SPECTRALLY CHARACTERISING THE EFFECTS OF THERMAL METAMORPHISM IN CM2 AND C2 CHONDRITES. H. C. Bates[1,2], K. L. Donaldson Hanna[2], A. J. King[1], N. E. Bowles[2] and S. S. Russell[1], [1]Dept. of Earth Sciences, Natural History Museum, London, UK, SW7 5BD (h.bates@nhm.ac.uk), [2]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK, OX1 3PU.

Introduction: JAXA's Hayabusa2 arrived at its target, the C-type asteroid Ryugu, in June 2018 and NASA's Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) arrived at its target, the B-type asteroid Bennu, in December 2018. The C- and B-type asteroids are part of the C-complex class [1], which has been linked to carbonaceous chondrite meteorites, particularly the aqueously altered CM and CI chondrites [2]. These meteorites are rich in organics and water, and are chemically pristine, so investigating them and their parent body asteroids will tell us about the early evolution of our Solar System.

Some aqueously altered CM and CI chondrites have also experienced thermal metamorphism [3,4]. Previous work has suggested that these could be good analogues for the C- and B-type asteroids [e.g. 5] including Ryugu [6]. The surfaces of C-complex asteroids might therefore contain a mixture of hydrated and dehydrated materials, and may have experienced a complex history of both fluid and thermal alteration. Unravelling the effects of these processes will be imperative for putting data from Hayabusa2 and OSIRIS-REx into geologic context.

OSIRIS-REx and the Mobile Asteroid Surface Scout (MASCOT) on board Hayabusa2 both carry thermal infrared (TIR) instruments: the OSIRIS-REx Thermal Emission Spectrometer (OTES) and the Mascot Radiometer (MARA). TIR spectra have many diagnostic spectral features associated with rock forming minerals, including fundamental vibrations and features related to the optical constants of the mineral [7]. Laboratory measurements in the TIR are generally made under ambient conditions; however previous work has shown that measuring under the appropriate near-surface asteroid conditions causes significant changes in spectral signature [8,9]. Therefore, in order to accurately compare between laboratory measurements and remote data collected from asteroids, it is critical to perform measurements under simulated asteroid environment conditions (SAE).

Here we present TIR emissivity measurements collected under SAE conditions, for a number of thermally metamorphosed CM2 and C2 chondrites. There have been limited studies of TIR spectra measured under SAE for carbonaceous chondrites [9], and none on thermally metamorphosed CM and CI chondrites, so this offers an opportunity to investigate the similarity of the spectral signatures of Bennu and Ryugu with new samples.

Samples: Nakamura [3] defined a heating scale for thermally metamorphosed CM and CI chondrites, from stage I to stage IV. Stage I samples have been heated to peak temperatures of <250^{o} C, and show little to no dehydration of hydrous phases. Here we investigated MacAlpine Hills (MAC) 87300, an ungrouped C2 chondrite, which has been suggested to be a stage I sample, but shows CM and CO affinities [3,10]. Stage II samples have been heated to temperatures of 300 – 500^{o} C, and are mostly composed of a highly disordered phase thought to be dehydrated phyllosilicates. We investigated the stage II CM2 Elephant Moraine (EET) 92069, and the anomalous CM Wisconsin Range (WIS) 91600 [4,11]. We also investigated the CM2 chondrites Pecora Escarpment (PCA) 02010 and PCA 02012, which are stage IV samples [12]. These have been heated to >750^{o} C and most hydrated silicates have re-crystallised back into anhydrous phases such as olivine and Fe-metal.

Experimental: TIR emissivity measurements were made in the Planetary Analogue Surface Chamber for Asteroid and Lunar Environments (PASCALE) within the Planetary Spectroscopy Facility at the University of Oxford. Under SAE conditions, the near-surface environment of an airless body is simulated by removing atmospheric gases so measurements are completed under vacuum (<10^{-4} mbar), cooling the interior of the chamber to <-150^{o} C using liquid N_2 and heating samples from above and below until the maximum brightness temperature of the sample is ~75^{o} C. This induces a thermal gradient in the upper hundreds of microns of the sample, which is what we would expect on the surface of Bennu near local midday [13]. Spectra were collected using a Bruker VERTEX 70v Fourier Transform Infrared (FTIR) spectrometer from 1800 – 200 cm^{-1} (5.5 – 50 µm) at a resolution of 4 cm^{-1}.

The bulk mineralogy of each sample was determined using position sensitive detector – X-ray diffraction (PSD-XRD), which can directly detect all crystalline phases and can observe the presence of non-crystalline phases. We used an INEL X-ray diffractometer with a curved 120^{o} detector in static geometry relative to the X-ray beam and sample, which was rotated throughout. Samples were measured for 16 hours and mineral standards for 30 minutes. Phase quantification involved a profile-stripping method [14].

Results & Discussion: Figure 1 shows the SAE emissivity spectra. There are clear spectral differences between samples that have been heated to different peak metamorphic temperatures. Spectra have been colour coded with the samples' heating stage (dark blue: stage I, green: stage II and red: stage IV).

