ASTEROID (93) MINERVA: SPECTRAL EVIDENCE OF PRIMITIVE, AMORPHOUS MATERIALS AND IMPLICATIONS.

M. M. McAdam[1], J. M. Sunshine[2], K. T. Howard[3,4], C. M. O'D. Alexander[5]. T. J. McCoy[6], S. J. Bus[7]. [1]Norther Arizona University, Department of Physics and Astronomy, Flagstaff AZ 86011. maggie.mcadam@nau.edu. [2]University of Maryland. [3]American Museum of Natural History. [4]Kingsborough Community College. [5] Department of Terrestrial Magnetism, Carnegie Institution. [6] National Museum of Natural History, Smithsonian Institution. [7]University of Hawaii, Institute for Astronomy.

Introduction: The least-processed carbonaceous chondrites in the CO [1] and CR chemical groups [2], as well as ungrouped samples [3] are characterized by the presence of up to 30 vol.% amorphous silicates in their matrices and chondrule rims [e.g., 1]. These phases appear to have condensed under disequilibrium conditions out of a vapor phase in the early Solar nebula. The preservation of amorphous materials in these meteorites indicate that they have meteorites have experienced minimal processing since the time of accretion of their parent bodies. Recently, a suite of these least-processed meteorites were spectrally characterized in the near and mid-infrared [3, 4]. These results indicate that the amorphous phases have unique spectral signatures in these wavelength ranges.

Asteroid (93) Minerva, observed by the IRTF+SPeX, appears to be spectrally similar to these least-processed meteorites in the near-infrared, indicating it contains abundant amorphous phases on its surface. Minerva may therefore hold important information about the timing of accretion of the carbonaceous chondrites and the parent body processes that preserve these materials.

(93) Minerva: (93) Minerva (**Fig. 1**) was observed using the IRTF+SPeX in April of 2003. This asteroid is located in the mid-Main Asteroid Belt (semi-major axis = 2.75 AU). It is a triple system [7], with two small satellites, likely formed through impact processes 1 Ga ago [7]. Minerva has an albedo of 0.062 +/- 0.013 [7] and a broad, weak feature centered at 1.4-µm similar to the unweathered least-processed CO meteorites. In **Fig. 1**, the SPeX observation of Minerva is compared to a least-processed, minimally terrestrially weathered CO (Allan Hills 77307), a more weathered least-processed CO (Dominion Range 08006) and two least-processed CR meteorites (Queen Alexandra Range 99177; Meteorite Hills 00426). Since the satellite-forming impact occurred relatively recently, Minerva's surface is fairly young and therefore this spectral signature is likely not caused by space weathering or other surface processes. Minerva's spectral feature and low albedo indicates its surface is likely comprised of abundant amorphous phases. Mid-infrared follow-up studies may help further understand Minerva's surface composition.

Spectral Signature of Amorphous Silicates: Near-infrared spectroscopy of the least-processed meteorite samples were obtained at the NASA/Keck RELAB facility using the bi-directional spectrometer (0.3-2.5-µm, i=30^{O}, e = 0^{O}, 10 nm resolution).

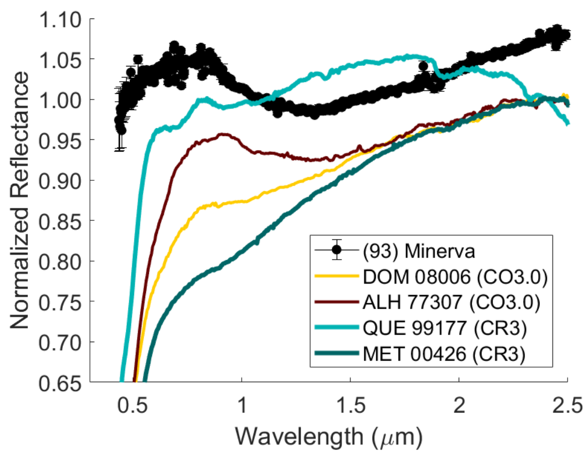

Fig. 1: (93) Minerva (observed by SPeX; normalized at 0.55-µm) compared to DOM 08006, ALH77307 (CO 3.0), QUE 99177 (CR3) and MET 00426 (CR3). Here Minerva appears to be most related to the least-processed, minimally weathered CO meteorites. Minerva appears to have a large abundance of amorphous phases on its surface.

The spectral signature (**Fig. 2**) of the amorphous materials is best characterized by the relatively unweathered COs. These meteorites show a broad, weak (2-5%) feature, centered at 1.4-µm. This feature is consistent with the amorphous phases. Terrestrial weathering significantly affects the near-infrared where spectral mixing is non-linear. For more weathered samples in the CO chemical group, the broad 1.4-µm feature is masked by the terrestrial weathering products. The least-processed CRs have similar weathering grades to the heavily terrestrially weathered COs and, similarly, they do not exhibit the 1.4-µm feature.

