The Stardust Mission: Analyzing Samples from the Edge of the Solar System

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Abstract

Comet samples returned to Earth by the NASA Stardust mission have provided a surprising glimpse into the nature of early Solar System materials and an epiphany on the origin of the initial rocky materials that once filled the cold regions of the solar nebula. The findings show that the cold regions of the early Solar System were not isolated and were not a refuge where interstellar materials could commonly survive. Wild 2, the sampled comet, appears to be a typical active Jupiter family comet, and yet most of its sampled micron and larger grains are familiar high-temperature meteoritic materials, such as chondrule fragments, that were transported to cold nebular regions. The rocky components in primitive asteroids and comets may differ because asteroid formation was dominated by local materials, whereas comets formed from mixed materials, many of which were transported from very distant locations.

INTRODUCTION

The Stardust mission collected solid particles from an active Jupiter family comet (JFC), comet 81P/Wild 2, and returned them to Earth for laboratory analyses. The comet samples, along with the Apollo and Luna samples from the Moon, the solar wind samples collected by the Genesis mission (McKeegan et al. 2011), and the asteroid samples collected by the Hayabusa mission (Nakamura et al. 2011), are the only materials returned by spacecraft from specific Solar System bodies. The comet samples were collected during a flyby encounter between the orbits of Mars and Jupiter, but like other JFCs, Wild 2 is expected to have spent nearly all of Solar System history in orbits beyond Neptune. The collected samples provide direct information on the origin of comets and ground truth evidence on the properties of the small nonvolatile components that formed comets and other outer Solar System bodies. For many reasons, the mission could not collect and return ice, and the returned samples consist of rocky materials composed of silicate minerals, amorphous silicates, sulfides, metal, oxides, nitrides, carbides, and organics.

The major surprise of the mission was that the rocky portion of the sampled comet, likely the bulk of its mass (Sykes & Walker 1992), is composed of familiar materials that, in most cases, have been seen in primitive meteorites. The comet can be considered to be a sediment that assembled from solid materials that were located in the outer regions of the Solar System at the time of its formation. This origin contrasts with that of primitive meteorites, most of which are sediments of dust, millimeter particles, and small rocks that accumulated in the inner Solar System, interior to the orbit of Jupiter. Accordingly, it is quite remarkable to find that a comet contains abundant meteorite-like materials that are clearly similar and likely identical to those that formed meteorite parent bodies an order of magnitude closer to the Sun. Although the comet solids are mostly familiar meteoritic materials, the ensemble of these materials does not appear to match that of any specific meteorite type. The apparent long-distance transport of inner Solar System meteoritic materials to the formation region of Wild 2 suggests that rocky components of other comets and outer Solar System bodies may have a similar origin, unless Wild 2 is an unusual comet.

The findings from this mission imply that the >2-μm rocky components that accreted to form Wild 2 were largely made in hot regions of the solar nebula by high-temperature processes. This result is quite surprising, because the traditional view of comets is that their components all formed in isolation from the hot nebular environments. Comet ices include water as well as supervolatiles such as CO that condense under nebular conditions at temperatures below 50 K. Because of their volatile contents, comet solids were long believed to be inherited from the interstellar medium (Greenberg & Li 1999, Li & Greenberg 2003). The solids were expected to be dominated by 0.1-μm interstellar grains coated with radiation-processed organic mantles. The results of the Stardust mission imply that the sampled comet has a much different history than originally envisioned, and they provide strong evidence of large-scale transport of solids across the full dimension of the protosolar nebula. The sampled comet is a mix of materials that were almost exclusively made inside the early Solar System, and they were made in both its lowest- and highest-temperature environments. The highest-temperature components formed above 2,000 K, whereas supervolatile ices formed below 50 K. These components clearly did not form in the same environment or at the same time, and the high-temperature materials presumably predate the more volatile components.

COMET 81P/WILD 2

Wild 2 is an active 4.5-km-diameter comet, with at least 20 active jets observed in long-exposure images taken during the 2004 flyby with the Stardust spacecraft (Sekanina et al. 2004). The kilometer-long jets are illuminated dust entrained in gas escaping from small active surface regions. Ground- and space-based observations imply an H_2O ejection rate of ~20,000 tons per day

(Farnham & Schleicher 2005, de Val-Borro et al. 2010) near perihelion as well as emissions of CN, CH_3OH, and HCN (Knight & Schleicher 2010, Dello Russo et al. 2012). The spectral emissions of Wild 2 have average to slightly high NH_2 abundance and depleted C_2, properties that classify Wild 2 as a Borrelly-type comet (Fink et al. 1999). The relative depletion of C_2 is characteristic for comets derived from the Kuiper belt, the distribution of prograde ice-bearing bodies just beyond Neptune (A'Hearn et al. 1995). The activity level of Wild 2 appears typical for JFCs and is higher than those of the small set of main-belt comets and active asteroids that appear to have formed in the asteroid belt (Hsieh & Jewitt 2006, Jewitt 2012).

