Nebular Alteration and GEMS
Z. Gainsforth (zackg@ssl.berkeley.edu)\textsuperscript{1}, A. L. Butterworth\textsuperscript{1}, A. J. Westphal\textsuperscript{1},
\textsuperscript{1}Space Sciences Laboratory, University of California at Berkeley, 7 Gauss Way, Berkeley, CA, 94720

Introduction:

IDP L2071 Cluster 17 Particle 3 contains GEMS and GEMS-like particles that show evidence of sulfidation as a nebular alteration. GEMS have rounded edges, an amorphous silicate matrix and nanocrystalline Fe and FeS beads. They are approximately chondritic in elemental composition, but with systematic depletions in O, Mg, S, Cr, Fe and Ni, all with respect to Si, and systematic ratios between various elements, e.g., the ratio Fe/Ni = chondritic though both are depleted relative to Si [1]. Recent work has shown that many irregularly shaped GEMS are actually aggregates of smaller subunits [4], and must therefore have undergone some degree of alteration. Some objects found recently in the Stardust collection may be related to GEMS [2].

Observations:

GEMS: The GEMS has an Mg-rich core with spherical sulfides inside. Many of the sulfides have attached taenite blebs. Mg-rich cores have been seen in other GEMS [3, 4]. The average composition matches GEMS for Al, Mg, Ca, S, Fe, Ni, Cr and Ti normalized to Si. The average Fe/Ni ratio of the GEMS is 18, chondritic. The sulfide has an Fe/Ni ratio of 55, and is therefore depleted in Ni relative to the rest of the GEMS. With HRTEM imaging we found a metal/troilite epitaxial relationship: taenite (111) || FeS (114).

GEMS-like: The GEMS-like object is located one micron away from the GEMS on the TEM grid. It has two vesicles: one contains a >100 nm sulfide inclusion similar to the one seen in the GEMS, and the other contains a >100 nm phosphide inclusion. The bulk Fe/Ni ratio is 12, and the average composition is GEMS-like in Al, Mg, Ca, S, Fe, Ni, Cr, and Ti, normalized to Si. The phosphide inclusion has a sulfide attached.

Discussion:

These two objects appear to be related due to their proximity and the common appearance of the sulfides. The first contains all the signatures we would expect to see in a GEMS but the vesicles in the second object suggest strongly that it is not a GEMS.

Irradiation origin: GEMS are hypothesized to form via irradiation in the interstellar medium [6]. The GEMS-like object is hard to explain by an irradiation origin because there is no obvious mechanism for irradiation to produce large smooth vesicles without also producing numerous small vesicles. Therefore, it seems unlikely that these objects formed via an irradiation origin.

Reduction of sulfides: Could the taenite form from heating a GEMS-like precursor: sulfides within a silicate matrix? Heating in vacuum could partially reduce sulfides to metal through loss of S. However, the Ni-content of the metal is 20x higher than the Ni content in the sulfide. We are not aware of any experiment that suggests such a partition should occur during reduction, but cannot rule it out.

Sulfidation of a precursor: They could be formed by sulfidation of silicate containing Fe-Ni metal in a region of the interstellar medium or solar nebula where S was in the gas phase [7], or could have formed by condensation [4]. If H₂S gas in the Solar nebula reacted with the metal inside a GEMS-like precursor it should have produced troilite [8]. Our recent work [9] on the samples from [5] found that sulfidation of Fe foil at temperatures near 500 °C produced Ni-rich metal as Fe was consumed into sulfide but Ni was not. It also produced P-enhanced regions, some of which became schreibersite a few hundred nm wide. On a foil sulfidized at 400 °C we observed a similar epitaxial relationship: BCC Fe (110) || FeS (114). Note that BCC Fe (110) has a similar d-spacing to FCC Fe (111).

The metal grains could have sulfidized in the nebula and then become embedded in the silicate later. However, there is no known mechanism for condensing silicate below the temperature of sulfide formation. Most likely, the precursor object was a silicate with embedded metal grains and was subsequently sulfidized.

References:


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Experimental:

We examined the sample using Transmission Electron Microscopy (TEM) at the National Center for Electron Microscopy at the Lawrence Berkeley National Laboratory. We used an FEI Titan TEM with beam voltages between 80-200 keV for imaging, electron diffraction and a 0.6 sr EDS detector for elemental mapping. We also used a Zeiss Libra 200MC TEM operating at 200 keV with an in column Omega energy filter for imaging and diffraction.

TEM brightfield image of a GEMS-like object containing a sulfide bead, phosphide bead, and vesicles. (A) Inset EDS map with Fe (red), S (green), P (blue) shows phosphide-rich core with sulfides surrounding. (B) Inset EDS map with Mg (red), Ni (green), S (blue) showing a second sulfide planet in a vesicle.