

Stardust cometary samples: The journey from outer space to electron microscope

C. H. van der Bogert

Comets are thought to contain very primitive and interstellar materials that accreted in the cold outer-reaches of the Solar System. To investigate these theories, the NASA Stardust mission was planned to collect cometary dust and return it to Earth for laboratory analysis. The comet 81P/Wild 2 was chosen as the target because it is a newcomer to the inner Solar System, and thought to be relatively pristine. It was transferred into its current orbit in 1974, through interactions with Jupiter - making it a Jupiter-family comet.

The dust particles were collected in January 2004, at an encounter speed of 6.1 km/s using aerogel capture media, and were returned to Earth in January 2006^[1]. It is estimated that more than 10,000 cometary particles from 1 to 300 μm in size were captured in the aerogel collector tray^[1]. Results of the initial analyses of the cometary particles have challenged us to reassess and modify models of early solar system processes and the formation of comets. Indeed, the minerals identified in the 81P/Wild 2 dust are an unequilibrated mixture of minerals exhibiting a surprisingly wide range of formation conditions ^[e.g. 2,3]. The unexpected presence of minerals that formed at high temperatures, such as Mg-rich olivine and Ca,Al-rich inclusions, requires that materials from a wider cross-section of the protosolar nebula than expected were transported into the region of space where 81P/Wild 2 formed ^[e.g. 2,3].

Much of the initial analytical work was done on so-called “terminal particles”

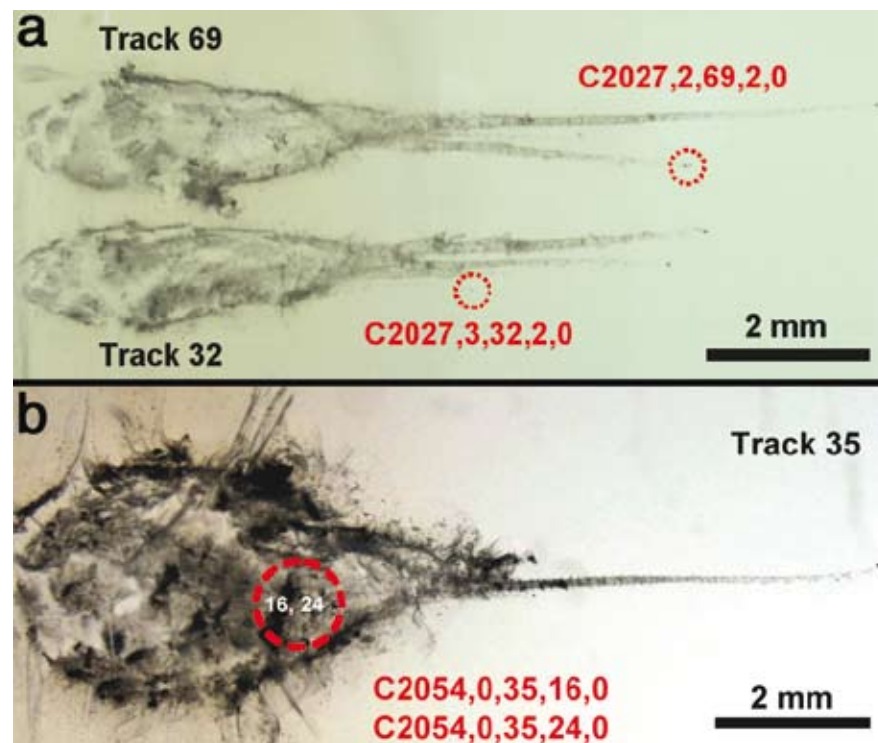


Fig. 1. Cross-sections of cometary dust impact tracks in Stardust aerogel cells showing (a) two terminal particles and (b) selected capture-melted particles from the margin of an impact track cavity, which were investigated in our study.

