DOES COMET WILD-2 CONTAIN GEMS?

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Introduction: It is expected that Comet Wild-2 dust should resemble anhydrous carbon-rich, chondritic porous (CP) interplanetary dust particles (IDPs) collected in the stratosphere because some CP IDPs are suspected to be from comets [1,2]. The rarity of carbonaceous grains and presolar silicates, as well as the presence of high-temperature inner solar nebula minerals in the Wild-2 sample (e.g. osbornite and melilite), appear incompatible with most CP IDPs [3-5]. However, it is premature to draw firm conclusions about the mineralogy of comet Wild-2 because only ~1% of the sample has been examined.

The most abundant silicates in CP IDPs are GEMS (glass with embedded metal and sulfides) [6]. Non-solar O isotopic compositions confirm that at least some GEMS in IDPs are presolar amorphous silicates [7,8]. The presence or absence of GEMS in the Wild-2 sample is important because it addresses, (a) the relationship between CP IDPs and comets, and (b) the hypothesis that other GEMS in IDPs formed in the solar nebula [9]. Here we show that most of the “GEMS-like” materials so far identified in Stardust aerogel were likely impact generated during collection. At the nanometer scale, they are compositionally and crystallographically distinct from GEMS in IDPs.

GEMS in IDPs: Most GEMS are 0.1-0.5 μm amorphous silicate spheroids [6,10]. Their bulk compositions are typically within a factor of ~3 chondritic [9]. They contain nanometer-sized inclusions of body centered cubic (bcc) low-Ni α-iron (kamacite) and low-Ni hexagonal pyrrhotite embedded in Mg-silicate glass [6,10,11]. Some GEMS contain “relict” sulfide and silicate crystals [6,10]. Often GEMS have Fe_3O_4 rims, a result of heating during atmospheric entry. Truly pristine GEMS may be rare in IDPs.

GEMS in comet Wild-2?: “GEMS-like” material is abundant in the Stardust tracks. Figure 1 shows a 200 keV darkfield image of a “GEMS-like” object in a ultramicrotomed thin section of a track in aerogel. The matrix is amorphous ~SiO_2, but in other cases, the silicate matrices contain up to 15 atomic % Mg, 5 % Al and 0.3 % Ca. The inclusions are Fe(Ni) sulfides and Fe(Ni) metal. Fe, Ni and S contents of the sulfides are highly variable. Some sulfides also contain Cu (Fig. 2) and Cr. Stoichiometric sulfides exhibit lattice parameters consistent with low-Ni hexagonal pyrrhotite. Sulfide grains with reduced metal cores are common (Figs 3a & 3b). Fe:Ni ratios in the metal are variable (up to ~ 40 at. % Ni) and some contain Cr. Two Fe(Ni) metal crystal structures have been identified, low-Ni bcc α-iron (kamacite) and high-Ni fcc γ-iron (taenite) (Fig. 4).

Discussion: The “GEMS-like” material in Stardust impact tracks differs significantly from GEMS in IDPs. First, the amorphous matrices are often almost pure (Mg-free) SiO_2. Second, the metal inclusions include both α and γ structures with a range of Fe:Ni ratios (Figs 3a & 4), and some contain Cr. Third, Fe(Ni) sulfide inclusions exhibit a range of Fe, Ni and S contents, and some contain Cu and Cr. Fourth, sulfide inclusions often have reduced cores (Figs. 3a & 3b).

It is possible that the above differences reflect modification of Wild-2 GEMS during hypervelocity impact into aerogel. However, much of the “GEMS-like” material was produced *in-situ* when comet grains decelerated in the aerogel. It is noteworthy that Cu (and Cr) are present both in sulfide inclusions in the “GEMS-like” material (Fig. 2) and in discrete cubanite (CuS) and Cu-rich Fe(Ni) sulfide crystals in the tracks [4]. Some sulfides melted or fragmented and were incorporated into aerogel “snowballs”, others melted and recrystallized as droplets, others melted with loss of S and *in-situ* reduction of Fe^{2+} and Ni^{2+} to metallic Fe(Ni) (Figs. 3a & 3b). In extreme cases, sulfides lost both S and Fe leading to highly Ni-enriched sulfides.

More interesting are Mg-rich “GEMS-like” materials in Stardust [12]. The simplest explanation is that they formed during impact when cometary Mg-rich silicates (glasses or crystals) *and* sulfides melted and mixed with aerogel. Another is that they are in fact GEMS from Wild-2, and this possibility cannot yet be ruled due to the limited statistics available.

