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The Stardust Interstellar Dust Collector Crater Origins and Hypervelocity Cratering at Oblique Angles in Aluminum Foil

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ABSTRACT

From 1999 to 2006 the NASA Stardust mission collected cometary particles from the Wild 2 comet and interstellar dust from the interstellar medium in two collectors made from aerogel tiles and aluminum foil. By studying their isotopic compositions, these particles can provide us with information about nucleosynthetic processes in stars. Both collector trays are being studied for traces of these particles, though a number of challenges have arisen in doing so. Identifying impact craters in the aluminum foil on the interstellar collector tray has been incredibly difficult. In addition to being only a few micrometers or less in diameter, many craters may have been caused by debris from the spacecraft instead. It is currently impossible to tell a crater's origin without much more detailed analysis. One way to determine a crater's origin is by examining the direction of impact. Interstellar dust is likely to have impacted the collector tray normal to its surface, while other debris impacted at a variety of angles. However, this directional information is not obvious in the craters on the aluminum foil strips. We examined the results of two hypervelocity test shots of particles into aluminum foil targets, varying the angle of impact and the particle sizes used. Auger elemental analysis was carried out on a number of craters across each foil. Many craters at higher impact angles (>60°) display the presence of deposited material around a crater, creating a spray pattern in the direction aligned with the direction of impact. No such patterns are observed for impacts closer to normal angles. When applied to the Stardust interstellar collector, such information may help in distinguishing craters caused by debris from those caused by interstellar dust, without the use of extensive analysis first.

1. INTRODUCTION

NASA's Stardust mission returned from orbit in 2006 after six years of collecting extraterrestrial samples. The Stardust collector's mission was to capture samples from the Wild 2 comet in addition to interstellar dust particles on collection trays made up of aerogel tiles and pieces of aluminum foil (Fig.1). Since its return, much work has been done to find and analyze impacts caused by the cometary particles. These samples were expected to contain a high concentration of early solar system material that could be studied in the lab. However, the interaction of these particles with the aerogel tiles at high speeds often caused the particles to undergo melting, destroying much of the material of interest[1,2] (Fig. 2). Although it was not originally intended for collecting particles, it is for this reason that the aluminum foil strips also became of interest in studying the residue left behind by colliding cometary particles[2].

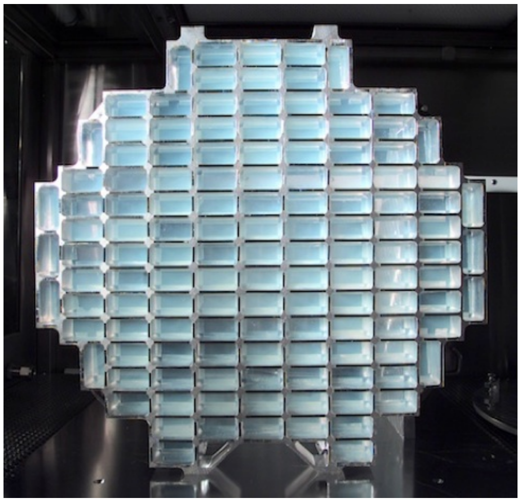

Figure 1. A Stardust collector tray consisting of aerogel tiles with aluminum foil between each tile

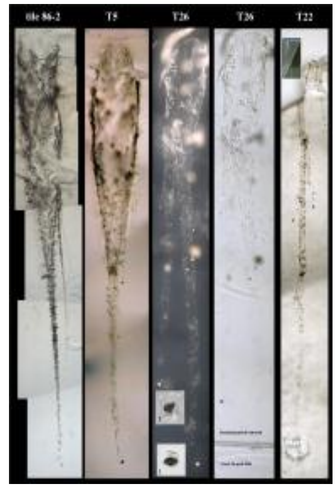

Figure 2. Cometary tracks found in the aerogel of the cometary collector[1]

Early solar system materials, or presolar grains, are of interest for laboratory investigation, as they can give us insight into the formation of our solar system and nucleosynthetic processes in stars. These particles are marked by their unusual isotopic compositions compared to average isotopic ratios normally observed in the solar system. Such compositions indicate that they are remnants that survived mixing and homogenization processes thought to have occurred during the formation of the solar system[3]. This presolar material would have come from the outflows of old stars or the remnants left behind by a supernova explosion, and as such, can be studied to help refine models of stellar evolution. Most presolar material available to study comes from materials that formed at the same time as the rest of the solar system and have since fallen to the Earth; these include meteorites, interplanetary dust particles, and micrometeorites. Comets are also among some of the oldest materials in the solar system, making them likely bodies to contain high concentrations of presolar grains[2].