The Wild 2 encounter science was summarized following the 2004 flyby (Brownlee et al. 2004, Duxbury et al. 2004, Green et al. 2004b, Sekanina et al. 2004, Tsou et al. 2004, Tuzzolino et al. 2004). The surface of Wild 2 is covered with depressions; some are kilometer-sized with steep walls and flat floors (Brownlee et al. 2004, Kirk et al. 2005). The exteriors of Wild 2 and other imaged comets differ remarkably from the often impact-gardened surfaces of other small Solar System bodies (**Figure 1**), and its surface was likely shaped by processes related to sublimation and ejection of solids into space (Belton 2010, Belton et al. 2013). The depth of the depressions suggests that Wild 2 has excavated material from depths of at least several hundred meters. It also has mesas, pinnacles, and roughness on most spatial scales—with the exception of its overall shape, which gives a smoothly rounded limb profile. It does not have the extensive smooth terrains seen on the other imaged JFCs, but it has several depressions whose flat floors may be filled with smooth material. The unusual surface features of Wild 2 (Basilevsky & Keller 2006) indicate that it has a different evolutionary history than other imaged comets and asteroids, and ubiquitous depressions suggest that essentially the entire surface has emitted dust and rocks into space.

Wild 2 is presently on a ~6-year orbit with perihelion near Mars's orbit and aphelion near Jupiter's. Before its 1974 close approach to Jupiter, it was on a ~43-year orbit that ranged from Jupiter to beyond Uranus. If the comet is a typical JFC, it should spend less than a million years on orbits that pass near Jupiter before interactions with Jupiter put it into an escape orbit from the Solar System (Duncan et al. 2004). Most JFCs spend only approximately 7% of their inner Solar System lifetime, with perihelia inside 2.5 AU, as active comets (Duncan et al. 2004). During its inner Solar System excursions, a typical comet may switch approximately ten times between orbital periods longer and shorter than 20 years (Levison & Duncan 1997). Before it entered its JFC orbital stage, Wild 2 probably had multiple outer-planet perturbations that led to a few-million-year planet-to-planet meander that moved it from a beyond-Neptune to an inner Solar System orbit (Levison & Duncan 1997). For most of Solar System history, Wild 2 was stored beyond Neptune below 50 K.

Wild 2 definitely formed in a cold region of the solar nebula, but refined understanding of its birth location is complicated by possible planet migration in the early Solar System. It is nearly certain that the outer planets migrated outward (Malhotra 1993), but more extreme migration scenarios include the Nice hypothesis (Tsiganis et al. 2005, Levison et al. 2011) and the Grand Tack hypothesis (Walsh et al. 2011), wherein planets and planetesimals undergo substantial reconfiguration. A'Hearn et al. (2012) provide evidence from $CO/CO_2/H_2$ abundances that typical JFCs may have formed interior to the region where long-period comets accreted, contrary to the long-held belief that the long-period Oort cloud comets formed closer to the Sun.

JFCs are expected to lose approximately one-quarter of their radius (Thomas 2009) during their active lifetime, and if Wild 2 is halfway through this period, it should have lost approximately 200 m from its original surface. Besides nominal cometary activity, comets can also lose mass by disruption or explosive ejection (Sekanina & Chodas 2007). Sekanina (2009) suggests that explosive events may be driven by runaway CO release that can occur when subsurface amorphous ice undergoes a phase transition to cubic ice.

