FINE-GRAINED CAIS IN COMET SAMPLES: MODERATE REFRACTORY CHARACTER AND COMPARISON TO SMALL REFRACTORY INCLUSIONS IN CHONDRITES. D. J. Joswiak[1], D. E. Brownlee[1], A. N. Nguyen[2] and S. Messenger[2], [1]Dept. of Astronomy, University of Washington, Seattle, WA 98195, [2]Robert M. Walker Laboratory for Space Science, ARES, NASA JSC Houston, TX 77058 (joswiak@astro.washington.edu).

Introduction: Examination of >200 comet Wild 2 particles collected by the Stardust (SD) mission shows that the CAI abundance of comet Wild 2's rocky material is near 1% and that nearly 50% of all bulbous tracks will contain at least one recognizable CAI fragment [1]. A similar abundance to Wild 2 is found in a giant cluster IDP thought to be of cometary origin. The properties of these CAIs and their comparison with meteoritic CAIs provide important clues on the role of CAIs in the early Solar System (SS) and how they were transported to the edge of the solar nebula where Kuiper Belt comets formed.

Previously, only two CAIs in comet Wild 2 had been identified and studied in detail [2,3]. Here we present 2 new Wild 2 CAIs and 2 from a giant cluster cometary IDP, describe their mineralogical characteristics and show that they are most analogous to nodules in spinel-rich, fine-grained inclusions (FGIs) observed in CV3 [4] and other chondrites. Additionally, we present new O isotope measurements from one CAI from comet Wild 2 and show that its oxygen isotopic composition is similar to some FGIs. This is only the second CAI from Wild 2 in which O isotopes have been measured.

Samples and Analytical Techniques: Two new CAIs, WF216 (2 µm) and TuleF4 (~1 µm) from SD tracks 80 and 172, respectively, were discovered as isolated grains in the bulbs of their tracks. Additionally, two CAIs, P3-4 (8x13 µm) and P6-14 (8x10 µm), were found in 50 handpicked fragments from a giant cluster IDP. The cluster IDP, collected in the stratosphere by a NASA U2 aircraft, is composed of thousands of individual grains that 'pancaked' during collection over a ~1.5 mm region. A significant body of evidence suggests the IDP was derived from a comet [1].

The four new CAIs were studied in detail with a Tecnai TF20 scanning transmission electron microscope (TEM) equipped with bright- and dark-field detectors and a EDAX X-ray analysis system. To prepare them for TEM study, the samples were embedded in acrylic resin, microtomed to ~<70 nm thickness and placed on thin-film C-supported TEM grids.

Microtome slices of Wild 2 CAI WF216 were analyzed for O isotopes with the Johnson Space Center NanoSIMS. Ion images of $^{16}O^-$, $^{17}O^-$, $^{18}O^-$, $^{28}Si^-$ and $^{27}Al^{16}O^-$ were simultaneously acquired with electron multipliers by rastering a ~0.5 pA 16 keV primary Cs+ ion beam over the samples. Measurements were performed at a mass resolving power of >10000 for oxygen. Isotopic compositions were determined by defining regions of interest in the images that corresponded to the CAI.

Results: Like the 2 previous Wild 2 CAIs, all four new CAIs consist of either single nodules or clusters of several nodules. They are mineralogically and texturally similar to the Wild 2 CAIs Inti and Coki [2,3]. The nodules range in size from ~1-6 µm, have concentric mineral structures composed of spinel as a major interior phase (or as inclusions), followed by anorthite and then Al,Ti clinopyroxene toward their exteriors (Fig. 1). CAIs P3-4 and P6-14 have discontinuous rims of forsterite and/or enstatite. Spinel compositions are Mg- and Al-rich although moderate amounts of Cr are present in the spinels in P3-4 and P6-14. In the four CAIs anorthite ranges from An_{96}-An_{100} and Al, and Ti are variable in the clinopyroxenes. Sub-100 nm osbornite inclusions (TiN), a highly refractory phase, are present in WF216 and P6-14 and Fe,Ni-rich refractory metal nuggets were observed in CAI P3-4. Measured bulk compositions of the four CAIs are similar to Type C CAIs and some FGIs [4].

The O isotopic composition of CAI WF216 is plotted in Fig. 2 along with the terminal particle from SD track 25 (Inti) [2] and melilite+spinel+anorthite +pyroxene-rich nodules in FGIs from CV3 chondrites [5]. WF216 falls at an intermediate value on the CCAM line and has a similar O isotopic composition as some of the FGIs but is more ^{16}O-poor than Inti.

Discussion: The four new CAIs presented here and two CAIs previously found in SD tracks [1,2] all have nodular structures and are largely composed of the moderately refractory minerals spinel, anorthite and Al,Ti clinopyroxene. No highly refractory CAIs such as Type A, corundum+hibonite or grossite-bearing assemblages were found from >250 comet fragments examined.

