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Amorphous Silicate Building Block Origins by Transmission Electron Microscopy

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As remnants of planet formation, samples of small solar system bodies are our best-preserved “fossils” from the solar system’s birth and include comet and asteroid samples returned to Earth by spacecraft and primitive meteorites, interplanetary dust particles (IDPs) and micrometeorites (MMs) that arrive via Earth-crossing orbits. These natural ‘astromaterials’ contain highly complex, extremely fine-grained aggregates of amorphous grains, crystalline minerals and organic matter, each potentially formed in very different astrophysical environments, including the hot solar nebula (>1000K) and cold presolar molecular cloud (<50K), by a variety of mechanisms prior to accretion into parent bodies. Superimposed on these components are secondary alteration effects of parent body processes, exposure to space and terrestrial environments, and the sample recovery process itself. Unravelling the complexity and overprints to address questions of formation environments of components and of parent bodies are key challenges. Of the components in these primitive samples, amorphous silicates (*a*-silicates) are a major focus of our current research because (1) they are among the least-understood astromaterials, (2) they occur in highest abundance in the most cosmically primitive IDPs and MMs, and (3) they are also the most abundant condensed solid in the interstellar medium from which planets form, suggesting an intriguing connection between some IDPs, MMs and dust grains in the interstellar medium [1-4].

Two recent advances in analytical electron microscopy, in particular, monochromated electron energy-loss spectroscopy (EELS) and multi-detector, high solid-angle, energy-dispersive x-ray spectroscopy, have been very revealing. Using FEI Titan TEM/STEMs at University of Hawaii and at the Molecular Foundry, LBNL, we used low-loss (0-30 eV) EELS to investigate various mechanisms of formation of *a*-silicates and the effects of space weathering by comparing local solid-state bonding environments [5]. Irradiation by energetic H and He in the solar wind (and galactic cosmic rays) causes structural and chemical changes, e.g. amorphization and preferential elemental sputtering of crystalline silicates. Access to the low-loss H-K and He-K core scattering edges provides evidence of space weathering phenomena on airless bodies. Finally, we are using multi-detector EDX platforms to rapidly map compositions and mineralogy of *a*-silicate grains in IDPs with nanometer spatial resolution, high sensitivity and low beam currents to better understand their petrographic relationships with other grains.

Figure 1 shows low-loss EELS spectra from irradiation-damaged SiC (Fig 1a, [6]) and *a*-silicates formed by high-temperature vapor phase condensation and irradiation damage (Fig. 1b-c). The irradiated SiC illustrates that amorphization by irradiation imparts characteristic low-loss fine structures. Similar fine structures are observed in spectra of *a*-silicates formed by irradiation and in IDPs (Fig. 1d), likely due to generation of dangling bond ‘defects’, but not those formed by vapor phase condensation. The H-K edge shown in Figure 1e is from H_2O/-OH in the *a*-silicate surface of an IDP exposed to the solar wind for 10^4-10^5 years; the He-K edge is from a vesicle at the surface of a He-irradiated silicate mineral [5]. Figure 2 shows an example of EDX spectral mapping in a thin section of an IDP to explore *a*-silicate grain compositions, textures and relationships with other IDP components.

TEM studies of minimally-altered, primitive samples provide new insight into the origin and evolution of solar system bodies, input for astrophysical dust modeling and interpretation of astronomical observations. Low-loss EELS provides a robust method for distinguishing formation mechanisms for *a*-silicates. H-K and He-K, diagnostic of space weathering amorphization, are also observable in this region. Finally, multi-detector EDX spectral maps allow petrographic visualization *at the nanometer scale* and quantitative analysis for a holistic understanding of *a*-silicates in these primitive materials [7].

