FINDING THE MOST PRIMITIVE ASTEROIDS: SPECTRAL IDENTIFICATION OF AMORPHOUS MATERIALS IN CO CHONDRITES. M. M. McAdam[1], J. M. Sunshine[1], K. T. Howard[2, 3], T. McCoy[4], C. M. O'D. Alexander[5]. [1]Univeristy of Maryland, College Park, MD 20742 mmcadam@astro.umd.edu, [2]Kingsborough Community College, [3]American Museum of Natural History, [4]Smithsonian Institution, National Museum of Natural History, [5] Carnegie Institution, Department of Terrestrial Magnetism.

Introduction: While CO chondrites are dominated by olivine and pyroxene [1], they are unusual in containing substantial amorphous silicates (15-31 vol.%), an Fe,Mg-rich phase that lacks long-range crystalline order [1]. Amorphous silicates are also abundant in primitive CR chondrite matrices and have been interpreted as a nebular condensate that cooled quickly and was accreted as matrix along with chondrules, CAIs and other phases. The preservation of amorphous silicates results from only mild thermal metamorphism and an absence of extensive interactions with water [1, 2, 3]. As such, CO chondrites might preserve among the best records of amorphous silicates from the solar nebula and, by extension, identification of asteroids rich in this material might provide insights into the nature of asteroid formation and accretion.

Previous near-infrared spectral studies of low metamorphic grade COs have indicated the presence of amorphous material [4]. Here, we present visible/near infrared (VIS/NIR) and mid-infrared (MIR) spectral evidence for amorphous material in eight low metamorphic grade COs as is consistent with their known modal mineralogy [5]. The unique spectral features of amorphous silicates allows us to study meteorites rich in amorphous material and to identify asteroids enriched in one of the most primitive building blocks of the Solar System.

Spectral Measurements: We examine the VIS/NIR and MIR spectra of eight CO3 chondrites: Allen Hills (ALHA) 77307, Dominion Range (DOM) 08004, Dominion Range 08006, Miller Range (MIL) 07193, Miller Range 07687, Miller Range 07709, Miller Range 090010, and Miller Range 090073. This suite of COs are relatively primitive and unheated with metamorphic grades between 3.0 and 3.2 and all with low weathering grade. Spectra were obtained at the Brown University NASA/Keck Reflectance Laboratory. VIS/NIR data were acquired with the bi-directional spectrometer from 0.3 and 2.5-µm at a resolution of 10 nm with an incidence angle of 30° and emergence angle of 0°. MIR data were measured with the FTIR spectrometer at a resolution of 4 cm^{-1}.

VIS/NIR Features: VIS/NIR spectra of COs (**Fig. 1a**) are characterized by weak features and flat to red slopes. After removing a continuum defined by a convex hull (**Fig. 1b**), two features become apparent: a narrow weak 0.5-µm absorption feature and a broad weak feature centered near 1.3-µm with strengths from 2-5%. Only carbonaceous chondrites with abundant (>13 vol.%) amorphous material (*e.g.* CO meteorites and C2-ungrouped Adelaide) exhibit these two absorption features. The 1.3-µm feature has previously been interpreted as Fe-bearing glass for COs of low metamorphic grade [4]. The 0.5-µm feature is also consistent with Fe^{3+} bearing glass [6, 7]. These two features are consistently present in the spectra of low metamorphic grade COs. The presence of the 0.5-µm feature is a further confirmation of the original interpretation of amorphous material [4].

MIR Features: In the MIR (**Fig. 1c**), spectral features are controlled by the dominant mafic minerals. Olivine and pyroxene produce the broad ~12.7-µm feature and cause the features on the short-wavelength shoulder. The 19.5- and 24-µm features are also due to olivine and pyroxene. However, COs with larger abundances of amorphous material have a broader 12.7-µm feature and a significant increase in slope between 9-11.5-µm. Additionally, a small feature at 22-µm is apparent in the spectra of all the CO meteorites.