The interstellar medium transports interstellar dust through our solar system from nearby stars in other regions of the galaxy. Such dust grains can be studied in parallel to presolar grains to provide more information on the processes other stars undergo. The other Stardust collector tray, which collected interstellar dust, is still undergoing analysis for impact craters. This work is proceeding more slowly due to the fact that these samples are more difficult to work with. In addition to being very small, making them difficult to find in the aluminum foil, many of the craters may have instead been caused by debris knocked off of the spacecraft[4]. For this reason, methods to help determine crater origin are needed for future analysis.

Currently, in order to locate craters in the Stardust interstellar collector tray, aluminum foil strips are cut from the array and a Scanning Electron Microscope (SEM) is used to image the foil area at a resolution of 106 x 80μm^2. These secondary electron (SE) images are manually scanned for crater-like features (Fig.3). Once found, these craters are marked, and further analyzed at a higher resolution to determine whether or not they are actual craters, or only debris on the foil surface[5]. Craters then undergo extensive elemental analysis to determine if they were created by an extraterrestrial particle. From this analysis, only 24 actual craters have been found across nine pieces of foil (~2.2% of the collection area), of which only four have been identified as having an extraterrestrial origin[6,7]. Most of the craters are instead due to secondary impacts from the spacecraft.

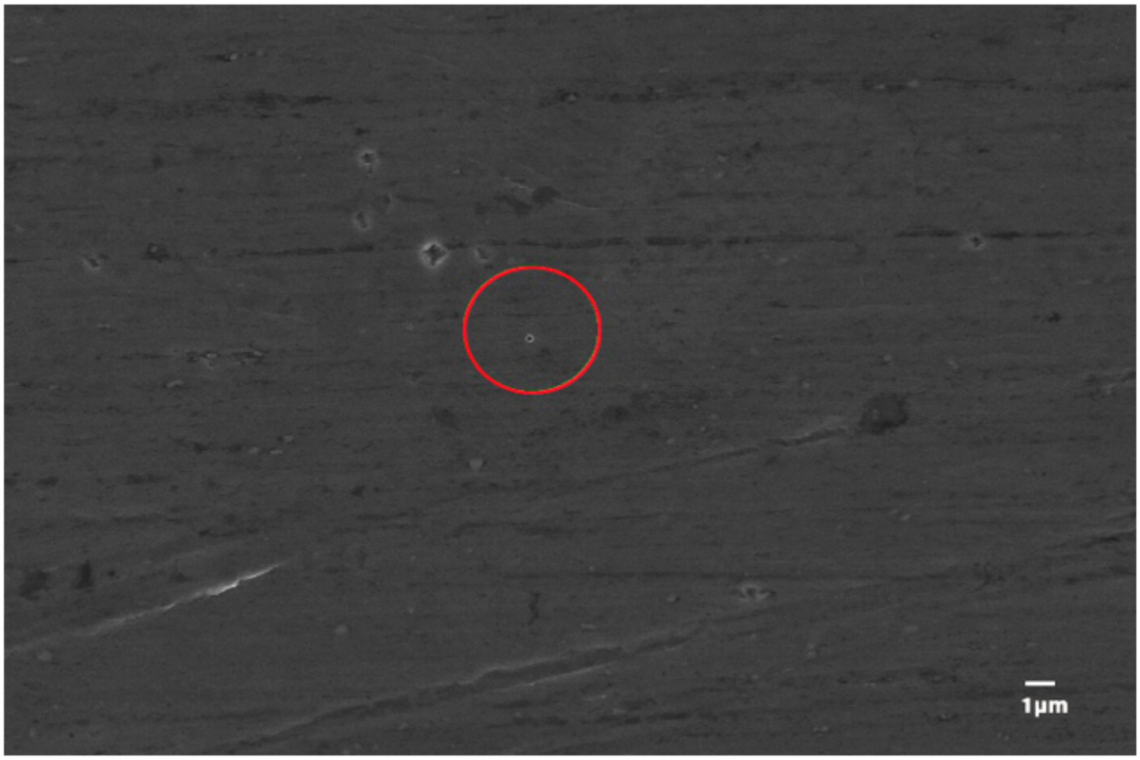

Figure 3. An example of a crater found on the interstellar collector. The crater is in the center of the red circle in the image.

