IMPACT EXPERIMENTS WITH Al_2O_3 PROJECTILES INTO AEROGEL.

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Introduction: The detailed mineralogical, compositional, and isotopic investigations of cometary dust retrieved by Stardust provide empirical evidence for the utility of aerogel in capturing analyzable residues of hyper velocity particles [1]. These residues are found along the walls and in the termini of unusually deep penetration "tracks" which typically form in such high-porosity, low-density materials as summarized by [2]. Nevertheless, a detailed theoretical understanding of the penetration process in aerogel is still in its infancy and constitutes a formidable problem in shock physics [3, 4, 5]. Specifically, the *P-T* histories of the recovered residues are difficult to ascertain, a prerequisite to evaluate potential particle alterations during the capture process.

We therefore embarked on a series of impact experiments under simple, if not idealized, conditions conducive to theoretical analysis. First, we used aerogel of constant density (0.02 g cm^{-3}), which was unlike the density-graded aerogel flown on Stardust. Second, we used spherical, high-purity, polycrystalline Al_2O_3 (α-corundum) projectiles. Not only are their relevant thermodynamic properties better known than those of soda-lime glass (SLG) projectiles used in most earlier experiments [6, 7, 8], but corundum is also highly refractory and very competent mechanically. The latter should minimize, possibly eliminate, mass loss due to ablation, as well as excessive deformation of the impactor [5], which may have affected all earlier SLG experiments. While these idealized boundary conditions may remove the present experiments to some degree from the penetration-behavior of natural impactors, they seem more suited for a basic examination of hypervelocity penetration in the highly porous aerogel. The increased complexities typical for natural impactors may be added incrementally to this baseline understanding in the future. This abstract represents a progress report on the dimensions and morphologies of penetration tracks produced under these simplified conditions.

Experiments: The experiments were conducted with the 5-mm light-gas gun at NASA JSC, using four-piece sabots to "shotgun" an ensemble of small particles. We acquired Al_2O_3 spheres that averaged 35, 60, and 105 μm in diameter with a standard deviation of ~10% and sphericities of better than 0.95 for ~90% (on the basis of our own size analyses using an SEM). We conducted one experiment with each of the above sizes at a constant impact velocity of 6.1 km s^{-1}; an additional series used the 60-μm projectiles at 3.11, 3.64, 5.21, and 6.04 km s^{-1} in an effort to isolate the effects of velocity. Each impact was normal to the face of the aerogel target.

Results: All tracks were exceptionally long and slender compared to those produced by SLG impactors [6, 7, 8]. A typical track is illustrated in Fig.1. Tracks tend to expand rapidly near the entrance hole to some maximum diameter (D_{Tmax}). The latter pertains over a sizeable portion of the track that is bounded by depth L_1 and L_2 (see Fig.1); the continuously tapering section at depth >L_2 is typically >80% of the total track length (L_T). Note some highly twisted and, on occasion, spiraled features in the track's main cavity (top row in Fig.1). SEM observations on bisected tracks indicate that these are interconnected networks of tiny granules, mixed with and bonded by melts of aerogel. The sections above L_2 seem dominated by melt phenomena, whereas all sections >0.3 L_T display solid-state, mechanical deformations only. Indeed, the 3.11 km s^{-1} case essentially repre-

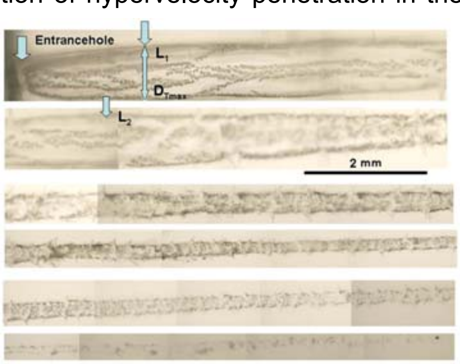

Fig 1.

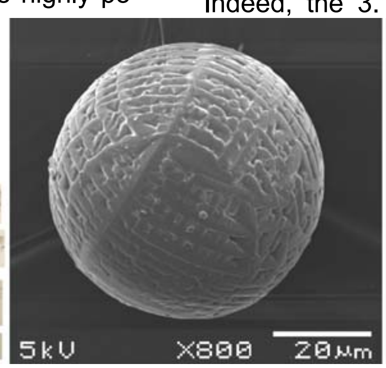

Fig 2a.

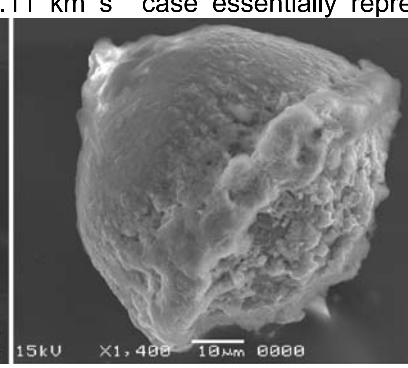

Fig 2b.

sents the lower 80% of the high-velocity experiments. A pristine 60 um projectile is illustrated in Fig. 2a, and compared to a specimen recovered from the 6.04 km s^{-1} test (Fig. 2b). The flat and granular face in Fig. 2b is pointing downrange. SEM analyses indicate that the pronounced ridge is molten or compressed aerogel. The sphere's surface is smooth and the initial surface texture, controlled by crystal faces, is destroyed, either by ablation and/or by the deposition of a thin film of melted aerogel. A conical tip at the rear and the lineated nature of some melt stringers suggest that molten material flowed towards the rear and accumulated at the projectile's trailing end. EDS analyses of individual melts reveal highly variable mixtures of Al and Si, suggesting prevalent projectile melting, presumably by ablation. In turn this implies surface temperatures >2054ºC at impact velocities of some 6 km s^{-1}.

