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Toward an understanding of phyllosilicate mineralogy in the outer main asteroid belt

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ABSTRACT

Proposed mineralogical linkages between CM/CI carbonaceous chondrites and outer Main Belt asteroids remain uncertain due to a dearth of diagnostic absorptions in visible and near-infrared (∼0.4–2.5 μm) spectra of the two sets of objects. Absorptions near 3 μm in both sets hold promise for illuminating the potential linkages. Spectral comparisons of meteorites and asteroids have been challenging because meteorite spectra have usually been acquired in ambient terrestrial environments, and hence were contaminated by atmospheric water. In this study, we compare near-infrared spectra of chondrites measured in the laboratory under asteroid-like conditions (Takir, D. et al. [2013]. Meteorit. Planet. Sci. 48, 1618–1637) and spectra of asteroids measured with the long-wavelength cross-dispersed (LXD: 1.9–4.2-μm) mode of the SpeX spectrograph/imager at the NASA Infrared Telescope Facility (IRTF) (Takir, D., Emery, J.P. [2012]. Icarus 219, 641–654). Using the 3-μm band shape, we find that spectral Group 2 CM and CI (Ivuna) chondrites are possible meteorite analogs for asteroids with the sharp 3-μm features, which are predominately located in the $2.5 < a < 3.3$ AU region. Spectral Group 2 CM chondrites contain phyllosilicate phases intermediate between endmembers Fe-serpentine and Mg-serpentine, with a petrological subtype ranging from 2.2 to 2.1 (Takir, D. et al. [2013]. Meteorit. Planet. Sci. 48, 1618–1637). No meteorite match was found for asteroids showing a rounded 3-μm feature, which tend to be located farther from the Sun ($3.0 < a < 4.0$ AU), or for asteroids with distinctive spectra like 1 Ceres or 52 Europa. The study of the 3-μm band in meteorites and asteroids has implications for the understanding of phyllosilicate mineralogy and its distribution in the outer Main Belt region.

1. Introduction

Outer Main Belt asteroids, spanning heliocentric distances $2.5 < a < 4.0$ AU, are dominated by low-albedo asteroids (e.g., C-, G-, F-, B-, P-, and D-types) (Gradie and Tedesco, 1982; DeMeo and Carry, 2013, 2014). Members of some of these asteroidal spectral classes, particularly among the C-complex, are widely thought to be the main source of CM and CI carbonaceous chondrites (Bell et al., 1989; Gaffey et al., 1993).

Many of these asteroids and all CM and CI chondrites exhibit evidence for past reactions with liquid water in the form of hydrated phases, including water- and hydroxyl-bearing minerals (Lebofsky, 1980; Vilas and Gaffey, 1989; Rivkin et al., 2002; McSween, 1979; Brearley, 2006). Several attempts have been made to link spectra of outer Main Belt asteroids with spectra of carbonaceous chondrites on the basis of the analyses of spectral slope, albedo, and the 0.7 μm absorption feature (Vilas and Gaffey, 1989; Vilas et al., 1994; Hiroi et al., 2001; Burbine et al., 2001; Clark et al., 2010, 2011).

In addition, analyses of the 3-μm absorption feature that include the band depth and the integrated intensity (found by numerically integrating the area of the absorption feature in a continuum-removed reflectance spectrum) have been used to characterize spectra of CM and CI carbonaceous chondrites (Miyamoto, 1989; Miyamoto and Zolensky, 1994; Sato et al., 1997). Miyamoto (1989) showed that curvatures of absorption bands near 3-μm of CM chondrites are similar to that of serpentine, and Miyamoto and Zolensky (1994) demonstrated that the integrated intensity of the 3-μm band is closely correlated to the observed hydrogen content of carbonaceous chondrites. Later work by Sato et al. (1997) correlated the reflectances at 2.90 μm and 3.20 μm, normalized to the reflectance at 2.53 μm, to the

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integrated intensity. These authors found that CM chondrites exhibit larger values of the integrated intensity of the 3-μm band than those of thermally metamorphosed carbonaceous chondrites, confirming previous inferences that CM chondrites contain greater proportions of hydrous minerals. Rivkin et al. (2003) used the meteorite analyses of Sato et al. (1997) to estimate the H/Si ratio for the asteroids that they observed, in order to establish connections between CM chondrites and outer Main Belt asteroids. However, these meteorite spectra were measured under ambient laboratory conditions and consequently are likely contaminated by significant amounts of adsorbed water.

Takir and Emery (2012) identified four groups of asteroids based on spectra in the 2.85–4.0 μm spectral range, and further noted a distinct orbital distribution of the four 3-μm spectral groups of asteroids. The "sharp spectral group" exhibits a characteristically sharp 3-μm feature (reflectance decreases with decreasing wavelength from ~3.1 to 2.85 μm spectral), attributed to OH-stretching in hydrated minerals (phyllosilicates). The majority of asteroids in this group are concentrated in the $2.5 < a < 3.3$ AU region. The "rounded spectral group", preferentially located in the $3.4 < a < 4.0$ AU region, is characterized by a rounded 3-μm band (reflectance increases with decreasing wavelength shortward of ~3.07 μm), attributed to H_2O ice (e.g., Rivkin and Emery, 2010; Campins et al., 2010). The "Ceres-like group", located in the 2.65–3.15 AU region, has a narrow 3-μm band center at ~3.05 μm superposed on a much wider absorption from ~2.8 to 3.7 μm. The "Europa-like group" has a 3-μm band centered at ~3.15 μm with longer wavelength band minimum and steeper rise on the long-wavelength edge of the absorption.