One way to determine crater origin on the interstellar collector, prior to this elemental analysis process, is by examining the impact angle of particles into the foil. It is believed that all interstellar dust will have impacted the collector perpendicular to its surface, while other debris may have impacted at any variety of angles[8]. In the aerogel tiles, directional information is easily apparent; the impacts leave tracks making it easy to determine the impact angle (Fig.2). This feature is not obvious in the aluminum foil to help identify the angle of impact. However, analysis done on craters from the Long Duration Exposure Facility (LDEF) spacecraft suggests that a crater created by an off-normal impact can produce a thin spray pattern of ejected material directed out from the crater[9,10] (Fig.4). By looking for such occurrences, crater origin may be more easily identified in the Stardust collector foil.

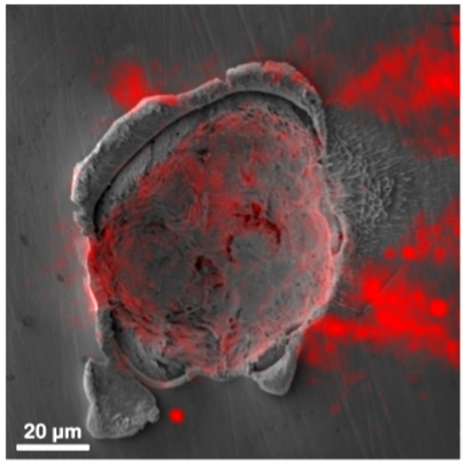

Figure 4. An SE image of a crater from the LDEF. The image is overlaid with an Fe elemental map, showing a thin spray pattern directed outward from the crater[10].

2. EXPERIMENT

To test whether or not hypervelocity impacts at oblique angles produce a spray pattern, two test shots were conducted at the University of Kent Light Gas Gun Facility. The light-gas gun uses an explosive force to propel a piston into H_2 gas, quickly building up pressure in the chamber. Once the pressure has built-up sufficiently, a rupture disk is broken letting the high-pressure gas pass through a barrel and launching the particles at very high speeds before hitting the target. In our experiment, particles were shot from a light-gas gun at 6 km/sec into a target of aluminum foil[8].

The first test shot was set up to examine how varying impact angle affected the appearance of a spray pattern. Aluminum foil was mounted on a curved target in order to produce a gradient of incident angles from 0° to 80° (Fig.5a). To retain information about the impact angle, markings were made on the foil so angles could be calculated based on the position of each crater. The shot was performed using 22.8µm glass beads as impact particles. For the second test shot, we were interested in whether or not the size of impact particles affected the spray pattern seen. More specifically, we were interested if particles closer to the size of interstellar dust could produce such patterns. San Carlos Olivine (Mg_2SiO_4) was ground down to grains less than 8µm in diameter. The aluminum foil target was mounted on a constant 60° inclined plane with a copper end piece to catch the secondary ejecta from the foil[8] (Fig.5b).

After receiving the test shot foils from the University of Kent, both target foils were mounted on pucks for analysis in the SEM and Auger spectrometer. Due to the size and curved shape of the first test shot target, it was first flattened and cut into three segments prior to being mounted for analysis. The copper end plate was removed from the second test foil and mounted separately as well. Maps of both test foils and the copper end plate were produced using an automated imaging program on a JEOL 840A SEM. Because larger particles had been used in the first test shot, some craters were visible without the aid of a microscope, and overview images were also taken using a reflected light microscope. Each target foil was scanned for craters using a PHI700 Auger Nanoprobe.

