TIR SPECTRAL SIGNATURE OF AQUEOUSLY AND THERMALLY METMORPHOSED CM AND CY CHONDRITES. H. C. Bates[1,2], K. L. Donaldson Hanna[3], 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. [3]Department of Physics, University of Central Florida, Orlando, Florida, USA, 32816.

Introduction: JAXA's Hayabusa2 will return samples from the C-type asteroid Ryugu in 2020 [1] and NASA's OSIRIS-REx will return samples from the B-type asteroid Bennu in 2023 [2]. Preliminary observations suggest a complex alteration history on both bodies: Hayabusa2 identified hydrated minerals on the surface of Ryugu, but also found evidence for dehydration [3]. Observations by OSIRIS-REx found hydrated minerals similar to highly aqueously altered CM and CI chondrites on Bennu [4].

In order to interpret the results from Hayabusa2 and OSIRIS-REx we need to analyse appropriate meteorite analogues. To that end we have collected thermal infrared (TIR) spectra for a suite of aqueously and thermally altered CM and CI chondrites. There have been few spectral measurements for meteorites under appropriate near-surface asteroid conditions, which are known to cause changes in spectral signature [5,6]. It is therefore critical to perform measurements under simulated asteroid environment conditions (SAE) in order to accurately compare between laboratory measurements and remote observations of asteroids. Here we present TIR emissivity measurements collected under SAE conditions, for a number of aqueously and thermally metamorphosed CM, CY and C2-ung chondrites.

Samples: We investigated three unheated CM chondrites: Alan Hills (ALH) 83100 (CM1/2), ALH 83102 (CM1/2) and Lonewolf Nunataks (LON) 94101 (CM2). We also analysed the heated chondrites (heating stages after [7]) Elephant Moraine (EET) 92069 (CM2, Stage II, 300 – 500 ^{o}C), Wisconsin Range (WIS) 91600 (CM-an, Stage II), Yamato (Y-) 793321 (CM2, Stage II) [9,10,11], Pecora Escarpment (PCA) 02010 and PCA 02012 (paired CM2s, Stage IV, >750 ^{o}C) [12], and the CY chondrites Yamato (Y-) 980115 (Stage III, 500 – 750 ^{o}C), Y-86789, Y-86789, and Belgica (B-) 7904 (all Stage IV) [13].

Experimental: Samples were ground to a powder with a particle size of <35 µm. TIR emissivity measurements were collected in the Planetary Analogue Surface Chamber for Asteroid and Lunar Environments (PASCALE) at University of Oxford. The near-surface environment of Bennu was simulated by removing atmospheric gases ($<10^{-4}$ mbar), cooling the interior of the chamber to <-150^{o} C 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 [14]. Spectra were collected using a Bruker VERTEX 70v Fourier Transform Infrared (FTIR) spectrometer from 1800 – 200 cm^{-1} (5.5–50 µm) using a wide range beam splitter at a resolution of 4 cm^{-1}.

Spectral features in thermally metamorphosed CM chondrites: Figure 1 shows the TIR spectra for representative unheated (blue), Stage II (green) and Stage IV (red) CM chondrites. PCA 02010 and ALH 83102 show very similar spectral signatures to PCA 20102 and ALH 83100 respectively, and so are not included in the figure. In the unheated sample spectra we see vibrational features caused by –OH and H_2O in the phyllosilicates between 1800–1300 cm^{-1}. These spectra also show a sharp emissivity peak (also known as a Christensen Feature or CF) near 1100 cm^{-1}, a transparency feature (TF) near 870 cm^{-1} and reststrahlen bands (RB) near 1015 cm^{-1}, 430 cm^{-1} and 275 cm^{-1}. These features are consistent with those observed in phyllosilicate spectra [5,14].

The Stage II sample spectra show a decrease in spectral slope between 1800–1300 cm^{-1}, and smaller –OH/H_2O vibrational features relative to those seen in the unheated CM spectra. These spectra have a broader emissivity plateau between 1300–900 cm^{-1}, and a TF at shorter wavenumbers compared to the unheated CM spectra near 800 cm^{-1}. The spectra show RB near 920 cm^{-1} and between 600–200 cm^{-1} that correspond with Mg-rich forsteritic olivine [16]. This is consistent with EET 96029 and Y-793321 containing ~12 vol% primary Mg-rich olivine having experienced a low degree of aqueous alteration prior to thermal metamorphism [10,11]. The abundance of primary olivine seems to be the main control on the observed TIR spectral features. The Stage II sample spectra also show a feature at 850–870 cm^{-1}, which is consistent with these meteorites containing ~14 vol% pyroxene [17].

The Stage IV PCA 02012 and PCA 02010 spectra show some similarities with the Stage II spectra including a TF at ~800 cm^{-1}, RB near 920 cm^{-1} and 870 cm^{-1} (both contain ~14 vol% pyroxene), and the same features between 600–200 cm^{-1}. They do, however, have much steeper spectral slopes between 1800–1300 cm^{-1}, overtone Si-O vibrational features near 1765 cm^{-1} and 1645 cm^{-1}, and a RB at 1060 cm^{-1}, which can all be attributed to olivine. Spectral contrast for all features is stronger than in the Stage II spectra. These differences are consistent with PCA 02012 and PCA 02010 containing a higher abundance (~20 vol%) of primary Mg-rich olivine. In contrast, the presence (~30 vol%) of secondary, poorly crystalline Fe-rich olivine in the Stage IV CMs does not have a strong effect on the spectra.

