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En route to a 2004 rendezvous with the comet Wild 2, NASA's *Stardust* probe spent 195 days with its cosmic dust collector, a large tray tiled with silica aerogel, facing the interstellar wind. The hope was that it would snag a few motes of extrasolar dust. Such particles are rare inside the solar system: Intense magnetic fields at the edge of the heliosphere effectively shield us from the smallest grains, but the occasional larger ones—those weighing more than a few femtograms—can barrel through that barrier. During its time spent just outside the Martian orbit, *Stardust* was bound to encounter some of those particles.

In 2006 the probe's aerogel tray (shown on the cover) was parachuted back to Earth, where a collaboration led by Andrew Westphal (University of California, Berkeley) and Rhonda Stroud (US Naval Research Laboratory) began to meticulously inspect its contents. With just over one-fourth of the collector's 1000-cm^2 surface area examined, the researchers now report that they've discovered seven grains that likely originated from outside our solar system.[1]

"We in the interstellar dust community have been awaiting these results for years," comments Adolf Witt (University of Toledo, in Ohio). "Up to this point, we've essentially had to infer properties of dust indirectly, through astronomical observations. Now they can be examined in the laboratory."

Search party

Whereas the interplanetary dust that inhabits our solar system consists mostly of debris from disintegrating comets and asteroid collisions, most interstellar dust originates in the outflows of dying stars. For observational astronomers, interstellar dust is mostly a nuisance: It obscures and distorts their view of the wider cosmos. For astrophysicists, the grains hold precious clues about how stars and galaxies evolve. In both cases, one wants an accurate picture of the material's structure and composition—either to correct for it in observations or to piece together the history of the astrophysical processes that formed and modified it.

Although interstellar dust particles can be as small as a few nanometers across, *Stardust*'s aerogel tray was designed to catch those about a micron in diameter or larger. At typical impact speeds, a particle of that size decelerates gently in the aerogel and, in the process, plows a track tens of microns long.[2] From the width, length, and orientation of the track, one can infer the particle's size, speed, and trajectory. Very small grains, by contrast, lack sufficient momentum to sweep out a detectable track.

It turns out, however, that even the micron-sized grains aren't so easy to spot amid the clutter of the porous aerogel's intrinsic defects. "And at the magnification necessary to identify the tracks, the collector is enormous," says Westphal. "When we did the math, we realized that if we were going to search for these impacts in a microscope, it would take us decades."

To speed things up, the researchers decided to take images of the aerogel with an automated microscope, place them online, and invite the general public to join in the search. All told, more than 30 000 citizen scientists are helping pore over millions of microscope images. Collectively, they have identified 69 candidate interstellar dust tracks, including the one shown in figure 1. Researchers in Westphal's lab identified two more, bringing the total to 71.

Of those, 46 were oriented at angles inconsistent with interstellar dust trajectories; 9 contained chemical residues that suggested they'd been made by fragments from the lid of the detector's protective canister; 1 couldn't be analyzed because it had landed in a region of particularly dense aerogel; and 12 were set aside for later study. (Given the risks inherent in transporting and testing samples, the researchers wanted to ensure that those 12 grains were preserved intact.)

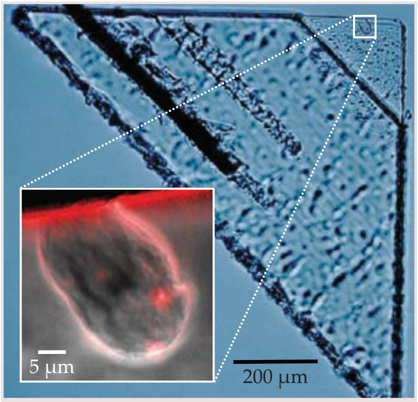

Figure 1. A micron-scale track in the aerogel slab shown here was carved out by Sorok, a dust grain that likely formed in interstellar space. The inset shows a close-up of the track, taken with a scanning transmission x-ray microscope. (Adapted from ref. 1.)

That left three candidate interstellar particles—two dubbed Orion and Hylabrook, by the citizen scientists who found them, and a third named Sorok. To check whether the particles could have had an interplanetary source, the team simulated trajectories of hypothetical ejecta from more than 1000 main-belt asteroids and comets. Those simulations gave less than a 1 in 50 chance that any one of the tracks could have been produced by an interplanetary grain. Put another way, the odds are better than 99.999% that at least one of the tracks was made by interstellar dust.

