THE NATURE AND RELATIONSHIP OF COARSE AND THE MYSTERIOUS FINE MATERIALS COLLECTED FROM COMET WILD 2. D. E. Brownlee[1], D. Joswiak[1] and G. Matrajt[1]. [1]Dept. of Astronomy, University of Washington, Seattle, WA, 98196, brownlee@astro.washington.edu, joswiak@astro.washington.edu.

Introduction: The submicron (fines) component of comet Wild 2 remains poorly understood because it was systematically degraded during high speed capture in silica aerogel. The bulbous aerogel capture tracks returned by the Stardust mission provide insight into both the relationship between coarse and fine fractions as well as insight into the nebular processes that made these components and transported them to the edge of the solar system. Improved understanding of the nature and relationships between coarse and fine fractions is important for relating the Wild 2 results to meteorite, IDP, astronomical data & results from other comets including the upcoming Rosetta comet encounter.

Sorting & bulbous tracks: The aerogel capture process used to collect Wild 2 comet particles functioned as a remarkable sorting device. Because the cometary components were only weakly bonded to each other, the unintentional sorting process of capture provided a highly effective means of separating fine and coarse components, a process that is not simple to do in the lab, in an unambiguous manner, even for the most primitive meteoritic samples. In general, solid comet components that were larger than a few microns, depending on the track size, penetrated to the lower portion of capture tracks while smaller components stopped in the upper regions of tracks where they were strongly thermally modified due to their low thermal inertia, exposure to high power and contact with the SiO_2 melt that lined the upper hollow track walls.

Fine/Coarse ratio: Impacting particles that did not contain appreciable fines produced thin (type A) capture tracks while those that contained fines produced type B or C tracks with bulbous upper regions. Burchell et al. [1] showed that 70% of the tracks shorter than 0.5 mm (the most abundant tracks) were type A, implying that the major portion of impactors smaller than about ~5µm did not contain a major fines component. This contrasts common 5µm IDPs that are aggregates of submicron grains and implying that Wild 2 material is relatively coarse. This is may be misleading because most of the total collected mass is probably in the largest bulbous tracks that have not yet been studied. Track volume is a good indicator of projectile mass [1] and bulbous tracks are the most voluminous. The proportion of bulbous tracks increases with length [1] implying that impactors >5µm were often composite and contained abundant fines or materials that disintegrated during capture. In all the tracks that that we have worked on, all of the deeply penetrating materials are either mineral grains or solid polymineralic materials [2]. None were aggregates of fines and capture clearly separated the comet material into its fundamental components. The Stardust impact detectors showed that large Wild 2 and Tempel 1 particles were loose aggregates disintegrating in the coma [3]. These aggregates were too fragile to survive capture intact.

Coarse-fine comparison: The >micron components are often very well preserved. They are often encapsulated by compacted unmelted aerogel, a protective cocoon that aided particle preservation with very sharp contacts between the sample and compacted aerogel. The study of these well preserved larger grains is providing a reasonably straightforward and highly detailed assessment of the relatively coarse-grained solid materials that accreted to make this comet. To date, all of the particles of >micron particles have solar system isotopic compositions and they appear to be nebular products from hot regions of the disk that were then transported to the edge of the solar nebula where Wild 2 accreted. The coarse-grained fraction clearly contains components that are closely related to chondrules, refractory inclusions and condensates. The chondrule components include both type I and type II chondrules as well as refractory chondrules. It seems likely that chondrule fragments of various types are a major source of the coarse-grained fraction. Evidence for condensates include LIME olivines (Mn-enriched forsterite) and phases containing nanophase inclusions of refractory metal nuggets and osbornite.

TEM coarse/fines studies: We are exploring the relationship between fine and coarse fragments by detailed TEM examination of components in large bulbous tracks, particularly tracks 77 and 149. Track 149 is the largest that we have processed and it is 4mm long and its deepest penetration made by a 22µm Fo_{86} olivine grain. The volume of the 650 µm wide bulb of this track is 40 times that of the thin cone-shaped track made by the 22µm terminal particle, suggesting that about 98% of the >100µm impactor was composed of either fines or unstable material.

These tracks were processed by flattening and embedding the entire track in a thin refractive index matching acrylic slab so that grains larger than 0.5 µm can be seen with high numerical aperture optical microscopes and clearly distinguished from compressed or melted aerogel. Fragments larger than a few microns are cut out of the slab and microtomed. The regions dominated by fines are studied by bulk microtomy but this is greatly hampered by the low particle spatial density even in highly compressed tracks.

