IDENTIFYING OFF-NORMAL HYPERVELOCITY IMPACTS IN ALUMINUM FOIL BY AUGER IMAGING: IMPLICATIONS FOR THE EXAMINATION OF THE INTERSTELLAR COLLECTOR.

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Introduction: While the primary mission of NASA's Stardust spacecraft was to comet 81P/Wild 2, it also carried a second collector which was designed to capture and return contemporary interstellar dust traversing the solar system [1]. The design of this interstellar collector is similar to the cometary one and contains both aerogel capture cells and Al foil surfaces. A Stardust Interstellar Preliminary Examination (ISPE) is currently underway to search for possible interstellar impact features, which are expected to be substantially smaller and fewer in number than the cometary ones [2]. The identification of captured material of true interstellar impacts is further complicated by the possibility that some impact features were created by interplanetary dust particles (IDPs) or are the result of secondary ejecta from a hit elsewhere on the spacecraft. One distinguishing characteristic between these different projectiles is that interstellar dust is expected to have hit the collector in normal direction, while both IDPs and secondary ejecta are more likely to have come from an off-normal direction. The pre-impact trajectory of dust particles in aerogel impacts can be determined directly from the track orientation and likely projectile types can thus easily be identified [2]. A similarly straightforward method for trajectory determination in Al foil impacts is not currently available. Even relatively high-angle impact craters are frequently circular in appearance [3] and odd crater shapes are often more a reflection of complex projectile structure and shape than of the impact angle [4].

Last year, we reported on the observation of a thin layer of spray ejecta emanating in a highly directional manner from one side of a hypervelocity impact crater in an Au target from the Long Duration Exposure Facility (LDEF) satellite [5]. We speculated that this feature was the result of an off-normal impact and that it may be possible to use the presence of such spray deposits for diagnostic purposes in the determination of impact angles [5]. However, this hypothesis could not be tested directly on the LDEF impact because no impact directional information was available. We have since performed laboratory experiments with hypervelocity dust shots under various impact angles into Al foils under controlled conditions, followed by Auger elemental imaging measurements to test this theory.

Experimental: Test shots were performed with the two-stage light gas gun at the University of Kent. In a first experiment, 22.8 µm diameter sodalime glass beads were shot at 'Al 1100' foil (similar to that on Stardust) with an impact speed of 6.05 km s^{-1}. The target foil was mounted onto a curved former as shown in Fig. 1, to create a continuous range of impact angles from normal (0°) to glancing (>80°) in a single shot. After the shot the foil was straightened for subsequent elemental imaging measurements in the Auger spectrometer. Calibration marks make it possible to positively determine the impact angle of each crater from its relative location on the foil. In a second test shot, aggregates of San Carlos olivine, ground to sizes <8 µm, were shot at the same type of Al foil under a fixed angle of 60° with an impact speed of 6.34 km s^{-1}.

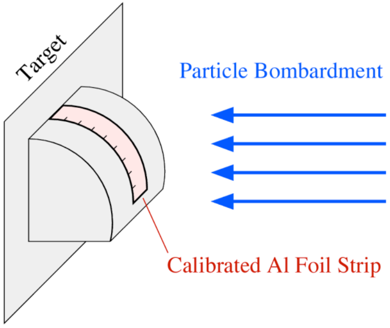

Figure 1: Schematic view of the foil target holder for the 'continuous range of impact angle' experiment.

For the San Carlos sample, we acquired scanning electron microscopy (SEM) overview maps with the JEOL 840-A instrument at Washington University, following the 'low contamination' protocol established for the ISPE foil analysis [6]. Secondary electron images and elemental distribution maps of individual impact craters were acquired with the scanning Auger Nanoprobe at Washington University. For the elemental maps we used a 10 kV, 10 nA electron beam and widely varying raster settings (64x64 to 256x256 pixels) and total analysis times (several minutes to >10 hours) in order to find the best operating conditions, as described below.

Results: The first craters we investigated with the Auger spectrometer were from the sodalime glass shots onto the curved Al foil. Elemental imaging of the spatial distribution of Si and Na in and around the impact craters did indeed show the deposition of projectile material outside the craters in forward direction, with respect to the original projectile movement. These deposit layers turned out to be extremely thin (likely <1 nm) and even with the high surface sensitivity of the Auger spectrometer [7] it took several hours to acquire usable images of these spray deposits (e.g., Fig. 2, top panel). However, we found that it is much simpler and faster to acquire images of the Al distribution, since the signal intensity is significantly larger for this element when looking at Al foils. In the Al images the impact spray is visible 'inverted', as an attenuation of the intensity of the Al signal due to the overlying spray material (Fig. 2, bottom panel). Using only the Al images in the search for impact spray patterns has the additional advantage that it does not require any *a priori* assumptions about the composition of the projectile.

