THE STARDUST COMET MISSION: STUDYING SEDIMENTS FROM THE SOLAR SYSTEM'S FROZEN ATTIC

Comets are ice-bearing bodies that eject solids and volatiles when they are sufficiently close to the Sun. The surviving inventory of these bodies is only a fraction of a vast population of ice-bearing planetesimals that once filled the cold regions of the early Solar System. The NASA Stardust mission collected thousands of solid particles during a close flyby of a 4.5 km diameter active comet and returned them to Earth in 2006. These samples of comet 81P/Wild 2 provided the first sample-based information on proven cometary materials. Detailed laboratory studies of these samples have provided "ground truth" insight into the origin of comets that could not have been obtained by either remote sensing or in situ methods.

Wild 2 is currently on an orbit that ranges from Jupiter to Mars but, like other Jupiter-family comets, it is believed to have spent nearly all of Solar System history beyond Neptune. Its depression-covered surface (Fig. 1) was probably shaped by sublimation, a process that may have eroded hundreds of meters off its original surface. Over 20 dust jets were observed during the flyby, and this ejection process allowed samples to be collected on a low-cost mission without landing. Dust particles impacted into low-density silica aerogel and aluminum foil at a speed of 6.1 km s^{-1} (Fig. 2). The aerogel capture process worked wonderfully for solids larger than a micron but it often degraded or melted smaller particles. Particles collected by Stardust are believed to be a sampling of solids that were at the edge of the Solar System at the time of its formation. They were packed in ice and do not appear to show evidence of parent-body thermal metamorphic alteration. The compositional range of adjacent olivine grains in dust particles and the preservation of moderate Cr abundances in olivine, along with other indicators used to gauge alteration levels in meteorites, imply that the comet is no more internally processed than the parent bodies of the most primitive meteorites.

The mission was named Stardust in part because it was commonly believed that the rocky portion of comets would be composed of presolar interstellar grains, the primary carriers of heavy elements involved in star and planet formation. This belief was partly based on the idea that comets formed in distant isolation from the inner regions of the Solar System where meteorite parent bodies formed and nebular processes destroyed nearly all presolar grains. The major surprise of the Stardust mission has been that all of the micron and larger grains that have been analyzed have isotopic compositions consistent with formation in the Solar System. Five submicron isotopically anomalous (inorganic) presolar grains have been identified, but their abundance is small. Due to capture degradation of submicron grains, the absolute abundance of presolar grains in the comet is difficult to determine, but the current best estimate is on the order of 1000 ppm (Leitner et al. 2010, 2012), a value that is small but higher than the ~100 ppm found in presolar grain–rich meteorites and micrometeorites and also higher than the typical ~375 ppm abundance in 10 µm interplanetary dust particles (IDPs). These findings imply that preserved isotopically anomalous interstellar grains are not a major component of this comet, and the fact that such grains do not dominate any IDP, which are likely of cometary origin, suggests that the early Solar System did not contain any refugia that preserved presolar solids with distinctive isotopic compositions. It is likely that the combination of nebular environments and migration processes destroyed nearly all of the initial solid materials from which the Solar System formed. These silicate-destroying processes should also have destroyed presolar organics. This finding casts doubt on the long-held notion that interstellar molecules played a significant role in making habitable planets in our Solar System and perhaps in any planetary system.

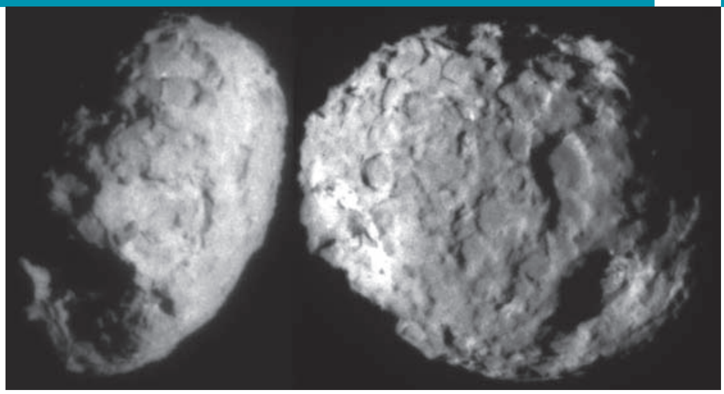

Figure 1 Orthogonal views of the surface of comet Wild 2. The complex surface of this and other imaged comets significantly differs from the impact-gardened surfaces of asteroids. Image: NASA (http://stardust.jpl.nasa.gov/photo/cometwild2.html)

