Chemical, mineralogical, and isotopic characterization of terminal particles from Stardust tracks

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Summary

We report on the past year of our consortium study of Stardust cometary tracks, with the goal of exploring the chemical, mineralogical and isotopic diversity of materials returned from comet 81P/Wild 2.

Table 1: Information on tracks extracted from Stardust Tile 31

<table>
<thead>
<tr>
<th>Track #</th>
<th>Length (μm)</th>
<th>Track Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>390</td>
<td>A</td>
</tr>
<tr>
<td>201</td>
<td>1800</td>
<td>A</td>
</tr>
<tr>
<td>202</td>
<td>5000</td>
<td>B</td>
</tr>
<tr>
<td>203</td>
<td>5200</td>
<td>B</td>
</tr>
<tr>
<td>204</td>
<td>800</td>
<td>C</td>
</tr>
<tr>
<td>205</td>
<td>220</td>
<td>C</td>
</tr>
<tr>
<td>206</td>
<td>200</td>
<td>A</td>
</tr>
</tbody>
</table>

Figure 1: Optical photomicrographs of Stardust tracks extracted from Tile 31. Tracks 200, 201, 204, 205, and 206 are reflected light images, while track 202 and 203 images are transmitted light.

Methods

We studied seven tracks extracted from aerogel tile C2031 (Table 1; Figure 1), using the following work-flow and techniques:

- **Keystone Extraction**
  - UCB Space Sciences Lab
  - Tracks were extracted from aerogel using the methods described in [1].

- **Synchrotron X-ray Microprobe**
  - Advanced Light Source, LBNL
  - We measured the elemental composition of particles using fluorescence mapping at 10 keV and a 6 x 6 μm beamstop. We used spot X-ray Absorption Near-Edge Structure (XANES) analyses [6] and chemical mapping [5] at the Fe edge to identify silicates, sulfides, and metals.

- **Keystone Microsurgery**
  - UCB Space Sciences Lab
  - We separated the terminal particles (TP) and fine-grained bulb material by laying the keystone on its side in a 4-μm-thick ultralene “surgical trap” with an access slit. We then sanded it into 100-300 μm thick wafers using the keystoning system.

- **Fine-grained Material**
  - High-Pressure Sapphire Press
  - UCB Space Sciences Lab
  - In preparation for measurements of oxygen isotopes in fine-grained material captured in the track bulb [3], we used a newly developed high-pressure sapphire press. This press uses a C-coated sapphire window to press dissected bulb halves into indium in the center of a polished Al2O3 round. The round includes polished standards surrounding the indium, in a configuration identical to our standard “buckler” mount [2,3].

- **Terminal Particles**
  - Embedding and Ultramicrotomy
    - Molecular Foundry, LBNL
    - Terminal particles were mounted with epoxy on the end of epoxy bulbs. After curing, we used the ultramicrotome to remove ~100-nm-thick slices, which were placed on TEM grids.

- **Transmission Electron Microscopy**
  - Molecular Foundry, LBNL
  - TEMs used were the Philips CM200/FEI set to 200 keV with an Oxford EDS detector, as well as the FEI Titan TEM with beam voltages between 80-200 keV, and a 0.6 μm EDS detector. Quantitative EDS analyses were made for individual phases in track 202 (TP5, TP6, and TP9, with a map time of ~11-30 min per phase).

- **Isotopic Analysis**
  - HIGP, University of Hawaii and Washington University
  - Fine-grained materials were measured in imaging mode using either the Cameca ims 1280 ion probe at UH or the Cameca NanoSIMS at Washington University. For terminal particles, the potted bulbs remaining after microtoming were mounted in our specially designed “buckler” mounts [2,3]. O isotopes were measured using the Cameca ims 1280 ion probe in multi-electron mode. A ~2 μm ~20 Pa Cα primary ion beam was used to measure individual phases within the TP’s [2,3].

Results

- **Track 200 (C2031,1,200)**
  - Microscopy and synchrotron analyses indicated a ~2–3 μm TP of mixed silicate and sulfide. TEM confirmed that the TP consists of two silicate phases surrounded by a rim of Fe-sulfide. EDS analyses were not quantitative as they were enriched in SiO₂ from aerogel contamination, and small grain sizes led to mixed analyses.

- **Track 202 (C2031,2,201)**
  - The terminal particle at the end of the track was ~2 x 4 μm. Synchrotron analysis showed Fe-bearing material dominated by sulfide. The TEM sections were mostly plucked (Fig. 3), and residual material was SiO₂, with some embedded sulfides. EBSD confirmed that the SiO₂ was melted and quenched aerogel. O-isotope analysis of the bulb’s fine-grained material is pending.

- **Track 203 (C2031,3,202)**
  - Track 202 has a 1500-μm diameter bulb and 14 terminal particles. Synchrotron analysis indicated that the terminal particles consist of 5 silicates, 3 sulfides, 2 metals, and 4 particles of mixed composition. TP5 and TP9 were identified by Fe XANES as sulficates (Fig. 4).

- **Track 204 (C2031,4,203)**
  - Synchrotron analysis of the two large TPs indicates they are sulfides. A chemical map of the bulb, similar to Fig. 5, indicates presence of small metal particles. Sulfur-isotope measurements of the TPs are pending.

- **Track 205 (C2031,5,204)**
  - Track 205 has no identifiable TP. Chemical mapping at Fe showed that the bulb is dominated by Fe²⁺-bearing material.

- **Track 206 (C2031,6,205)**
  - The very small TP is identified as a sulfide from its faint signal during synchrotron X-ray analysis.

Table 2: Quantitative EDS analyses for phases in Track 202 terminal particles are shown in Table 2.

- **Track 202 TP5**
  - Consists of olivine and pyroxene; the pyroxene composition is slightly non-stoichiometric, possibly due to the presence of multiple-valence cations.

- **Track 202 TP6**
  - Consists of olivine, pyroxene, and spinel. The spinel phase is primarily almina-magnesia spinel, with ~5% fit to chromeite, and an excess of SiO₂ from aerogel.

- **Track 202 TP9**
  - Contains olivine, two pyroxenes, and glass. The pyroxenes primarily vary in Al and Ca. All phases show excess of SiO₂ from aerogel. The glass phase was small, yielding mixed analyses.

Table 2: EDS analyses for phases in Track 202 TP5, TP6, and TP9.

TP5 and TP6 were measured for O-isotopes. Their O-isotope compositions (open symbols, Fig. 5) are consistent with other Wild 2 silicates. Ion probe analysis of TP9 is pending.

References:

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Figure 3: Microtomed sections of Track 202 TP2 showing aerogel and sulfide.

Figure 4: TEM and EDS maps of micrometric silicates in Track 202: TP5, TP6, and TP9.

Figure 5: O-isotope compositions of Track 202 TP5 and TP 6, compared to previously measured Stardust particles.

In Fig. 6, we show the scatter-plot of Fe chemical-map data indicating the presence of discrete Fe metal particles in the bulb of track 202. These particles are not identifiable visually, so could not be targeted for extraction using the wafering technique. These might be isolated in the future using new fluorination techniques [6-8].

Figure 6: Fe spectral features for particles in Track 202 bulb material.

Figure 7: Sulfur isotope measurements of Track 202.

Figure 8: Sulfur-xenon analysis of Track 202.

Figure 9: Sulfur-xenon analysis of Track 202.

Figure 10: Sulfur-xenon analysis of Track 202.