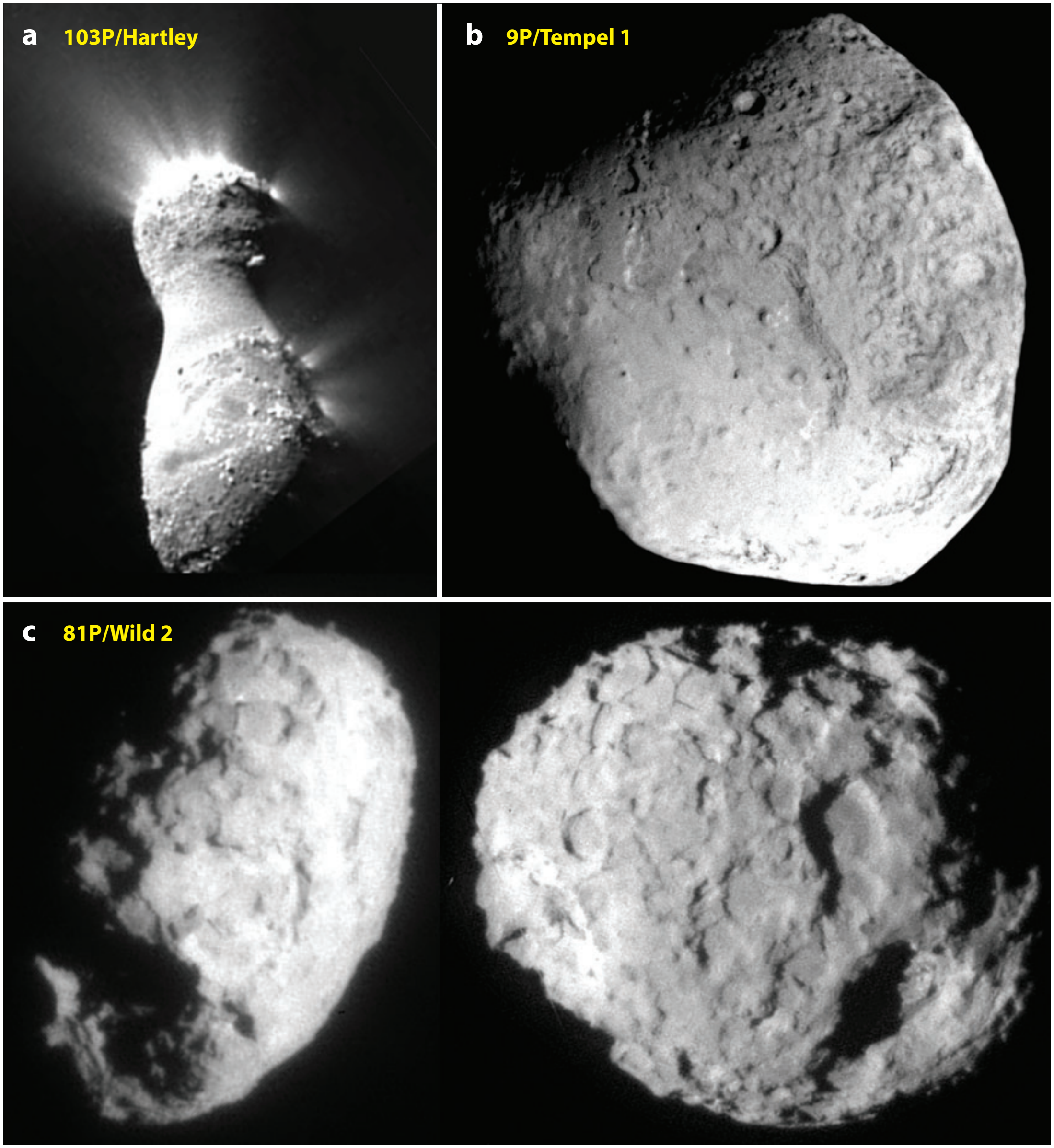

Figure 1

Diverse surface morphologies of (*a*) 2.2-km-long 103P/Hartley, (*b*) 6.3-km-diameter 9P/Tempel 1, and (*c*) orthogonal views of 4.5-km-diameter 81P/Wild 2. All three Jupiter family comets showed jets in long-exposure images. The Hartley image was taken by Deep Impact and the others by Stardust, both NASA Discovery missions.

COLLECTION OF HIGH-SPEED COMET PARTICLES

Particles in the Wild 2 coma were collected on a flyby trajectory that passed within 234 km of the comet's surface at a relative speed of 6.1 km s^{-1} (Brownlee et al. 2006). Most were collected by impact into low-density silica aerogel, but a small fraction were captured as residue lining