Hot HF vapor etching: To more effectively concentrate fines in bulb regions, we have developed a new method where we remove all melted and compressed aerogel with >100 ºC HF vapor. Above 100 ºC, water is not formed by the conversion of silica to SiF_4. The dry HF processing removes aerogel and does not redistribute samples or alter olivine below the outer few atomic layers. Etching of compressed track slabs is done on optically flat sapphire disks. The etching converts a 100µm aerogel slab to a micron thick layer of fine comet particles that is then embedded in acrylic and microtomed into 50 nm TEM sections. TEM studies show both similarities and differences between coarse and fine materials but we were most impressed by the similarities. To first order, the preserved fines are similar to >5µm grains implying that unmelted fines are similar to the coarse fraction. Fig. 1 shows Mn and Fe abundances in 43 olivine grains from tracks 77 & 149. The grains ranged in size from <0.5µm to >20µm but we do not see a significant dependence between size and composition. Neither of these tracks have olivines that show the strong correlation between Mn and Fe seen in OC, CR, CO and CM chondrule ferrous olivines [4], indicating that Wild 2 olivines could not be dominated by chondrule fragments from any of these sources. It is interesting that unequilibrated olivine populations in the tracks differ in the range of Fe content and the two tracks also differ in ratios of Fo/En. Is possible the differences are due to fragmentation of larger grains in the track but we did not see clear evidence for this.

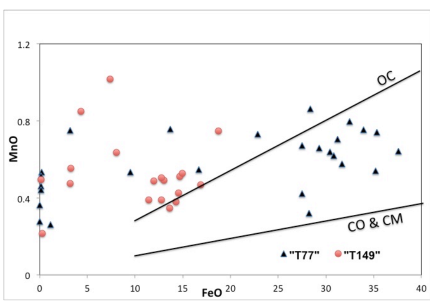

Figure 1 Mn compositions for coarse and fine olivine from tracks 77 and 149.

Melted fines: The fines in bulbous track walls are difficult to directly study because many of the silicate fines melted and mixed with melted silica aerogel while metal and sulfides dispersed as fine immiscible beads. Unlike the case for larger particles, the submicron fraction often was in contact with larger masses of >1700 ºC silica. Bulb regions do contain unmelted <µm grains of olivine and pyroxene and other phases, but as has been previously pointed out [5], the survival of small grains is biased and strongly material dependent. It appears that most of the fines melted and were probably dominated by phases more easily melted than Mg-rich of olivine or pyroxene. What was the bulk of the fines and why did it melt and become diluted by molten silica? Two obvious possibilities are phyllosilicates and amorphous silicates such as GEMS (Glass with Embedded Metal and Sulfide) [6]. GEMS are common fines in anhydrous IDPs and possible altered GEMS have been seen in the most primitive chondrite matrix [7]. Phylloslicates are a possibility but they have not been definitively observed in Wild 2 samples. Zolensky et al. [8] have discussed reasons why they are unlikely to be a major phase even though they might be a minor phase, consistent with magnetite seen in some tracks [9]. The abundance of anhydrous phases in both Wild 2 samples and chondritic porous IDPs argues against pervasive aqueous alteration in Wild 2 and many other comets. Parent body aqueous alteration products, including phyllosilicates, magnetite and carbonates formed in many solar system planetesimals, including large Kuiper belt objects and their collisional fragments were likely accreted by all comets.

Conclusions: Although much is known about Wild 2 grains larger than a few microns, the true nature of the fine component that rapidly decelerates and produces bulbous aerogel tracks remains somewhat enigmatic. The melted "missing" fines are important because they are likely to be a major cometary component and one that strongly influences remote sensing and insitu data taken with telescopes and landed instruments. Our data suggests that the unmelted fines are related to the coarse fraction but that the melted fines are something else. The typical fines differ from the coarse fraction and unmelted fines because they more easily melted and because they appear to have chondritic elemental composition and something that the coarse fraction does not.

Besides work on aerogel tracks, continued work on residue in Al foil impact craters [10] from the Stardust collector can provide direct information on the composition of submicron fines. We believe the understanding the fines will require a careful combination of track and microcrater studies along with studies of the well preserved fines in selected IDPs that can be shown to be closely analogous to Wild 2 samples. The minor abundance of presolar grains in the fines [11] implies that most formed the solar system and it is fascinating that they may have a quite different origin than the coarse fraction.

References: [1] Burchell, M. J. et al. (2008) *Meteoritics & Planet. Sci., 43, 23.* .[2] *Joswiak, D. (2012) MAPS 47,471.* [3] Green, S. F. et al. (2011) *EPSC-DPS Joint Meeting* 2011 1122. [4] Berlin, J. (2011) MAPS 46, 513. [5] Leroux, H.(2012) MAPS 47, 613. [6] Ishii H.A. et al. 2008. *Science* 319:447. [7] Keller, L. & Messenger*, S. (2012) LPS 43, 1880.* [8] Zolensky, M. et al. (2008) *MAPS,43, 261.* [9] Stodolna et al. (2012*) GCA 87,35.* [10] Kearsley, A. et al. (2008) *MAPS, 43, 4.* [11] Floss et al. (2012) *Meteoritics & Planet. Sci. Supp. 75, 5143.*