ANALYSIS OF A SUPERNOVA OLIVINE AGGREGATE IN THE CO CHONDRITE DOMINION RANGE 08006: IMPLICATIONS FOR THE MEASUREMENT OF PRESOLAR GRAINS IN SAMPLES OF ASTEROIDS BENNU AND RYUGU. L. B. Seifert[1], P. Haenecour[1], T. J. Zega[1,2]. [1]Lunar and Planetary Laboratory, University of Arizona, 1629 E University Blvd. Tucson, AZ, 85721-0092, lseifert@lpl.arizona.edu. [2]Materials Science and Engineering, University of Arizona.

Introduction: Primitive asteroids offer a glimpse into the early solar system and provide insight into its formation and evolution. The laboratory analyses of samples returned from missions such as OSIRIS-REx and Hayabusa2 could provide ground truth to astronomical datasets. One key area of interest in sample-return missions are primitive materials such as circumstellar dust grains, which formed around ancient stars and in the ejecta of stellar explosions. The analysis of these important materials is one of the main science goals of the OSIRIS-REx and Hayabusa2 missions [1-2] and requires the development of successful coordinated analytical protocols and techniques to maximize the information that we will be able to gain from them.

Previous studies have shown that core-collapse supernovae (SNe) are the second largest contributor of circumstellar dust grains to the solar system [3]. A supernova occurs when a massive star falls out of hydrostatic equilibrium and its stellar core contracts, rebounds, and sends a shock wave propagating through the circumstellar envelope. The propagation of the shock wave triggers rapid nucleosynthesis and results in a radial explosion away from the star. Solids condense in this ejected material, and some of these circumstellar grains are transported through the interstellar medium (ISM). A fraction of such grains are preserved in asteroid parent bodies and transported to Earth via meteorites [4].

Information on the structure and chemistry of silicate grains derived from SNe is severely limited. To date, only eight supernova silicates were analyzed for detailed structure and chemistry using transmission electron microscopy (TEM) [5-9]. Nonetheless, these studies reveal diverse structures and morphologies, including single crystals, aggregates and amorphous phases, highlighting the varied chemical and physical conditions in the ejecta of SNe. Here we report on a supernova (SN) silicate grain identified in the Dominion Range (DOM) 08006 CO3.0 chondrite. We expect to find similar materials in returned samples and therefore sample-preparation and analytical protocols developed here will be important for the Hayabusa2 and OSIRIS-REx missions.

Methods: Local isotopic enrichments were identified via NanoSIMS raster-ion-imaging of C and O isotopes in a thin section of DOM 08006 and elemental compositions were provided by Auger spectroscopy [10]. We chose one anomalous region, DOM-35, thought to originate in SN ejecta for detailed chemical and structural analysis using TEM.

A cross-section of DOM-35 was prepared using well established focused-ion beam scanning-electron microscopy (FIB-SEM) techniques [11] with the Thermo Fischer Scientific Helios G^3 FIB located at the Lunar and Planetary Laboratory (LPL). The section was then analyzed with LPL's 200 keV aberration-corrected Hitachi HF5000 scanning transmission electron microscope (S/TEM). The HF5000 is equipped with secondary electron (SE) detectors, STEM-based bright-field (BF) and dark-field (DF) imaging detectors, as well as an Oxford Instruments X-Max^N 100 TLE EDS system with dual 100 mm^2 windowless silicon-drift detectors with large (2.0 sr) solid angle.

Results: NanoSIMS analysis of DOM 08006 revealed an O-anomalous region with enrichments in both ^{18}O and ^{17}O relative to solar-system values, with $^{17}O/^{16}O = 4.0E^{-4} \pm 2.0E^{-5}$ and $^{18}O/^{16}O = 3.34E^{-3} \pm 7.0E^{-5}$ [10], which is consistent with a supernova origin [12]. The O-anomaly has an oblate shape (Fig. 1), measuring roughly 235 × 235 nm, as confirmed by TEM data.

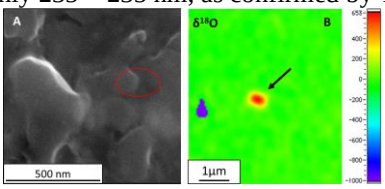

Figure 1: (A) SE image of hotspot (red circle) within DOM 08006 matrix. (B) NanoSIMS $\delta^{18}O$ image with arrow indicating the oblate hotspot and enrichment in ^{18}O.

TEM-EDS mapping of the overall FIB section reveals a matrix containing Si, O, Mg, Ca, Fe and large grains containing Fe and S. DOM-35 contains O, Mg, and Si, with localized enrichments in (Fig. 2).