Much of the initial analytical work was done on so-called “terminal particles” (Figures 1a and 2), which are coherent, strong mono- to multi-mineralic grains that penetrated deepest into the aerogel, and were the least altered of the samples. Cometary material was also deposited along the impact tracks (Figures 1b and 3), but it was moderately to significantly processed during capture, which occurred at an impact velocity of 6.1 km/s. By understanding the effects of capture in aerogel, through laboratory experiments^[e.g. 4 & refs. therein], and physical^[5], compositional and mineralogical^[e.g. 6] analyses of the materials in the impact tracks, we can interpret how these materials are compositionally and structurally related to the original pre-capture cometary particles. This information is critical for

further refining our understanding of the formation and evolutionary conditions of 81P/Wild 2, and for the particles' comparison with other materials, such as interplanetary dust particles (IDPs) and meteorites.

Approach

The purpose of our work is to use transmission electron microscopy (TEM) to compare capture-melted and terminal particles within the context of the conditions during capture, to derive the particles' pre-capture characteristics. Microanalytical techniques, like TEM, along with high angle annular dark field (HAADF) imaging and energy dispersive spectroscopy with scanning TEM, are critical for the identification and analysis of the Stardust cometary particles due to their small size.

Samples

Terminal particles

Terminal particles represent materials that survived capture with minimal impact effects. Both of the studied particles (C2027,2,69,2,5 #25 and C2027,3,32,2,6 #20) exhibited a thin coating of compressed and melted aerogel. Both samples were largely crystalline mineral phases including enstatite and anorthite (e.g., Figure 2)^[7].

Capture-melted particles

Samples extracted from the bulbous entry cavities are frequently mixed composition glasses, likely representing cometary materials that melted and mixed with aerogel during the capture process^[7]. TEM grids C2054,0,35,16,9 #44 and C2054,0,35,24,5 #19 were both composed mainly of silica-rich glass with varying concentrations of Fe, Mg, and Si as determined by both TOF-SIMS and EDX analyses (Figure 3^[7,8]). These glasses contain finely dispersed FeNi and FeS spherules, which melted during the capture process and subsequently recrystallized. The

compositions and textures of these materials are homogeneous overall, exhibiting solar abundances of both major and minor elements^[8,9].

Possible contaminants

The capture-melted particles also contained or were associated with carbonate and TiO₂ grains, thought to be contaminants^[6,10]. Some of these grains were directly in contact with the capture-melted particles, while others were simply in the same microtome section. Some were coated with melted and compressed aerogel, attesting to their dynamic participation in the capture process.

Discussion

Based on our analyses, we propose that the Stardust cometary particles we analyzed, consisted of a mixture of single and multi-mineralic grains, embedded in a fine-grained, high porosity matrix prior to their encounter with the aerogel. During impact into the aerogel, the matrix was stripped from the larger mineral grains, melted and mixed

