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Insight from the unexpected

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The NASA Stardust mission returned samples from comet 81P/Wild 2, an active Jupiter-family comet that is believed to have formed at a heliocentric distance beyond the orbit of Neptune. The study of the samples has provided a critical first look at the micrometer and larger solid materials that were at the edge of the solar system at the time that Kuiper Belt comets formed. Analysis of the samples has involved a number of challenges and surprises. These issues and the full implications of the information that the samples provide were intently discussed at the Timber Cove II meeting October 26–28, 2008. The meeting was sponsored by the Institute of Geophysics and Planetary Physics (IGPP) and it was held at a ruggedly beautiful and remote location on the Sonoma coast of northern California once protected by a Russian fort. Seventeen of the papers presented at the meeting are presented in this volume.

An issue of primary importance discussed at the meeting was modification of comet samples during deceleration from ~6 km/s capture in the silica aerogel capture medium. The high-speed capture disrupted many comet particles into fragments and some of these had brief contact with thin flows of molten silica. Some materials, such as the interiors of grains larger than a micrometer, show little evidence of alteration; however, some smaller grains and some organic materials were severely modified. The exteriors of sulfide crystals, in particular, appear to have been especially susceptible to abrasion, mixing with molten aerogel and smelting out of metallic iron (Ishii et al. 2008; see lower left cover image). Both the continued examination of collected samples as well as laboratory capture and numerical simulations have significantly improved the ability to distinguish between modified and unmodified cometary material (this issue, Burchell et al.; Couslon; Dominguez; Ebel; Fries et al.; Jacob et al.; Kearsely et al.; Stodolna et al; Velbel et al., and Wozniakiewicz et al.). The capture situation is somewhat analogous to examining a small pulverized meteorite composed of both fusion crust and preserved interior fragments. The most affected materials were submicron grains and organics, although the effects were not uniformly distributed among all tracks. Probably the most dramatic case of preservation of organic compounds is the recent discovery of extraterrestrial glycine (Elsila et al. 2009).

Of the many surprises from the collection was the fundamental finding that the comet contains such a high abundance of solid grains larger than a micrometer in size. A common expectation was that comets solids would be dominated by submicrometer grains, but even the shape of the tracks showed that this is not the case. While some particle capture tracks do have wide bulbous shapes consistent with the fragmentation of small weakly bonded components, the majority of tracks are long and "carrot shaped." Non-bulbous tracks are made by solid particles that do not severely disrupt during capture and most of the Stardust tracks made by particles of a few micrometers in size are of this type. Captured solid grains up to at least 40 micrometers across have been sectioned and analyzed (Nakamura et al. 2008).

The origin of the cometary materials was also a surprise. A common expectation was that comet solids were predominantly composed of presolar grains, both pristine amorphous interstellar grains as well as some that had experienced partial crystallization in the solar nebula by solid-state annealing at temperatures near 1000 K. While isotopically anomalous presolar circumstellar grains have been found both in craters in Al foil lining the collector and in the walls of impact tracks in aerogel, they are rare. At present, the abundance of identified circumstellar grains is small and appears to be less than commonly found in primitive chondrites. This remarkable finding has profound implications for the origins and distribution of solids in the solar nebula. If materials like interstellar amorphous silicate grains did not survive in high abundance in the Kuiper Belt, it seems unlikely that they survived in abundance elsewhere either. However, if silicates were destroyed, it is difficult to imagine that presolar organic materials could have survived in abundance anywhere in the early solar system. The majority of circumstellar silicate grains are heavily processed during their ~10^8 year lifetimes in the interstellar medium becoming interstellar amorphous silicate grains in the process. During a

group discussion, the audience was reminded by an astronomer that although surviving presolar circumstellar grains are expected to be isotopically anomalous, most interstellar grains are expected to be isotopically normal (solar).

