ALS MICROSCOPES VIEW A COMET

Particles from Comet 81P/Wild 2 Yield Clues to How the Solar System Formed

NASA's $200-million, seven-year-long Stardust mission returned to Earth thousands of tiny particles snagged from the coma of comet 81P/Wild 2. Four ALS beamlines and the researchers using them were among the hundreds of scientists and dozens of experimental techniques in facilities around the world that contributed to the preliminary examination of the first samples. Adding to recent advances in cometary science showing the important role played by mixing of materials in the accretion disk where the planets of the Solar System had their birth, the first round of Stardust results suggest that the mixing started earlier in the planetary formation process and is more extensive than previously thought.

Materials brought back from a known extraterrestrial source, such as the Apollo samples from the Moon in the 1970s, provide critical clues to the history of the Solar System and interpretation of extraterrestrial samples like meteorites and cosmic dust particles. Stardust's success depended on two technical achievements, a trajectory allowing it to pass within 240 km of the comet's nucleus at a speed of just 6 km/s and a special low-density material called aerogel molded into a collector grid. Particles were brought to a standstill as they penetrated into the aerogel with limited heating or alteration. Thousands of tiny particles, typically leaving carrot-shaped tracks, were trapped, most of them smaller than 10 micrometers in size.

After its launch in 1999, Stardust reached the comet in 2004, then returned its precious cargo to Earth in a capsule on January 15, 2006. At NASA's Johnson Space Center in Houston, a few of the captured particles were quickly distributed for inspection by Preliminary Examination Teams (PETs). At the ALS, measurements were made at four beamlines. "Keystones" of aerogel, wedges containing complete tracks and the terminal particles at their tips, were first removed under the microscope using computer-driven micromanipulators that sliced the aerogel with glass needles.

X-ray absorption near-edge structure (XANES) yields a distinctive spectral signature for each chemical constituent in a sample and is particularly useful for identifying organic compounds. At Beamlines 5.3.2 and 11.0.2, it was possible to combine this technique with the scanning transmission x-ray microscope (STXM) to image the spatial distribution of the compound. Initially it was planned to do infrared (IR) microspectroscopy at Beamline 1.4.3 only on the terminal particles, concentrating primarily on the silicates in those particles. But because the aerogel slowed the particles relatively gently, team members were also able to capture volatile organics along most of the length of the track, building up a two-dimensional image of the different organics at different stages of entry. Minerals were the main target of studies at Beamline 10.3.2. The team used a combination of three techniques for mapping the bulk chemistry and mineralogy of the Wild 2 samples. In x-ray fluorescence, one obtains an elemental map. By means of XANES and the related technique of extended x-ray absorption fine structure, or EXAFS, one can also determine the atomic environment of specific elements. X-ray diffraction yields the crystalline structure of minerals.

In all, the Wild 2 samples proved to be highly variable. Some contained minerals supposedly formed only near a star or in some other high-temperature environment. One such sample contained aluminum-titanium-calcium-rich minerals similar to those found in inclusions in the Allende meteorite. From this tangle, the picture that emerged is of cometary particles containing primarily silicate materials formed within the Solar System, including some grains born in the high temperatures existing only close to the Sun. These particles then were carried to the outer reaches of the Solar System, the Kuiper belt region outside Neptune's orbit, where they were incorporated into Comet Wild 2 along with organic compounds and other volatile materials.

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Publications about this research: D. Brownlee et al., "Comet 81P/Wild2 under a microscope," *Science* **314**, 1711 (2006); S.A. Sandford et al., "Organics captured from Comet 81P/Wild 2 by the Stardust spacecraft," *Science* **314**, 1720 (2006); L.P. Keller et al., "Infrared spectroscopy of Comet 81P/Wild 2 samples returned by Stardust," *Science* **314**, 1728 (2006); G.J. Flynn et al., "Elemental compositions of Comet 81P/Wild 2 samples collected by Stardust," *Science* **314**, 1731 (2006).