Cosmic foil

Roughly 15% of the exposed surface of the *Stardust* collector is aluminum foil, which covers the frame that holds the aerogel tiles in place. Although a dust particle that collides with the foil is typically pulverized on impact, it leaves behind a residue-filled crater that offers clues to the particle's original size, speed, and chemical makeup. So while Westphal's team was inspecting the aerogel tiles, Stroud's team was using scanning electron microscopy to probe the foil sheets.[3]

The team's search turned up 20 impact craters, including the one shown in figure 2. Of those, 16 contained residues indicating they were probably made by fragments from the probe's solar panels. The remaining four were apparently formed by cosmic dust particles between 0.2 µm and 0.4 µm in diameter. Although it's possible that those particles could have had interplanetary origins, models of micrometeoroid distributions suggest the scenario is unlikely: Where *Stardust* collected its samples, submicron-sized interplanetary dust is almost certainly too scarce to have accounted for all the craters—and probably too scarce to have accounted for any.

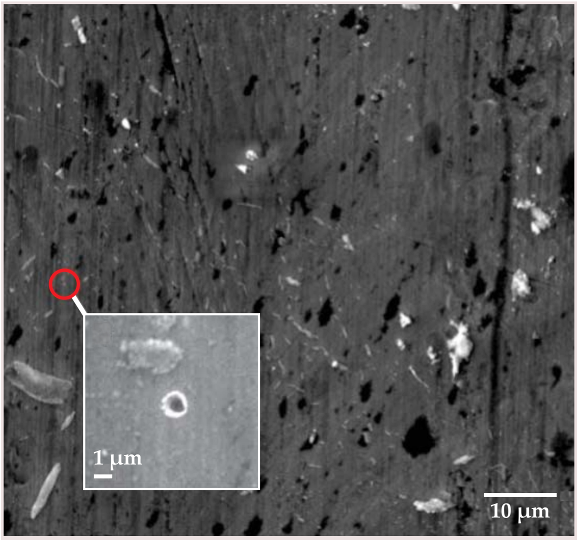

Figure 2. The impact crater circled in red in this scanning electron microscope image, and enlarged in the inset, was made by a dust particle colliding with the aluminum foil that coats the frame of the *Stardust* probe's dust collector. An automated search algorithm identified the crater amid the defects in the surrounding foil. (Adapted from ref. 3.)

Both the aerogel and the foil candidates' interstellar provenance can potentially be clinched by isotopic analysis. The ratio of oxygen-18 to oxygen-17 in our solar system is significantly higher than the mean value observed in our surrounding interstellar medium, possibly because a supernova dumped ^{18}O-rich material into the protosolar cloud as the system was forming more than 4 billion years ago. Mass spectrometry measurements showing ^{18}O/^{17}O ratios consistent with the interstellar value would provide unambiguous evidence of the particles' origins. So far, however, the *Stardust* team has measured isotope ratios for only two of the foil craters (the other two were damaged during transport between labs), and the results were inconclusive.

Diverse dust

To date, much of what's known about interstellar dust particles has been gleaned from the absorption features they imprint on stellar spectra and from peaks seen in their thermal emissions. But those features, relatively broad and weak, leave considerable room for interpretation. As a result, several competing models of interstellar dust have emerged. New data from the *Stardust* samples could help refine some of those models and weed out others.

Typical dust models, for instance, assume that interstellar grains are compact and spherical,[4] but evidence suggests that six of the seven grains uncovered in the *Stardust* sample—including Orion, shown in figure 3—were porous, multiparticle aggregates. Likewise, several prominent absorption features in dust spectra are commonly attributed to aromatic hydrocarbons such as graphite, but the *Stardust* candidates show hardly a trace of carbon. What's more, astronomical spectra indicate that interstellar dust is only about 2% crystalline; although the grains probably start out as crystalline silicates, irradiation by high-energy ions in the interstellar medium is thought to render them amorphous. Yet Orion and Hylabrook, the only two particles recovered intact, were both largely, if not mostly, crystalline.