1800 – 1300 cm^{-1}: In the spectra of the unheated Murchison meteorite we see broad features between 1650 – 1400 cm^{-1} caused by fundamental vibrations of phyllosilicates [9]. The crystalline structure of these hydrated phases becomes disordered upon heating and these features are no longer observable in spectra. This is the case for MAC 87300 and EET 96029, suggesting they have experienced enough heating to dehydrate and disorder the phyllosilicates. This observation is supported by an absence of peaks from crystalline phyllosilicates in the XRD patterns of these two meteorites. The lack of features in the spectra and XRD pattern of MAC 87300 suggest that it was heated to a higher temperature than previously estimated [15].

WIS 91600 shows a broad feature between 1550 – 1410 cm^{-1}. We see features in the XRD pattern of this sample which are indicative of crystalline phyllosilicates (also observed by [4]), suggesting thermal metamorphism did not fully dehydrate the phyllosilicates. We attribute the TIR feature to the presence of partially dehydrated phyllosilicates, and suggest that WIS 91600 was heated to the lower end of the stage II temperature range (~300^{o} C).

PCA 02010 and PCA 02012 show a doublet feature at 1770 cm^{-1} and 1640 cm^{-1} and a steep spectral contrast. These features correspond well with spectra of olivine standards and poorly crystalline and/or fine-grained olivine that recrystallised from phyllosilicates is observed in the XRD patterns of these IV samples.

1300 – 900 cm^{-1}: MAC 87300, EET 96029, PCA 02010 and PCA 02012 show a double feature in this region, at ~1160 cm^{-1} and ~1040 cm^{-1}. Previous measurements of Murchison show a similar doublet feature in the same location [9]. Spectra of phyllosilicate and anhydrous silicate standards both show a feature near ~1160 cm^{-1}, so it is difficult to uniquely distinguish them [16]. The feature at 1040 cm^{-1}, however, corresponds only to phyllosilicates. Its presence in even the most extensively heated samples suggests that this feature is not related to the crystalline structure of the phyllosilicates and can therefore be used to identify dehydrated phyllosilicates. This region can be used in conjunction with the 1800 – 1300 cm^{-1} region to confirm *post* aqueous alteration thermal metamorphism.

WIS 91600 only has a single feature near ~1070 cm^{-1}. There is evidence this sample experienced a different aqueous alteration history to the CMs and likely contains phyllosilicates with different compositions [17]. Further comparisons to known spectral standards will determine the causes of this unique spectrum.

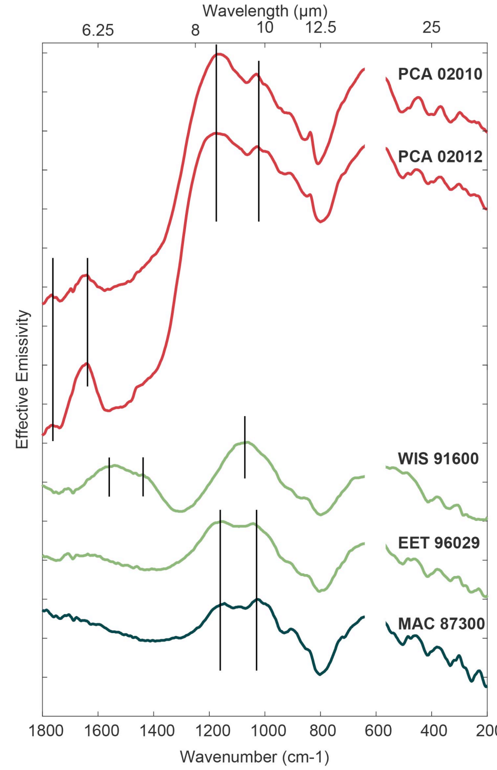

Figure 1: Emissivity spectra for the thermally metamorphosed CM and C2 chondrites. Data are normalized to unity at the point of maximum emissivity and offset for clarity. Samples are ordered with increasing thermal metamorphism from bottom to top. Features of interest are indicated with vertical lines, see text for details.

Conclusions: We show that TIR spectra can be used to identify regions of thermal metamorphism on Ryugu and Bennu, which will be invaluable when interpreting Hayabusa2 and OSIRIS-REx data. Future measurements on additional aqueously and thermally altered chondrites will investigate spectral features that could help in unravelling the complex history of processing on C-complex asteroids.

References: [1] DeMeo,F.E. et al. (2009) *Icarus*, *202*, 16 [2] Burbine,T.H. et al. (2002) *Asteroids III, 653* [3] Nakamura,T. (2005) *JMPS,100* [4] Tonui,E.K. et al. (2014) *GCA,126,*284 [5] Hiroi,T. et al. (1993) *Science,261,*1016 [6] Perna,D. et al. (2017) *A&A,599* [7] Salisbury,J.W. (1993) *Cam.Uni.Press,79* [8] Donaldson Hanna,K.L. et al., (2012) *JGR,117* [9] Donaldson Hanna,K.L. et al. (2019) *Icarus, 319,*701 [10] Russell,S.S. et al. (1995) *Meteoritics, 30,*569 [11] Lee,M.R. et al. (2016) *GCA, 187,*237 [12] Alexander, C.M.O'D. et al. (2013) *GCA,123,*244 [13] Hergenrother, C.W. et al. (2014) *arXiv:1409.4704* [14] Cressey,G. et al. (1996) *Powder Diffraction,11,*35 [15] Zolensky,M et al. (1993) *GCA,57*, 3123 [16] Baldridge,A.M. et al. (2009) *Remote Sensing of Environment,113,*711 [17] Yabuta,H et al. (2010) *MAPS,45,*1446.