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Mineralogical Studies of Silicate Stardust in the Laboratory

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Silicate dust is pervasive throughout the cosmos and has been observed in interstellar space, around evolved oxygen-rich stars, protoplanetary disks, and in our Solar System. The chemical and physical properties of this dust have traditionally been inferred through remote astronomical observations. Spectral observations of circumstellar dust indicate mainly amorphous, Fe-bearing grains having non-stoichiometric compositions intermediate between olivine and pyroxene compositions (Molster and Kemper, 2005; Tielens et al., 1998; Sargent et al., 2010), and variable proportions of extremely Mg-rich crystalline pyroxene and olivine (de Vries et al., 2010; Molster et al., 2002). Spectral data for dust originating from supernovae and novae are scarce and suggest that these sources mainly produce Mg-rich amorphous silicates (Arendt et al., 2014; Evans et al., 1997). Crystalline silicates are rare in the diffuse ISM (<1%; Kemper et al., 2004), most likely due to grain amorphization and destruction in the ISM (Jones and Nuth, 2011).

The discovery of preserved silicate stardust grains in meteorites, interplanetary dust particles (IDPs), and dust returned from comet Wild 2 by NASA's Stardust mission has allowed for direct, detailed study of individual grains of silicate stardust in the laboratory. This has essentially opened new windows into the fields of astrophysics and astromineralogy. The exotic isotopic compositions of these silicate stardust grains, determined by isotopic mapping with the NanoSIMS ion microprobe, reflect origins in asymptotic giant branch stars, supernovae, and novae. We have performed coordinated isotopic, chemical and mineralogical characterization of these ~100–500 nm-sized grains by NanoSIMS and transmission electron microscopy (TEM) analyses. Microtome sections of IDPs are first analyzed by TEM and isotopically anomalous grains are subsequently identified by NanoSIMS isotopic mapping. Stardust grains in meteorites are first identified by NanoSIMS analysis, and grain cross-sections are then prepared by focused ion beam (FIB) milling for TEM analysis.

Our studies show that the majority of the silicate grains are amorphous with non-stoichiometric Fe-bearing chemical compositions, generally consistent with astronomical observations (Nguyen et al., 2016). However, approximately 1/3 of the analyzed grains were found to be crystalline pyroxene and olivine, considerably higher than the crystalline silicate fraction in the ISM. While the pyroxene grains are Mg-rich, the olivine grains have more substantial Fe-contents, also in contradiction with astronomical observations. Thus far, we do not observe any systematic mineralogical differences among grains from different stellar sources. Our studies have uncovered details of circumstellar grain properties that cannot be seen remotely. For example, "compound"grains have been identified, including an amorphous Fe-rich silicate with olivine and pyroxene inclusions and a crystalline spinel grain encased in amorphous silicate glass (Nguyen et al., 2017; Nguyen et al., 2014). Laboratory studies of interstellar silicates have yet to show evidence of organic mantles predicted by some models of interstellar dust lifecycles (Greenberg and Li, 1997). Rare evidence for amorphization in space was also observed in two silicate stardust grains (Nguyen et al. 2016). A chemically uniform grain with a composition of the mineral enstatite is mostly amorphous but retains a crystalline core. The grain likely condensed as a single, solid crystal, but the outer portions were later amorphized in the ISM. An amorphous supernova grain having the chemical composition of enstatite most likely condensed as a crystal and was later rendered amorphous. The laboratory analysis of silicate stardust grains complements astronomical observations and provides an extraordinarily detailed look into the chemical makeup, structure, and lifecycle of silicate dust in the Galaxy.

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Primary author: Dr NGUYEN, Ann (Jacobs/NASA Johnson Space Center)

Co-authors: KELLER, Lindsay (NASA Johnson Space Center); MESSENGER, Scott (NASA Johnson Space Center); NAKAMURA-MESSENGER, Keiko (NASA Johnson Space Center); RAHMAN, Zia (Jacobs/Nasa Johnson Space Center)

Presenter: KELLER, Lindsay (NASA Johnson Space Center)

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