



## Spectral reflectance “deconstruction” of the Murchison CM2 carbonaceous chondrite and implications for spectroscopic investigations of dark asteroids

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### ARTICLE INFO

#### Article history:

Received 18 September 2017

Revised 5 January 2018

Accepted 10 January 2018

Available online 4 February 2018

#### Keywords:

Meteorites

Spectroscopy

Regoliths

### ABSTRACT

Carbonaceous chondrites (CCs) are important materials for understanding the early evolution of the solar system and delivery of volatiles and organic material to the early Earth. Presumed CC-like asteroids are also the targets of two current sample return missions: OSIRIS-REX to asteroid Bennu and Hayabusa-2 to asteroid Ryugu, and the Dawn orbital mission at asteroid Ceres. To improve our ability to identify and characterize CM2 CC-type parent bodies, we have examined how factors such as particle size, particle packing, and viewing geometry affect reflectance spectra of the Murchison CM2 CC. The derived relationships have implications for disc-resolved examinations of dark asteroids and sampleability. It has been found that reflectance spectra of slabs are more blue-sloped (reflectance decreasing toward longer wavelengths as measured by the 1.8/0.6 $\mu$ m reflectance ratio), and generally darker, than powdered sample spectra. Decreasing the maximum grain size of a powdered sample results in progressively brighter and more red-sloped spectra. Decreasing the average grain size of a powdered sample results in a decrease in diagnostic absorption band depths, and redder and brighter spectra. Decreasing porosity of powders and variations in surface texture result in spectral changes that may be different as a function of viewing geometry. Increasing thickness of loose dust on a denser powdered substrate leads to a decrease in absorption band depths. Changes in viewing geometry lead to different changes in spectral metrics depending on whether the spectra are acquired in backscatter or forward-scatter geometries. In backscattered geometry, increasing phase angle leads to an initial increase and then decrease in spectral slope, and a general decrease in visible region reflectance and absorption band depths, and frequent decreases in absorption band minima positions. In forward scattering geometry, increasing phase angle leads to small non-systematic changes in spectral slope, and general decreases in visible region reflectance, and absorption band depths. The highest albedos and larger band depths are generally seen in the lowest phase angle backscattering geometry spectra. The reddest spectra are generally seen in the lowest phase angle backscatter geometry spectra. For the same phase angle, spectra acquired in forward scatter geometry

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<https://doi.org/10.1016/j.icarus.2018.01.015>

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are generally redder and darker and have shallower absorption bands than those acquired in backscatter geometry. Overall, backscatter geometry-acquired spectra are flatter, brighter, and have deeper 0.7  $\mu\text{m}$  region absorption band depths than forward scatter geometry-acquired spectra. It was also found that the 0.7, 0.9, and 1.1  $\mu\text{m}$  absorption bands in Murchison spectra, which are attributable to various Fe electronic processes, are ubiquitous and can be used to recognize CM2 chondrites regardless of the physical properties of the meteorite and viewing geometry.

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## 1. Introduction

Carbonaceous chondrites (CCs) are among the most useful meteorites for addressing issues related to the formation, history, and dynamics of the early solar system, the delivery and distribution of water in the solar system, and prebiotic chemistry relevant to the origin and evolution of life on Earth. A major driver of spectral reflectance studies of CCs is for establishing linkages between CCs and specific parent bodies. The importance of this is underscored by the fact that potential CC asteroidal parent bodies are the targets of two current sample return missions: OSIRIS-REx to asteroid (101955) Bennu (1999 RQ<sub>36</sub>) (Lauretta, 2015), and Hayabusa-2 to asteroid (162173) Ryugu (1999 JU<sub>3</sub>) (Tsuda et al., 2013). Determining the surface mineralogy and physical properties of the dark asteroids targeted for sample return prior to the encounters can help to select sampling sites of highest scientific value and sampleability, as well as understand the evolution of these bodies (e.g., whether they are rubble piles or intact fragments).

Available Earth-based spectroscopic data for both Bennu and Ryugu are uncertain in terms of their mineralogies and whether spectrally diagnostic features may be present. For instance, 0.4–2.5  $\mu\text{m}$  telescopic spectra of Bennu appear to lack absorption features (Binzel et al., 2002, 2015; Clark et al., 2011); however weak absorption bands are allowed by the signal-to-noise ratio of the data. For asteroid Ryugu, most of the observational data suggest that it is spectrally featureless, although some reflectance spectra show weak, and sometimes persistent, minor absorption bands (Binzel et al., 2002; Lazzaro et al., 2013; Moskovitz et al., 2013), and one set of observations suggest the presence of absorption features that are consistent with CM2 chondrites (Vilas, 2008).

