

SULFUR MOBILIZATION IN STARDUST IMPACT TRACKS. H. A. Ishii¹, S. Brennan², J. P. Bradley¹, P. Pianetta², A. T. Kearsley³ and M. J. Burchell⁴, ¹Institute of Geophysics & Planetary Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA (hope.ishii@llnl.gov), ²Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center, Menlo Park, CA 94025, USA, ³Department of Mineralogy, Natural History Museum, London, SW7 5BD UK, ⁴School of Physical Sciences, University of Kent, Canterbury, Kent CT2 7NH UK.

Introduction: The first solid cometary samples captured from a known parent body, Comet 81P/Wild 2, were delivered to Earth in 2006 by the NASA Stardust mission. The Preliminary Examination results have been recently published. (See [1] for an overview.) Relative to solar values, bulk composition results showed an unexpected depletion in S [2]. Element abundances in particle residues in impact craters in the aluminum foil capture medium were normalized to Si and the relevant CI chondrite (solar) element abundance. Because of overwhelming Si background from the silica aerogel capture medium, element abundances for particle impacts in aerogel were normalized to Fe and the CI chondrite abundance. Sulfur depletion is present in both the impact craters in foils and in the impact tracks in aerogel, so the depletions are likely not due to enrichments in the normalizing elements (Si and Fe, respectively). The degree and mechanisms of sulfur loss are relevant as indicators of potential loss or differential fractionation of other volatile and moderately volatile elements and of chalcophile elements such as Se expected to be present in trace quantities.

Sulfur depletion has been reproduced in laboratory light gas gun experiments. Capture of FeS particles at Stardust capture speeds in Stardust aluminum foils results in S depletions on the order of 20 to 40 at% measured by x-ray spectroscopy in scanning and transmission electron microscope studies [3]. Electron microscopy on Stardust and gas gun-fired analogue samples support S loss on impact of sulfides into the aerogel capture medium, as well. In Stardust impact tracks, a range of (Fe,Ni):S ratios are observed from fully reduced metal to stoichiometric (Fe,Ni)S (primarily low-Ni) [4]. Nanoscale reduced metal beads with sulfide rims mixed with melted and densified aerogel are present as debris along Stardust impact tracks [4,5] and pyrrhotite (FeS) analogue impact tracks [6]. The presence of reduced metal in laboratory-fired sulfides is evidence for S volatilization resulting in elemental fractionation during the capture process in aerogel, and the same processing was experienced by the Stardust sulfide component.

Some volatile loss via escaping vaporized cometary material is unavoidable in particle residues remaining in impact craters in foil. The extent of fractionation may be linked to the size of residue [3] with greater S

depletion from very thin residues in smaller craters like those dominating the Stardust cometary particle fluence. In impact tracks in aerogel, on the other hand, it might be expected that the large surface area of cold aerogel surrounding impact tracks would act as an efficient, high surface area collector for recondensing S vapor. To better understand the apparent S depletion in aerogel, we explored the hypothesis that volatiles such as S may be mobilized and recaptured over greater lateral ranges than more refractory components in an impact track. This was accomplished by measuring element abundance profiles perpendicular to the impact track direction in two Stardust impact tracks, both containing a sulfide component but with differing terminal particle chemistries [2,7], and in a laboratory-generated pyrrhotite impact track for which the initial composition of the particle is well-characterized.

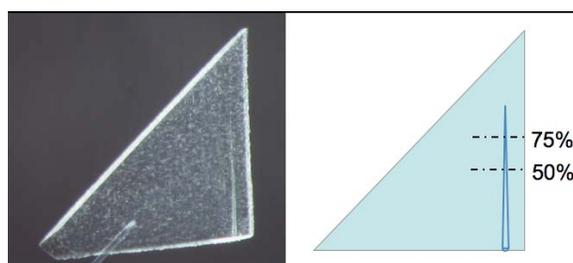


Figure 1. Stardust Track 12 (C2044,0,52). Optical image (left) and schematic (right) showing examples of spectroscopy traverses at 50% and 75% depth. Total track depth is 1.6 mm.

