Refractory-rich Materials in Comets: CAIs, Al-rich Chondrules and AOAs from Comet Wild 2 and a Giant Cluster Interplanetary Dust Particle (IDP) of Probable Cometary Origin and Comparison to Refractory-rich Objects in Chondrites D. J. Joswiak and D. E. Brownlee. University of Washington, Dept. of Astronomy, Seattle WA 98195 joswiak@astro.washington.edu

Introduction: Since the recognition of calcium-aluminum-rich inclusions (CAIs) in the 1960's [1], CAIs and other refractory-rich materials in chondrites have been extensively investigated providing valuable insights into early solar system materials and solar nebula evolution. In comets, only a few refractory-rich materials have been studied in detail [2-5] and no systematic investigation of the range and variability of refractory-rich materials has been done. Although some refractory inclusions have been found in individual stratospheric IDPs [6], their source regions are unknown. In comets, important questions to be answered include: Do comets contain the same types and ranges of refractory materials as chondrites? What chemical and physical properties do refractory-rich particles in chondritic meteorites and comets have in common? Do refractory-rich grains in comets have similar origins and evolutionary paths as counterparts in chondrites?

We studied six refractory grains from comet Wild 2 and a giant cluster IDP of probable cometary origin [7]. The comet particles consist of Ca, Al and Ti-rich minerals and are identified as CAIs, Al-rich chondrules and an AOA based on bulk compositions and mineralogy (see below). Here we report the results from our investigations and compare the particles to comparable materials in chondrites.

Methods: Six fine-grained particles (three from comet Wild 2 and three from U2-20GCP) with refractory minerals were examined. Each of the three Wild 2 grains, Inti (10 x 15 µm), F216 (~1 µm) and Bidi (4 x 6 µm), are from different aerogel tracks. The Inti particle is a new previously unstudied CAI fragment from track 25. The grains were prepared for TEM examination as described in [8,9]. Three refractory-rich transparent particles, P3-4 (7 x 14 µm), P1-1 (~4 x 7 µm) and LT1 (~7 µm) were obtained from > 30 handpicked grains from U2-20GCP. All six grains were individually mounted in acrylic resin and sectioned with a Leica ultramicrotome to thicknesses < 70 nm. Chemical compositions were obtained on the microtome sections with a Tecnai TF20 STEM equipped with an X-ray detector. Quantitative bulk compositions of each particle were measured by summation of irregular area-normalized rasters obtained from multiple microtome sections.

Mineralogy: A summary of the mineralogy of the six cometary particles is given in Table 1. The comet particles contain assemblages similar to those reported in type C CAIs, Al-rich chondrules and AOAs from chondrites [10-12]. The two CAI particles Inti and F216 are composed of concentrically-zoned minerals with spinel occupying the inner-most portions followed successively by anorthite (An) and Al,Ti-diopside. Both are mineralogically and texturally similar to fine-grained spinel-rich inclusions from the reduced CV3 chondrites Efremovka and Leoville [10,13]. In F216 minor amounts of melilite are present, typically associated with spinel or anorthite, while in the Inti fragment, melilite and perovskite were not observed though both minerals are found in minor amounts in other CAI fragments from track 25 [2]. In both CAIs sub 100-nm Ti,V nitrides were observed in anorthite.

The Al-rich chondrule P3-4 consists of nodules of anorthite (with spinel inclusions) surrounded by Al,Ti-diopside. Enstatite sporadically surrounds each nodule and is in contact with the feldspar and high-Ca pyroxene. Sub-100 nm euhedral Fe,Ni-metal nuggets containing Mo, Ru, Os, Ir and Pt were observed in the anorthite. The Al-rich chondrule P1-1 is composed of anorthite + Al,Ti-diopside + Fo_{99} olivine. Unlike P3-4, no inclusions were found. The third Al-rich chondrule, Bidi, is composed of a mixture of anorthite + Al,Ti-diopside + $Fo_{97\text{-}98}$ olivine. Further details of this chondrule are in [4].

The single AOA particle LT1 is modally dominated by $Fo_{90\text{-}95}$ olivine but also contains Al,Ti-diopside and minor anorthite [5]. Sub-100 nm refractory Fe,Ni metal nuggets containing Mo, Ru, Rh, Os, Ir and Pt were observed.