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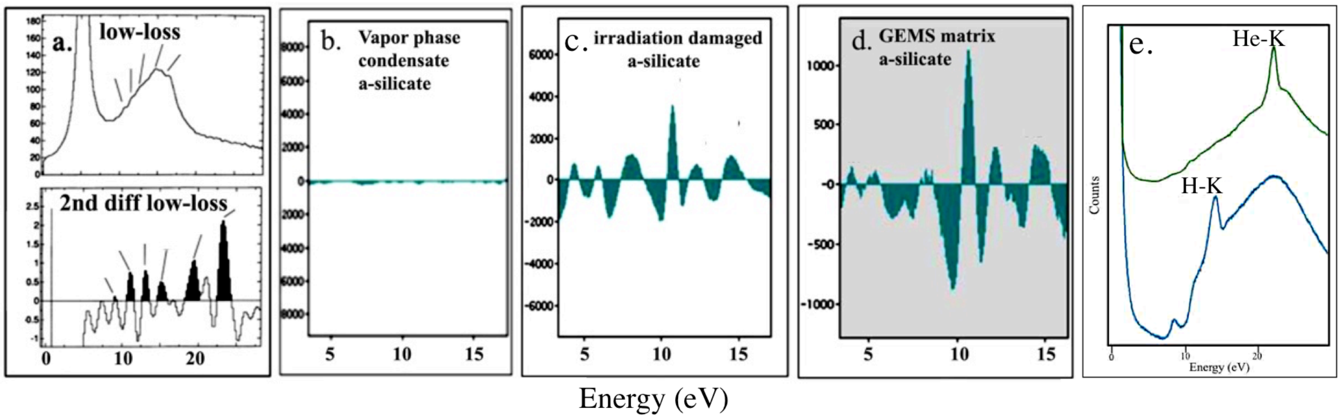

Figure 1. (a) Spectrum and second derivative from H^+/ He^+- irradiated SiC [6]; 2nd derivative spectra from (b) vapor-condensed, (c) irradiated, and (d) IDP *a*-silicates [4]. (e) H- and He-K edges in silicates.

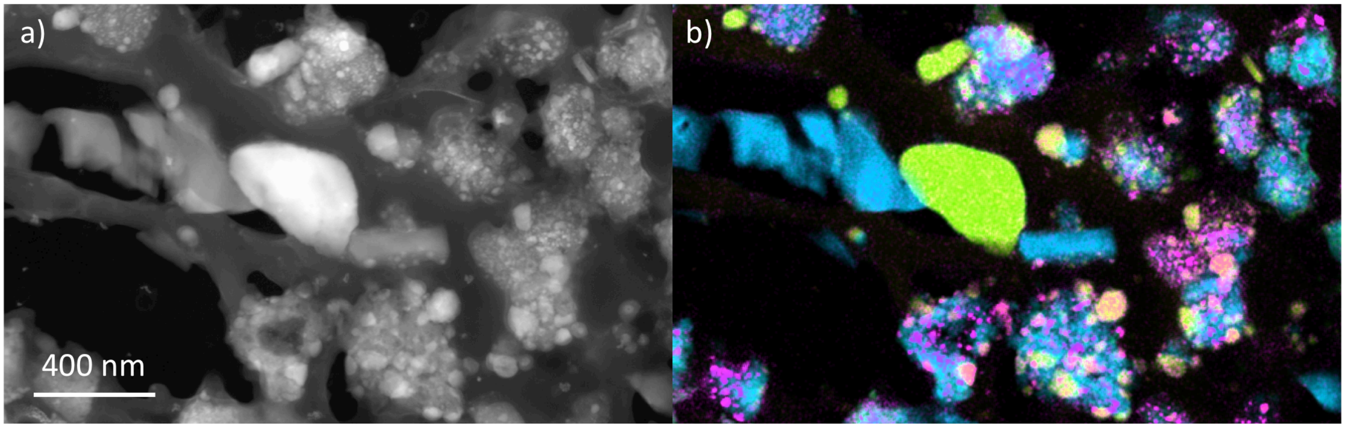

Figure 2. *a*-silicates in IDP U217B18. (Left) 200 keV HAADF STEM image. (Right) EDX map acquired at 200 kV, 0.7 nA with 3.3 nm pixels and 3-pixel averaging. (Blue, yellow, green, magenta=Mg, S, Fe, Ni.) Scale bar is 500 nm.