

# Thermal Infrared Spectra of Heated CM and C2 Chondrites and Implications for Asteroid Sample Return Missions

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**Introduction:** JAXA's Hayabusa2 arrived at its target asteroid, the C-type asteroid Ryugu, in June 2018 and NASA's Origins, Spectral Interpretation, Resource Identification and Security Regolith Explorer (OSIRIS-REx) is on its approach to its target, the B-type asteroid Bennu, with arrival due in December 2018. The C- and B-type asteroids are part of the larger C-complex class [1,2], which have been linked to carbonaceous chondrite meteorites, in particular the aqueously altered CM and CI chondrites [3–5]. These meteorites are rich in organics and water, and are considered 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 [6,7]. Previous work has suggested that thermally metamorphosed CM and CI chondrites could be good analogues for the C- and B-type asteroids [8–10] including Ryugu [11,12]. The surfaces of C-complex asteroids might contain a mixture of hydrated and dehydrated materials having 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 in order to determine surface mineralogy, the OSIRIS-REx thermal emission spectrometer (OTES) and the Mascot Radiometer (MARA). TIR spectra have many diagnostic spectral features associated with rock forming minerals [13]. These include the Christiansen feature (CF), between 7.5 – 9  $\mu\text{m}$ , which is an emissivity maximum diagnostic of composition [13], the reststrahlen bands (RB), which are the fundamental vibrations of silicate minerals between 8 – 12  $\mu\text{m}$  and 15 – 25  $\mu\text{m}$ , and the transparency feature (TF), which is an emissivity minima between 11 – 13  $\mu\text{m}$  caused by volume scattering in optically thin minerals [13]. 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 shifts in the position of the CF, and increases the spectral contrast between the CF and RBs [14–16]. Therefore, in order to accurately compare between laboratory measurements and data collected from asteroids, it is critical to perform measurements under simulated asteroid environment conditions (SAE).

Here we present TIR emissivity measurements, collected under ambient and SAE conditions, for a number of thermally metamorphosed CM and C2 chondrites. These SAE measurements should be more directly comparable to observations by OSIRIS-REx and Hayabusa2. There have been limited studies of TIR spectra measured under SAE for carbonaceous chondrites [16], and none on thermally metamorphosed CM and CI chondrites, so this offers a new opportunity to investigate the spectral signatures of Bennu and Ryugu.

**Samples:** Nakamura (2005) 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 metamorphic temperatures of <250  $^{\circ}\text{C}$ , and show little to no dehydration of hydrous phases. Here we have investigated the sample MacAlpine Hills (MAC) 87300, an ungrouped C2 chondrite which previous work has suggested is a stage I sample, but shows CM and CO affinities [6,17]. Stage II samples have been heated to temperatures of 300 – 500  $^{\circ}\text{C}$ , and are mostly composed of a highly disordered phase thought to be dehydrated phyllosilicates. We investigated the CM2 Elephant Moraine (EET) 92069, and the anomalous CM chondrite Wisconsin Range (WIS) 91600, both of which have been suggested to be stage II samples [7,18]. We did not study any stage III samples, which have been heated to temperatures of 500 – 750  $^{\circ}\text{C}$  and show some recrystallization of anhydrous phases, but we did investigate the CM2 chondrites Pecora Escarpment (PCA) 02010 and PCA 02012, which are stage IV samples [19]. Stage IV samples have been heated to >750  $^{\circ}\text{C}$  and have experienced widespread recrystallization of anhydrous phases such as olivine and metal.

**Experimental:** TIR emissivity measurements were made under ambient and SAE conditions in the Planetary Analogue Surface Chamber for Asteroid and Lunar Environments (PASCALE) within the Planetary Spectroscopy Facility at the University of Oxford [16]. Under ambient conditions the sample was heated from below to  $\sim 80$   $^{\circ}\text{C}$  whilst the chamber was held at an ambient pressure ( $\sim 1000$  mbar  $\text{N}_2$ ) and temperature ( $\sim 28$   $^{\circ}\text{C}$ ). Under SAE conditions, the near surface environment of Bennu is simulated by removing atmospheric gases from the chamber so measurements are completed under vacuum ( $<10^{-4}$  mbar), cooling the interior of the chamber to  $<-150$   $^{\circ}\text{C}$  using liquid  $\text{N}_2$  and heating the samples from above and below until the maximum brightness temperature of the sample is  $\sim 75$   $^{\circ}\text{C}$ . 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. Spectra were collected using a Bruker VERTEX 70v Fourier Transform Infrared (FTIR) spectrometer at a resolution of  $4\text{ cm}^{-1}$  from  $1800 - 200\text{ cm}^{-1}$  ( $5.5 - 50\text{ }\mu\text{m}$ ).

