SPECTROSCOPIC CHARACTERISATION OF PRIMITIVE CO3 CARBONACEOUS CHONDRITES

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Introduction: Primitive CO3 carbonaceous chondrite meteorites provide a detailed record of the geological processes and events that have shaped our solar system over the last 4.5 billion years. They contain a fine-grained (≤ 1 µm) matrix (> 50 vol%) of amorphous and crystalline silicates, oxides, sulphides and metals that have remained largely unaltered since the time they accreted into an asteroid [1].

The reflectance spectra of CO carbonaceous chondrites have linked them to the rare K-type asteroids [2, 3]. However, their low albedos also suggest a possible relationship to the dark C-complex asteroids, which may have played a role in delivering volatile and organic species to the terrestrial planet-forming region of the protoplanetary disk [4]. The Dawn mission provided detailed characterization of the C-type dwarf planet Ceres, and in the last few months OSIRIS-REx successfully sampled the B-type asteroid Bennu, while Hayabusa2 returned ~5.4 g of material from the Cg-type asteroid Ryugu back to Earth. Many C-complex asteroids closely resemble the CI and CM carbonaceous chondrites, which contain abundant (>70 vol%) hydrated silicates. Nevertheless, there is evidence that the surfaces of Ryugu and Bennu are heterogeneous [5, 6] and may contain regions of anhydrous silicates similar to those found in the CO chondrites. A possible genetic link between the CO and CM chondrites is hinted at by similarities in isotopic and elemental compositions [1]. It has therefore become important to characterise the spectral properties of CO chondrites so we can identify features associated with their mineralogical composition in the remote observations of primitive C-complex asteroids.

Cloutis et al. [3] reviewed visible and near-infrared (IR) reflectance spectra for CO chondrites of petrologic subtype from 3.0 to 3.6. They reported a ubiquitous olivine feature at ~1 µm, which is related to the Fe^{2+} content in olivine. They also found that thermal metamorphism led to an overall increase in the reflectance and a bluing of the spectra (i.e. decrease in reflectance with increasing wavelength). McAdam et al. [7] presented visible, near- and mid-IR spectra of well characterised CO chondrite samples but largely focused their efforts on the primitive subtype 3.0's. They found that the least processed COs have characteristic features at 1.4 µm and 21 µm related to the amorphous Fe-bearing silicates in the matrix. Here, we present visible, near- and mid-IR reflectance spectra for CO chondrite powders across the entire petrologic range (3.0 – 3.8). The bulk modal mineralogy and Fe-oxidation states of the powders have previously been characterized [8], allowing us to directly link spectral features to compositions.

Methodology: Spectra from a suite of 12 CO3 chondrite powders (~50 mg and grainsize ≤ 25 µm) from petrologic subtype 3.0 to 3.8 were collected at the Planetary Emissivity Laboratory at the Institute of Planetary Research, German Aerospace Center (DLR). We collected visible, near- and mid-IR reflectance spectra on powders that have been previously characterised using X-ray diffraction (XRD) and Mössbauer spectroscopy. Spectra of each CO were acquired from 0.4–25 µm at different phase angles (15°, 30°, 45° and 60°) using a bi-directional reflectance setup with a Bruker Vertex 80V FTIR instrument. The powders were not heated prior to analysis but spectra were collected under vacuum.

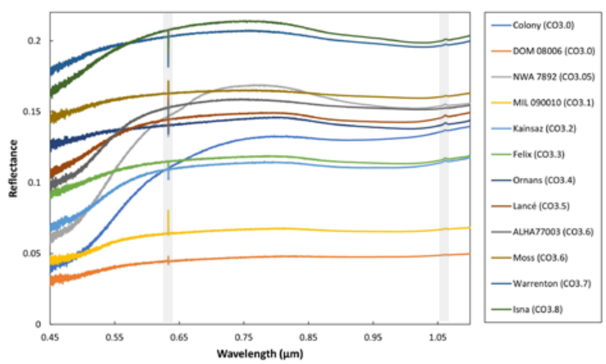

Figure 1. *Visible and near-IR spectra of the CO chondrites showing the variations in slope and a broad feature near ~ 1.05 µm. Instrument artifacts are highlighted in grey.*

Results: Fig. 1 shows that the visible and near-IR spectra of the CO chondrites are generally featureless, although there are clear variations in the overall slope (0.65 / 0.45 µm reflectance ratio), with Colony (CO3.0) and NWA 7892 (CO3.05) having the steepest slopes. The "flattest" spectra are observed for the more thermally metamorphosed falls Ornans (CO3.4), Moss (CO3.6), and Warrenton (CO3.7). Moreover, a feature at ~ 1.05 µm is observed in the spectra of all samples (Fig. 1). We also observe differences in the intensity of the 3 µm band depth. The deepest 3 µm bands are seen for Colony, NWA 7892, and ALHA77003 (CO3.6). DOM 08006, MIL 090010 (CO3.1), Kainsaz (CO3.2), Lancé (CO3.5), and Isna (3.8) have intermediate band depths, whereas the feature is weakest for Felix (CO3.3), Ornans, Moss, and Warrenton (Fig. 2).