Selected-area electron-diffraction (SAED) patterns were acquired across the hotspot and reveal DOM-35 is an olivine aggregate. The left portion of the aggregate is a single crystal of forsterite (Fo_{85}) and the right portion is a polycrystalline assemblage. Measurements of the polycrystalline region, together with EDS spectroscopy indicates an Fe-rich olivine (Fo_{65}).

Discussion: Conditions within SNe are not well understood due to their highly energetic environments. It is therefore challenging to constrain the conditions of such environments via comparison of grain data

with thermodynamic models. However, a few studies are available in the literature. For example, Fedkin et al. [13] used model compositions of thin layers of ejecta within the main burning zones of type-II SNe, computed by [14], to construct the chemical compositions of minerals condensed by equilibrium processes in 15-, 21- and 25-$M_\odot$ SNe. The resulting minerals, compositions, sequences of condensation and temperatures of condensation are similar for all three masses [13]. Olivine is a predicted condensate in the H, He/N, O/C, O/Ni and O/Si SN layers [13]. The compositions of the H and He/N layers are reducing because they are close to solar composition, therefore, forsterite is the favorable condensate, and X_{Fa} cannot exceed 0.002 above 1000 K. In the deeper, more O-rich zones forsterite is favorable between 1500 and 1600 K, and the fayalite content is between $0<X_{Fa}<0.03$ due to the low atomic Fe/Mg ratio. Below these zones, temperatures are too low for the formation of silicates. In order to produce a more fayalitic composition, mixing between SN layers is required. Alternatively, Nozawa et al. [15] demonstrated that forsterite is a predicted condensate in both unmixed and mixed SN ejecta through non-steady-state nucleation and grain growth.

We can place constraints on the progenitor SNe of DOM-35 via comparison of the grain data to these models. In comparison to [13], the $^{16}O/^{18}O$ ratio of DOM-35 is most consistent with a 15 $M_\odot$ SN, and the stoichiometric single-crystal forsterite (Fo_{85}) is consistent with equilibrium condensation in a 15 to 25$M_\odot$ SN between 1063-1575 K. We note that Nozawa et al. [15] developed a model in which forsterite could condense in unmixed SN ejecta through non-steady-state nucleation and grain growth. However, mixing between SN layers is required to produce the Fe-rich composition of the polycrystalline region of DOM-35 (Fo_{65}). Moreover, astronomical observations of SNe remnants show that the ejecta are heterogeneous, clumpy, and large scale mixing is occurring, *e.g.* [16]. Thus, while we cannot completely rule out forsterite condensation in an unmixed zone of the progenitor star to DOM-35, it seems unlikely that both a single-crystal forsterite grain and Fe-rich polycrystalline olivine aggregate could otherwise accrete together without significant transport occurring within or between zones.

We note that, to our knowledge, only two other stoichiometric SN silicates, B10A [5] and 2_4 [8], were previously identified in meteoritic samples. The data from both of these grains are consistent with equilibrium condensation, the former at 1560 K in a solar-metallicity star with a mass 15 $M_\odot$, but mixing was required to produce its Fo_{83} composition [5]. The single-crystal forsterite in DOM-35 is similar in crystal structure and chemical composition to SN grain B10A [5], but its isotopic composition is significantly different. Thus, while it is conceivable that the single-crystal forsterite in DOM-35 formed under similar thermodynamic conditions as B10A, the data imply different nucleosynthetic origins.

Spectroscopic characterization of asteroids Bennu and Ryugu indicate a CM-chondrite-like petrology [17-18]. CM chondrites show evidence of aqueous alteration [19], and have also been shown to contain SN grains [*e.g.* 20], therefore SN grains from returned samples may show signs of processing. Applying the analytical techniques, of the kind we report here, to similar grains in returned samples from OSIRIS-REx and Hayabusa2 will aid in deciphering characteristics consistent with condensation in the host circumstellar envelope compared to those that resulted from secondary processing on asteroids Bennu and Ryugu.

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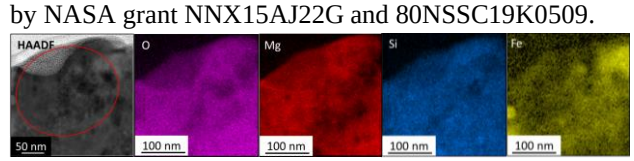

Figure 2: EDS maps of DOM-35 with HAADF image showing anomalous region with red circle for comparison.