

COOKED GEMS — INSIGHTS INTO THE HOT ORIGIN OF CRYSTALLINE SILICATES IN CIRCUMSTELLAR DISKS AND THE COLD ORIGIN GEMS. D. E. Brownlee¹, D.J. Joswiak¹, J. P. Bradley², G. Matrajt¹ and D.H. Wooden³, ¹Astronomy Dept. 351580, Univ. of Washington, Seattle, WA 98195, ²Lawrence Livermore National Lab., Livermore, CA 94035, ³NASA Ames, 245-3/245-6, Moffet Field, CA 94035. Email brownlee@astro.washington.edu

The comparison of interstellar, circumstellar and primitive solar nebula silicates has led to a significant conundrum in the understanding of the nature of solid materials that begin the planet forming processes. Crystalline silicates are found in circumstellar regions around young stars and also evolved stars ejecting particles into the interstellar medium (ISM) but they are not seen in the interstellar medium itself [1], the source material for star and planet formation. Crystalline silicates are minor to major components of all known early solar system materials that have been examined as meteorites or interplanetary dust samples. The strong presence of Mg-rich crystalline silicates in Oort cloud comets [2] and their minor presence in some Kuiper belt comets [3] is also indicated by 11.2 μ m peak in \sim 10 μ m “silicate” infrared feature. This evidence strongly indicates that Mg-rich crystalline silicates were abundant components of the solar nebula disk out to at least 10 AU, and present out to 30 AU [4].

The apparent lack of crystalline material in the ISM is remarkable but consistent with predicted effects of sputtering and irradiation. Low-energy particles (4 to 50 keV) in supernova shocks, can completely amorphize submicron crystalline silicates [5,6]. The presence of crystalline silicates in protoplanetary disks is often attributed to devitrification (annealing in astronomical literature) due to heating to \sim 1000K either close to the star or in regions heated by shocks. Harker and Desch [7] discussed the feasibility of shocks in the 5–10 AU region producing crystalline silicates and also discussed difficulties of either process producing crystalline silicates in regions of the nebula where short period comets formed. The wavelength positions of the spectral features in the 10–50 μ m region of comet Hale-Bopp and protoplanetary disks indicate that the crystalline silicates are nearly pure Mg end-members (Fo $>$ 90 and En $>$ 90) [8]. Also, the radiative equilibrium temperatures of the cometary crystals are consistent with their high Mg content [7]. On the other hand, ISM amorphous silicates are deduced to be iron bearing [1]. Thus, a difficulty with the annealing hypothesis is the Mg-rich crystalline silicates cannot be formed from iron bearing amorphous precursors. Although not detected astronomically, the presence of crystalline presolar silicate grains in meteorites,

micrometeorites and IDPs [9] proves that crystalline silicates are at least a minor component of the ISM.

To provide sample-derived insight into the concept of nebular annealing of initial amorphous silicates, we did heating experiments on GEMS, primitive components of IDPs that are largely composed of amorphous silicate and with roughly chondritic major element abundances. We mounted micotome slices of GEMS on carbon films supported by gold grids. These were examined in the TEM before heating, and then they were placed in quartz holder and heated for several hours in pure flowing nitrogen at one atmosphere pressure. The samples begin to show heat related changes at 700 °C and severe transformation at temperatures between 800 and 850 °C that actually led to melting. At just about 700 °C the typical GEMS texture of silicate glass with fine embedded metal and sulfides transforms to an igneous-like texture of silica rich glass and prominent subhedral to euhedral grains of moderately iron rich olivine and pyroxene. At such a temperature, this remarkable transformation occurs by sub-solidus processes. While some GEMS contain relict silicate grains, they are subtle and quite unlike the distinct minerals seen in the heated samples. The observed 1000K temperature for the onset of divitrification is similar to laboratory studies done on synthetic analogs [10,11].