Implications of Minerva's Surface Composition: While it appears that Minerva has abundant amorphous materials on its surface, it is not entirely clear if Minerva is most similar to the CR chemical group or the CO group. Since the least-processed CR meteorites have terrestrial weathering that masks the 1.4-µm feature, it is not possible to definitively say which chemical group Minerva is related to at this point. This distinction is significant since these two chemical groups are characterizes by different parent body processes. The secondary modification of the COs is dominated by the effects of thermal metamorphism, while the modification of the CRs is dominated by aqueous alteration. Despite the preservation of large volumes of amorphous phases in the least-processed samples studied, the least-processed COs have experienced some thermal metamorphism (up to 200^{O}C) [8, 9] and may have accreted with some water [e.g., 10]. However, the amount of coaccreted water in the COs is less than what is observed in the CRs. The least-processed CRs have interacted to some degree with water [e.g., 2, 10]. This makes the detection of amorphous phases on Minerva's surface significant, since it is an intact parent body that may help determine how amorphous phases are preserved in meteorites.

There are two main explanations for preserving amorphous phases on an asteroid. The first is that Minerva could have accreted late (>4 Ma after CAI formation), missing the heat-flux from aluminum-26 (^{26}Al). These short-lived radioactive nuclei are the main driver of thermal metamorphism and aqueous alteration. Without this heat-flux, the processes of thermal metamorphism or aqueous alteration could not have occurred on this asteroid. A prediction of this scenario is that Minerva should have mineralogically uniform between its surface and interior.

Alternatively, Minerva could have accreted in time to experience ^{26}Al heat-flux (2-4 Ma after CAI formation), which stratified the body [e.g., onion-shell model; 11, 12]. In this scenario, the outer layers of Minerva remained relatively unaffected by the internal processes (thermal metamorphism or aqueous alteration), preserving amorphous materials on the surface. This indicates that Minerva's internal composition should be different from its exterior. Large impact craters may exhume interior materials onto Minerva's surface. Observing Minerva's surface with rotationally resolved spectroscopy could therefore identify spectral heterogeneity. Marchis, et al [7] presented SPeX observations of Minerva that do not exhibit this same 1.4-µm feature. This would indicate that some rotational heterogeneity may exist.

Future observations of Minerva will be able to determine if there is compositional heterogeneity on Minerva's surface. If heterogeneity is observed, this would indicate an onion-shell model for Minerva's accretion. The mineralogical differences between the surface and interior will allow us to determine which parent body processes dominated Minerva's history. If aqueous phases are observed, this would indicate Minerva is similar to the CRs. If crystalline, anhydrous phases are observed on Minerva's surface, this would indicate it is related to the CO chemical group. Either the observation of mineralogical heterogeneity or homogeneity will provide insights into how amorphous phases are preserved on asteroids and constraining the formation timing of carbonaceous chondrites.

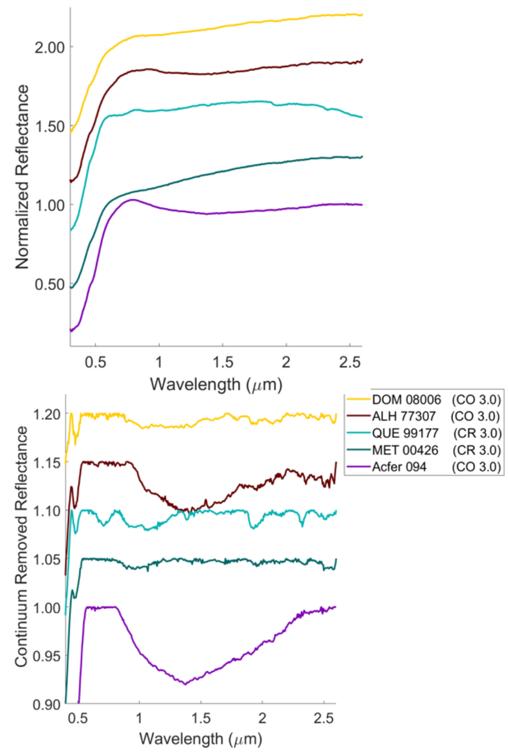

Fig. 2: Near-infrared spectra of least-processed meteorites. Top to bottom with petrologic type and weathering grade: DOM 08006 (CO 3.0, A/B), ALH 77307 (CO 3.0, Ae), QUE 99177 (CR3, B), MET 00426 (CR3, Be) and Acfer 094 (C-ungrouped 3.0). Top: normalized offset near-infrared spectra show that the least-processed meteorites with minimal terrestrial weathering appear to have relatively flat slopes with a broad weak feature at ~1.4-µm. Bottom: continuum removed, offset reflectance spectra. Here, the 1.4-µm feature is stronger for the unweathered samples.

Acknowledgments: Spectra were acquired using the Brown University NASA Keck RELAB a multiuser facility. A special thanks to T. Hiroi who collected the RELAB spectra on our behalf. This research is funded by the NASA Earth and Space Sciences Fellowship, by NASA Cosmochemistry grant NNX11AG27G and NASA Planetary Geology and Geophysics grant NNX10AJ57G.

References: [1] Alexander et al. (2017) GCA, 221, 406. [2] Abreu and Brearley (2010) GCA, 74, 1146. [3] Greshake (1997) GCA, 61, 437. [4] McAdam et al. (2016) LPSC abstract 2291. [5] McAdam et al., in review. [6] Lee and Bland (2004) GCA, 68, 893. [7] Marchis et al. (2013), Icarus, 224, 178. [8] Bonal et al. (2007) GCA, 71, 1605. [9] Bonal et al. (2016) GCA, 189, 312. [10] Le Guillou et al. (2014) GCA, 131, 344. [9] Doyle et al. 2015 Nat. Comm. 6, 7444 [11] Taylor et al. (1987), Icarus 69, 1. [12] Huss (2006) MESS II, 943, 567.