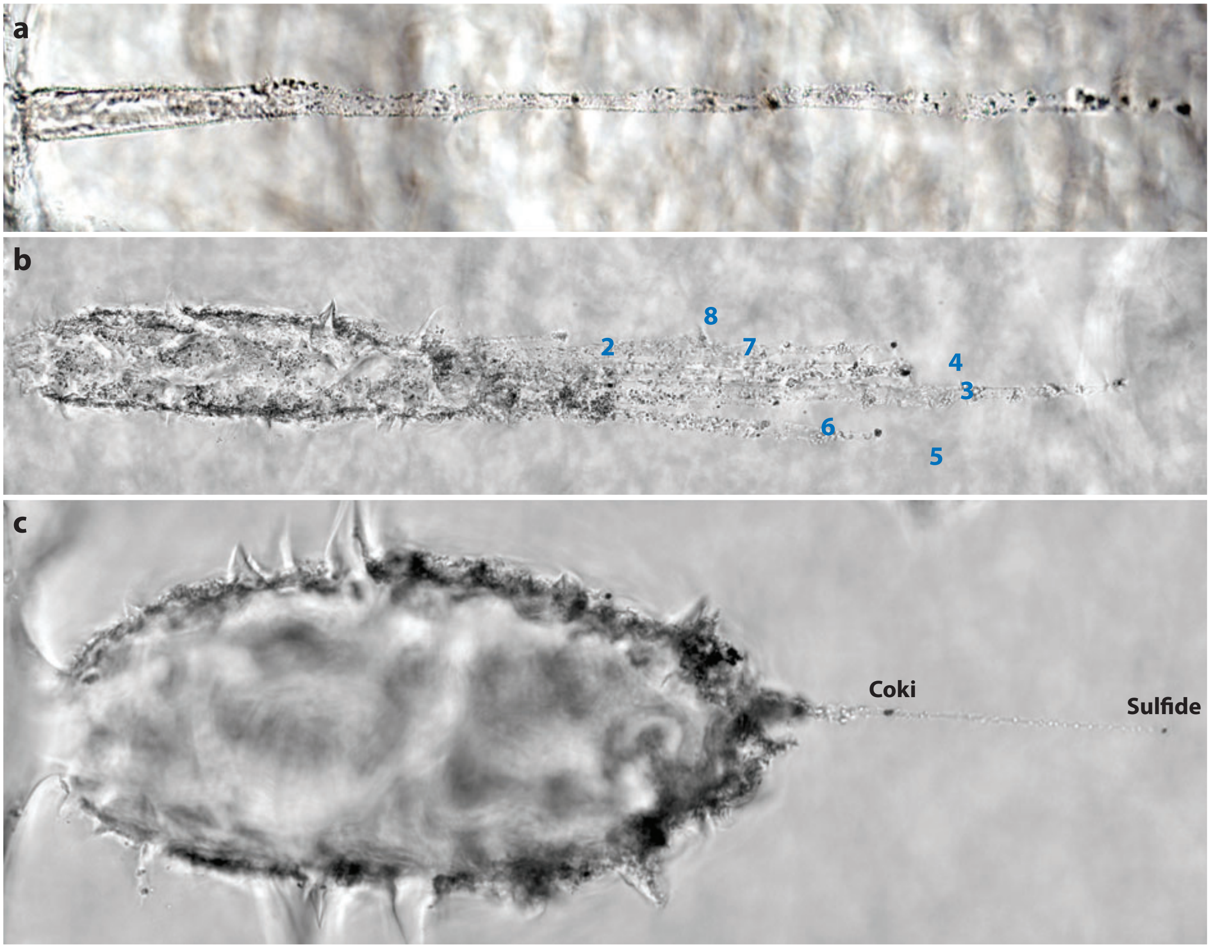

Figure 2

Optical images of three comet particle tracks in aerogel. Particles entered on the left and formed tracks ranging from the carrot-shaped track in panel *a*, caused by a largely nonfragmenting particle, to the highly bulbous track in panel *c*, formed by a weak aggregate of fine-grained components. The terminal particle at the right end of track in panel *c* is a sulfide, and the next particle to its left is a calcium-aluminum inclusion named Coki. The fragmented track in panel *b* is from Nakamura-Messenger et al. (2011).

the bottoms of hemispherical impact craters in aluminum foil that wrapped some of the support structure (Wozniakiewicz et al. 2012). The aerogel collector was an array of more than 100 3-cm-deep rectangular tiles whose density ranged from 0.01 g cm^{-3} at the entry side to 0.05 g cm^{-3} at the rear end. In the aerogel, nonfragmenting particles decelerated over a path on the order of 100 times their diameter.

The comet contained different types of particles, and their capture behavior differed dramatically in the aerogel (**Figure 2**). The track shapes alone provide important information on the nature of impacting particles (Brownlee et al. 2012, Burchell et al. 2008, Trigo-Rodriguez et al. 2008, Kearsley et al. 2012). Solid competent particles that did not fragment during capture produced thin carrot-shaped hollow tracks with a single terminal particle at the end (**Figure 2**). Particles that separated into a modest number of major fragments produced tracks terminated by multiple roots; the largest components generally penetrated to the deepest depths. Particles that were weak aggregates of fine particles or composed of unstable materials produced broad bulbous tracks. For fragmenting particles, the track formation process served as an effective size sieve, separating large solid components that penetrated deep into the track from smaller discrete components that stopped in the upper track regions and lined the hollow bulb cavity. The ratio of bulbous to carrot-shaped tracks provides insight into the ratio of fine to coarse components in the comet. The hollow track cavity forms because of aerogel melting and compression, and the total track volume is proportional to the mass of the impacting particle (Burchell et al. 2008). The interaction of hypervelocity projectiles in aerogel is complex, due to a range of issues including differences in particle properties and the fact that some but not all particles build up a thick layer of compacted insulating aerogel. The observed range of track shapes and the implications of these shapes for particle properties have been studied by extensive laboratory experiments with particles traveling at 6 km s^{-1} (Kearsley et al. 2012).

