

REFLECTANCE SPECTROSCOPY OF METEORITE INSOLUBLE ORGANIC MATTER (IOM). H. H. Kaplan¹, R. E. Milliken¹, and C. M. O'D. Alexander². ¹Brown University, Dept. of Earth, Environmental, and Planetary Sciences, Providence RI 02912 (email: Hannah_Kaplan@Brown.edu). ²DTM, Carnegie Institution of Washington, 5241 Broad Branch Rd., Washington DC 20015.

Introduction: Carbonaceous chondrites meteorites, which are believed to come from C-type asteroids, contain soluble (SOM) and insoluble (IOM) organic matter that record chemical processes in the early solar system and aqueous/thermal alteration on asteroid parent bodies. IOM is a macromolecular substance that makes up the majority of extraterrestrial organic matter. Much has been written about structure and composition of IOM from techniques such as nuclear magnetic resonance (NMR) spectroscopy, gas chromatography (GC or GC-MS), and transmission spectroscopy [e.g., 3,4,5], but there have been relatively few studies of IOM using reflectance spectroscopy [6].

The ongoing Hayabusa2 (JAXA) and OSIRIS-REx (NASA) missions will ultimately return samples from C-complex asteroids to Earth for detailed study, but they will also characterize the surface compositions of their targets using remote sensing methods that include visible-near infrared reflectance spectroscopy [1,2]. To better understand how these data can be used to identify and interpret organic signatures, it is first necessary to build spectral libraries of appropriate materials and develop quantitative links between composition, organic abundance, and spectral properties.

Reflectance spectroscopy of bulk meteorites has been used previously to study composition, distinguish between petrologic classes and determine degrees of aqueous and thermal alteration [e.g., 7, 8]. Sedimentary rocks and their associated kerogens have also been studied with the aim of linking IR reflectance properties to total organic carbon (TOC) and H:C ratios (a proxy for organic maturity) [Kaplan et al., *in prep*], and we have now begun to apply these methods to meteorites and their IOM.

In this study, we measured the spectra of 18 IOM samples in RELAB at Brown University. These IOM samples were previously separated from bulk meteorite samples and their elemental and isotopic compositions are reported in [9, 10]. RELAB spectra of bulk meteorites were compared to the corresponding IOM spectra and the compositional data. Applications for *in situ* analysis of asteroid IOM content/composition and mapping of small-scale chemical variation in meteorite chips are discussed.

Methods: The CsF-HF technique for demineralization [5] was used to isolate the IOM and methods for measuring bulk H and C are reported in [9]. H:C for each sample was calculated from the bulk measurements and can be generalized as the aliphatic:aromatic

organic ratio. Bulk C content and H:C are the primary measurements that we compare with spectral parameters for each sample.

Reflectance spectra of IOM were acquired with the bidirectional reflectance spectrometer in RELAB from 0.35 – 2.5 μm using standard incidence and emergence angles ($i = 30^\circ$ and $e = 0^\circ$). These spectra were joined to longer wavelength FTIR spectra (2 – 25 μm) at 1.7 μm , where each FTIR spectrum represents an average of over 200 scans. If IOM particles were clumped and enough sample was available, then the clumps were ground and the spectra re-measured. Samples were also placed on glass slides and imaged with an FTIR microscope to estimate particle size (Fig. 1).

In addition to the IOM spectra, 79 meteorite spectra were identified in the RELAB database that represent 60 unique meteorites with corresponding compositional data. These spectra were collected over many years for many different researchers, so some are of particulate samples (of different size ranges) whereas others represent meteorite chips. Most have not been measured with the goal of analyzing organics, thus terrestrial organic contamination cannot be ruled out.

The spectral continuum was identified and removed over specific wavelength ranges to facilitate the study of band depth (strength) and band area for select organic absorptions, and these features were also modeled with Gaussian and Lorentzian curves to estimate amplitude (where noise or overlapping absorptions make band depth measurements unreliable).

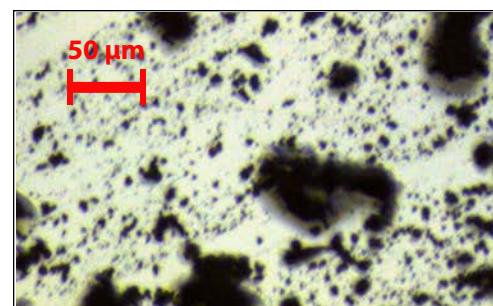


Figure 1: FTIR Microscope image of Murchison IOM on a glass slide. Particle size is $\ll 50 \mu\text{m}$, though multiple particles can form clumps, usually no greater than 50 μm .

Results and Discussion:

IOM Spectra. A selection of IOM spectra and corresponding bulk meteorites are shown in Fig. 2. IOM spectra are notably dark at all wavelengths with absolute reflectance values typically < 0.1 . Many exhibit a red slope at visible wavelengths that continues into the

near infrared. The first major absorption is at $2.7 - 3.1 \mu\text{m}$ ($3704 - 3225 \text{ cm}^{-1}$) due to OH/H₂O, which 9 out of 15 ground samples exhibit; the rest have flat or sloped spectra with no absorptions until $\sim 6 \mu\text{m}$. It is possible this OH/H₂O absorption is partly due to adsorbed rather than structural OH/H₂O. At $\sim 3.4 \mu\text{m}$ ($3000 - 2850 \text{ cm}^{-1}$) there is a triplet absorption that arises due to aliphatic C-H bond stretch. Finally, there are a series of more complex absorptions at $5.5 - 7 \mu\text{m}$ ($1818 - 1430 \text{ cm}^{-1}$) that are due to a range of vibrations, including carbonyl, water/OH, C-H bend, and C=C stretch.

