Microanalysis of Hypervelocity Impact Residues of Possible Interstellar Origin

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The NASA Stardust spacecraft deployed two collector trays, one dedicated to the collection of dust from Comet Wild 2, and the other for the capture of interstellar dust (ISD). The samples were returned successfully to Earth in 2006, and now provide an unprecedented opportunity for laboratory-based microanalysis of materials from the outer solar system and beyond. Results from the cometary sample studies have demonstrated that Wild 2 contains much more refractory condensate material and much less pristine extra-solar material than expected, which further indicates that there was significant transport of inner solar system materials to the Kuiper Belt in the early solar system [1]. The analysis of the interstellar samples is still in the preliminary examination (PE) phase, due to the level of difficulty in the definitive identification of the ISD features, the overall low abundance, and its irreplaceable nature, which necessitates minimally invasive measurements [2]. We present here coordinated microanalysis of the impact features on the Al foils, which have led to the identification of four impacts that are possibly attributable to interstellar dust. Results from the study of four ISD candidates captured in aerogel are presented elsewhere [2].

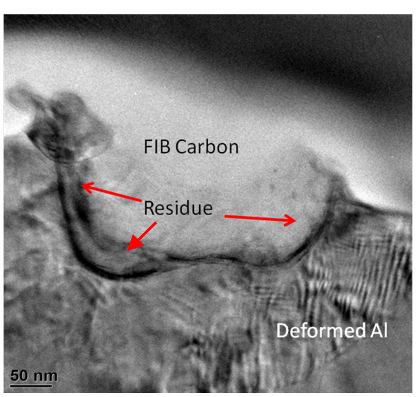
Members of the Stardust Interstellar PE team use a combination of automated scanning electron microscopy, automated image analysis and manual image searching to identify craters in the Al foils. First-order elemental analysis is performed with one of three techniques: Auger electron spectroscopy (AES) at Washington University in St. Louis, and FEG-SEM-based energy dispersive X-ray spectroscopy (EDX) with either a conventional Si(Li) detector at the MPI for Chemistry in Mainz, or a custom annular-quad SDD detector at Sandia National Laboratory. Craters for which no definitive signature of terrestrial origin was found were subsequently sectioned with focused ion beam lift-out, and analyzed with scanning transmission electron microscope-based EDX at the Naval Research Lab. To test the feasibility of using isotopic composition to provide a more definitive answer as to the interstellar vs. solar origin of the impacting grains, preliminary NanoSIMS measurements were made, at the Carnegie Institution of Washington, on craters known to be of solar origin. The microanalysis results are summarized in Table 1.

The majority (20 out of 24) of the analyzed craters can be attributed to either indigenous defects in the foil, or secondary impacts from spacecraft debris generated by impacts on the solar cell array, which can be recognized due to the concentration of elements of low cosmic abundance, e.g., B, F, Ce, Ti and Zn, that are components of the solar cell cover glass. Four craters have residues that clearly indicate a cosmic origin (Fig 1). Statistical analysis of the expected abundance, velocities and trajectories of interplanetary and interstellar dust, indicate that an interstellar origin is more likely. These results suggest that sulfur is a common constituent of interstellar dust.

References
[1] D. Brownlee, et al., *Science* **314**, 1711 (2006).
[2] A. J. Westphal et al., *LPSC Abstracts*, #2084 (2011).

Table 1. Elemental Analysis of Residues. Results in bold are from craters identified as cosmic in origin: 1044N1 12a-0277, 1061N1 036@33, 1061N1 69@22, and 1061N 135@30, respectively. Elements listed in italics are tentative identifications. Al, C, and O were detected in all analyses in addition to the elements listed**.** Empty brackets denote no additional elements detected.

Diameter (μm)	**Elements Detected (AES)<SEM-EDX> [AQ-EDX]{STEM-EDX}**
0.24	(B,Mg,Si,Ti,Ce)
0.28	**<Mg,Si,Fe>{Mg,Si,S,Fe}**
0.29	(F,Mg,Si)
0.29	[]{*Mg*,Si,Ti,Fe *Ce*}
0.35	(Mg,Si)
0.35	{}
0.37	**(Mg,Si,Fe){Mg,Si,S,Fe,Ca,Cr}**
0.39	**(Mg,Si,Fe){Mg,Si,S,Fe,Ni}**
0.44	<Si, *Ce, Zn,Na*>
0.45	[Si]{Si,Na,Ti,Zn,Ce}
0.46	**(Si,Fe){Mg,Si,S,Fe,Ni,*Ca,Cr*}**
0.46	{}
0.56	(B,F,Mg,Si,Ti,Ce)
0.58	<Si,Fe>
0.61	(Mg,Si)
0.63	(B,Si,Ce,Mg)
0.65	(Mg,Si)
0.66	(Si)
0.74	<F,Mg,Si,*Na,Zn,Ce*>
0.84	<Si,Fe,Ni>{Si,Ti,Fe,Ni-impurity}
1.0	(Si,Na,Ce,Zn){Mg,Si,K,Ti,Fe,Zn,Ce}
1.1	[]{Fe impurity?}
1.2	(){Fe impurity?}
1.6	[Si,*Ce*,*Zn*,*Na*]{Mg,Si,K,Fe,Ti,Zn,Ce}



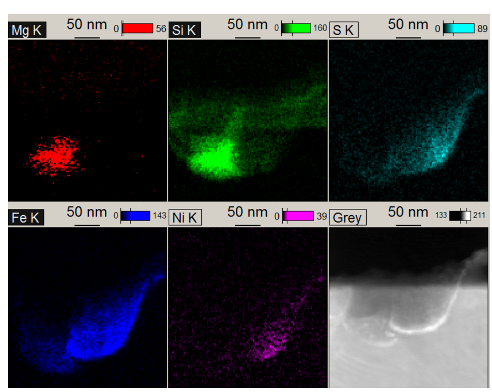


FIG 1. (left) Bright-field TEM image of a 0.37 μm crater due to the impact of a cosmic dust grain. (right) STEM-EDX net count maps and dark-field image of the cross-section of the 0.39 μm crater.