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- **Solar System Formation Model**
  - *Gas, dust, and ice condense within an interstellar dust cloud*
  - *Condensation collapses under its own self-gravity*
  - *Glowing sun and accretion disk with protoplanets result*
  - *Accretionary processes yield today's planets and other bodies*
- **Stardust Mission to Comet 81P/Wild 2**
  - *Launched in 1999, reached comet in 2004, samples returned in 2006*
  - *Aerogel tiles in grid capture thousands of tiny particles*
  - *Selected particles inspected by numerous Preliminary Examination Teams*
  - *Three ALS x-ray microscopes take part (Beamlines 5.3.2, 10.3.2, 11.0.2)*
  - *ALS IR microscope (Beamline 1.4.3) complements x-ray measurements*
- **Mixing of Particles in Accretion Disk Play Important Role**
  - *Particles contain abundant minerals mostly formed within Solar System*
  - *Some particles formed close to sun and transported radially outwards*
  - *Comet Wild 2 forms in the Kuiper belt from minerals, organics, ice mixes*
  - *Mixing occurred earlier and more extensively than earlier believed*

D. Brownlee (University of Washington) et al., *Science* **314**, 1711 (2006); S.A. Sandford (NASA–Ames Research Center) et al., *Science* **314**, 1720 (2006); L.P. Keller (NASA–Johnson Space Center) et al., *Science* **314**, 1728 (2006); G.J. Flynn (SUNY Plattsburgh) et al., *Science* **314**, 1731 (2006).

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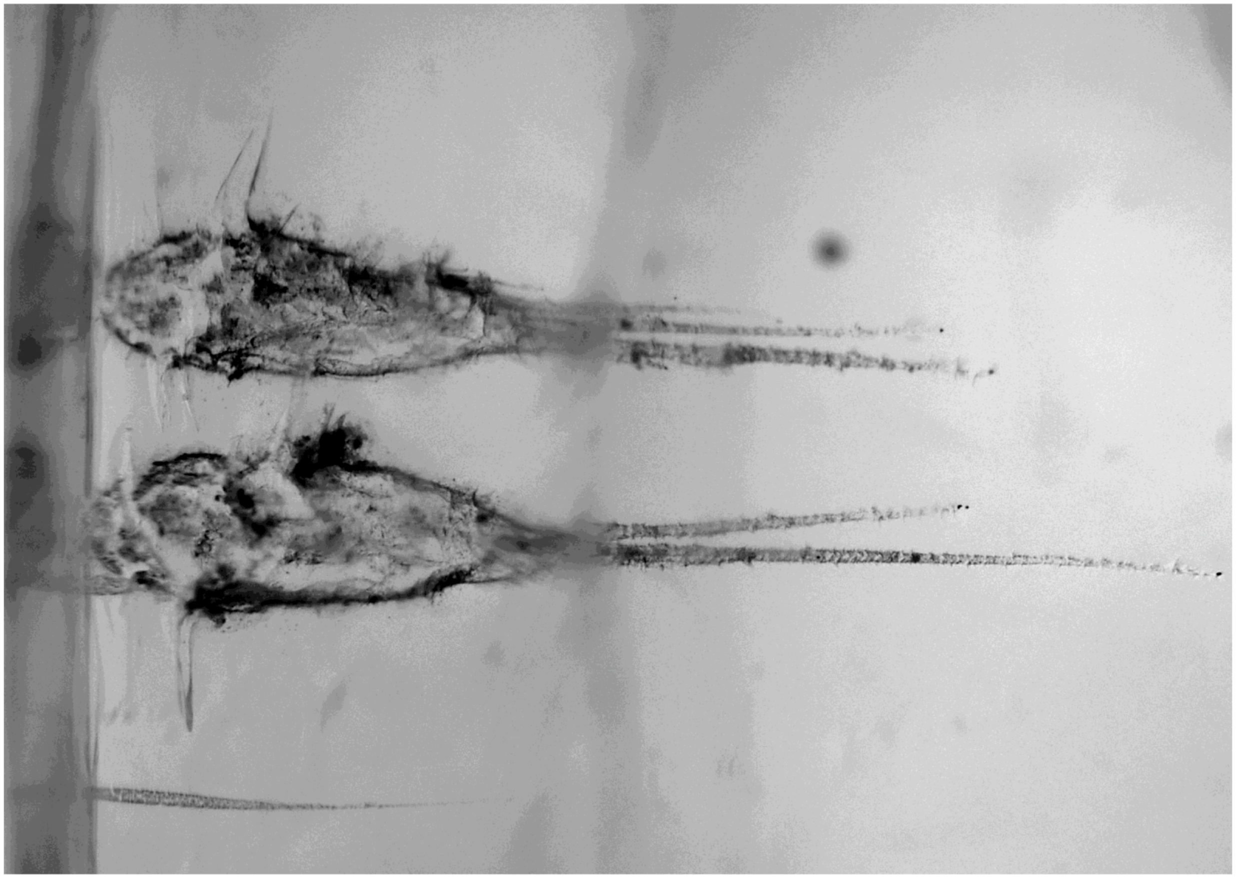

NASA/JPL-Caltech/University of Washington

Tracks left by two comet particles after they struck the Stardust spacecraft's comet dust collector. The collector is made up of a low-density glass material called aerogel. Comet particles are extracted from these and other similar tadpole-shaped tracks.