SE images were taken along with Al, Na, O, and Si elemental maps for each crater on the first target foil (See appendix A1). These elements are present in the glass beads and were imaged to see if the projectile material had accumulated around the crater area, obscuring the Al foil, and creating a spray pattern[8,10]. SE images and Al and Mg elemental maps were taken for craters found on the second test foil. Mg is prominent in this type of olivine, and was therefore imaged along with Al to see if spray patterns were created, similar to the elements chosen to analyze for the first test shot.

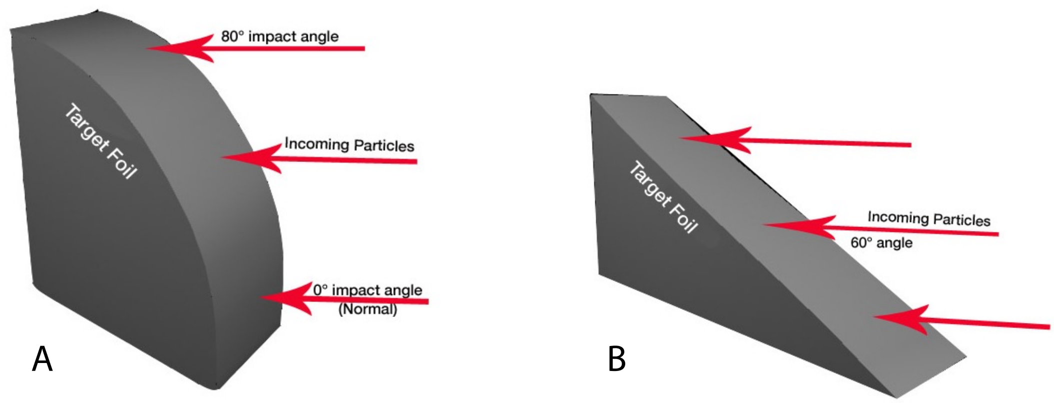

Figure 5. The arrangement of impact particles and target foils in the hypervelocity test shots. (a) Curved foil with 22.8μm glass beads. (b) 60^{o} impact angle with < 8μm San Carlos Olivine

3. RESULTS & DISCUSSION

Craters from the first oblique angle test shot (using 22.8 μm glass bead projectiles) confirmed the presence of a spray pattern from craters caused at high angle impacts. Close to 50 craters over the spectrum of impact angles underwent elemental analysis and ~15 craters, all at angles $>60^{o}$, had spray patterns in the forward direction originating from the crater (Fig.6). The spray patterns become increasingly visible with increasing angle of impact. Although not every crater from a high angle impact displays a spray pattern, no crater from a low angle or normal impact has a spray pattern[8].

For those craters that displayed them, spray patterns could be seen most easily in the Al elemental maps (Fig.6b). Compared to the aluminum foil background, each of the other three elements analyzed were present in low concentrations. This required higher resolution images to be taken, leading to longer analysis times to see the material deposited by the impacts emanating from each crater. It was found to be easier to look for surface regions in the elemental images where there were depletions in Al, or, where the spray from an impact was obscuring the foil. Due to the high concentration of Al, this allowed lower resolution elemental images to be taken more quickly[8]. For this reason, craters imaged later in the process only had Al elemental images taken, occasionally accompanied by Si elemental images, at lower resolutions.

Examining the second test shot (using < 8μm San Carlos olivine projectiles), the entire foil was scanned for craters less than 10μm in diameter. SE images were taken of each crater, with most craters found having diameters of ~5μm. Close to 150 craters were identified and, afterwards, elemental analysis was performed on 50 craters from different areas of the target foil. As mentioned above, only Al and Mg elemental images were taken. Fewer elements were needed for analysis, based off the results from the first test shot, which showed that Al elemental images were the most useful and quickest for displaying the spray patterns. Mg elemental maps were taken to ensure the olivine, and not other debris, caused each crater.