MIR Modeling: In order to enhance the spectral features due to amorphous phases, the crystalline component of the CO spectra were removed using a linear mixing model. Spectral end-members of natural olivines and pyroxenes were combined based on their known modal fraction [1]. A spectrally neutral darkening agent was also included in the model. The residual spectra for all the COs is shown in **Fig. 2** and compared to annealed iron smokes [8]. Annealed iron smokes were synthesized to simulate amorphous components seen in the spectra of comets. Qualitatively, iron-rich annealed smokes have similar features particularly at 9- and 22-µm to the residual CO spectra. Iron smokes that have been annealed to higher temperatures also have features around 12- and 16-µm. The amorphous materials in the COs, while Fe-rich certainly contain some magnesium as well. This may explain the shifts in position of the 12- and 16-µm features in the COs compared to the smokes.

Implications: Multiple asteroids are known to exhibit VIS/NIR features consistent with the COs, most notably 10 Hygiea. However, in some cases, this absorption feature has been previously interpreted as magnetite [9]. Based on the correlation between VIS/NIR features and diagnostic features of amorphous silicates in the MIR, it is likely that these bodies are rich in amorphous silicates. While the origin of amorphous

silicates is controversial, these are primitive phases that would have been rapidly destroyed by parent body processing. The presence of amorphous silicates indicates that an asteroid has experienced only minimal heating and limited interactions with fluid. Remote identification of amorphous silicates provides a tool for identifying the least processed parent bodies in the Asteroid Belt.

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References: [1] Howard, K. T., *et al*, (2014) LPSC abstract #1830. [2] Howard, *et al.*, (2009), *GCA*, *73*, 4576, 4589. [3] Howard, K. T., *et al.*, (2011), *GCA*, *75*, 2735-2751. [4] Cloutis, E. A., *et al.*, (2012), *Icarus*, *220*, 466-486. [5] Howard, K. T., *et al.*, (2015), LPSC abstract #2244. [6] Carli, C., *et al.*, (2016), *Icarus*, *266*, 267-278. [7] Bell, P. M., *et al.*, (1976). *Proc. Of 7th Lun. Sci. Conf.* 2543-2559. [8] Hallenbeck, S. L., *et al.*, (2000), *ApJ*, *535*, 247-255. [9] Yang and Jewett, (2010) *AJ*, *140*, 692-698.