**Results:** Emissivity spectra are presented in Figure 1. The stage IV PCA 02010 and PCA 02012 samples are spectrally similar with the main diagnostic features located at similar wavelengths, and show a feature near  $6\text{ }\mu\text{m}$ , which is not present in the stage II samples. This could indicate it is representative of the higher abundances of anhydrous phases in the stage IV samples. The spectra show a steep spectral contrast leading up to the CFs, which are identified near  $8.5\text{ }\mu\text{m}$ , and emissivity maxima near  $9.7\text{ }\mu\text{m}$ . The TFs for the stage IV samples are identified near  $12.5\text{ }\mu\text{m}$ .

The spectral shapes of EET 96029 and MAC 87300 are also similar to each other, with CFs identified near  $8.7\text{ }\mu\text{m}$  with additional emissivity maxima near  $9.7\text{ }\mu\text{m}$ , and TFs at  $12.5\text{ }\mu\text{m}$ . The similarity between EET 96029 and MAC 87300 requires further investigation, as they not only are classified differently, but also have different thermal histories.

The spectrum of WIS 91600 is different from the other meteorites investigated here. It has a broad emissivity maximum centred near  $6.5\text{ }\mu\text{m}$  followed by an emissivity minima, and a CF near  $9.4\text{ }\mu\text{m}$ . The CF at longer wavelengths suggests it is dominated by a different mineralogy in comparison to the other meteorites investigated here. Its TF is identified at similar wavelengths to the other samples near  $12.5\text{ }\mu\text{m}$ . The spectra suggests WIS 91600 has a distinct mineralogy when compared with the other stage II samples, and further investigation into its composition is required to determine which mineralogy is dominating the spectra.

There are clear spectral differences between samples that have been heated to different peak metamorphic temperatures. In order to better investigate these differences, exact mineralogy for each sample is necessary, so specific features can be tied to known compositions. Position-sensitive detector X-ray diffraction (PSD-XRD) is a method that has been used to determine modal mineralogy for a number of CI, CM, CV and CR chondrites [20–24]. It is able to directly detect all crystalline phases, and additionally investigate the presence of non-crystalline phases. Further studies are planned to obtain the PSD-XRD patterns for the exact samples used in this study, so modal mineralogy can be established and linked with our lab spectral measurements.

## References

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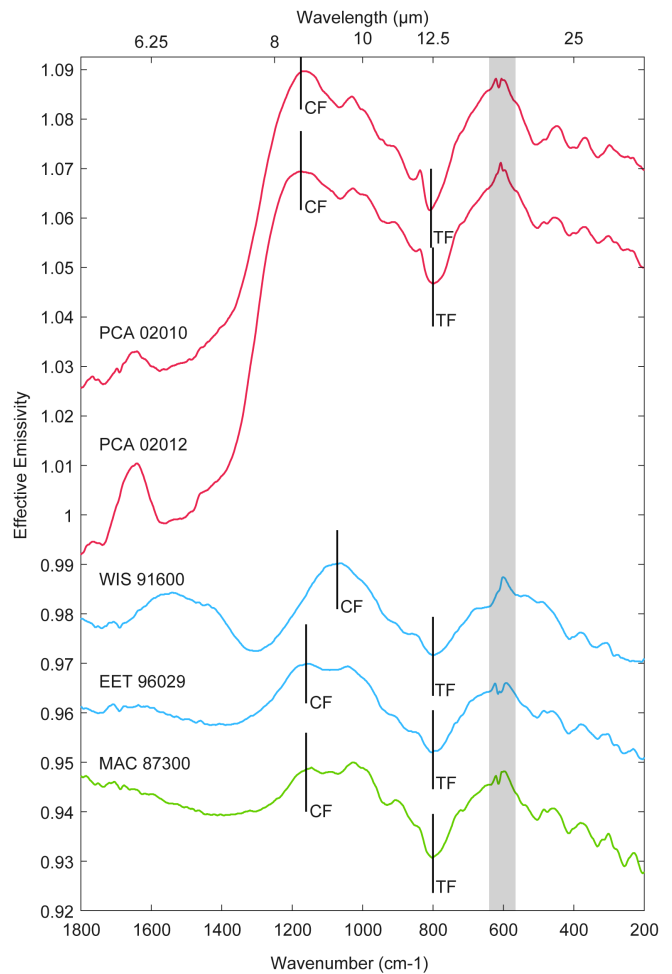


Figure 1: Emissivity spectra for the thermally metamorphosed CM and ungrouped chondrites investigated here. Green spectra are stage I, blue spectra are the stage II samples and red spectra are the stage IV samples. Data are normalized to unity and offset for clarity. The positions of the CF and TF are indicated. The grey box near  $600\text{ cm}^{-1}$  indicates noise related to poor signal-to-noise resulting from the beam splitter.