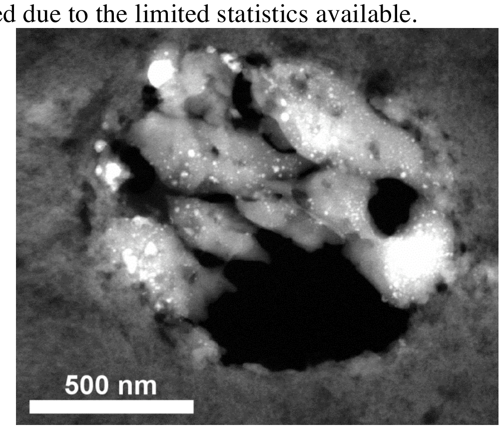

Fig 1: High angle annular darkfield (HAADF) image of “GEMS-like” object in a Stardust impact track in aerogel.

Conclusion: Our early PET observations established that "GEMS-like" materials are widespread in the Stardust sample [4,12]. However, the nanoscale properties of this material (Figs. 1-4) are distinct from those of GEMS in IDPs, which underscores the limitations of interpreting nanomaterials based on appearance and bulk properties alone. Most and possibly all of the "GEMS-like" material so far identified in the Stardust tracks formed *in-situ* during hypervelocity impact of sulfides and silicates into the Stardust aerogel. If it ultimately turns out that there are no GEMS in the Wild-2 sample, a hot solar nebula origin for some of the GEMS in IDPs [9] is less probable.

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Acknowledgement: This work was in part performed under the auspices of the U.S. Department of Energy, NNSA by the University of California, LLNL under contract No. W-7405-Eng-48. This work was also supported by NASA grant NNH06AD67I to JPB at LLNL.

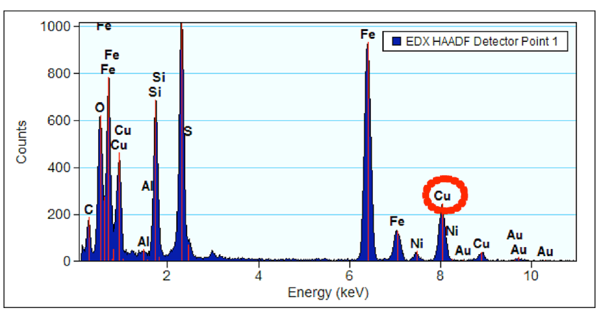

Fig 2: Energy-dispersive x-ray spectrum of a Cu-containing FeNi sulfide inclusion in "GEMS-like" material in Stardust aerogel. (Specimen is mounted on a gold grid). Cu-bearing sulfides have not yet been identified in GEMS in IDPs.

Fig 4 (right): Lattice-fringe image of a ~12 nm diameter fcc γ-FeNi (taenite) crystal (~16.8 at. % Ni) in "GEMS-like" material in Stardust aerogel. The FFT of the image (lower left) indicates the [011] zone axis. Taenite has not yet been identified in GEMS in IDPs.

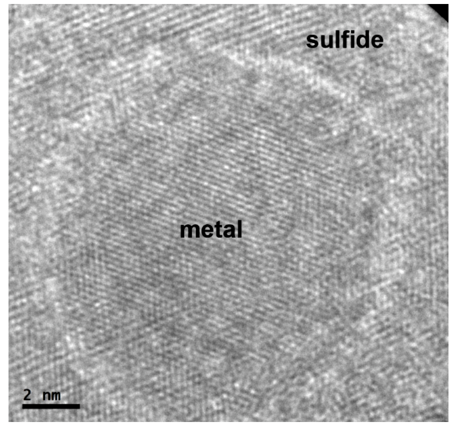

Fig 3a: Lattice-fringe image of an FeNi metal grain (~ 4.8 at. % Ni) at the core of a sulfide crystal (see also Fig 3b).

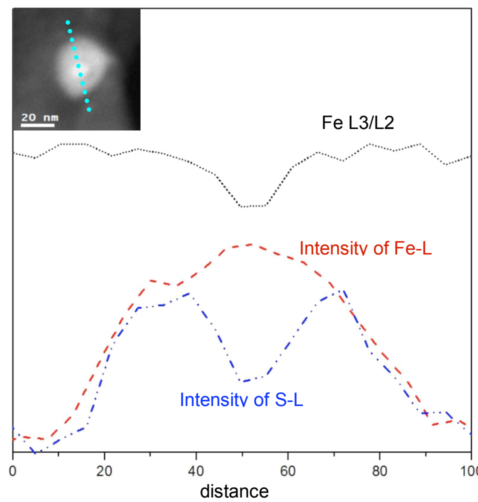

Fig 3b: Intensity profiles of S and Fe L-edges from an EELS line-scan across the sulfide crystal with a metal grain in the core (inset, dashed line is the trace of the line scan). The profile of Fe L3/L2 ratio confirms that Fe in the core has a lower valency than the surrounding sulfide. Sulfide crystals with metal cores have not yet been identified in GEMS in IDPs.