X-RAY MICROSCOPY AND TOMOGRAPHY OF STARDUST TERMINAL PARTICLES. S. Brennan[1], H.A. Ishii[2], P. Pianetta[1], J.P. Bradley[2], [1]Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center, Menlo Park, CA 94025, USA, [2]Institute of Geophysics & Planetary Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA (sean.brennan@stanford.edu).

Introduction: The NASA Stardust mission returned the first solid cometary samples to Earth in 2006 from Comet 81P/Wild 2. The results of the Preliminary Examination [1,2] provided an overview of the captured material. Cometary material was collected in silica aerogel to provide more gradual deceleration. Although studies of analogue samples using light gas-gun shots have been performed [3], there seem to be significant differences in mechanical properties between the pyrrhotite samples used in the terrestrial experiments and the actual 81P/Wild 2 material. Thus, 2-D and especially 3-D images of the impact tracks and associated impact debris in aerogel may help elucidate the deceleration process.

We have recently installed a multi-keV transmission X-ray microscope (TXM) using a zone plate as an imaging optic at the multipole wiggler end station 6-2 on the Stanford Synchrotron Radiation Laboratory (SSRL). The beam line monochromates and focuses a tunable x-ray beam onto entrance slits positioned 1 m (vertical) and 0.5 m (horizontal) upstream of a condensing optic which uniformly illuminates a 14 micron field of view at the sample. The astigmatic optical system is needed because of the much smaller vertical divergence of the incident beam. The photon energy range of the TXM is from 5 keV up to 10 keV, but is optimized for the 8 keV (~ Cu Kα) photon energy. The zone plate, downstream from the sample, images the field of view onto an x-ray sensitive area detector. We have recently achieved 40 nm resolution with this instrument. It is especially effective in imaging terminal particles from the Stardust mission because, after keystoning, no further sample preparation of the terminal particle is required. The longer penetration depth of X rays compared to electrons means that the full terminal particle and its surrounding aerogel can be imaged. One of the advantages of attaching the microscope to a tunable x-ray source such as a synchrotron is that the same sample can be imaged at different photon energies, for instance above and below the Fe K-absorption edge at 7113 eV. This allows us to directly observe those parts of the image which are dominated by iron. By taking a sequence of images as the sample is rotated about an axis perpendicular to the beam direction, one can create a tomographic reconstruction of the particle in three dimensions. By combining tomography with the tunability of the X-ray source one can get a three-dimensional map of the iron-containing materials in the vicinity of the terminal particle.

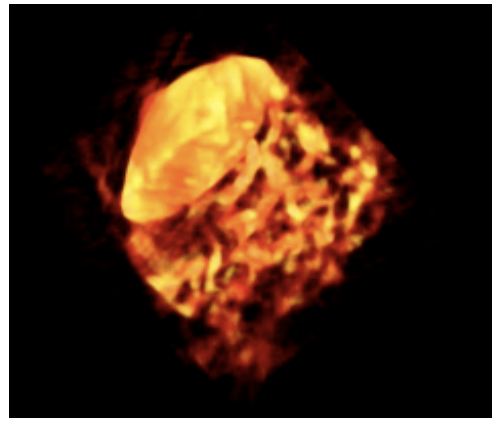

Figure 1. Stardust Track 12 (C2044,0,52). Two-dimensional image from the 3-D tomographic reconstruction using X rays above the Fe K-absorption edge. Particle direction of travel is from lower right to upper left. Agglomerated material is visible in the wake of the prolate spherical particle.

Materials and Methods: A Stardust impact track in aerogel keystone [4] was provided by NASA Astromaterials Curation: Track 12 (C2044,0,52), 1.6 mm in depth. Two tomographic data sets were collected, one at 7100 eV (below the Fe K-absorption edge) and at 7130 eV (above the K-edge). We collected 179 images at each energy, with one degree rotation between images. Post-processing includes re-registration of the particle (due to run-out of the sample stages) and flat-field normalization prior to tomographic reconstruction.

Results and Discussion: Fig. 1 shows a two-dimensional view of the 3-D reconstruction for the terminal particle taken at an energy above the Fe absorption edge. The brighter the pixel in the image, the more absorption has occurred in that pixel. The direction of travel of the particle is from lower-right to upper left in the image. One sees a prolate spheroid with a equatorial diameter of ~ 8 microns, being ~5 microns in the direction of travel. There is a generally uniform density of aerogel around the particle, but there is some evidence of a higher-density aerogel in front of the particle and a large collection of ~100 nm particles sitting in its wake. Fig. 2 shows the same terminal particle, now with an incident photon energy of 7100 eV, below the Fe absorption edge. While the terminal particle itself is little changed by the change in photon energy, the collection of ~100 nm particles is observed to have significantly lower absorption (weaker intensity). This suggests that this collection of particles is dominated by Fe-containing materials. We propose that these 100 nm particles arise from pyrrhotite which has been melted and/or ablated during the impact process. and have been swept into the wake behind the terminal particle as part of the deceleration process.

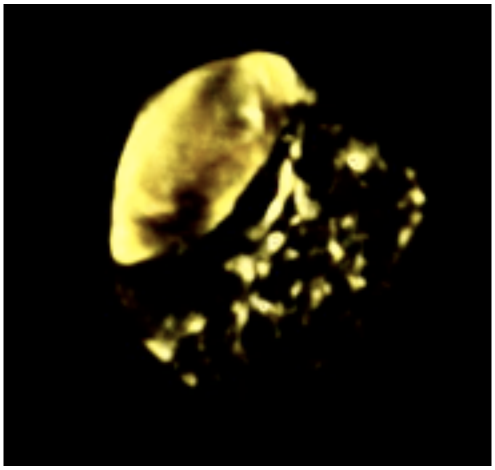

Figure 2. Two-dimensional image of the Track 12 terminal particle using x-rays of 7100 eV, below the Fe K-absorption edge. The ~100 nm particles do not absorb as strongly at this photon energy.

Conclusions: X-ray imaging has clear advantages over other, more destructive methods: Imaging the terminal particle *in-silico* without further sectioning enables us to view the particle within its post-capture environment. Tomographic techniques create a 3-dimensional image which can be rotated and studied in the computer environment. The Stardust mission ~6 km/s capture of cometary particles has resulted in considerable alteration of the cometary sample during the deceleration process. This is also observed in the decoupling of the volatile element S from non-volatile Fe in impact tracks in silica aerogel[5]. Although to date only tomography and imaging have been done on these samples, future efforts will include attempts to perform X-ray absorption near-edge spectroscopy which will further elucidate the chemical state of the Fe in the wake of the prolate spheroid terminal particle.

References: [1] Brownlee D. E. et al. (183 coauthors) (2006) *Science, 304*, 1711 – 1716. [2] Flynn G. J. et al. (80 coauthors) (2006) *Science, 304*, 1731 – 1735 and Supporting Online Material. [3] Burchell M.J. et al. (1999) *Meas. Sci. Tech., 10*, 41-50. [4] Westphal A.J. et al. (2004) *MAPS, 39*, 1375-1386. [5] H.A. Ishii, et al., these proceedings.

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