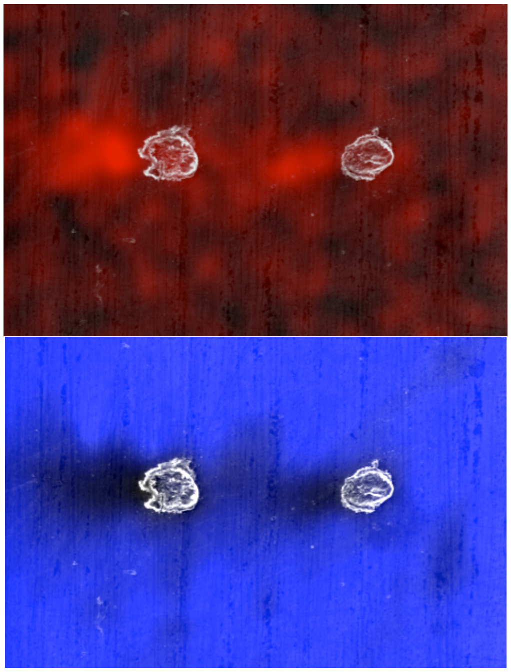

Figure 2: Overlay of Auger elemental distribution maps of Si (red) and Al (blue) on an SEM image of two ~40 µm impact craters. The projectiles hit the foil from the right side at an angle of 59°.

Since the exact outline of the spray pattern is not relevant for determining whether the impact was caused by an off-normal projectile and what the impact direction was, we found that we can further optimize the Auger measurement protocol by reducing the pixel size of the Al elemental maps, which makes it possible to perform the search for spray patterns in a matter of minutes. An example is shown in Fig. 3, where a low-resolution Al map is overlain on a higher resolution SEM image. This image also shows that it is possible to distinguish other variations in the Al signal (e.g., due to contaminants on the foil surface) from sprays that are directly spatially associated with an impact crater. We are currently investigating the relationship between the presence of sprays and the impact angles by imaging craters from the sodalime glass shot. While not all off-normal impacts show sprays, our preliminary data indicate that the probability increases with increasing angle. We are also studying the relationship between sprays and impact sizes by imaging craters from the San Carlos olivine shot, where smaller and more varied projectile sizes provide a much wider array of crater sizes. It is important to note that so far we have *not* found any 'false positives' with sprays around normal-incidence impacts.

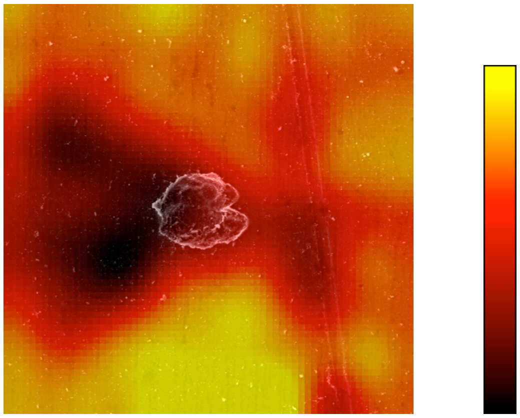

Figure 3: Overlay of an Al elemental map (in 'hot' scale false color) on an SEM image of a ~20 µm impact crater, which was created by an impact from the right side at an angle of 72°. Note that the elemental map is of much lower pixel resolution than the SEM image.

Conclusions: We have shown that thin impact sprays can indeed be used to identify off-normal hypervelocity impacts. The measurement of these sprays is non-destructive and has the potential to provide information that is not otherwise available. Such Auger measurements could routinely be performed on all ISPE impact craters before a specific analysis plan for follow-up studies is decided.

References: [1] Brownlee D. E. et al. (2003) *J. Geophys. Res. 108*, 1. [2] Westphal A. J. et al. (2009), *LPS XL*, Abstract #1786. [3] Burchell M. J. and Mackay N. G. (1998) *J. Geophys. Res. 103*, 22. [4] Kearsley A. T. et al. (2008) *Meteorit. Planet. Sci. 43,* 41. [5] Stadermann F. J. et al. (2009), *LPS XL*, Abstract #2120. [6] Kearsley et al. (2010) *LPS XLI*, (this conference). [7] Stadermann F. J. et al. (2009) *Meteorit. Planet. Sci. 44*, 1033.

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