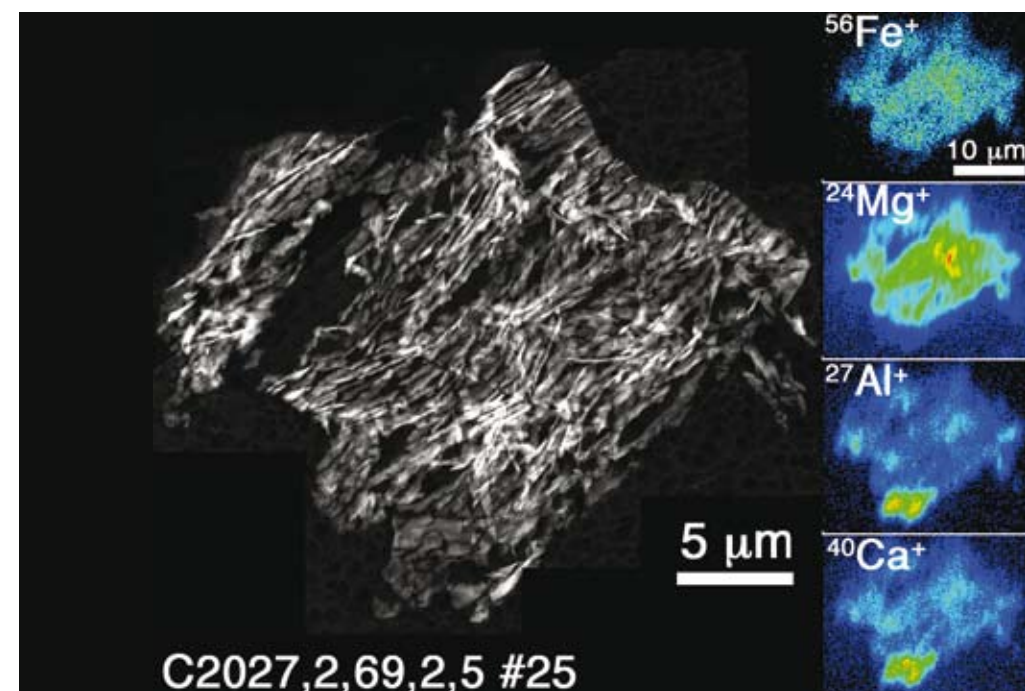


Fig. 2. TEM HAADF image of an ultramicrotomed Stardust cometary terminal particle, with selected TOF-SIMS secondary ion images from [7].

with aerogel, and deposited along the track walls. The larger mineral grains survived as terminal particles (Figure 4, from [6]). During the formation of the impact cavity, melted and compressed aerogel moved outwards from the paths of the particles. One result of the cavity formation may have been to concentrate the contaminants already present in the aerogel into the walls of the cavities. This effect would explain why some contaminants have aerogel coatings and why most of the contaminants we have observed so far were present in capture-melted particles from these locations^[7].

As observed in impact experiments with particulates into aerogel [e.g. 4 & refs. therein], the captured grains may also have suffered significant reduction in size during the capture process. The rounded surfaces of the studied grains are consistent with the abrasion and ablation of the original particle surfaces. This ablated material was probably also incorporated into the melted and compressed aerogel along the track walls, contributing to the complex composition of the capture-melted materials. The sorting of materials with different physical properties can

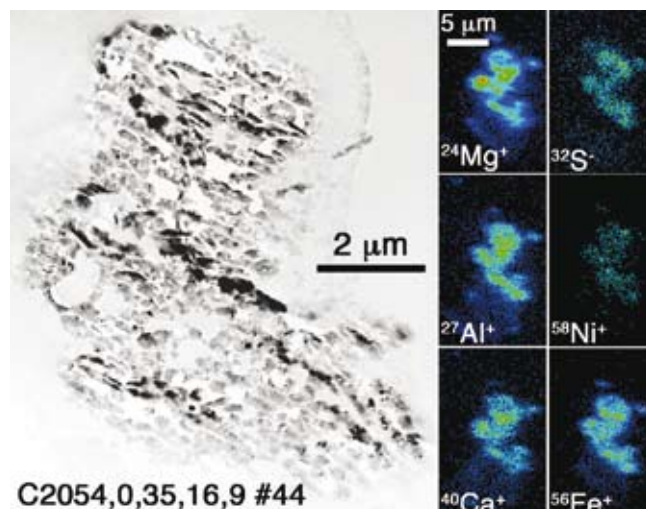


Fig.3. TEM bright field image of an ultramicrotomed capture-melted particle, with selected TOF-SIMS secondary ion images from [8].

explain the compositional and structural differences between the two types of particle fragments. Our model, based on the differences between the captured materials as investigated using TEM, is consistent with the findings of Hörz et al.^[5] for the formation of “type B” Stardust impact tracks. The samples we studied were, in fact, extracted from such type B tracks.

Comparative studies between Stardust particles from tracks with other morphologies, and between experimental shots into aerogel and the Stardust