Materials and Methods: Two Stardust impact tracks in aerogel keystone [8] were provided by NASA Astromaterials Curation: Track 12 (C2044,0,52), 1.6 mm in depth, and Track 9 (C2044,0,42), 0.5 mm in depth. (Track 12 is shown above in Fig. 1.) Pyrrhotite dust was fired into 25 kg/m³ silica aerogel at 5.91 km/s to generate the laboratory analogue impact tracks [9] which were extracted for analysis [10]. All impact tracks were analyzed in the hard x-ray scanning fluorescence microprobe end station at SSRL's Beam Line 6-2 with a 14 keV beam and focused spot size of 5 μm. Full spectra were acquired in traverses running perpendicular to the impact track direction. (See Fig. 1). Dwell times of 1000 s per

point were required to obtain sufficient S signal for profile fitting.

Results and Discussion: Sulfur distribution profiles were found to be significantly wider than Fe profiles in all impact tracks. Fig. 2 shows the Fe and S profiles normalized to the same peak height at the 75% depth in Track 12. Both the 50% and 75% depth S profile widths are $\sim 11\times$ the Fe width. In Track 9, a traverse at 50% depth showed a $\sim 6\text{-}7\times$ wider S profile relative to Fe. In the pyrrhotite gas gun shot, a traverse at 75% depth showed $\sim 8\text{-}9\times$ wider S profile relative to Fe; however, overlapping S fields from neighboring impacts complicated profile fitting in this track. In measuring S distributed so broadly, absorption and low signal-to-noise are challenges in all tracks.

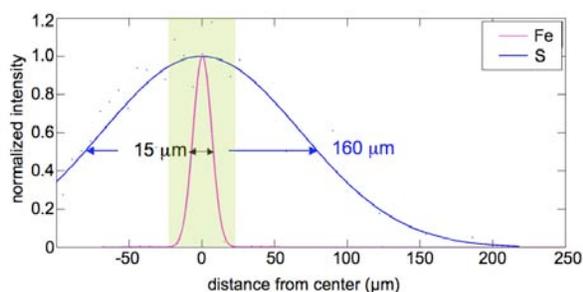


Figure 2. Fe and S profiles (normalized by peak intensity) across Track 12 at 75% depth. The S profile width is $\sim 11\times$ that of Fe. (S has 15x lower peak intensity than Fe at this depth.)

Mapping methods used previously to define the extent of cometary impact track material for quantitative element abundances [2,7] rely on the elastically scattered signal and/or the Fe fluorescence signal from each pixel as an indicator of the presence of cometary material. Our track traverse results clearly demonstrate that these methods miss a large fraction of the S due to its wide dispersion in the aerogel. In Fig. 2 (Track 12), for example, less than half of the S is located within the extent of the Fe profile indicated by the shaded region. S is significantly under-reported due to its decoupling from Fe (and other non-volatiles) and mobilization into the surrounding aerogel. Due to the different relative profiles widths between S and Fe (likely to be variable with depth) in different impact tracks, it is not possible to determine with any confidence the percentage of S in each track that was missed by earlier quantitative approaches. However, the non-reported S may well compensate the apparent depletions observed in the aerogel [2]: If the S/Fe profile width ratios are 11 on average, then $\sim 25\%$ of the S present is included in current quantitative estimates.

Conclusions: The Stardust mission ~ 6 km/s capture of cometary particles has resulted in decoupling of

the volatile element S from non-volatile Fe in impact tracks in silica aerogel. S volatilized and mobilized resulting in distribution profiles as much as an order of magnitude wider than Fe profiles. As a result, S has been underreported in previous bulk element abundances [2,7]. In order to accurately measure bulk-level abundances of captured volatiles such as S, revised data acquisition and analysis of areas encompassing hundreds of microns around an impact track are required. Chalcophile elements and other volatile and moderately-volatile elements are likely to display similar decoupling (fractionation) and mobilization as S.

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] Kearsley A.T. et al. (2007) *MAPS*, 42, 191-210. [4] Zolensky M. E. et al. (75 coauthors) (2006) *Science* 304, 1735 – 1739. [5] Leroux H. et al. (2007) *MAPS*, in press. [6] Ishii, H. A. et al. (2007) *Science*, 319, in press. [7] Ishii H. A. et al. (2007) *MAPS*, in press. [8] Westphal A.J. et al. (2004) *MAPS*, 39, 1375-1386. [9] Burchell M.J. et al. (1999) *Meas. Sci. Tech.*, 10, 41-50. [10] Ishii H.A. & Bradley J.P. (2006) *MAPS*, 41, 233-236.

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