Bulk compositions: Bulk compositions obtained from the six comet grains are plotted in the Mg_2SiO_4-Al_2O_3-Ca_2SiO_4 phase diagram in Fig. 1 [11]. The particles extend from the anorthite (+spinel) primary phase volume toward olivine and parallel a portion of the trend calculated for equilibrium condensation of solids from a solar nebula gas. The two CAIs, Inti and F216, plot in the An + L primary phase volume and fall on or toward the Ca_2SiO_4 side of the An – Di join and overlap the bulk compositions of type C CAIs and fine-grained spinel-rich inclusions [10,13]. The Al-rich chondrules P3-4 and P1-1 plot near the anorthite-forsterite cotectic and fall in the region of the diagram with Al-rich chondrules in chondrites [11]. The bulk composition of P3-4 without enstatite was also measured. It falls near the An-Di join in the An + L field and close to type C CAIs. Texturally, this Al-rich chondrule is more similar to CAIs than chondrules. Bidi, the third Al-rich chondrule [4] is less refractory than P3-4 and P1-1 but also plots in the Al-rich chondrule field in the diagram, while LT1, an AOA, falls near the upper end of bulk AOAs.

Discussion: The six comet particles define a nearly linear array in Fig. 1 and are ~parallel to a late-stage portion of the calculated equilibrium condensation trend of bulk nebular solids at $P_{tot} = 10^{-5}$ atm [14] (green arrow, Fig. 1). The near coincidence between the equilibrium condensation trend and refractory materials in chondrites (CAIs and Al-rich chondrules) has been noted [11]. It is unclear whether Al-rich chondrules and type C CAIs, which converge near the An-Di join, represent a single trend or formed independently. We note that the bulk composition of Al-rich chondrule P3-4 from the giant cluster IDP plots close to the field of type C CAIs if its composition is measured without the enstatite rim material. This may be evidence that Al-rich chondrules are related to type C CAIs by the addition of Si-rich material as discussed in [11,14].

Comparison of the comet particles in Fig. 1 to the range of refractory inclusions shows that the most refractory materials in chondrites such as type A CAIs, hibonite-spinel and grossite-rich inclusions are conspicuously absent from the comet samples indicating that comets may have preferentially accreted second generation refractory materials that had been moderately processed in the nebula. This is an unexpected but intriguing result in light of suggestions that the particles that reach the comet accretion regions may represent a democratic sampling of solids that formed or were transformed in the hot regions of the nebula [15].

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Particle	Source	Spinel	Melilite	Olivine	Anorthite	Ca-pyroxene	Object type
Inti	Wild 2	✓	Ak_{3-16}	–	An_{97-100}	Al-Ti Diop	CAI
F216	Wild 2	Incl in An	Ak_{4-6}	–	An_{96-98}	Al-Ti Diop	CAI
P3-4	U2-20GCP	Incl in An	–	–	An_{94-96}	Al-Ti Diop	Al-rich chond
P1-1	U2-20GCP	–	–	Fo_{99}	An_{97-99}	Al-Ti Diop	Al-rich chond
Bidi	Wild 2	–	–	Fo_{97-98}	An_{94-100}	Augite	Al-rich chond
LT1	U2-20GCP	–	–	Fo_{88-94}	An_{98}	Al-Ti Diop	AOA

Table 1: Refractory particles from comet Wild 2 and a giant cluster interplanetary dust particle (U2-20GCP) which has a likely cometary source. Particles are listed in approximate order of decreasing volatility.

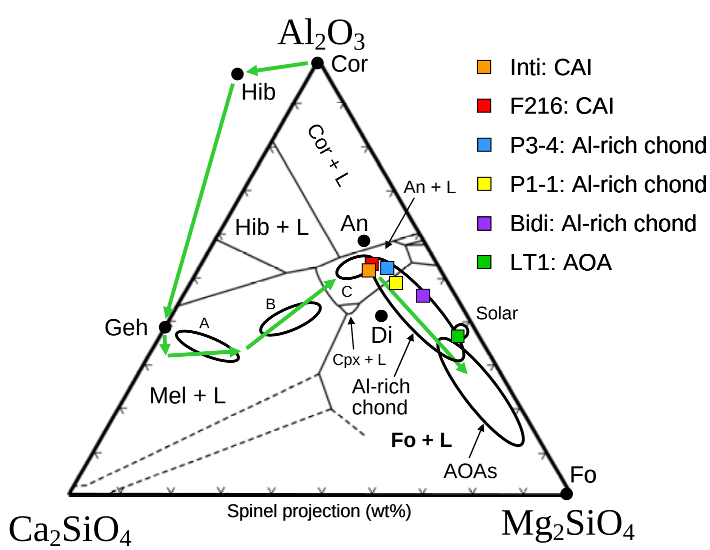

Fig 1: Bulk compositions of six fine-grained refractory comet particles projected from spinel on a Mg_2SiO_4-Al_2O_3-Ca_2SiO_4 phase diagram [10]. The comet particles fall on a linear array and are subparallel to the equilibrium condensation trend at $P_{tot} = 10^{-5}$ atm (green arrows) for type C CAIs and Al-rich chondrules [14]. The suite of comet particles noticeably does not include the most refractory materials observed in chondrites and may indicate that comets sampled materials from more evolved nebular reservoirs. A,B,C=type A, B, C CAI, respectively.