* [17] Morbidelli et al. (2005) *Nature, 435,* 462-465.