Spectroscopic properties of CCs are also important for understanding the nature of dark materials on the surface of Vesta (e.g., McCord et al., 2012; Nathues et al., 2014) and the surface composition of asteroid Ceres (e.g., Chapman and Salisbury, 1973; McCord and Gaffey, 1974; Lebofsky, 1978; De Sanctis et al., 2015; Ammannito et al., 2016), both of which are primary targets of the Dawn spacecraft (Russell and Raymond, 2011). CM-type material has been invoked as a leading candidate for the dark material that is widespread on the surface of Vesta (Nathues et al., 2014; Palomba et al., 2014). This is consistent with the presence of CM-like xenoliths in HED meteorites that are presumed to originate from Vesta (Cloutis et al., 2011b, and references therein). In some howardites, the CM-like material can comprise the majority of the sample (e.g., PRA 04401: McCoy and Reynolds, 2007; Herrin et al., 2010, 2011).

In addition to dedicated spacecraft missions, dark, presumed carbonaceous, asteroids are also common and scientifically important targets for telescopic observations, including those in the main asteroid belt and in near-Earth space (e.g., Popescu et al., 2011; Izawa et al., 2015; Takir et al., 2015).

CM carbonaceous chondrites are the most common class of hydrated CCs, representing 1.5% of meteorite falls (carbonaceous chondrites represent < 4% of all falls; Norton, 2002). They generally exhibit different degrees of (probable) post-accretional aqueous alteration, with petrologic grades ranging from ~1 to ~3 (Grady

et al., 1987; McBride et al., 2002; Trigo-Rodríguez et al., 2006; Rubin et al., 2007; Righter, 2008; de Leuw et al., 2009). A number of CM-type meteorites also show evidence of post-aqueous thermal alteration (Cloutis et al., 2012b, and references therein). CM2 chondrites consist largely of ferromagnesian phyllosilicates, followed by anhydrous silicates (olivine, pyroxene), and minor components (present at the few percent level) that include magnetite, Fe-sulphides, Ca–Mg–Fe carbonates, and organic material (e.g., Brearley and Jones, 1998; Bland et al., 2004; Zolensky et al., 2008; Howard et al., 2009).

In addition to the CM2 meteorites being a well-defined group, CM2-type materials are common as xenolithic material in other types of meteorites, including ordinary chondrite breccias, howardites, lunar samples, and others (e.g., Buchanan et al., 1993; Zolensky et al., 1996; Gounelle et al., 2003).

Reflectance spectra of CM chondrites are characterized by a ubiquitous series of absorption features near 0.75, 0.9, and 1.1  $\mu\text{m}$ , that are attributable to phyllosilicate Fe<sup>2+</sup>–Fe<sup>3+</sup> charge transfers (0.75  $\mu\text{m}$  band) or Fe<sup>2+</sup> crystal field transitions (0.9 and 1.1  $\mu\text{m}$  bands) (Clark et al., 1990). For Fe<sup>2+</sup>Fe<sup>3+</sup>-bearing phyllosilicates, the 0.9 and 1.1  $\mu\text{m}$  bands will appear together (Cloutis et al., 2011b). Phyllosilicates, primarily Fe-bearing serpentine and cronstedtite (an Fe<sup>3+</sup>–Fe<sup>2+</sup>-bearing phyllosilicate), are the most common phase in CMs, comprising ~65–85 vol%, and with serpentine/cronstedtite ratios varying between different CMs (Bland et al., 2004, 2008; Howard et al., 2008, 2009, 2010a, 2010b). Absorption bands attributable to these phases are seen in CM reflectance spectra, and hence are indicative and characteristic of these phases in hydrated CCs (such as CMs). In particular, the 0.7  $\mu\text{m}$  absorption feature appears to be nearly exclusively confined to CM chondrites (Cloutis et al., 2011b). CM-type chondrites that have been subsequently thermally metamorphosed (termed ATCCs: Aqueously altered and Thermally metamorphosed Carbonaceous Chondrites) may continue to exhibit these absorption features, albeit generally with their depths decreasing with increasing thermal metamorphism (Cloutis et al., 2012b).

Other hydrated CCs, such as CI1 chondrites, do not, or rarely, display such bands because their more pervasive aqueous alteration leads to the production of more Mg-rich phyllosilicates (Howard et al., 2010a, 2010b). In CI1 reflectance spectra, when the 0.7  $\mu\text{m}$  phyllosilicates band is present, it is usually located at shorter wavelengths (< 0.7  $\mu\text{m}$ ) than the corresponding absorption bands in CM2 chondrites (> 0.7  $\mu\text{m}$ ; Cloutis et al., 2011a). The cause of this difference is unknown, but likely relates to structural differences between the major phyllosilicates in CIs (saponite + serpentine) versus CMs (serpentine + cronstedtite) (Bland et al., 2004, 2008; Howard et al., 2009, 2010a, 2010b, 2015).

CR chondrites also include some hydrated members (Cloutis et al., 2012a) and their spectra rarely display the 0.75, 0.9, and 1.1  $\mu\text{m}$  absorption bands, either because of: (1) lower degrees of aqueous alteration (resulting in lower production of phyllosilicates) (Bland et al., 2008), or because their phyllosilicates may be more Mg-rich than those in CM2s, perhaps due to differences in pre-aqueous compositions between CRs and CMs (Noguchi, 1995). Other ungrouped, aqueously altered CCs, such as Tagish Lake (petrologic grade ~2) also do not exhibit these absorption bands,

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