STARDUST CRATERS AND TRACKS: IN SPACE AND IN THE LABORATORY. M. J. Burchell[1], A. T. Kearsley[2] and F. Hörz[3]. [1]School of Physical Sciences, Ingram Building, Univ. of Kent, Canterbury, Kent CT2 7NH, UK. M.J.Burchell@kent.ac.uk, [2]Department of Mineralogy, Natural History Museum, London, SW7 5BD, UK. [3]NASA Johnson Space Centre, Houston, Texas, USA.

Introduction: The high speed impacts that cause cratering are simply the result of orbital and in-fall speeds and are not per se limited to large bodies and geological scale events. Hypervelocity impacts (speed greater than ~ 1 km s^{-1}) also occur for small impactors. Use has been made of this for decades to harvest small dust grains in space. In addition, studies of micro-meteorite impact craters on lunar samples and laboratory studies of space weathering by micro-impacts have all combined laboratory studies with study of the properties of natural solar system materials.

Recently, the "harvest" collection concept was used by the NASA Stardust mission [1] which flew past comet 81P/Wild-2 in 2004 at an encounter speed of 6.1 km s^{-1} [2], returning dust samples to Earth in 2006 [3]. Stardust sampled the cometary dust both by cratering in aluminium foils and via capture in aerogel [4]. The problem in the subsequent analysis is to determine the pre-impact properties of the dust grains from the observed features in the foil and aerogel (two very different materials, one highly porous). There is a need to understand the impact processes in detail. Although the typical impactor is < 100 um in size, possible insights applicable to large structures may be gained as well, such as the scaling of target and projectile densities or mineralogical and compositional alterations of the projectiles, including selective vaporization.

Some simplifications apply to the Stardust calibrations; the impact speed (6.1 km s^{-1}) and direction (normal or near normal incidence) and the target materials are well known and constant for every impact, and the projectile speed and size regimes are accessible by experiment. For Stardust a large programme of laboratory calibrations was undertaken. This began before the samples were returned and has continued since, informed by the features observed in the data. The method involved direct comparison of observed features with those recreated in the laboratory using two stage light gas guns. Attempts to use numerical modeling of the impacts are still at a preliminary level.

Cratering in Foils: The foil used on the Stardust cometary collector was aluminium Al 1100. It was ~101 μm thick, with exposed area 153 cm^2. Craters were readily observed on the foil after return to Earth (Fig. 1). Due to the resolution in the analysis, these are split into two groups: Large craters are those above 10 μm dia., small craters were those below 5 μm dia. The large craters were located by low resolution optical scans of many strips of foil post flight. The small craters were found via higher resolution SEM work on a small part of the area of a limited number of foils [4].

The initial calibration [5] was made using spherical soda lime glass beads, fired in a series of shots using light gas guns at the Univ. of Kent and NASA. Each shot contained a monodispersive sample of beads, sizes from 10 – 80 μm dia. The results were fairly circular craters (in plane view) with smooth walls and slightly irregular overhanging lips at the crater edges, very similar to Fig. 1.

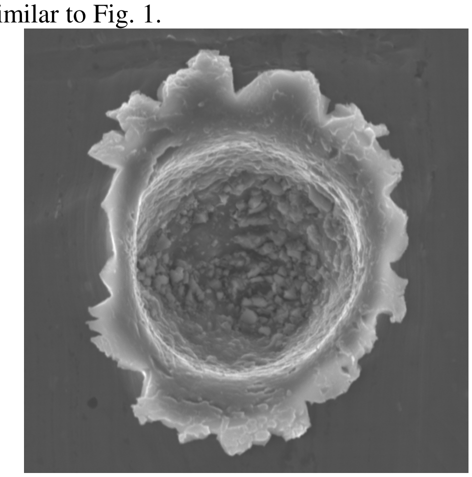

Fig 1. Comet Wild 2 olivine dust grain impact onto Stardust foil C086N,1 at 6.1 kms^{-1}. Crater dia is approx. 50 microns. (Top view)

During the post flight analysis a wide range of crater shapes and wall textures were visible in the Stardust data. Accordingly, more shots were carried out at Kent, varying projectile density and shape [6], mineral composition, etc. The full range of characteristics of the observed Stardust craters can now be reproduced.

