A MICROSTRUCTURAL EXAMINATION OF A REFRACTORY-SIDEROPHILE NUGGET FROM THE NORTHWEST AFRICA 8323 CV3 CHONDRITE.

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Introduction: Calcium-aluminum-rich inclusions (CAIs) are mm- to cm-sized objects in chondritic meteorites whose constituent phases are thermodynamically predicted and isotopically age dated to be among the first-formed solids in our solar system [1-5]. Micron to sub-micron sized inclusions rich in Fe, Ni, and high-Z elements such as Os, Ir, Pt and W, are observed in CAIs in the form of refractory metal nuggets (RMNs), fremdlinges, and 'nugget like objects' (NLOs) [1, 6]. Thermodynamic calculations place the condensation temperatures of siderophiles such as Os, Ir and, Ru well in excess of major CAI phases [2, 7-9]. Such refractory grains can therefore serve as thermal probes of the early solar protoplanetary disk. Here we report on a refractory grain identified in the Northwest Africa (NWA) 8323 CV3 chondrite. This work in part of an ongoing effort to examine the structure and crystal chemistry of CAIs down to the atomic level in order to gain new insights into the thermochemistry of the early solar system.

Sample and Analytical Techniques: A Cameca SX-100 electron microprobe (EMP), located in the Kuiper Materials Imaging and Characterization Facility (KMICF) at the Lunar and Planetary Laboratory, University of Arizona was used to identify a fluffy type-A (FTA, 'Cloud') CAI in a thin section of the NWA 8323 chondrite (Arizona State University CMS collection #1895_1_2). Wavelength-dispersive spectroscopy was used to identify grains rich in transition and rare-earth metals. One such grain 'Bright3' was extracted and thinned to electron transparency (<100 nm) using a Thermo Fisher (formerly FEI) Helios NanoLab 660 G3 focused-ion-beam scanning-electron microscope (FIB-SEM) located at KMICF, following methods described by [10]. The section was then analyzed using the 200 keV spherical-aberration-corrected Hitachi HF5000 scanning transmission electron microscope (S/TEM) located at KMICF. The HF5000 is equipped with an Oxford Instruments X-Max N 100 TLE energy-dispersive spectroscopy (EDS) system with dual 100 mm^2 windowless silicon-drift detectors (Ω = 2.0 sr). Selected-area electron-diffraction (SAED) patterns were acquired for determination of phase.

Results: EMP data show that the mineralogy and nodular morphology of Cloud are consistent with previous descriptions of fluffy type-A CAIs [11]. Bright3 is an elliptical grain measuring 1.3 µm × 0.8 µm that occurs within the melilite interior of Cloud and contains Fe, Ni, Pt, Os and Ir. STEM high-angle annular dark-field (HAADF) imaging and EDS mapping of the FIB section show that the refractory nugget is surrounded by an anorthite-like silicate ($Ca_{0.98}Al_{2.03}Si_{1.99}O_8$) and melilite ($Ca_{1.95}[Al_{0.93}Mg_{0.07}][Al_{0.94}Si_{1.09}]O_8$). EDS mapping reveals that Bright3 contains spatial correlations among Fe, Ni and Pt, and also among Os, Ir and Ru. Si, Ca, and O correlate locally in an oblong region (90 nm × 150 nm). An SAED patten from the Os, Ir, and Ru region indexes to an Os-Ir-Ru alloy.

Discussion: RMNs are sub-micron to micron-sized, single-phase alloy grains [1,7,12]. Some RMNs contain cores rich in Os, Ir, Ru and Rh, and boundaries rich in Pt [12], while others are composed of metallic cores surrounded by sulfides [7]. In comparison, fremdlinge are large complex aggregates, tens of microns in size, with cores composed of Fe-Ni alloys and Fe-sulfides, surrounded by silicates, phosphates, sulfides and oxides [12-14]. NLOs are composed of refractory metal and oxide, with sizes comparable to RMNs [6]. The composition and morphology of Bright3 does not precisely match these previous descriptions of inclusions rich in high-Z elements but is similar in size and polyphasic nature to NLOs.

The abundance of refractory siderphiles such as Os, Ir, Ru and Pt, points towards a high-temperature origin for Bright3. Equilibrium thermodynamic calculations predict condensation temperatures of 1917K, 1639 K, 1613 K and 1415 K respectively for Os, Ir, Ru and Pt and the alloying of solutes, e.g., Fe, Ni and W, at levels proportional to their partial pressures, following the initial condensation of the refractory metal [7]. We hypothesize that the polyphasic nature of Bright3 is the result of high-temperature alloying, followed by localized oxidation prior to the condensation of the surrounding silicates.

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