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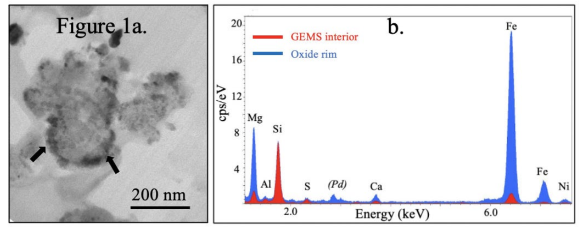

Significance of the elemental and isotopic compositions of GEMS

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Sub-solar element/Si ratios in GEMS have been interpreted as indigenous and indicative of high-temperature, vapor phase condensation in the solar nebula [1]. However, GEMS are high surface-area, mostly amorphous nanomaterials inherently predisposed to secondary alteration. We have investigated the causes of sub-solar element/Si ratios in GEMS by employing recent advances in analytical electron microscopy, specifically combined energy-dispersive X-ray spectroscopy and electron energy-loss spectroscopy and spectrum imaging with single-nanometer-scale spatial resolution. We find that the sub-solar element/Si ratios are caused by a combination of terrestrial contamination and pulse heating during atmospheric entry that causes Fe in pyrrhotite inclusions to oxidize, and Mg, S, Ca, and Fe to become depleted relative to Al and Si. Fe-rich oxidized rims, that form on the surfaces of some GEMS during atmospheric entry, trap outgassing elements and serve as “witness plates” to the changes in element/Si ratios that accompany atmospheric entry (Fig. 1). Although sub-solar element/Si ratios in GEMS are not informative about their origin, their isotopic compositions are informative: Most GEMS fall close to the terrestrial oxygen isotope composition, consistent with the expected bulk average composition of presolar interstellar dust [2]. $^{15}N/^{14}N$ ratios indicate that GEMS accreted together with organic matter subjected to ion-molecule reactions [3]. Collectively, GEMS' properties are consistent with cold (>50 K) accretion in the extreme outer nebula and interstellar environments.

References: [1] Keller & Messenger (2011) *Geochim. Cosmochim. Acta* 75, 5336–5365. [2] Zhukovska, Gail & Trieloff (2008) *Astron. Astrophys.* 479, 453–480. [3] Ishii, Bradley, Bechtel, Brownlee, Bustillo, Ciston, Cuzzi, Floss, & Joswiak (2018) *Proc. Natl. Acad. Sci.* 115, 6608–6613.

Figure 1: (a) Brightfield image of oxide rim (arrowed) on GEMS. (b) EDX spectra (normalized to Si) from a GEMS' interior and oxidized rim.