"The collected particles diverge from many of what we in the astronomical community take as routine assumptions," comments William Reach, of the Stratospheric Observatory for Infrared Astronomy. "It's a real eye-opener."

The *Stardust* samples may also help resolve a conundrum that's puzzled astronomers for nearly two decades. Between 1992 and 2007, the *Ulysses* probe launched by NASA and the European Space Agency reported more than a thousand impacts with interstellar dust particles, some of them tens of picograms in mass.[5] (Because the impacts didn't abate even after the probe maneuvered out of the ecliptic plane of the solar system, they couldn't have been caused by interplanetary debris.) To explain the strong extinction of short-wavelength starlight by interstellar dust clouds, astronomers typically assume that virtually all interstellar dust is small, no heavier than a picogram or so.

If interstellar dust is indeed as porous as the *Stardust* samples imply, however,

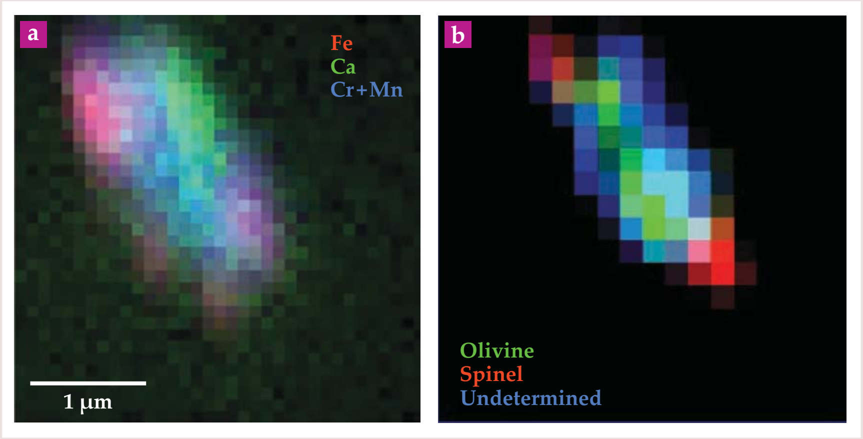

Figure 3. Orion, a candidate interstellar grain retrieved during the *Stardust* mission. **(a)** An x-ray fluorescence image showing a heterogeneous distribution of iron, calcium, chromium, and manganese suggests the grain is a multiparticle aggregate. **(b)** A phase map derived from scanning transmission x-ray microscopy reveals several crystalline phases: silicate-rich olivine, magnesium-rich spinel, and two unidentified phases. (Adapted from ref. 1.)

astronomers may have misjudged the particles' propensity to extinguish light. The amount of passing light that a grain absorbs or scatters is roughly proportional to its cross-sectional area, and low-density, porous grains would tend to have larger cross sections than were assumed in astronomical models.

Westphal cautions against drawing far-reaching conclusions from the tiny sample they've amassed so far. He, his coworkers, and their legion of citizen scientists still have plenty of aerogel and foil left to inspect. But they're patient. "We can make measurements on these samples for decades to come," Westphal says. "If we're careful, we'll be able to analyze them with instruments that don't yet exist."

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Tailor-made molecules grow into identical carbon nanotubes

Organic chemistry and surface science combine to overcome a long-standing materials challenge.

Carbon nanotubes (CNTs)—graphene sheets wrapped into hollow cylinders a nanometer or two in diameter—have inspired a vast array of proposed applications based on their many extraordinary characteristics. They're mechanically strong, flexible, and lightweight. And their structure-dependent electronic and optical properties make them ideal components for FETs, photonic systems, and more. (See the article by Phaedon Avouris, PHYSICS TODAY, January 2009, page 34.)

A CNT's atomic structure is defined by a pair of indices (n,m), which together determine its diameter and the orientation of the graphene lattice with respect to the tube's axis. (See the article by Cees Dekker, PHYSICS TODAY, May 1999, page 22.) When n and m are equal, the electronic bandgap is zero, and the CNTs are metallic. When $n - m$ is a multiple of three, the bandgap is small, and the CNTs are deemed semimetallic. Most other index pairs result in a larger bandgap that's different for each structure.

The CNT community has grappled for decades with the challenge of pro-