A stunning outcome of the sample studies is that the majority of 1–100 µm grains in Wild 2 are familiar materials that are found in primitive meteorites. The ice and organics in the comet may have formed in cold regions, but the solids—most of the comet's mass—were formed by the same high-temperature nebular processes that made the bulk of solids that accreted to form meteorite parent bodies. If we think of asteroids and comets as collections of cosmic sediments, respectively accumulated in the inner and outer Solar System, it is astonishing that they contain similar rocky materials.

The most common large grains appear to be chondrule fragments, common meteoritic components that were pulse heated to 1700–2050 K (Hewins and Radomsky 1990) as freely orbiting nebular components. Wild 2 contains examples of a wide range of chondrule types, including Fe-rich, Fe-poor, and Al-rich. As seen in meteorite chondrules, ^{16}O-rich relict olivine grains have been found in these igneous objects that

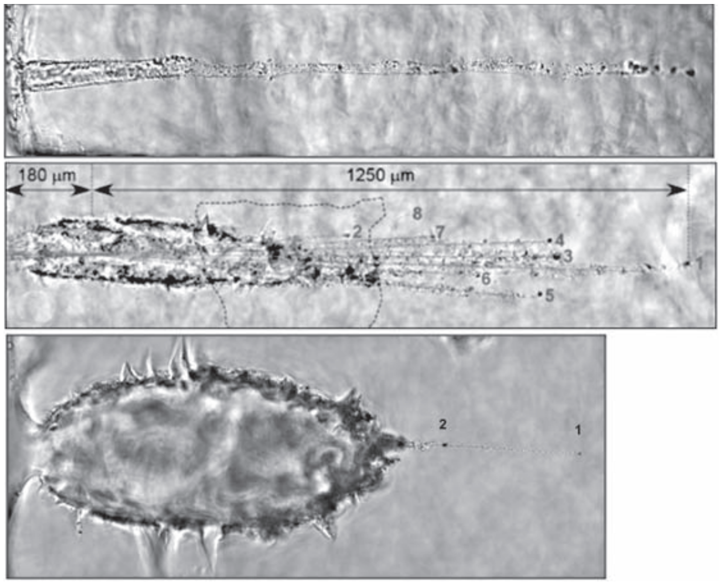

Figure 2 These three aerogel impact tracks illustrate dramatic structural differences between impacting Wild 2 particles, which traveled left to right in the images. The particle that made the top track (290 µm long; T58) was solid and did not experience fragmentation, while the center track (T113; Nakamura-Messenger et al. 2011) was made by a weakly bonded aggregate of solid particles that were each several microns in size. Most of the mass that produced the bottom track (1.4 mm long; T141) was composed of either very fine or thermally unstable components that stopped in the upper track portion, producing the large hollow, bulb lined with melted and compressed silica aerogel. The deepest penetrating particle, labeled 1, is a sulfide, and particle 2 is a CAI. A 0.4 µm, isotopically presolar SiC grain was found on the bulb wall. Images: NASA (http://stardust.jpl.nasa.gov/photo/cometwild2.htm)