Small micon-sized CAIs have been reported in chondritic meteorites and include spinel-rich, fine-grained inclusions (FGIs) [4] and corundum+/-hibonite+/-spinel-rich objects found in a few primitive chondrites [6]. The minerals, textures and bulk compositions of all the cometary CAIs resemble single nodules or clusters in fine-grain inclusions (FGIs) which are most often observed in CV3 chondrites [4]. FGIs are aggregates of fine-grained nodules which are composed of concentric moderately refractory minerals which are dominantly composed of spinel, melilite, anorthite and Al, Ti clinopyroxene+/-minor perovskite.

The O isotopic composition of Wild 2 fragment WF216, which lies on the CCAM line midway between the range of FGIs, suggests that this object was altered in the nebula similar to FGIs in CV3 chondrites which also experienced alteration with nebular gases [4,5]. It was then transported to the outer SS and ultimately accreted to comet Wild 2.

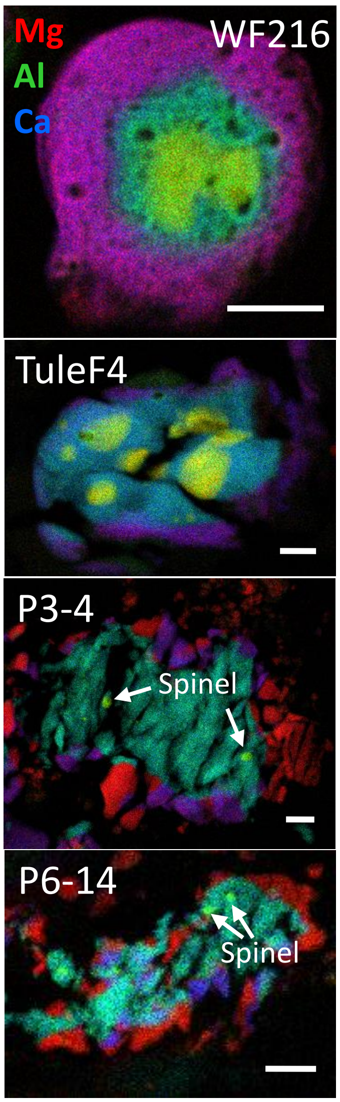

Fig. 1: Composite Mg-Al-Ca element maps of 4 new CAIs found in comet Wild 2 and a giant cluster IDP of probably cometary origin. All CAIs consist of moderately refractory minerals with spinel (yellow to lime green) present in the cores or as inclusions followed by anorthite (teal) and then Al, Ti clinopyroxene (purple). Discontinuous rims of forsterite and/or enstatite are present on P3-4 and P6-14 (red). Scale bars: WF216 and TuleF4 = 0.2 µm, P3-4 and P6-14 = 1µm.

In chondrites, FGI aggregates whose sizes range up to several mm are made up of vast numbers of nodules (~10-50 µm). This suggests that the preponderance of FGI-like nodules in the comet samples may reflect the high abundances of nodules that were produced in the solar nebula and transported as clusters or as single nodules to the outer SS. Alternatively, the lack of the most refractory inclusions in comet samples may be due to 1) inefficient transport of the highest temperature materials to the outer SS, 2) preferential destruction of the higher temperature CAIs or 3) limited sampling of comet samples.

Conclusions: Of the four new CAIs found in comet samples none are composed of highly refractory minerals typical of the most refractory CAIs in chondrites. The new comet CAIs and 2 others [2,3] are all composed of moderately refractory mineral assemblages arranged in concentric layers closely resembling nodules from spinel-rich, fine-grained inclusions observed in CV3 and other chondrites. The intermediate O isotopic composition measured in one CAI is consistent with alteration in the nebula similar to FGIs. These observations combined with the large number of nodules present in FGIs suggest that the comet CAIs were produced in nebular regions where FGIs were manufactured and then transported to the outer SS.

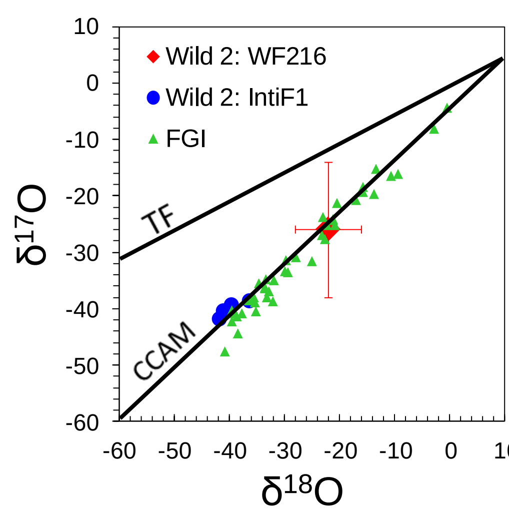

Fig. 2: Oxygen isotopic composition of CAI WF216 from comet Wild 2 compared to Wild 2 CAI IntiF1 [2] and fine-grained inclusions from CV3 chondrites [5]. 1σ error bars shown.

References: [1] Joswiak et al. (2017) MAPS, In press. [2] McKeegan et al. (1996) *Science*, 314: 1724-1728. [3] Matzel et al. (2010) *Science* 328: 483-486. [4] Krot et al. (2004) *MAPS* 39: 1517-1553. [5] Aléon et al. (2005) *MAPS* 40: 1043-1058. [6] Needham et al. (2017) *GCA* 196: 18-35.