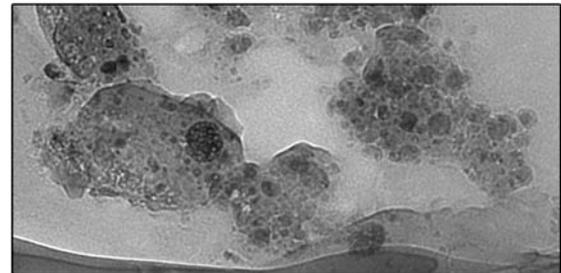
The transformed igneous-like texture is seen in whole IDPs and in minor sections of IDPs and it is often referred to as equilibrated aggregate or coarse grained silicate material. It often contains relatively Fe rich olivines surrounded by a very silica rich glass. We now believe that these previously mysterious pre-atmospheric heating components are likely to be GEMS transformed by heating above 900K. We also believe that the mysterious silica-rich spots seen in EDX point count analyses of anhydrous IDPs are also likely to be formed by sub-solidus thermal transformation of amorphous silicates.

The dramatic and abrupt thermal transformation of GEMS, including their loss of fine grained metal is strong evidence that GEMS in IDPs were not heated above 900K either in shocks or by passage into the inner warm regions of the solar nebula. The observed silicate grains are moderately Fe rich and it

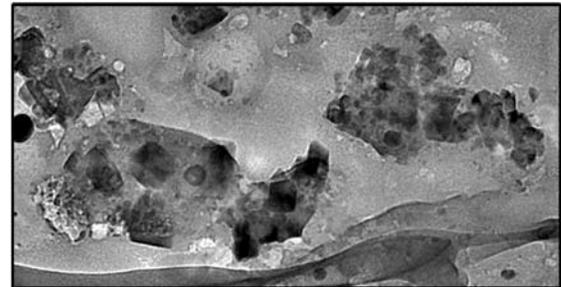
is not apparent that the thermal transformation of GEMS or other natural radiation processed Fe bearing silicates can produce either Fo or En. The heated GEMS are largely devoid of metal and the oxidation of GEMS metal provides an important clue on the origin of GEMS. The annealing of GEMS produces crystals that are too Fe-rich to account for the Mg-rich cometary crystalline silicates. Furthermore, the preponderance of GEMS and not coarse-grained silicate materials in IDPs indicates that most of the subgrains in chondritic porous IDPs were not heated above 900 K. This indicates that a substantial fraction of IDP subgrains neither originated nor were not transported from hot regions of the nebula nor subject to shock heating.

Future heating experiments may clarify the mechanism(s) of formation of GEMS. If all GEMS formed by a common mechanism they may transform or even melt over a relatively narrow temperature range. However, if there are multiple populations of GEMS formed by different mechanisms each population should melt at significantly different temperatures.

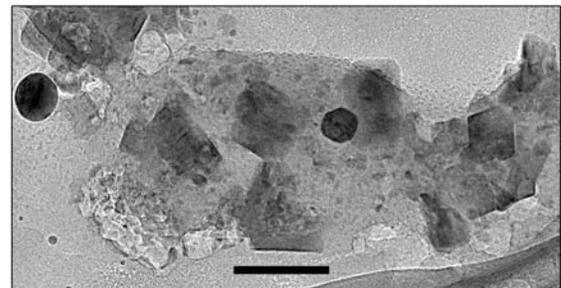
[1] Kemper F. et al. (2004) *Astrophys. J.* 609, 826-837. [2] Wooden D. H. et al. (2004) *ApJ.* 612, L77-80. [3] Reach W. T. (2004) AAS/Division for Planetary Sciences Meeting Abstracts 36. [4] Morbidelli A. and Levison H.F. (2003) *Nature* 422, 30-31. [5] Carrez, P. et al. 2002, *MAPS*, 37, 1599-1614. [6] Demyk K. et al. (2004) *Astron. & Astrophys.* 420, 233-243. [7] Harker D. E. and Desch S. J. (2002) *Astrophys. J.* 565:L109-L112. [8] Fabian D. et al. (2001) *Astronomy and Astrophysics* 378, 228-238. [9] Messenger S. et al. (2003) *Science* 300, 105-108. [10] Thompson S. P. et al. (2003) *MAPS* 38, 457- [11] Hallenbeck S. L. et al. (1998) *Icarus* 131, 1998.



Initial - U217B19 GEMS13



After heating to 970K



Enlargemen of above bar = 100nm