HYPERVELOCITY IMPACT EXPERIMENTS OF ISOTOPICALLY ENRICHED PROJECTILE MATERIALS: UNDERSTANDING PRESOLAR GRAIN LOSS IN STARDUST COMETARY SAMPLES.

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Introduction: Although NASA's Stardust mission to comet 81P/Wild 2 was named based on the expectation that the comet would be dominated by material of interstellar and circumstellar origin, analysis of the returned samples demonstrated that Wild 2 contained abundant material from the hot inner regions of the solar system [e.g., 1]. Moreover, initial isotopic investigations of the foil samples suggested unusually low abundances of presolar grains [2, 3]. However, hypervelocity impact experiments carried out under conditions similar to those experienced by the cometary samples demonstrated the preferential destruction of both O-rich and C-rich presolar grains during collection of the Stardust samples, and suggested that presolar grain abundances in the comet were similar to those observed in primitive IDPs [4].

While this study demonstrated the fact of presolar grain loss from the cometary samples upon impact into the collection media, the mechanism for this preferential loss remains unclear. The ^{18}O enrichment of one presolar grain found in a small Wild 2 crater was distributed over much of the crater area, suggesting projectile melting and dilution of the isotopic anomaly in the melt mixture [4, 5]. However, four other O-rich presolar grains found in comet Wild 2 craters [2–4] did not show evidence of melting. Apparent preferential loss of presolar grains can also occur if the grains break up into smaller fragments upon impact, as their isotopic signatures will then be more likely to be diluted with surrounding material [4]. Finally, grain survival also depends on the nature of the projectile [6], with preferential survivial of the more refractory components.

In an ongoing effort to understand the nature of the impact process and its effects on the samples returned from comet Wild 2, we report here initial results of a hyperveolocity impact shot of isotopically enriched samples into Al foil under Stardust-like conditions.

Experimental: A sample comprised of 5 µm SiO_2 and larger (~35 µm) soda lime spheres was isotopically enriched at Imperial College. The resulting sample was fired at Stardust flight spare Al 100 foil with the two-stage light gas gun at the University of Kent, at impact speeds similar to those experienced by the comet Wild 2 samples (~6 km/sec) [e.g., 7]. Samples of the original projectile material were mounted on high purity Au foil for analysis by SEM–EDX and NanoSIMS.

NanoSIMS analyses of both the projectile material and residues in the Al foil impact craters were carried out in raster ion imaging mode using a ~1 pA Cs^+ primary ion beam. Secondary ions of $^{12}C^-$, $^{16}O^-$, $^{17}O^-$, $^{18}O^-$, and $^{28}Si^-$ were collected simultaneously, along with secondary electrons. The total areas measured were 12,900 µm^2 of projectile material and 33,700 µm^2 of impact craters on the Al foil.

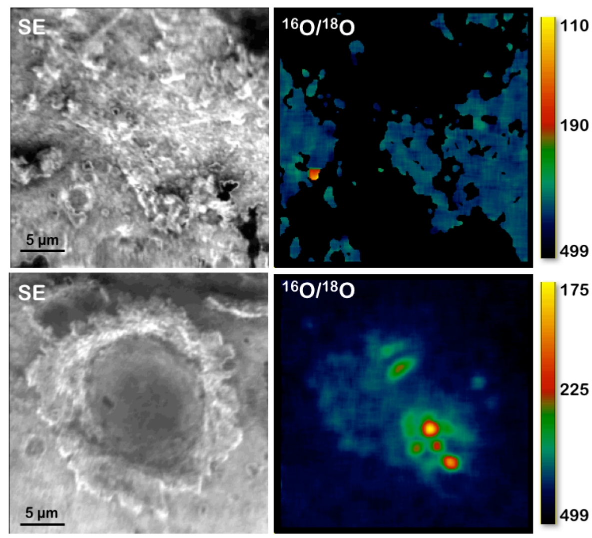

Figure 1. Secondary electron and false color $^{16}O/^{18}O$ images of surviving isotopically anomalous residue in the rim (upper images) and bottom (lower images) of impact craters A8 crater 8r3 and A13 crater 1, respectively.

Results: SEM-EDX analysis of the projectile material revealed that the SiO_2 and soda lime spheres melted during the isotopic enrichment process, resulting in a glassy mixture dominated by SiO_2, with variable minor amounts of MgO, Na_2O and CaO. NanoSIMS analyses of 59 different areas indicated that the material was isotopically uniform, with an overall average oxygen isotopic composition of $^{16}O/^{17}O = 473 \pm 57$ and $^{16}O/^{18}O = 2.35 \pm 0.42$, compared to the terrestrial values of 2625 and 499, respectively.

The areas measured on the impact foil consisted of individual craters 10–20 µm in diameter, regions along the bottoms and rims of larger craters, and areas containing numerous small (< 10 µm) craters. Most of the areas measured on the impact foil were isotopically normal, i.e., terrestrial in composition: of 78 individual regions measured, we identified isotopically anomalous material in only 12 areas.

For the most part, the anomalies are present as individual isolated hotspots, but in two craters multiple hotspots are present (Fig. 1). The sizes of the hotspots range between 300 nm and 1 µm in diameter, and have $^{16}O/^{18}O$ ratios that range from 86 – 398 (Table 1). In most cases the $^{16}O/^{17}O$ ratios are indistinguishable from the terrestrial value, within errors, but two hotspots have retained a ^{17}O-rich signature (Table 1).