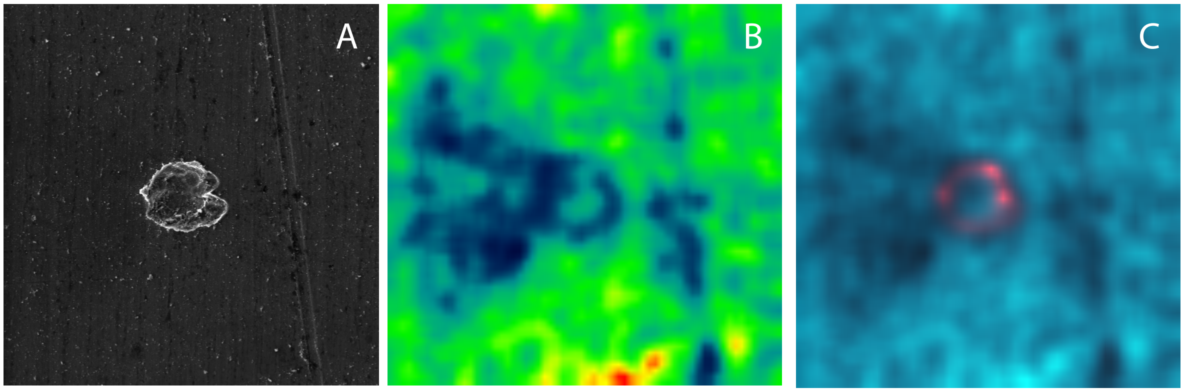

Figure 6. A crater from the first test shot, displaying the presence of a spray pattern emanating from the crater after being impacted from the right. (a) An SE image of the crater. (b) An Al elemental map of the area around the crater. Darker/blue areas indicate an area depleted in Al, or in this case an area that has been covered by ejected material. (c) A composite image of the crater and Al elemental map.

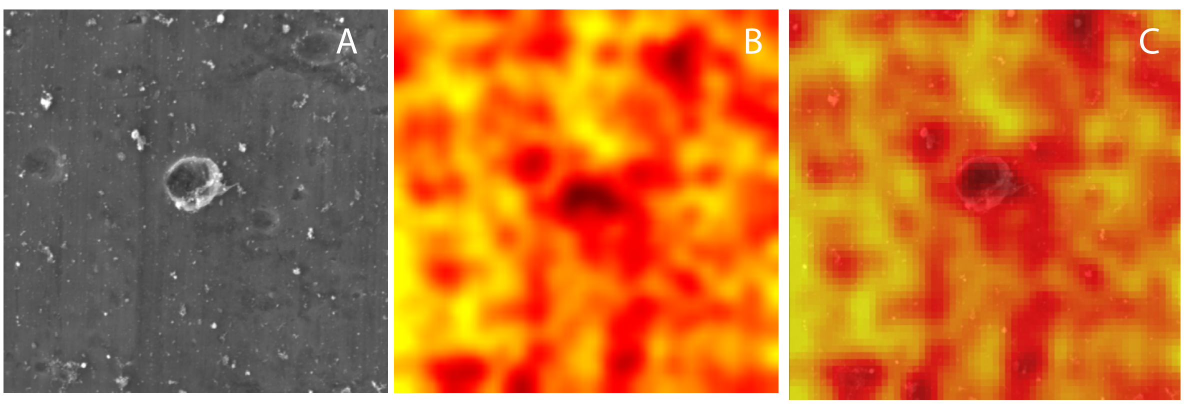

Figure 7. A crater from the second test shot, displaying the presence of a spray pattern emanating from the crater after being impacted from the left. (a) An SE image of the crater. (b) An Al elemental map of the area around the crater. Red areas indicate an area depleted in Al or covered by ejected material. (c) A composite image of the crater and Al elemental map.

Seven to ten of these craters did display spray patterns originating from craters in the forward direction (Fig.7). This indicates that spray patterns are, in fact, created for impacts of smaller sizes. The imprecision in the number of spray patterns observed is due to the fact that much of the foil area was also covered in other debris from the light-gas gun as well as natural deformities in the foil's surface. In some of the Al elemental images, this made it difficult to determine if what looked like a spray pattern was due to debris covering the foil's surface, or if the debris was instead obscuring the expected spray patterns. Some, but not all, of these discrepancies were made clear by examining the Mg elemental maps.