Table 1: Average dimensions of aerogel penetration tracks using Al_2O_3 impactors.

D_P	V	L_T	D_{Tmax}	L_1	L_2	V_T	D_R	
(µm)	(km s^{-1})	(mm)	(mm)	(mm)	(mm)	(mm^3)	(µm)	
35	6.18	17.52	0.395	0.91	1.70	2.27	35.2	*D_p* **=** *projectile diameter*
60	6.04	34.57	1.042	2.14	4.81	9.95	63.2	*V = impact velocity*
105	6.10	61.05	1.350	3.48	9.65	39.01	112.1	*L_T = track length, total*
60	5.21	37.67	0.702	1.51	3.40	5.77	59.8	*D_{Tmax} = Max. track width*
60	3.64	36.63	0.423	1.29	2.61	3.58	62.3	*L_1 = beginning of D_{Tmax}*
60	3.11	37.67	0.425	n.a.	n.a.	1.49	62.7	*L_2 = end of D_{Tmax}*
								V_T = track volume
								D_R = diameter of residue

Table 1 summarizes the average track dimensions, generally 10 to 20 measurements per experiment, using an optical microscope. Figs. 3a and b illustrate that the Al_2O_3 tracks are typically a factor of 2 deeper than those produced by SLG projectiles under comparable conditions [2, 6, 7]. At constant velocity, L_T scales approximately linearly with projectile size (Fig. 3a), but there is only a modest dependence on velocity at constant impactor size (Fig. 3b) over the range investigated. Similar trends were observed in earlier experimental studies [2, 6, 7}. The displaced track volumes are illustrated in Fig. 3c as a function of kinetic energy, and are compared to those for SLG shots [2, 7, 8]. The present track volumes were modeled via two inverted cones that were separated by a cylinder of D_{max} and length (L_2 - L_1). Although complex in detail, this figure illustrates that target density exerts strong control over the displaced mass. Furthermore, despite their great depth, the Al_2O_3 tracks have smaller D_{Tmax} than comparable SLG features, thus accounting for the relatively modest increase in volume.

Conclusions: Penetration tracks in 0.02 g cm^{-3} aerogel produced by Al_2O_3 projectiles are a factor of 2 deeper, yet narrower than those produced by SLG impactors.. This suggests that the present projectiles are less prone to deformation and flattening upon impact than glass impactors. Still more bulbous tracks that are abundant in the Stardust aerogels mandate impactors that disperse laterally even more so than SLG [9]. Additionally, we can demonstrate that the temperatures at 6 km s^{-1} exceeded 2050°C, the melting point of Al_2O_3. Melting and mass loss by ablation is most likely a significant process during the capture of cometary particles on Stardust.

References: [1] Brownlee, D.E. *et al.* (2006) *Science* **314**, 1711-1716. [2] Burchell, M.J. *et al.* (2006) *Ann. Rev. Earth Planet. Sci.* **34**, 385-418. [3] Anderson, W.W. and Ahrens, T.J. (1994) *J. Geophys. Res.* **99(E1)**, 2063-2071. [4] Dominguez, G. et al. (2004) *Icarus* **172**, 613-624. [5] Trucano, T.G. and Grady, D.E. (1995) *Int. J. Impact Engin.* **17**, 861-872. [6] Hörz, F. *et al.* (1998) NASA TM-98-201792. [7] Burchell, M.J. *et al.* (2001) *Met. Planet. Sci.* **36**, 209-221. [8] Burchell, M.J. *et al.* (2008) *Met. Planet. Sci.*, in press. [9] Trigo-Rodriguez, J. *et al.* (2008) *Met. Planet. Sci.*, in press.

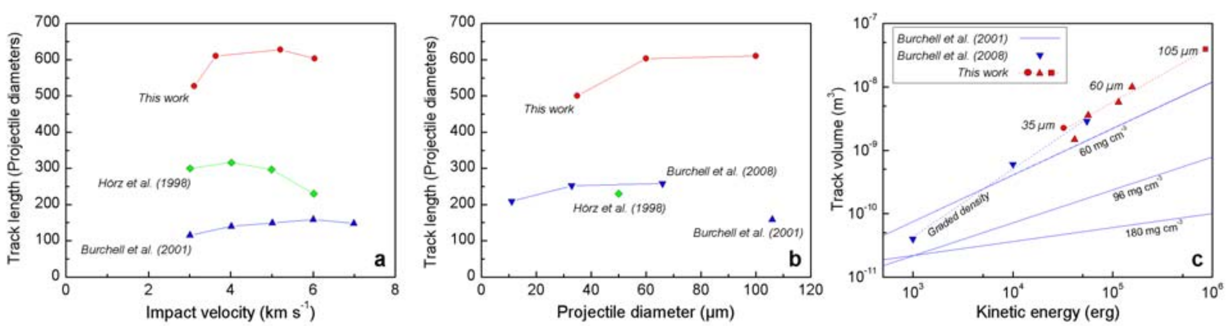

Figure 3: Summary of track dimensions: This work: Al_2O_3 into 0.02 g cm^{-3} aerogel; Hörz et al. (1998): SLG, 50 µm D_p into 0.02 g cm^{-3}; Burchell et al. (2001): SLG, 106 µm into 0.06 g cm^{-3} in Figs. a and b and additional densities in c; Burchell et al. (2008): SLG into Stardust aerogel, < 0.02 g cm^{-3}.