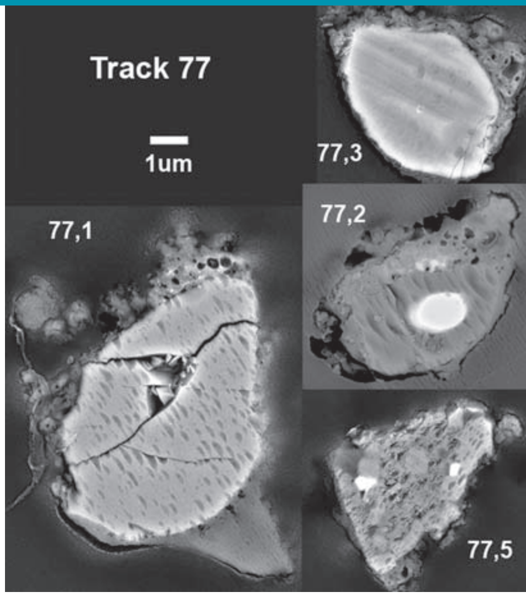

Figure 3 Backscattered electron microscope images of the microtomed faces of four fragments in a single track (T77). 77,1 Fo_{62-67} olivine with a small kosmochloric augite grain on its perimeter. 77,2 is Fo_{62} olivine with an egg-shaped kamacite, (Fe,Ni), in its interior. The metal grain contains a small grain of schreibersite, $(Fe,Ni)_3P$. 77,3 is Fo_{52} olivine with a small, Cr-rich spinel in its center. 77,5 is a complex mix of Fe-rich olivine, kosmochloric diopside, and small amounts of albite. The two bright grains are pyrrhotite and pentlandite. This track also comprised a range of other phases, including forsterite, Mn-rich (LIME) forsterite, Mn-rich pigeonite, enstatite, and pyrrhotite. The aligned surface features are chatter pits formed during the cutting process. In all images, the vesicular and smooth gray materials making sharp contact with the grain perimeters are, respectively, melted and compressed aerogel. Image: www.lpi.usra.edu/meetings/lpsc2010/pdf/2146.pdf

clearly predate the final melting of their host (Nakamura et al. 2008). In addition to chondrules, Wild 2 also contains calcium–aluminum-rich inclusion (CAI) fragments (Simon et al. 2008). CAIs, which are rich in rare earth elements, are the oldest solids formed in the nebula, and they are distinguished by their ^{16}O-rich compositions (similar to that of the Sun) and a host of refractory phases that condense above 1400 K. Although the origin of chondrules and CAIs is uncertain, it is clear that they formed at extremely high temperature. The Wild 2 samples include a rich diversity of anhydrous silicates, sulfides, and metal phases (Fig. 3). A remarkable finding is the presence of LIME (low-iron, high-manganese) forsterites that have ^{16}O-rich compositions and are likely to be condensates.

Even though the collected sample was limited in mass and largely made of grains smaller than 100 µm, it contains a remarkable mix of high-temperature nebular materials. The most direct conclusion from this is that the comet's rocky components are inner Solar System materials that were transported to the edge of the solar nebula where they could accumulate low-temperature ice and organics. Supporting this notion is the observation that the comet appears to contain a wider diversity of materials than are found in specific chondrite groups. Chondrite groups have distinctive properties because much of their mass was made from local materials that in some cases have restricted ranges of properties, such as oxygen isotope composition and minor element composition of olivine. It appears that a major difference between asteroids and Wild 2 is that asteroids were largely constructed from locally made materials whose properties give meteorite groups distinctive characteristics, while comets like Wild 2 contain a broader mix of nebular materials.

The simplest interpretation of this finding is that comets represent the Solar System's frozen attic and that their rocky materials were transported and mixed over distances of tens of astronomical units. The abundance of high-temperature nebular solids at the edge of the Solar System is strong evidence for massive outward transport of inner Solar System materials by a variety of nebular processes (Shu et al. 2001; Bockelée-Morvan et al. 2002; Cuzzi et al. 2008; Ciesla 2010; Boss 2012). An alternative view is that the high-temperature components originated in the outer Solar System, perhaps inside transient Jupiter-mass objects that formed in the outer Solar System but were disrupted (Bridges et al. 2012).

The studies of Wild 2 samples have shown that the rocky fraction of this comet is a fabulous mix of fine- and coarse-grained materials that are remarkably similar to high-temperature components found in asteroidal meteorites. The samples do not show evidence for the appreciable thermal or aqueous alteration that has modified essentially all meteorite samples. The diverse set of minerals and rocks in the comet are inconsistent with astronomical predictions. If Wild 2 solids were nearly all derived from inner portions of the protosolar nebula, it is perhaps likely that the rocky contents of other comets have a similar origin. Comets differ in volatile contents but their rocky materials may all be the same. If this is correct, then it is also possible that Pluto, its similar-size neighbor Eris, Neptune's moon Triton, and perhaps tens of Earth masses of comet bodies that were ejected from the early Solar System were made from these materials. With this in mind, future comet sample returns, more ambitious than Stardust, could provide profoundly improved insight into the nature of the nebular dust and small rocks that played important roles in the formation of the Solar System.

More information about the Wild 2 samples can be found in the April 2012 *Meteoritics and Planetary Science* issue, which resulted from a meeting that was held at Timber Cove, California, and was dedicated to Frank Stadermann, a Stardust pioneer who, along with his wife Christine Floss, discovered the first presolar grain in a comet.

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