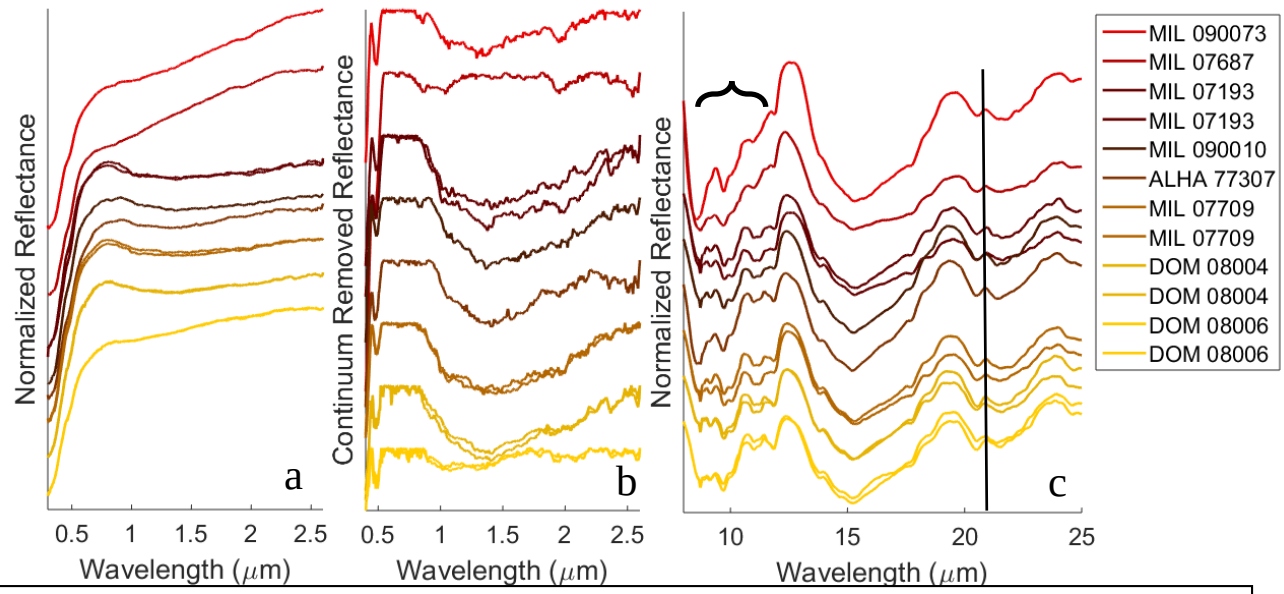

Fig. 1: CO meteorites ordered bottom to top by increasing amorphous silicate content. (a) VIS/NIR data. COs are characterized by weak features and variable though generally flat slopes. (b) Upon continuum removal two features appear: a weak ~0.5-µm absorption and a broad feature near 1.3-µm with 2-5% strength. This feature only appears in the spectra of meteorites with abundant amorphous material. (c) MIR spectra of CO meteorites are controlled by the dominant olivine and pyroxene producing features at 12.5, 19.5 and 24-µm. COs with larger abundances of amorphous material have a broader 12.5-µm feature with a larger slope on the short wavelength shoulder, indicated by bracket. Additionally, this phase causes a 22-µm feature (vertical line).

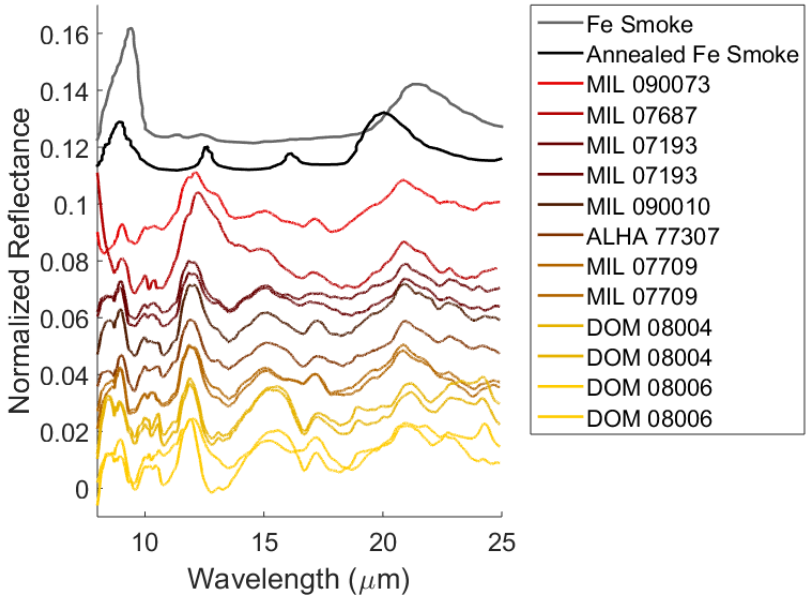

Fig. 2: Residual spectra compared to annealed Fe-smoke. Simple linear mixing models (including neutral darkening agent) with modal proportions of mafics are used to remove mafic component. All COs exhibit similar features in their residuals: 9-, 12.5-, 15- and 21-µm. These features are qualitatively similar to Fe-smokes taken from [7]. The differences may be explained by the relative abundance of Fe and Mg in the amorphous material. Since the smokes are likely much more Fe-rich, the presence of Mg could shift the spectral features.