The dynamics of materials transport and mixing in the nebula were discussed (this issue, Ciesla and Ogliore et al.). Detailed mineralogical and isotopic studies confirm that high-temperature inner nebula materials familiar in chondrites were transported to accretion region of Wild 2. These include materials such as forsterite, chondrule fragments, and calcium-aluminum-rich inclusions (CAIs) fragments (Brownlee et al. 2006; Zolensky et al. 2006; Nakamura et al. 2008). These familiar "meteoritic" components appear to be materials that formed in the inner solar system by the same processes that formed meteoritic components. In most cases, it is clear that these components did not form by solid-state annealing of submicron interstellar grains. Although Wild 2 contains a broad mix of "meteoritic" materials, they are unequilibrated with respect to each other. For example, olivine grains separated by less than a micron can have quite different Fe contents. Wild 2 solids may be dominated by inner solar system materials, but it is clear that they were not detectably modified by parent body processes once they accreted along with the ice component. The large-scale transportation of these materials provide important constraints on models of grain transport in the early solar system.

A challenge for the future, and hopefully future Timber Cove conferences, is more detailed comparison of the Wild materials with those found in meteorites, micrometeorites, and interplanetary dust particles (IDPs), some of which are believed to be of cometary origin. Are the Wild 2 materials identical to those found in meteoritic materials or are there differences (this issue, Dobrică et al.; Joswiak et al.; Rietmeijer; Stodolna et al.; Wirick et al.)? Did all of these materials form in similar regions at similar times? Although ages have yet to be published for Wild 2 material, if the cometary chondrule fragments and CAI fragments have the same origins as their meteoritic counterparts, then this implies that inner solar system "comet building" materials were transported to the Kuiper Belt over the several million year time span between CAI formation and chondrule formation.

Comet samples provide a potential for shedding new light on the origin of chondrites. All meteorite samples have resided in inner solar system (asteroid) parent bodies and even the 3.0 chondrites have experienced detectable alteration inside a heated and compacted parent. Comet samples have probably never been inside a large parent body, and the fact that they were encased in ice implies that they were not heated above ~180 K during their long-term storage in the Kuiper Belt. The chondrule and CAI materials seen in this comet are likely to have come directly from where they were formed without intermediate storage and secondary alteration in inner solar system bodies. Whatever the process was that transported inner solar system materials to the Kuiper Belt, it must have happened early, when the nebula was undergoing vigorous evolution.

The "meteoritic materials" in the Stardust sample provide an interesting sampling of nebular materials that were transported over large distances. It appears that all of the rocky materials in comet Wild 2 formed elsewhere and were transported to comet formation regions. This contrasts with chondrites that can be considered to be composed of two classes of materials: A) materials such as CAIs and presolar grains that formed elsewhere and in previous times and B) materials that formed locally and gave chondrite classes their distinctive properties. Chondrites contain perhaps a few percent of the type A materials, while, based on Wild 2, the rocky components of comets comprise perhaps 100% type A material. Because the comet is dominated by widely transported material instead of locally made components, comet Wild 2 solids are not actually assignable to any chondrite type, even though they are made of "meteoritic materials." A challenge for the future is to see if the type A materials in comets and chondrites are the same. If they are not the same, then why are they different? Both comets and asteroids are collections of solar nebula detritus. Were they collecting at the same times and sampling the same grain reservoirs? The unique significance of "meteoritic materials" in the Stardust sample is that they are geo-forensic examples of the raw ingredients of some asteroids.

The Wild 2 sample is an exciting challenge, even for state-of-the-art analytical instruments and facilities (e.g., this issue, Bradley and Dai; Wirick et al.). The expectation that the sample would be dominated by presolar materials (i.e., circumstellar and interstellar grains) does not appear to have been realized, at least based on the material examined to date. Instead of cometary rocky components being dominated by in-falling interstellar material, they appear to be dominated by material that was outflowing from the inner reaches of the solar nebula. This radical departure from common pre-mission expectations underscores the fundamental importance of returned samples in calibrating our perceptions of the early solar nebula environment and the nature of small bodies beyond the giant planets. The Stardust mission implies that comet rocky materials are a fabulous resource of materials made in the solar system that were transported across the full dimensions of the solar system.

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