FIB/STEM STUDY OF 2 STARDUST ISPE CRATERS FROM FOIL 1031N,1

B. A. Haas[1], R. M. Stroud[2], and C. Floss[1], [1]Laboratory for Space Sciences and Physics Department, Washington University, St. Louis, MO 63130, USA (bahaas@wustl.edu), [2]U.S. Naval Research Laboratory, Washington, DC 20375, USA (rhonda.stroud@nrl.navy.mil).

Introduction: NASA's Stardust spacecraft aimed to return the first solid samples from the contemporary interstellar dust (ISD) stream. The Stardust Interstellar Dust Collector was exposed to the ISD stream for 195 days in 2000 and 2002, and functioned with two primary collection media: light-weight silica-based aerogel tiles and strips of aluminum foil [1]. However, the low flux of ISD, the small size of ISD particles, and the extreme collection velocities (> 20 km s^{-1}) made analysis of the collector materials difficult [2].

The Stardust Interstellar Preliminary Examination (ISPE) successfully identified 25 craters on the aluminum foils with SEM imaging, four of which were found to have likely resulted from ISD impactors based upon their elemental composition and crater morphologies [3]. Two asymmetric sub-micron craters from foil 1031N,1 (216@45 and 239@11) appeared to be promising candidates for containing ISD [4], but Auger spectra from the craters were incapable of distinguishing between a terrestrial or interstellar origin for the impactors [2]. Coordinated FIB/STEM analysis provides higher resolution elemental characterization of the crater residues allowing for the detection of minor elements that can clarify the origins of these impact features.

Experimental Methods: Initial identification of the craters with SE imaging was performed by a JEOL 840a SEM equipped with Noran System Seven software [4]. Verification of the crater candidates, as well as elemental characterization of the residues within the craters, was performed with the PHI 700 Auger Nanoprobe at Washington University. Auger spectra were acquired using a 10 kV, 10 nA beam over an energy range of 30-2130 eV [2].

Cross sections of the craters were prepared and extracted with a FEI Nova 600 FIB-SEM at the Naval Research Laboratory (NRL). The craters were covered in a protective carbon coating and thinned to 100-150 nm to preserve sufficient material for potential future isotope analyses. High-resolution images of the crater cross sections and EDS maps of the crater residues were obtained using a Nion UltraSTEM 200 aberration-corrected STEM operated at 200 keV at NRL. Elemental quantification of STEM-collected spectra was performed with Cliff-Lorimer routines.

Prior Auger Analysis: Auger analysis of the 1031N,1 craters performed during the ISPE detected Mg and Si in addition to the Al, C and O seen in all studied craters. Carbon present in the spectra was likely due to the presence of a thin layer of organic contamination present on the foils [5]. Elements indicative of terrestrial or spacecraft contamination (e.g. B, F, and Ce) were not observed in the spectra [2].

Results and Discussion: The cross section of crater 216@45 revealed that the crater was shallow. The crater's bowl-shaped bottom suggests the impactor was a compact object with a single center of mass. The diameter of the crater, measured from the inside of the crater lips, was 650 nm, while the crater's depth was 270 nm, resulting in a depth/diameter ratio of 0.42. Crater 239@11 was similarly shallow and bowl-shaped, with a diameter of 675 nm and a depth of 260 nm, resulting in a crater depth/diameter ratio of 0.39. However, depth/diameter ratios can be affected by a variety of factors, such as the angle of incidence, density of impactor, impact velocity, and volatile contents, and thus are not entirely indicative of terrestrial contamination [6, 7]. Asymmetry in the crater shapes can result from an oblique impact or a highly nonspherical impactor [2].

Thin (10-50 nm) impactor melt layers were present in the crater bottoms. Asymmetry in the crater shapes was reflected in the melt layer distributions, with melt being more prevalent on one side of each crater. STEM-EDS isolated on the residue layers showed an abundance of Mg, Si, O and Al, consistent with the earlier Auger studies. The Si/Mg ratio in both craters was large, with values for crater 216@45 and 239@11 being 5.4 and 4.1, respectively. Crater 216@45 also contained significant F (6.3 at. %), and crater 239@11 contained significant Ce (0.5 at. %) alongside trace Ti.

The presence of Ce and F are within the crater residues, along with the asymmetric crater shapes, indicates that the impactors that produced these craters are the result of secondary ejecta produced by a micrometeoroid impact to the spacecraft [2]. Residues resulting from secondary solar cell array fragments can vary greatly in composition depending on the ratio of antireflection coating to solar-cell cover-glass. However, Ce and F are known components of solar-cell cover glass, and Ti, though a possible component of ISD, is also present in Stardust's solar cells [2]. These results raise the number of ISPE craters caused by solar cell secondary impacts to 13 out of 25, demonstrating the difficulty in studying the Stardust Interstellar Dust Collector foils.

References: [1] Westphal A. J. et al. (2014) *Meteoritics & Planetary Science* 49:1720-1733. [2] Stroud R. M. et al. (2014) *Meteoritics & Planetary Science* 49:1698-1719. [3] Westphal A. J. et al (2014) Science 345:786-791. [4] Floss C. et al. (2011) *LPS XLII*, Abstract #1576. [5] Kearsley A. T. et al. (2010) *LPS XLI*, Abstract #1593. [6] Kearsley A. T. et al. (2008) *Meteoritics & Planetary Science* 43:41-73. [7] Price M. C. et al. (2012) *Meteoritics & Planetary Science* 47:684-695.