D. Brownlee et al., *Science* **314**, 1711 (2006); S.A. Sandford et al., *Science* **314**, 1720 (2006); L.P. Keller et al., *Science* **314**, 1728 (2006); G.J. Flynn et al., *Science* **314**, 1731 (2006).

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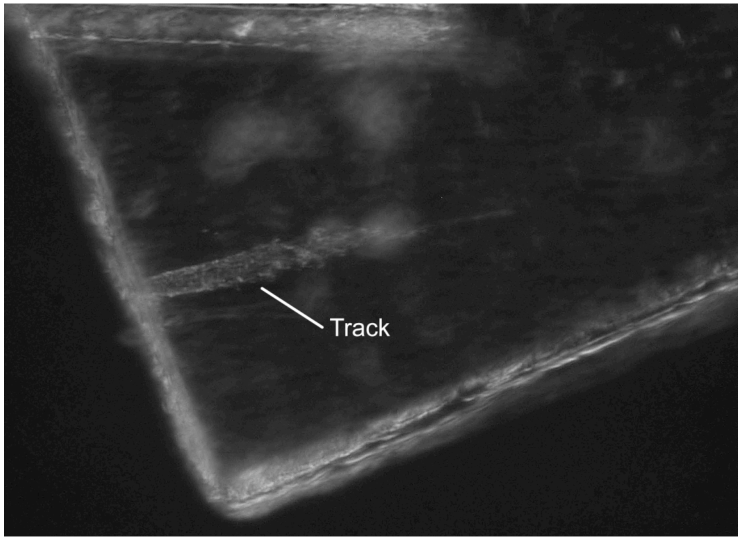

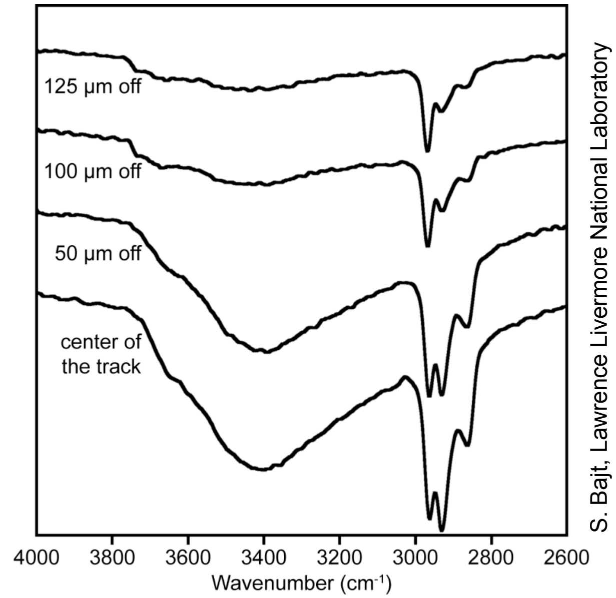

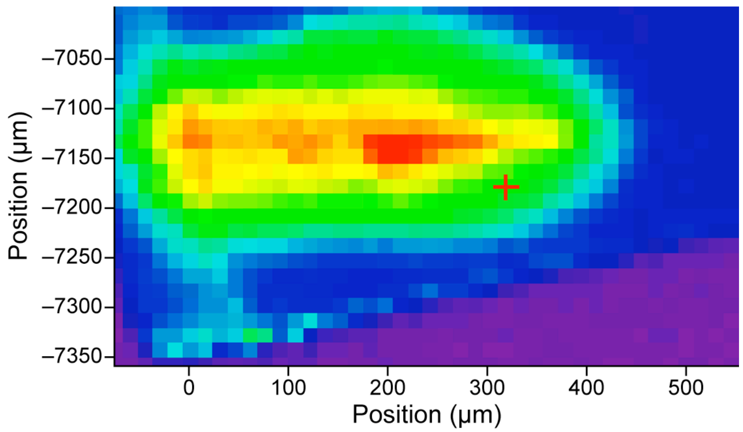

Some particle tracks (top left) revealed shedding of organic compounds and their diffusion into the surrounding aerogel. The spectra (top right) show the intensities of a methylene group peak on and off the track. Peak distribution is mapped in the false color image. Intensity is greatest in and near the track, but methylene is present in the aerogel over 100 micrometers away.