In an analogous study of laboratory spectra of CM chondrites, Takir et al. (2013) recognized three spectral groups of CM chondrites (in addition to the CI chondrite Ivuna) on the basis of the 3-μm band center and shape of spectra, showing that distinct parent body aqueous alteration environments experienced by different carbonaceous chondrites can be distinguished using reflectance spectroscopy. Spectral Group 1, which is the group exhibiting the lowest degree of aqueous alteration, is characterized by 3-μm band centers at longer wavelengths and is consistent with the occurrence of cronstedtite (Fe-serpentine). Spectral Group 3, which is the most highly altered group, is characterized by 3-μm band centers at shorter wavelengths and is consistent with the occurrence of antigorite (Mg-serpentine). Spectral Group 2 is transitional between Groups 1 and 3 and represents an intermediate mineralogy between the two serpentine endmembers. Spectral comparisons of meteorites and asteroids have been challenging because meteorite spectra have usually been acquired in ambient terrestrial environments, and hence were contaminated by atmospheric water. Here, our meteorite reflectance spectra were measured under dry conditions (vacuum and elevated temperature) to mimic space conditions and minimize the adsorbed water that affected previous analyses (Miyamoto and Zolensky, 1994; Sato et al., 1997; Rivkin et al., 2003).

The goal of the present study is to apply the 3-μm spectral indicators (e.g., band center, band shape, band depth) in CM and CI chondrites to asteroids spanning the $2.5 < a < 4.0$ AU region in order to constrain the nature of aqueous alteration and its distribution in the outer Main Belt. Of particular interest is the question of the abundance and distribution of H_2O in the early Solar System and its significant role in the evolution of the alteration mineralogy of outer Main Belt asteroids.

2. Methodology

Reflectance spectra of CM and CI carbonaceous chondrites used in the present study were measured by Takir et al. (2013) under dry conditions (vacuum and elevated temperature) to remove adsorbed water, for subsequent comparison with reflectance spectra of asteroids. Takir et al. (2013) also quantified the degree of alteration in these chondrites, using previously defined alteration parameters, including petrological subtype, which is based on an alteration sequence that varies downward from moderately altered petrologic type-2.6 chondrites to highly altered type-2.0 chondrites (Rubin et al., 2007). The petrological and geochemical parameters, which were determined using microprobe analyses and microscope observations, were found to be consistent with each other and with some of the spectral indicators of the 3-μm band, namely the band center and shape.

Reflectance spectra of asteroids used in the present study include those that were presented in Takir and Emery (2012), observed using the long-wavelength cross-dispersed (LXD: 1.9–4.2-μm) mode of the SpeX spectrograph/imager at the NASA Infrared Telescope Facility (IRTF). The present study also includes 5 new asteroid spectra. New asteroid data were reduced and analyzed using the methodology described in Takir and Emery (2012). Table 1 includes the observing parameters for those telescopic observations of asteroids that are presented here for the first time.

In this paper, we are comparing meteorite and asteroid spectra on the basis of the 3-μm band shape in the NIR region. To characterize the shape of the 3-μm absorption feature in meteorites and asteroids, we chose representative wavelengths at 2.90 μm and 3.20 μm for nominal band depth calculation (Fig. 1). We used a chi-squared test to quantitatively compare spectra of meteorites and asteroids and to determine possible matches. Spectra of meteorites and asteroids were normalized to unity at 2.2 μm. The final chi-squared value used in the test is the sum of three chi-squared values from the first order polynomial fits across three representative regions: the 1.95–2.50 μm, 2.85–3.25 μm, and 3.50–4.00 μm (Fig. 2):

$$\chi^2 = \chi^2_{1.95-2.50} + \chi^2_{2.85-3.25} + \chi^2_{3.50-4.00}. \quad (1)$$

The representative regions exclude the 2.50–2.85-μm region because the Earth's atmosphere is nearly opaque to incoming radiation at those wavelengths, and the 3.25–3.50-μm region because some meteorite spectra exhibit strong organic absorptions. In Takir et al. (2013), we suggested four possible explanations for the spectral appearance of organics in these meteorites.

In this chi-squared test, the predicted data are the meteorite data and the observed data are the asteroid fits. To compute chi-squared values, we interpolated asteroid fits so they were on the same wavelength grid as meteorite spectra. The lowest chi-squared value represents the possible match between spectra

Table 1
Observing parameters for asteroids observed with the LXD mode of SpeX at NASA IRTF.

Asteroid	Date (UT)	Time (UT)	Int (min)	Airmass	Standard star	Spectral type	B–V[a]	V–K[a]
41 Daphne	04/17/2012	5:07–8:04	140	1.0–1.8	SAO 97046	G0	0.62	1.41
211 Isolda	01/10/2013	10:21–12:42	120	1.0–1.3	HD 259551	G0	0.67	–
98 Ianthe	01/12/2013	10:18–13:04	140	1.1–1.2	HD 69027	G0	0.69	1.73
488 Kreusa	01/13/2013	10:13–11:33	80	1.0	HD 67149	G0	0.58	1.38
13 Egeria	01/12/2013	13:49–14:47	60	1.1–1.3	SAO 61716	G5	0.72	1.59

[a] B–V and V–K are the star's colors.