We also found one ~17 µm diameter crater with abundant surviving isotopically anomalous residue (Fig. 2), with an average oxygen isotopic composition of $^{16}O/^{17}O = 1123 \pm 58$ and $^{16}O/^{18}O = 9.3 \pm 0.2$.

Table 1. Projectile and crater O isotopic compositions

Sample	$^{16}O/^{17}O$	$^{16}O/^{18}O$	Area (µm^2)
Projectile	473 ± 57	2.35 ± 0.42	——
A4 crater 3	2476 ± 306	246 ± 9	0.14
A8 crater 8r3	1279 ± 302	98 ± 6	0.24
A12 crater 4	2707 ± 255	298 ± 14	0.06
A13 crater 1	2450 ± 143	256 ± 4	0.19
A13 crater 2	2482 ± 79	360 ± 4	0.13
A13 crater 5	2637 ± 204	252 ± 5	0.09
A13 crater 7	2089 ± 129	86 ± 1	0.20
crater 3-4	2323 ± 456	132 ± 6	0.07
crater 8-1	2593 ± 240	334 ± 11	0.10
A12 crater 1	2638 – 2828	360 – 396	1.87
A13 crater 1	2345 – 2690	256 – 398	6.54
A11 crater 2	1123 ± 58	9.3 ± 0.2	230

Discussion: Our results demonstrate that much of the original isotopically anomalous projectile material was lost upon impact. Using ^{28}Si as a proxy for the presence of projectile residue in the impact craters, we estimate that only 4% of the ^{18}O- and ^{17}O-rich projectile material survived the impact process. That fraction drops by a factor of 10 if the residue from A11 crater 2 (Fig. 2) is not considered. These results are consistent with a previous hypervelocity impact experiment using Acfer 094 as the projectile material [4]. In that study, impact into the Al foil resulted in the loss of more than 90% of the presolar silicate and oxide grains expected to have been present in the original projectile material.

Work on both the Stardust foils and on analog foils [8–11] has demonstrated the ubiquitious formation of melt layers in the impact craters. However, like many of the O-rich presolar grains found in the Stardust samples, most of our hotspots do not show obvious evidence for melting (e.g., Fig. 1, top), suggesting that grain fragmentation is important in the impact process. These fragments may be shattered remnants that avoided melting or mixing with melt residue. However, the hotspots found at the bottom of crater A13 crater 1 (Fig. 1, bottom) are spread out over larger areas of the crater bottom, indicating that grain survival also occurs amidst projectile melting and dilution with the melt mixture.

We note, moreover, that all surviving material experienced significant isotopic dilution, relative to the original isotopic composition of the projectile material. The $^{16}O/^{18}O$ ratios of the hotspots are between 35 and 170 times higher than the $^{16}O/^{18}O$ ratio of the original projectile. While some of this can be attributed to dilution with surrounding isotopically normal material, even the residue in A11 crater 2 is diluted by a factor of four relative to the projectile $^{16}O/^{18}O$ ratio. This could indicate melting of the Al substrate and mixing with the melt residue, as as been observed in both Stardust and Acfer 094 analog impact craters [9,11].

Conclusions: Our study demonstrates the complexity of the impact process and indicates multiple mechanisms for presolar grain loss.

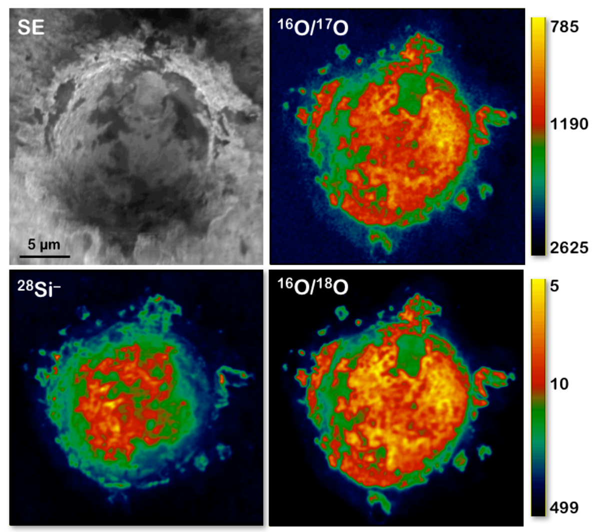

Figure 2. Secondary electron and false color $^{16}O/^{18}O$ and $^{16}O/^{18}O$, and secondary ion images of surviving isotopically anomalous residue in the impact crater, A11 crater 2.

References: [1] Brownlee et al. (2006) *Science 314,* 1711. [2] McKeegan et al. (2006) *Science 314,* 1724. [3] Stadermann et al. (2008) *M&PS 43,* 299. [4] Floss et al. (2013) *Ap.. J. 763*, doi:10.1088/0004-637X/763/2/140. [5] Leitner et al. (2010) *LPS XLI*, #1607. [6] Croat et al. (2015) *M&PS 50,* 1378. [7] Kearsley et al. (2006) *M&PS 41,* 167. [8] Leroux et. al. (2008) *M&PS 43*, 143. [9] Wosniakiewicz et al. (2011) *M&PS 46*, 1007. [10] Haas et al. (2106) *LPS XLVII*, #1597. [11] Haas et al. (2016) *M&PS 51*, #6386.

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