NONDESTRUCTIVE 3D CONFOCAL LASER IMAGING WITH DECONVOLUTION OF SEVEN WHOLE STARDUST TRACKS WITH COMPLEMENTARY XRF AND QUANTITATIVE ANALYSIS

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Introduction: The Stardust mission to comet Wild 2 trapped many cometary and ISM particles in aerogel, leaving behind 'tracks' of melted silica aerogel on both sides of the collector [1]. Collected particles and their tracks range in size from submicron to millimeter scale. Interstellar dust collected on the obverse of the aerogel collector is thought to have an average track length of ~15µm [2,3]. It has been our goal to perform a total non-destructive 3D textural and XRF chemical analysis on *both* types of tracks. To that end, we use a combination of Laser Confocal Scanning Microscopy (LCSM) and X Ray Florescence (XRF) spectrometry [4]. Utilized properly, the combination of 3D optical data and chemical data provides total non-destructive characterization of full tracks, prior to flattening or other destructive analysis methods.

Our LCSM techniques allow imaging at 0.075 µm/pixel, without the use of oil-based lenses. A full textural analysis on track #82 is presented here as well as analysis of 6 additional tracks contained within 3 keystones (#128, #129 and #140). We present a method of removing the axial distortion inherent in LCSM images, by means of a computational 3D Deconvolution algorithm, and present some preliminary experiments with computed point spread functions. The combination of 3D LCSM data and XRF data provides invaluable information, while preserving the integrity of the samples for further analysis. It is imperative that these samples, the first extraterrestrial solids returned since the Apollo era, be fully mapped nondestructively in 3D, to preserve the maximum amount of information prior to other, destructive analysis.

Samples and Imaging: Four keystones containing a total of seven tracks were imaged: T82 (898µm carrot), T128a (520µm carrot), T128b (250µm carrot), T128g (40µm carrot), T128d (30µm carrot), T129 (600µm carrot), and T140 (>4100µm bulbous).

LCSM images were taken at the American Museum of Natural History Microscopy and Imaging Facility. Scans of varying magnification on regions of tracks #82, #128, #129, and #140 were performed without disturbing the keystone. The Zeiss LSM 510 at the AMNH currently images using dry microscopy at a maximum resolution of ~70nm/voxel edge. Earlier work demonstrated the feasibility of wet microscopy with resolution at or better than 0.04 µm/pixel edge on a stardust analog sample [5]. Table 1 lists for each scan the effective magnification (mag), scan speed/pixel dwell time (*t*, µsec), pixel size resolution (*r*, µm/pixel edge), and number of slices (*n*):

Scan Label	Mag.	*t* (µsec)	*r*	*n*
T128 field	20x	4 / 6.4	0.45	312
T128 alpha	63x	3 / 12.80	0.07	158
T128 beta	63x	4 / 6.4	0.07	116
T128 gamma	60x	3 / 12.80	0.04	24
T128 delta	40x	4 / 6.4	0.04	34
T129 field	20x	3 / 12.80	0.45	221
T129 field	63x	4 / 6.4	0.07	120
T140 field	1.5x	6/1.60	3.6	107

Table 1: LCSM Scan Conditions (Field scans are wide views of large keystone volumes).

Tracks 128a and 128b were also analyzed in November 2008 using XRF at Argonne National Labs' APS facility, GSECARS beamline 13ID.

Image Analyis: Image stacks acquired by LCSM were subsequently combined into voxel based volumetric maps. Track features such as terminal particles, spiral deposition and radial fractures were identified using either 3D visualization software or 2D projections (Figure 1). Tracks were outlined (segmented) manually to fully quantify track geometry. Quantitative track parameters such as cross sectional area and cumulative volume were calculated along tracks. We are able to measure the track entrance size accurately, which allows accurate estimation of the original impactor size [6,7]. Among many track characteristics, we can calculate the skewness of a track's centroid along a direct line from the entry point to the terminal particle. Skewness plots quantitatively reveal in carrot shaped tracks the spiraling (rifling) effects that may be present [8]. Separate skewness in the X and Y directions as a function of track depth is calculated as well as an absolute skewness value.

Results: Track #82 (C2092,1,82,0,0) contains a single 898µm long track in a keystone mounted on a standard fork and 25mm glass rod. Its 3D geometry indicates a spiraling impactor, with a large area of particulate deposition about halfway down the track, coinciding with a noticeable kink in track structure. Additional XRF analysis indicated a Zr rich grain of interest near this kink and a terminal particle that appears to be composed of two separate grains [5]. A full quantitative textural analysis of this track has been completed and is presented in our online resources [9].

Keystone #128 (C2012,4,128,0,0) contains 4 separate tracks of sizes 520, 250, 40, and 30µm.
These have been nicknamed alpha, beta, gamma and delta, respectively. Figure 1 shows a projection of a field scan (450 nm/pxl reolution) of this keystone, with the two largest tracks, alpha and beta clearly visible.

This keystone was mounted on a standard fork until mounting for XRF analysis, at which point the keystone became detached from its fork. Keystone #128 is now housed in a kapton box, suitable for XRF analysis. This keystone was imaged using LCSM before being housed in kapton. While it is possible to image Stardust keystones in kapton using LCSM, the proper optical corrections have not yet been determined.