It should be noted that, although the craters from the second oblique impact test shot are much smaller than those on the LDEF or from the first test shot, they are still larger than those found on the stardust interstellar collector. As shown here, the deposited spray patterns are visible from smaller craters and it seems as though crater size only has a limited effect on the appearance of a spray pattern.

The second test shot target also included a copper endplate used to collect secondary ejecta from the aluminum foil. The end plate was scanned and SE images were taken of a number of craters. However, no elemental analysis has been conducted on them. These could yield more information on secondary impact craters, but was unnecessary for the interests of this study.

4. CONCLUSIONS

The hypervelocity test shots showed that spray patterns are clearly visible originating from craters in the forward direction. These spray patterns only become apparent at higher, off-normal impact angles (usually > 50˚ or 60˚). It also appears that projectile size does not affect the occurrence of a spray pattern. However, large amounts of surface debris present on the second test shot target, as well as in areas of the Stardust interstellar collector foils, can obscure spray patterns making it difficult to identify them.

When applied to the Stardust interstellar collector, the results from the oblique angle test shots should prove helpful in distinguishing between craters caused by interstellar dust and those from other debris. A spray pattern is indicative of an off-normal impact that does not belong to interstellar dust. By looking for the appearance of these spray patterns, many potential craters can be ruled out before more complicated analysis is performed. In this way, once craters are identified, the use of this method should speed up the analysis process.

Ideally this method could be tested on craters that have already been found on the interstellar collector foils, in addition to applying these techniques for determining a crater's origin to craters that are still being found. If those difficulties mentioned in observing spray patterns become prominent when applied to the Stardust collectors, more methods may be required to help discern crater origins.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1]Brownlee D. et al., 2006, *Science*, 314, 1711.
[2]Floss C. et al., 2013, *The Astrophysical Journal*, 763, 140
[3]Zinner E., 2014, *Treatise on Geochemistry,* **2**, 181.
[4]Westphal A. J. et al., 2008, Lunar and Planetary Science Conf. XXXIX, Abstract # 1855.
[5]Floss C. et al., 2011, Lunar and Planetary Science Conf. XLII Abstract # 1576.
[6]Stroud R. M. et al., 2012, Lunar and Planetary Science Conf. XLIII Abstract # 2001.
[7]Stroud R. M. et al., 2011, Lunar and Planetary Science Conf. XLII Abstract # 1753.
[8]Staderman F. J. et al., 2010, Lunar and Planetary Science Conf. XLI, Abstract # 1349.
[9]Burchell M., Mackay N., 1998, *Journal of Geophysical Research*, 103, 22761.
[10]Staderman F. J. et al., 2009, Lunar and Planetary Science Conf. XL, Abstract # 2120.

A1. APPENDIX I: Auger Spectroscopy

Auger electron spectroscopy is a technique used for the surface analysis of a sample that makes use of the Auger electron effect. This effect has its basis in atomic physics, whereby electrons are ejected from a sample's atoms at energies characteristic to each element.

When a sample is being bombarded by an electron beam, as in an SEM, those electrons are reflected back once they contact the sample. These are then detected by scintillators and amplified to form an SE image. Due to the high energy of incoming electrons (typically in the keV range), the electron beam can also excite core electrons, ejecting them from the atoms. This leaves behind a hole in the atom's electron energy levels that an electron from a higher orbital can de-excite to fill. This process releases a photon, usually in the form of an X-ray, which can be detected by EDX methods. Occasionally, if the photon is energetic enough, it will be reabsorbed by an outer-shell electron, ejecting that electron instead. Typically these Auger electrons only have energies < 3keV, making it difficult for those electrons ejected in the center of a sample to reach a detector. However, the electrons emitted from the first few nanometers of the sample's surface are able to be detected. The detector is very sensitive to the sample's surface, allowing for the characterization of elements on the surface at a high resolution.

The high resolution and sensitivity allows for the detection of the spray patterns in this study, which would otherwise be overpowered by the large background of aluminum foil. Elemental characterization is especially useful in conjunction with NanoSIMS searches for presolar grains. Once an area has been located with an isotopic anomaly in C, N, or O, an Auger spectrum may then be taken at a higher resolution and magnification of that same area in search of other elements a presolar grain may contain.