NASA Returns Rocks from a Comet

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Cometary particles returned by the Stardust Discovery Mission are primarily silicate materials of solar system origin. Some of the grains were formed at high temperatures close to the Sun, but then transported far out to the Kuiper belt region of the solar system before being incorporated in the comet.

Until now, extraterrestrial materials available for study have come from the inner solar system, including meteorites that have fallen from the sky and the returned lunar samples. Meteorites include unequivocal samples of Mars and the Moon as well as an impressive variety of asteroidal materials.

The Stardust Discovery Mission has, for the first time, returned cometary materials for analyses in terrestrial laboratories. Initial results are reported in this issue of Science. Launched in 1999, the Stardust spacecraft encountered comet P81/Wild 2 in January 2004, passing through the dust cloud surrounding the cometary nucleus and capturing an estimated 1000 particles in the size range of 5 to 300 micrometers (I). These were successfully returned to Earth in January 2006.

Wild 2 is a Jupiter family comet; evidence suggests that it formed in the Kuiper belt of objects beyond the orbit of Neptune and was then diverted into the inner solar system by orbital perturbations from Neptune and Jupiter. Thanks to Stardust, we now have material to study from a body that unequivocally originated in the outer regions of the solar system.

In the inner solar system, volatile constituents, primarily H2O, sublimate from a comet nucleus. Dust grains imbedded in the ices are swept out with the outflowing gas, becoming part of a large cloud of gas and dust, or coma. The cometary dust is there for the taking—the challenge is to capture the particles without destroying both the dust and the spacecraft in the process. Two clever technological achievements led to the success of Stardust: (i) design of a spacecraft trajectory by Chen-Wan Yen (Jet Propulsion Laboratory) that produced a relatively low encounter velocity of 6.1 km/s and (ii) development of an aerogel capture medium by Peter Tsou (Jet Propulsion Laboratory).

Wild 1 has been in the inner solar system far longer? Or are these differences due to mixing of comets from different reservoirs into the population of Jupiter family comets? Or do they merely represent different mixing ratios for the cometary nuclie? Stardust has certainly brought us plenty of food for thought. Combining the Stardust results with those from other recent comet missions will keep the theoreticians working for some time, while we hope for visits to other comets in the future.

References
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Aerogel is a highly porous silica foam that has a density comparable to that of air (Fig. 1). The low density slows down impacting particles gradually, allowing them to escape melting and/or vaporization. The capture event leads to millimeter-sized tracks (Fig. 2). Most material is left as fragments along the walls of the track, but there is usually an intact terminal particle.

Sample return missions result in major scientific progress because terrestrial laboratories use the latest technology and eliminate the limitations imposed by remote spacecraft instrument operations. This is amply demonstrated by the results reported in this issue. An incredible array of analytical firepower has been unleashed to unlock the secrets of Wild 2. Some of the instruments have diameters that are kilometers in size. Yet, the amount of cometary material consumed in this work is a negligible part of the 1 to 10 micrograms of material returned.

The Wild 2 samples recovered by Stardust are small rocks. None of the particles studied represents a single mineral; all are mixtures of minerals, typically submicrometer in size. Fortunately, we have the capability to at least begin the studies of such complex samples. The most abundant minerals are the crystalline silicate minerals, olivine and pyroxene, along with troilite (FeS) (2). These are very stable phases, common in planetary materials; however, finding them here is somewhat surprising because many expected that cometary material would be similar to interstellar material, in which most silicates are believed to be amorphous. In contrast, cometary amorphous material in the returned samples is rare or nonexistent, although it is worth noting that aerogel melting produced silica glass, and silica glass mixed with cometary materials makes the identification of cometary amorphous material difficult (2).

Two major conclusions can be drawn from the Stardust analyses, one anticipated and one unexpected. As anticipated, isotopic analyses could determine whether cometary materials were made in the solar system or were aggregated presolar materials. Stars synthesize elements heavier than Li with wildly varying isotopic compositions, and rare circumstellar grains of such material have been recovered from meteorites. However, with important exceptions, the isotopic compositions of elements are very homogeneous in inner solar system materials, and it is widely accepted that this homogenization occurred in situ, within the solar system. Stardust isotopic data reveal a few isotopically anomalous presolar grains, but most appear isotopically indistinguishable from inner solar system materials. The Wild 2 rocks are solar system rocks (3).

The unanticipated result was the discovery of a single grain made of high-temperature minerals found in meteoritic Ca- and Al-rich inclusions (CAIs) (2), which are products of gas-solid separation at high temperatures only possible in the inner solar system very close to the Sun. Moreover, the Stardust CAI has the same distinctive oxygen isotopic composition as that found in meteoritic CAIs (3). It appears inescapable that, during the formation of the solar system, materials formed near the Sun were mixed as far out as the Kuiper belt and there incorporated into objects which eventually became comets. Such mixing has been proposed but observational proof was lacking (4).

There is considerable interest in carbonaceous matter from comets. A large number of essentially pure C grains (known as CHON particles for the elements observed in them) were observed in the comet Halley flybys (5), but such grains are very rare in Stardust samples studied to date (2, 6, 7). Nevertheless, the impacts released labile cometary organic compounds (7), and further study of these is of considerable importance.

The large number of authors of the present papers is typical—and appropriate—for the initial results of big projects. However, the Stardust papers are relatively unique in that essentially all of the coauthors collected data, which allowed the application of many different techniques. Redundant verification by independent techniques is difficult in big projects and prohibitively expensive in many cases. Here, not only have a large number of scientists participated in Stardust analyses, but the data they produced can be independently verified to be correct. Anomalous results will quickly be checked.

The results reported here are only the first chapter in unlocking the secrets of Wild 2. The samples are available, and they will be preserved as they await more detailed study by both current techniques and more advanced analytical techniques yet to be developed, some of which may be inspired by the availability of Wild 2 material.

References
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