NONDESTRUCTIVE XRF AND QUANTITATIVE VOLUMETRIC IMAGE ANALYSIS OF STARDUST TRACKS 140, 151 & 152.

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Introduction: The cometary collector of the NASA Stardust mission returned over 1000 particles, each trapped by a density-graded aerogel medium at a relative velocity of 6.1 km/s. Particles captured at hypervelocity speeds in aerogel form "tracks" or cavities in aerogel, composed of disaggregated cometary material, and sintered or compacted aerogel [1,2]. Each track can be viewed as a timeline, uniquely characterizing a single capture event. Combination of 3D morphological and chemical data with microphysical models should allow a reconstruction of track formation events and eventually the original impactor [3,4]. We use a combination of 3D Laser Confocal Scanning Microscopy (LCSM), X Ray Fluorescence (XRF), and X Ray Diffraction (XRD, to characterize track components morphologically, chemically and mineralogically. Our goal is to collect the maximum amount of data on each track with non-invasive methods, prior to other, destructive techniques.

Samples: Over the past two years we have imaged with LCSM a total of ten tracks, housed in seven keystones. We have discovered several tracks and terminal particles not known from previous optical microscopy. We have also imaged numerous other analog samples for calibration and testing purposes. Our suite of images includes tracks ranging in length from <50 μm to >4000 μm and spanning the 3 major track types [4,5,6]. Complementary XRF data has been collected or attempted on all but two of these tracks. Table 1 lists all cometary tracks we have processed thus far, and their length (μm), and number of terminal particles (TPs):

Track	Length	TPs	*Mount*	*Type*
T82	898	1	Fork	A
T128 α	520	2	Fork	A
T128 β	250	1	Fork	A
T128 γ	43	1	Fork	A
T128 δ	30	1	Fork	A
T129	700 (inc)	2	Fork	A
T140	4400	2	Coverslip Box	B
T151	3121	4	Kapton Sleeve	A
T152	2515	3	Fork	A
T164	541	3	Kapton Box	B

Table 1: LCSM Track data (All tracks are in keystones. Keystone T128 has 4 tracks in it).

Imaging and Analysis Techniques: LCSM images of all tracks were taken at the Microscopy and Imaging Facility at the American Museum of Natural History. All scans are preformed on tracks encased in whole keystones at low laser power to ensure sample safety. Full maps of tracks are acquired using a correct Nyquist sampling rate to provide the highest possible resolution images. Confocal images acquired at optimal resolution (<80 nm/pixel) have a small field of view (<200 μm in X and Y), thus we have developed a method for stitching imaged "blocks" to reconstruct entire tracks in 3D.

Stitched track images provide a clear view of track morphology and features, including large particles, deposition profiles and radial fractures. In several cases, previously unseen tracks and terminal particles have been revealed by confocal imagery. Clarity of confocal images is improved through the use of a 3D deconvolution algorithm using a theoretical point spread function (PSF) for aerogel. Proper deconvolution of confocal imagery is essential and greatly reduces uncertainty in image analysis [4]. Deconvolved and stitched track images are later manually segmented to quantify track geometries. We have developed a rapid analysis algorithm, as a complement to other methods, which calculates track volume, cross sectional area and skewness, all as a function of penetration depth [5].

Tracks 140, 151 and 152 were analyzed with synchrotron XRF at Argonne National Labs' APS facility, GSECARS beamline 13ID in June 2009. XRF data has been processed with techniques described elsewhere [6,7]. These tracks were also analyzed with synchrotron XRD and XRF at Brookhaven National Labs' NSLS facility, beamline X26A in August 2009.

Results: Track 140, (C2061,2,140,0,0) is a 4400 μm long type B track. The bulbous portion of this track is ~3800 μm in length and has 2 major styli, each with one large terminal particle at its end. Smaller styli can be seen extending radially outward from the bulb area, but are much shorter in length and have much smaller terminal particles as well. Analyses of background elements (e.g. Br) in aerogel indicate uneven compaction of aerogel extending radially around the bulb.

Track 151, (C2112,1,151,0,0) is a 2995 μm long type A track with a small bulbous portion extending ~1mm down the track. The bulb is less defined than that of other tracks and gradually forms a stylus. Track 151 has 4 major terminal particles. Upon transport from JSC the keystone housing Track 151 fell off its forklift and was slightly damaged, most noticeably in the bulbous portion. We have housed this track in a rigid kapton sleeve. All analyses have been performed while the keystone is in this housing.

Track 152, (C2035,2,152,0,0) is a 2515 µm long type A track with a small (~315 µm long) bulbous section in the beginning of the track. Track 152 has 3 terminal particles; the largest 2 reside at the end of the track, and a smaller particle at a depth of ~1700 µm. A scaled 2D projection of the 3D confocal map and corresponding XRF Fe intensity map of Track 152 can be seen in the figure below. Much larger, full resolution images can be seen at our internet resources [8].

Combining the morphological data from confocal imagery with elemental data from XRF provides unparalleled insight into track formation impact events. The initial impactor pulled inwards on the aerogel surface upon impact, creating a dish shaped dimple with a depth of 33 µm, and a radius of 112 µm. The initial track opening is 80 µm in width but quickly closes to a minimum width of 45 µm. At a depth of 135 µm a large radial crack appears near the top of the keystone, and the next radial crack appears 130 µm from that depth, an aerogel fragmentation pattern similar to those produced by hypervelocity analog shots [9]. Maximum bulb width is achieved between the 2 major radial cracks, and at a depth of 205 µm. In the bulbous area spatial Zn concentration correlates directly with Cu but not Fe, the typical marker element for XRF. At a depth of ~345 µm there is a large deposition of material (mostly Fe rich) and a dramatic skewing of the track ~18º off normal. The first 700 µm of the skewed portion of the track is marked by a large amount of smaller particulate material deposited radially and one large, mostly continuous, radial fragment. The cross sectional profile in this region is also markedly non-circular. The region prior to the terminal particles is marked by a generally linear decrease in cross sectional area, but deposition in this region appears periodic in the XRF map. The two largest terminal particles are at the end of the track, the smaller one is roughly spherical and ~6 µm in diameter, and it is enriched in Cu but depleted in Ni and Cr, relative to the CI norm. The largest of the terminal particles is bifurcated; the smaller fragment is relatively spherical and is ~5 µm in diameter, while the larger fragment is oblong with a length of ~9.5 µm and a width of ~6.5 µm. The bulk composition of this particle is also enriched in Cu and depleted in Ni and Cr, relative to the CI norm.

Conclusions: LCSM has provided unmatched imagery of cometary tracks of a variety of sizes. Analysis yields several important track parameters including volume of aerogel vaporized, degree of compression of aerogel around track walls, and total cometary matter deposited. 3D imagery and corresponding data analysis is not only crucial for a deeper understanding of particle histories, but is also complement to any efforts towards modeling hypervelocity capture [9,10,11,12]. We look forward to applying calculated track parameters, in conjunction with track formation theory, and quantitative analysis of analog tracks to calculate the energy of volatilization for each track and to clarify the impact histories of grains extracted from many different tracks.

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