D. Brownlee et al., *Science* **314**, 1711 (2006); S.A. Sandford et al., *Science* **314**, 1720 (2006); L.P. Keller et al., *Science* **314**, 1728 (2006); G.J. Flynn et al., *Science* **314**, 1731 (2006).

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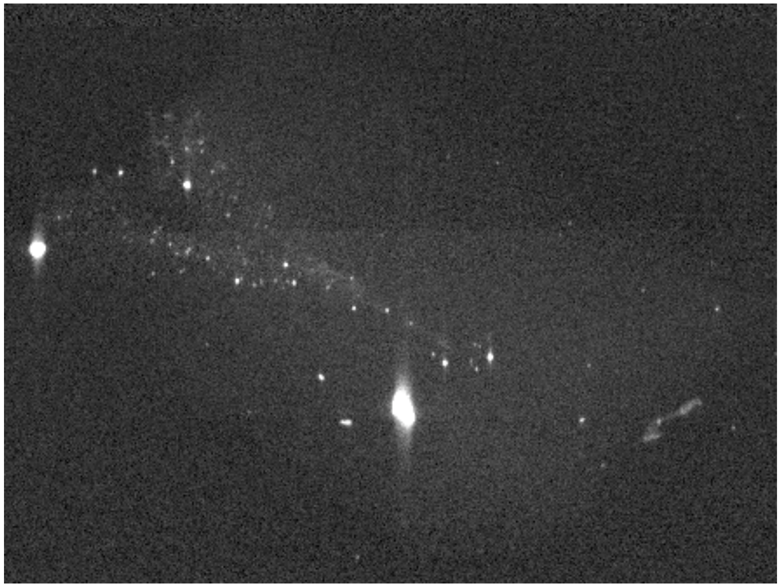

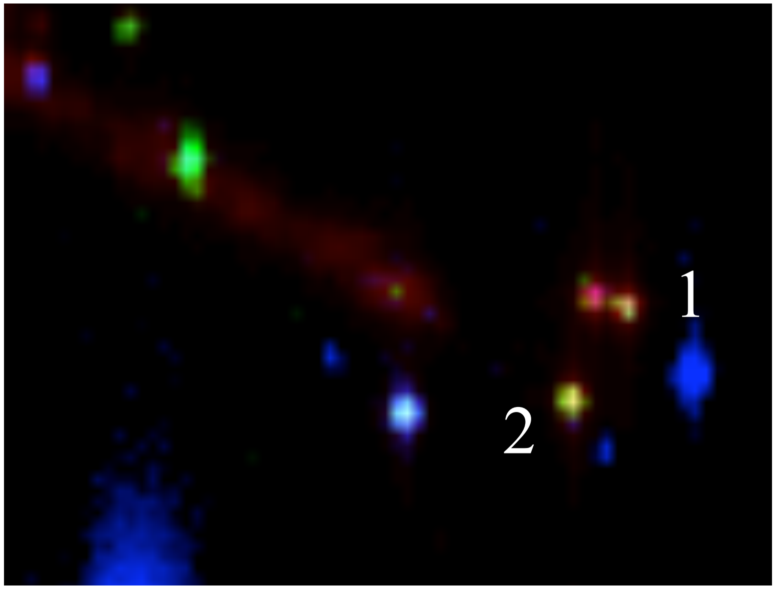

Matthew Marcus, ALS

The calcium problem: which spots from x-ray microfluroescence maps are really from the comet? Left: Large, bright spots outside the track in this calcium map are contaminants in the aerogel. Right: In this higher-magnification image, Ti is mapped in red, Mn in green, and Ca in blue. Thus, the bright blue spot (particle 1 in the track) contains Ca and little or no Mn or Ti, so it is aerogel contaminant, whereas the greenish spot (particle 2 in the track) contains all three elements, which is typical of minerals formed at high temperature in the inner solar system.

D. Brownlee et al., *Science* **314**, 1711 (2006); S.A. Sandford et al., *Science* **314**, 1720 (2006); L.P. Keller et al., *Science* **314**, 1728 (2006); G.J. Flynn et al., *Science* **314**, 1731 (2006).