FIB-TEM STUDY OF 6 SUBMICRON CRATERS FROM STARDUST FOIL C2113N-A.

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Introduction: NASA's Stardust spacecraft flew through the coma of comet 81P/Wild 2 and returned to Earth with our first unambiguously cometary material. However, the collected cometary material experienced extensive alteration due to the high collection velocity (6.1 km/s) [1]. Previous investigations of the Stardust collector foils have succeeded in observing surviving crystalline material [2,3,4], but further studies are required to fully characterize the comet's fine component.

Experimental Methods: We imaged a subsection of Stardust foil C2113N-A with ~10 nm resolution with a Mira Tescan SEM, locating 20 crater candidates with diameters < 0.5 μm. The crater residues were elementally characterized with energy dispersive X-ray spectroscopy (EDS). 10 of these craters returned measurable Si, Fe, S, or Ca signals, and 6 of these craters were selected for further study. Cross sections of these craters were extracted and thinned to 100-150 nm with a FEI Quanta 3D Focused Ion Beam (FIB), maximizing the preservation of cometary material for potential future isotope analyses. High-resolution imaging and EDS characterization of the crater residues were performed with a JEOL 2000FX Transmission Electron Microscope (TEM).

Results: The extracted craters ranged in size from 200-350 nm, measured from the inside edges of the crater lips. Five of the craters contained a rounded, bowl-shaped crater bottom suggestive of a single, compact impactor, whereas one of the craters contained a double indentation indicative of a complex aggregate grain. Cometary residue was present as a glassy melt layer in five of the craters. One crater lacked any observable residue. The melt layer thicknesses varied greatly between the craters, ranging from 20-150 nm deep. No surviving crystalline material was found in the cometary residue.

TEM-EDS analysis indicated that the craters were the result of aggregate impactors primarily composed of low-Ni iron sulfides as well as Si-rich materials. Ca and Mg were also present in several of the craters, and trace K and Mn were present in a single crater residue. Fe/S ratios within the melts were frequently small with the majority of sampled iron sulfides having Fe/S ≤ 1. The impactor material, though thoroughly melted along the crater bottoms, remained heterogeneous in composition, and the abundances of S and Si within the melt layers were frequently anti-correlated.

Discussion: We focused our study on craters with diameters < 0.5 μm as our previous analog crater studies have demonstrated that smaller craters are more likely to contain surviving crystalline material [5,6]. The lack of crystalline material in these craters is consistent with our studies of Stardust foils [7,8] but is inconsistent with previous investigations [2,3]. However, the majority of Stardust craters that have been studied with FIB-TEM techniques were > 1 micron in size and thus may have been sampling a coarser component of Wild 2. Determining whether or not the impactors were amorphous prior to collection is difficult given the violent nature of the collection process, but our lack of crystalline material suggests that amorphous material may constitute a significant fraction of the Wild 2 fine component.

Our craters' low Fe/S ratios indicates that the majority of the Fe present within our crater residues is the result of iron sulfide impactors rather than silicates. Some S-loss within the craters is likely given previous analog foil results [6], however the effect appears minimal in these craters. We did not observe Fe without a corresponding significant S component, but variation in Fe/S ratios in iron sulfides does allow for a small portion of the observed Fe to have originated from non-sulfide impactors. Ca abundances within the craters are more difficult to explain. Ca has been commonly observed in Stardust crater residues [11], but its source in the fine component of Wild 2 has not been well constrained. Al contamination in our residue layers makes the identification of CAIs difficult, though the lack of Ti in our residues suggests an alternative Ca source [12]. Kool (kosmochloric Ca-rich pyroxene and olivine) grains are a common source of Ca in the Stardust aerogels, but our lack of Fe outside of iron sulfides, low Mg abundances, and lack of Cr and Na also suggest an alternative Ca source within our crater residues. Ca-rich pyroxenes are a potential Ca source. The crater sizes, the melt layers' low-Ni iron sulfide compositions, and the lack of crystalline material within the melt layers are all consistent with GEMS (glass with embedded metal and sulfides) impactors [10].

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