Morphologically, T128a is interesting, exhibiting spiral behavior as well as small amounts of particulate deposition along most of the track. There is a small bifurcation present about 1/3 down the track with a small secondary terminal particle in that region. Additionally, there is a large particle of high interest about 3/4 down the track slightly smaller than the terminal particle. Figures 2 and 3 show the results of quantitative analysis in T128a (Quantitative analyses for all other tracks are omitted due to space concerns, but can be located in our internet resources) [9].

Track 128b is a carrot shaped track, which also exhibits some spiraling behavior despite being much less skewed than T128a. Additionally, there are no secondary terminal particles to be found in T128b, although the track is slightly skewed in the opposite direction of T128a. The entry points of T128a and T128b are about 150µm apart yet exhibit very different features. T128g and T128d are small carrot shaped tracks within the same keystone, each with single terminal particles. Tracks of this size are difficult to locate with a 20x lens, thus there may be similar tracks in this and other keystones that may have been missed.

Keystone #129 (C2012,5,129,0,0) contains one, incomplete, 700µm track, and has been imaged using LCSM. Morphologically, T129 is roughly cylindrical and straight in shape, with a small secondary terminal particle present about 1/2 way down the track, creating a small area of skewness.

Keystone #140 is a bulbous track which is significantly larger than any track we have imaged in the past (>4100µm), use of lower magnification lenses is required to image this track with LCSM, yet it is easy to see radial fragmentation extending beyond the keystone, and a large terminal particle region not orthogonal to the plane of incidence. Unlike previous tracks, keystone 140 has not yet been quantitatively analyzed.

Discussion: Recently we have acquired full use of a 3D deconvolution software suite and have made extensive use of an iterative deconvolution method. We have been using a theoretical point spread function for aerogel, calculated using our microscope parameters. We are working to further improve these results by experimentally determining a PSF using 1µm beads embedded in flight grade aerogel.

The combination of 3D LCSM and XRF data creates unique datasets, which allow unparalleled insight into the morphology and chemical makeup of whole Stardust tracks. We intend to use this data to several ends which include, but are not limited to, reconstruction of the original impactor, and quantifying volatiles present during track formation.

Conclusions: We have demonstrated high resolution and non-destructive 3D LCSM and XRF imaging on high value Stardust tracks. It is of the utmost importance to map all tracks in 3D prior to other, destructive analyses so as to preserve the maximum amount of information.

References: [1] Burchell M.J. *et al.* (2006) *Ann. Rev. Earth Planet. Sci*. 34: 385-418. [2] Westphal A.J. *et al.* (2004) *Meteor. Planet Sci., 39*, 1375-1386. [3] Westphal et al. (2006) LPSC XXXVII, #2225. [4] Ebel D.S., *et al.* (2007) LPSC *XXXVIII*, #1977. [5] Greenberg, M. *et al.* (2008) *LPSC XXXIX* #1800. [6] Burchell M.J. *et al.* (1999) *Planet. Space Sci.,* 47, 189. [7] Iida Y. *et al.* (2008) *LPSC XXXIX* #1563. [8] Nakamura-Messenger K. *et al.* (2007) *LPSC XXXVIII* #2191. [9] See. http://research.amnh.org/~debel/tomo-aps/lcsmTech.html

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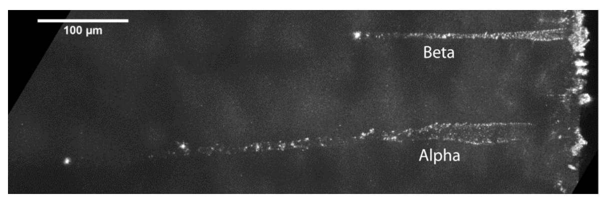

Figure 1: T128 Projection – This is a cropped and scaled maximum intensity projection; most details cannot be viewed on an image of this size.

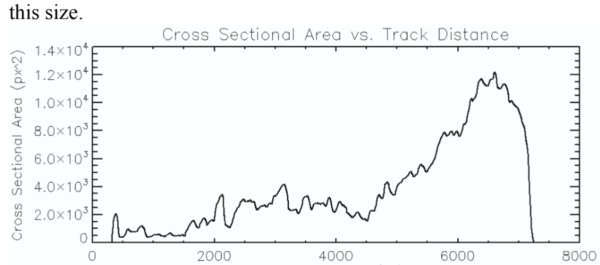

Figure 2: T128a Cross sectional area and volume – The entry point of the cometary material is on the right side of the image.

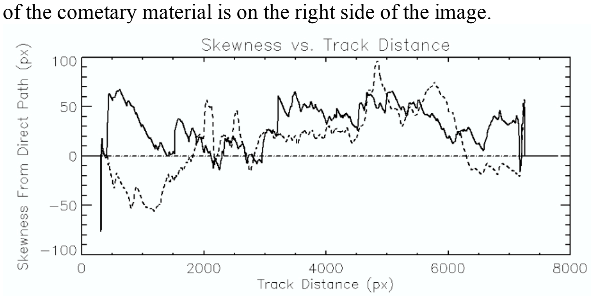

Figure 3: T128a Skewness profile – The solid line represents skewness in the X direction and the dashed line represents the Y direction.