Reproducing the full range of crater depth – diameter ratios observed in the Stardust data was informative. For monolithic grains two main features were found to control this parameter: the grain shape (spherical or more elongated along one axis) and density. Spherical projectiles of density similar to the target produced hemispherical craters with lower density produced shallower craters and elongated impactors striking along their main axis produced deeper craters. Combined with residue analysis on the Stardust craters, this helps constrain both projectile density and shape.

A second important group of craters were those with very shallow shapes (small depth / dia. ratio) and multiple pits in the crater floor. One of the 7 large craters in the initial analysis sample meets this description and had 12 internal pits. A simple hypothesis for such an impact feature is that it consisted of 12 discrete grains striking near simultaneously over a region of some 100 or so μm^2. This is incompatible with the observed flux rate, but if a single extended grain with multiple components were to have struck this naively would produce the required crater shape. This suggests a highly porous grain, or a grain with dense (mineral) cores held together in a much lower density and more volatile glue (organic). Traditionally, such a hypothesis is hard to test in a light gas gun facility, as it would collapse during the initial acceleration in the gun. However, two new approaches were applied. First individual mineral grains (size down to less than 10 μm) were glued together using organic glues. Second, pellets of sintered SiO_2 grains [7] (individual grain size 1.5 μm) were used. Both types of projectile (one of widely differing density materials and the other a highly porous material) were sufficiently robust to survive launch in the gun and produced the desired crater shape (shallow crater with multiple pits). It is not necessarily clear which type of impactor made the Stardust craters, or it may have been a combination of both.

Aerogel Tracks: Although hypervelocity impacts are widely held to involve complete disruption of the projectile, this is in fact a misconception. If the target material is porous, the shock pressures on impact are reduced. In the limit, if a highly porous material with relatively thin solids is used, the projectile can tunnel into the target, with relatively minimal alteration or disruption. Aerogel is such a target material, it can be made with densities down to just a few kg m^{-3}. A recent review of the use of aerogel as a cosmic dust collector is given in [8].

For Stardust aerogel data, two calibrations were required. The first was to use soda lime glass beads (as with the foil calibration) to produce a track size vs. impactor size calibration. The second was to use a range of impactor materials to produce the variety of track types observed in the Stardust aerogels. These types were classified into 3 groups (A, B, C) depending on their morphology. Type A were narrow, relatively long tracks with a single grain at their end. Type B had broad initial cavities with one or several narrow tracks emerging underneath, each containing a fragment of a dust grain. Type C tracks had solely a broad cavity with no distinct tracks emerging from them. Associating these classes of tracks with impactor properties was a key feature of the calibration work. The preliminary results are in [4]. Type A tracks were found to be due to well consolidated, homogeneous impactors similar to olivine grains. Type B (example shown in Fig 2) were either non-cohesive impactors with a variety of individual grain sizes and various compositions, or they could have been due to volatile rich impactors which disrupt on impact. Type C were similar to B but with no large discrete components and which disaggregated into sub-micron particles in impact. It appears that radial dispersion of solids played a more prominent role in the formation of these bulbous structures than the liberation and expansion of vapors. .

Fig. 2. Example of Type B impact (C092_T1) from Stardust cometary aerogel tray (Level 3 images). Impact direction was from the top. (Side view)

Conclusions: An extensive light gas gun impact programme was carried out to assist in the interpretation of the interpretation of the impact features on the Stardust spacecraft. This was unusual compared to most impact studies in that the size and speed of impact features in space can be directly reproduced in the laboratory. A feature of the work was two greatly dissimilar target materials (one highly porous) yielding very different results from similar impacts. The results successfully reproduce many of the features observed on Stardust. As well as crater and track morphology, studies of laboratory samples has permitted detailed understanding of the amount of the impactors retained at the impact sites and degree of impact processing it has undergone.

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