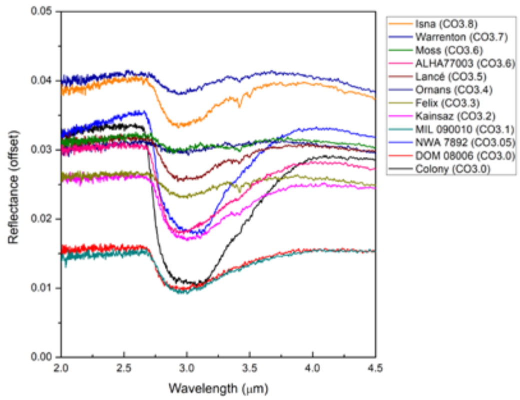

Figure 2. *3 μm band for CO chondrites of petrologic types 3.0 to 3.8.*

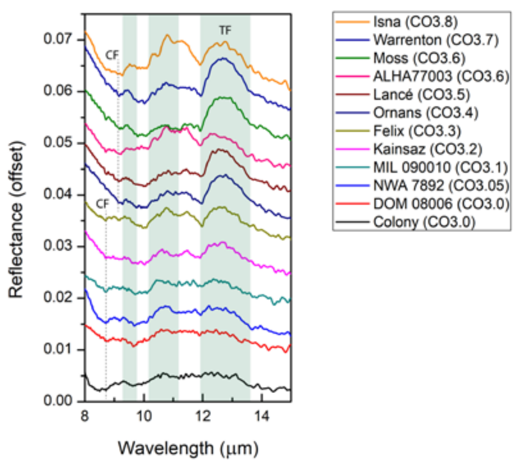

Figure 2. *Mid-IR spectral reflectance features of CO chondrites. Highlighted are the Christiansen Feature (CF), the Si-O stretching features and the Transparency Feature (TF).*

In the mid-IR there are strong features from silicates (Fig. 3). The Christiansen Feature (CF) is located at ~8.7 μm for CO3.0 to CO3.3 chondrites and shifts to ~9.2 μm for the CO3.4–3.8 meteorites. Si – O stretching features are recognisable in the regions 9.27 – 9.82 μm and 10.1 – 11.1 μm, while the Transparency Feature (TF) is in the range 11.9 – 13.9 μm (Fig. 3).

Discussion: Variations in the spectral slope observed in the visible and near-IR regions of the CO chondrites can be related to a combination of parent body thermal metamorphism and terrestrial weathering**.** The steepest slopes are observed for Colony and NWA 7892, which were both recovered from hot desert environments. The spectrum of the Antarctic find ALHA77003 also has a steep slope, and these three meteorites have the deepest 3 μm bands, likely due to the presence of terrestrial –OH/H_2O-bearing phases. For example, our XRD analyses indicated that Colony contains ~5 vol% in Fe-(oxy)-hydroxides.

Felix, Ornans, Moss and Warrenton have the shallowest 3 μm features and some of the flattest spectra in the visible (Fig. 1). These four meteorites are all observed falls, and therefore their shallow 3 μm feature is likely reflecting OH/H_2O related features.They also show increasing overall reflectance with increasing thermal metamorphism, as it was also reported by Cloutis et al [3].

DOM 08006 and MIL 090010 are characterised by the lowest reflectance, flat slopes (Fig. 1), and 3 μm features with intermediate depth (Fig. 2), which is likely related to the oxidised nature of the amorphous silicates characterising the matrix of primitive these samples [10]. Moreover, the olivine feature at ~1.05 μm described also by Cloutis et al [3] show some variation in relation to thermal metamorphism.

In the mid-IR (Fig. 3), the effects of weathering are likely less significant, with the features related to the silicate mineralogy, which are influenced by parent body metamorphism [3, 7]. The spectral contrast of vibrational bands increases with increasing petrologic subtype (Fig. 3). These changes are related to variations in sample mineralogy with increasing petrologic subtype as olivine and pyroxene abundances increase from 30 to 50 vol% and from 25 to 35 vol%, respectively. Increase in the olivine and pyroxene abundance is consequence of the crystallization of the Fe-bearing amorphous silicates thermal metamorphism. Olivine features become more defined as was seen by McAdam et al. [7], and the CF shifts as the olivine changes its composition towards richer Fe^{2+} members [11].

Spectra from Bennu are dominated by vibrational features associated with phyllosilicates [11] (similar to what is observed in CM chondrite spectra) but the spectra in this study should help identify regions where anhydrous silicates are dominant on the asteroid surface.

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References: [1] Weisberg, M. K. et al. (2006) *MESS II 19–52*. [2] Burbine et al. (2001) *M&PS 36:245* [3] Cloutis et al. (2012) *Icarus* 220:466. [4] Alexander et al. (2012) *Science* 337:721 [5] Tatsumi (2020) *Nat.Astron.* [6] DellaGiustina et al. (2020) *Nat.Astron.)*.[7] McAdam et al. (2018) *Icarus 306:32*. [8] Bonato et al. (2016) *M&PS 51:A172*. [9] Bates et al. (2020) *M&PS 55:77*. [10] Bonato et al. (2018) *49th LPSC #1917*. [11] Hamilton et al. (2019) *Nat Astron. 3:332*.