Spectral features in the CY and CM-an chondrites: Figure 1 also shows the TIR spectra for WIS 91600, Y-980115, B-7904 and Y-86789. The Y-86720 spectrum is similar to that of Y-86789 and is not shown. The WIS 91600 spectrum shows a broad emissivity peak between 1800–1300 cm^{-1}, which could be a result of its poorly crystalline, dehydrated phyllosilicate component (~70 vol%) [9,18]. The spectrum also shows an emissivity peak near 1080 cm^{-1}, a RB near 870 cm^{-1}, a TF near 800 cm^{-1}, plus features near 410 cm^{-1} and 285 cm^{-1} that are likely due to Mg-rich olivine (~11 vol%), although the spectral contrast in this region is low. The WIS 91600 spectrum also has a RB feature at 340 cm^{-1}, which can be attributed to its unusually high magnetite abundance of ~10 vol% [19]. This feature has been identified in Bennu spectra suggesting magnetite is present on its surface [4].

Y-980115 has a similar spectral signature to WIS 91600, which could be because of its high ratio of poorly crystalline/crystalline silicates [13]. The Stage IV Y-86789 spectrum shows Si-O overtone features between 1800–1300 cm^{-1}, a complex emissivity plateau between 1250–850 cm^{-1}, a TF at 800 cm^{-1}, and RB between 600–200 cm^{-1}. The spectral signature of Y-86789 is likely a result of its high olivine content (63 vol% [13]). The difference in shape compared to the Stage IV CM spectra in the 1250–850 cm^{-1} and 600–200 cm^{-1} ranges may be related to the Stage IV CYs containing only secondary, poorly crystalline Fe-rich olivine and no primary Mg-rich olivine. B-7904 does contain some primary Mg-rich olivine, potentially explaining the subtle differences between its spectrum and the other CY spectra, and its similarity to the PCA 02010 and PCA 02012 spectra between 600–200 cm^{-1}. Differences between B-7904's spectrum, and the CM chondrite spectra in other spectral ranges may be due to its recrystallized olivine content being much higher than the Stage IV CM samples (61 vol% [13] compared to ~27 vol%).

Conclusions: The TIR spectral signature in CM chondrites is controlled by the primary, Mg-rich olivine content, which in turn is determined by the degree of aqueous alteration. Samples which have experienced less aqueous alteration show overtone and vibrational bands associated with forsteritic olivine throughout the whole spectral range. Due to the absence of this primary olivine phase in the CYs, their spectra seem to reflect the secondary, poorly crystalline Fe-rich olivine. It is therefore difficult to determine whether thermal metamorphism has occurred from TIR spectral signature alone, unless high degrees of aqueous alteration occurred. Additionally, spectral features due to magnetite are identifiable when abundances are ~10 vol%, and as these features have been detected in the Bennu spectrum, this implies comparable abundances on its surface.

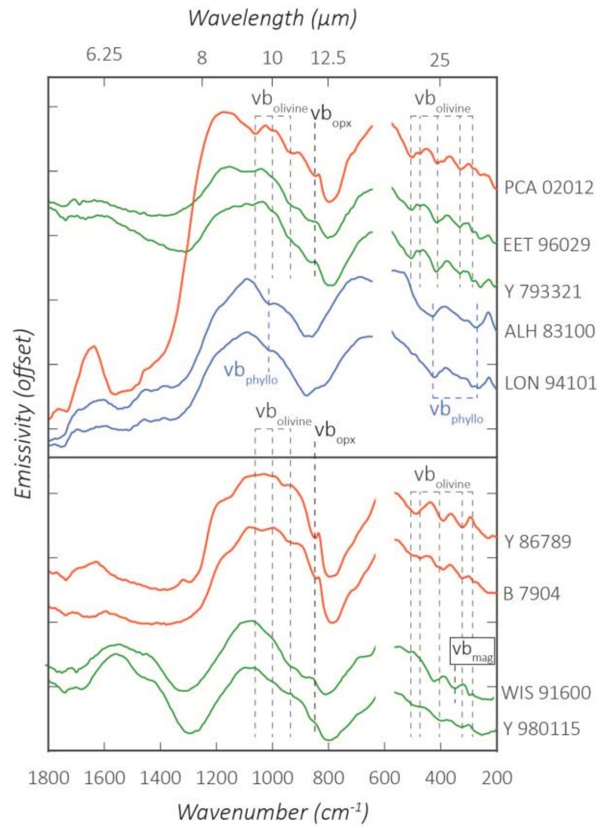

Fig. 1: TIR spectra for representative unheated (blue), Stage II (green) and Stage IV (red) CM, CY and C2-ung chondrites. Lines represent vibrational features for olivine and pyroxene relative to PCA 02012, phyllosilicate vibrational bands relative to the unheated CM chondrites, and the magnetite vibrational band in WIS 91600.

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