The $\sim 3.4 \mu\text{m}$ absorption is the most diagnostic organic feature in the VIS-NIR spectra. Comparing the strength of this absorption to H:C reveals that IOM must have H:C > ~ 0.4 before this absorption band is observed in the FTIR data (Fig. 3). A similar study of 36 kerogens isolated from terrestrial shales suggests that these absorptions do not appear until H:C > ~ 0.2 [Kaplan et al., *in prep*].

Meteorite Spectra. Meteorite spectra are also dark, but the majority display absorptions near $3 \mu\text{m}$, particularly due to OH/H₂O. However, the complex organic absorptions from $5.5 - 7 \mu\text{m}$ are absent or have fewer features than in the IOM spectra. Of the 79 meteorite spectra, 56 have organic absorptions at $3.4 \mu\text{m}$. A comparison of meteorites that have organic absorptions in their spectra with those that do not reveals no significant difference in bulk C, H:C, albedo, or particle size between the two groups. This may be due to significant heterogeneity within a given sample, causing chips/particulates measured in RELAB to have no relation to the compositional data that was measured from different aliquots of the meteorite. Alternatively, this may suggest that the organics visible in the meteorite spectra may be terrestrial contaminants that are not reflected in the compositional data for the samples (which were determined for relatively uncontaminated, separated IOM).

The comparison of H:C to band depth at $3.4 \mu\text{m}$ for bulk meteorite samples shows a similar trend to the IOM (Fig. 3) in which band depth increases with H:C for values > ~ 0.4 . Some meteorites (e.g., those with H:C < 0.2) have significantly stronger organic absorptions than their corresponding IOM. Similar measurements of bulk sedimentary rocks and their kerogen suggest that spectra of the isolated organic matter always exhibit stronger organic absorptions than the bulk rock powders.

Again, this difference may be due to heterogeneity or contamination in the meteorites. Future work will focus on *in situ* spectral mapping of meteorites using an FTIR microscope to further study sample heterogeneity and to collect data with the explicit goal of study-

ing the spectral properties of organics hosted within a complex inorganic (mineral) matrix.

Conclusions: VIS-NIR-IR reflectance spectra of IOM from 18 different C chondrites have been measured. Of these, 9 show clear evidence of aliphatic organics; these samples all have H:C > 0.4, suggesting this may be a threshold for observing organics in C chondrites or their parent asteroids. However, the RELAB meteorite spectra corresponding to these IOM samples may be affected by contamination or meteorite samples are too heterogeneous to be properly matched with the compositional data currently available. Future work will include numerical modeling of meteorite spectra using IOM spectra as end members in order to better understand how reflectance spectra may be used to detect and quantify organics on C-type asteroids.

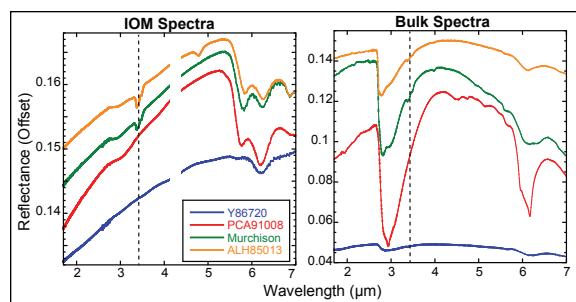


Figure 2: Reflectance spectra (offset) of meteorites and their IOM for four C chondrites: Y-86720 (blue), PCA 91008 (red), Murchison (green), and ALH 85013 (orange).

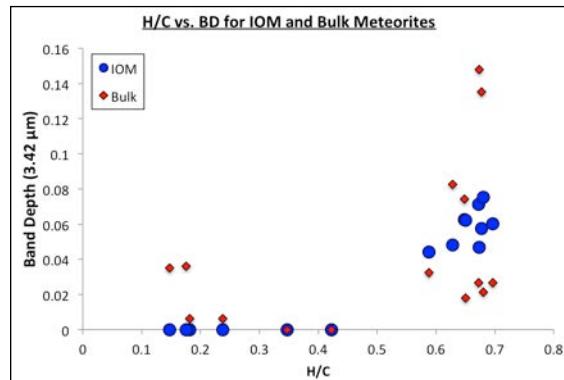


Figure 3: H:C in IOM (reported in [8,9]) is compared to the strength (band depth) of the $3.4 \mu\text{m}$ aliphatic organic absorption in IOM and bulk meteorite spectra. This absorption appears when H:C > 0.4.

- References:** [1] Pilorget, C. and Bibring, J.-P. (2013) *Planetary Space Sci.*, 76, 42-52. [2] Lauretta, D. S. et al. (2012) *43rd LPSC*, #2491. [3] Huang, Y. et al. (2005) *GCA*, 69, 1073-1084. [4] Cody, G. and Alexander, C. (2005) *GCA*, 69, 1085-1097. [5] Orthous-Daunay (2013) *Icarus*, 223, 534-543. [6] de Bergh, C. et al. (2008) *The Solar System Beyond Neptune*, 483-506. [7] Gerenne, A. et al. (2016), *Icarus*, 264, 172-183. [8] McAdam, M. et al. (2015) *Icarus*, 245, 320-332. [9] Alexander, C. et al. (2007) *GCA*, 71, 4380-4403. [10] Alexander, C. et al. (2013), *GCA*, 123, 244-260.