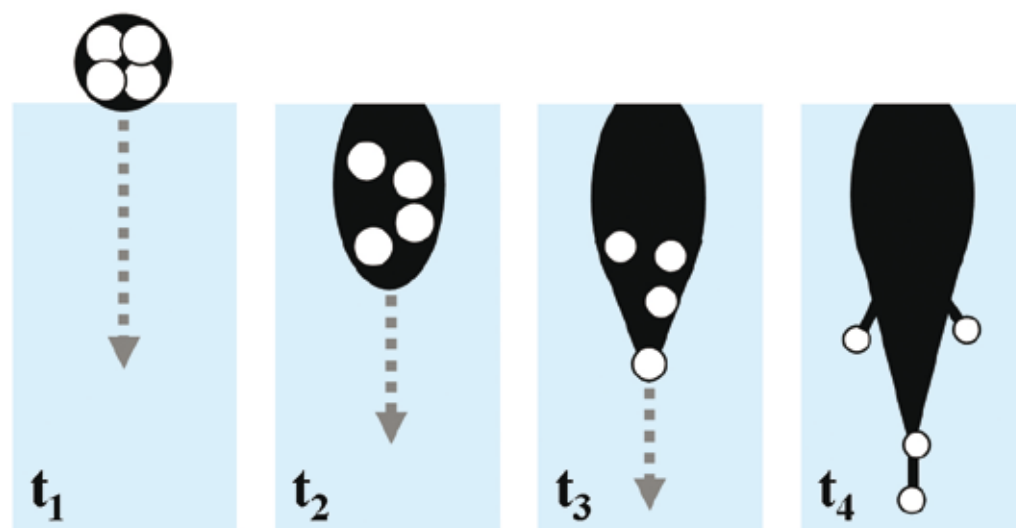


Fig.4. Simplified time-step schematic of capture-processing and sorting of fine-grained matrix components (black) and discrete mineral grains (white), with concurrent grain-size reduction of the mineral grains during impact with aerogel [6].

samples will help further develop our understanding of the capture process and its effects on the original cometary materials. These data are necessary for interpreting the Stardust samples in the context of Solar System evolution.

Outlook

The Stardust mission has provided an unprecedented opportunity for scientists to study materials from a known comet using cutting-edge microanalytical techniques. The micron-sized cometary particles inform us about processes that occurred billions of years ago and on the scale of the Solar System (10's to 100's of astronomical units in size). The Stardust samples are, thus, a sort of Rosetta stone that we can use to unlock the secrets of the early Solar System.

Such small and highly valuable samples help drive the development of new preparation and microanalytical techniques. Indeed, a portion of the returned samples have been archived by NASA for analysis using future techniques and equipment. Stardust samples will certainly continue to provide many interesting and valuable results in years to come.

References.

- ^[1] Brownlee D. E. (2003) *Journal of Geophysical Research* 108, doi: 10.1029/2003JE2087.
- ^[2] Zolensky M. E., et al. (2006) *Science* 314, 1735-1739.
- ^[3] Brownlee D. E., et al. (2006) *Science* 314, 1711-1716.
- ^[4] Burchell M. J., et al. (2006) *Annual Review of Earth and Planetary Sciences* 34, 385-418.
- ^[5] Hörz F., et al. (2006) *Science* 314, 1716-1719.
- ^[6] van der Bogert C. H., et al. (2008) *Asteroids, Comets, Meteors*, Abstract #8527.
- ^[7] Stephan T. and van der Bogert C. H. (2008) *Lunar and Planetary Science XXXIX*, Abstract #1508.
- ^[8] Stephan T. (2008) *Meteoritics & Planetary Sciences* 43, 233-246.
- ^[9] Stephan T. (2007) *Space Science Reviews*, doi:

10.1007/s11214-007-9291-2.

^[10] Wirick S., et al. (2007) *Lunar and Planetary Science XXXVIII*, Abstract #1534.

Acknowledgements

This work was supported by Deutsche Forschungsgemeinschaft #STE576/17-2 and Oxford University/EU-ESTEEM #026019.

Carolyn H. van der Bogert

Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Germany
vanderbogert@uni-muenster.de

Dr. Carolyn van der Bogert is a planetary geologist and research scientist at the Institut



für Planetologie at the Westfälische Wilhelms-Universität in Münster, Germany. She currently studies Stardust cometary particles using transmission electron microscopy.

She received her Ph.D.

in Geological Sciences at Brown University in Providence, USA in 2004. Her dissertation focused on high strain-rate deformation as an impact cratering process, which she explored through axial welding experiments on ordinary chondrite meteorites and common terrestrial rocks. These were analyzed using a variety of techniques, including electron microprobe, transmission electron microscopy, and reflectance spectroscopy. She was the recipient of a NASA/Rhode Island Space Grant Fellowship, a NASA Graduate Student Research Fellowship, the Charles Wilson Brown Dissertation Fellowship, a Zonta International Amelia Earhart Fellowship, and the Stephen E. Dwornik Planetary Geoscience Student Paper Award.