Most solid particles larger than a few microns were protected by their thermal inertia, and their interiors are typically well preserved. Evidence for lack of alteration includes preservation of distinctive petrographic features, differing composition of adjacent compatible grains, and differing oxygen isotopic compositions of adjacent grains. Unlike larger grains, separate submicron components were often degraded or melted because the short-lived thermal pulse from capture penetrated to their interiors (Brownlee et al. 2006, Burchell et al. 2008, Trigo-Rodriguez et al. 2008, Niimi et al. 2011, Kearsley et al. 2012). The size-dependent effects of capture produced a collection bias that complicates straightforward comparison of Wild 2 with other meteoritic materials and with astronomical data. Hundreds of submicron Wild 2 grains have been studied, but the survivors are a biased set; some are well preserved and others are not (Leroux 2012). Many melted and were lost because they dissolved into the thin layer of molten silica that streamed across particles during the high-speed phase of their deceleration. The interiors of many of the preserved submicron grains were in close proximity with molten aerogel at nearly 2,000°C, and unfortunately, most grains of this size were not well preserved. As a result, the nature of the submicron fraction of Wild 2 remains problematic (Leroux 2012). Particles with high melting points, such as Mg-rich olivine, are often well preserved, but the melted fraction could have included less robust materials such as hydrated silicates or amorphous silicates (Noguchi et al. 2007). The electronically measured size distribution of particles impacting the leading edge of the spacecraft shows that the bulk of the mass was in millimeter and larger particles, but the fluence of particles >0.1 mm was too small to be sampled by the 0.1-m^2 collector (Price et al. 2010). The size distribution measured from the Stardust collection (Price et al. 2010), combined with particle impact sensor data from the front of the spacecraft, indicates that more than 90% of the impacting mass of particles smaller than 700 μm in diameter was in particles larger than 100 μm. Some of the larger particles are solid materials, but many are surely aggregates of smaller components.

Burchell et al. (2008) found that essentially all the tracks shorter than 100 μm were long, thin tracks consistent with formation by solid, nonfragmenting materials and that approximately half of the 1-mm-long tracks were bulbous and half were thin. This suggests that roughly half of the aerogel tracks made by >10-μm particles were made by loose aggregates but that nearly all of the micron particles were solid. Impact craters on aluminum as well as dust detector data indicate that the size distribution of solids emitted from Wild 2 extends well down into the submicron region. Like primitive meteorites and interplanetary dust particles (IDPs), Wild 2 appears to be an aggregation of components ranging in size from less than 1 μm to at least 100 μm. The mineralogical diversity of the collected particles indicates that Wild 2 is an unequilibrated object that is as least as unmodified as the most primitive meteorites. Evidence for lack of equilibration inside the Wild 2 parent body includes a diverse range of Mg/Fe ratios in olivine grains that are only a few microns apart, a wide range of Ni contents in sulfides, and high Cr abundances in olivine. Consistent with its ice retention, Wild 2 appears not to have been transformed by internal heating—at least not to the degree that produced detectable metamorphic changes inside meteorite parent bodies.

COMA PARTICLES AS COMET SAMPLES

The collected Wild 2 coma particles range in size from less than 1 μm to more than 100 μm. The largest ones were collected in silica aerogel, and the smallest ones were best studied as material lining the inside of submicron craters on aluminum spacecraft surfaces. With collection at a heliocentric distance of 1.8 AU, particles <100 μm would be expected to have lost ice components before collection. The liberation of abundant submicron grains from gas-producing regions and the impact detector evidence for disintegration of aggregates (Clark et al. 2004; Green et al. 2004a,b, 2007) provide strong support for the lack of internal processing of the type that transformed meteorite parent body materials into rather strong rocks. Significant processing inside the comet, such as contact with liquid water, would lead to formation of cohesive material that could probably not release appreciable numbers of submicron particles during ice sublimation. The rocky grains liberated by sublimation in ice-bearing regions are likely the same grains that initially accreted to form the comet.

The sampling strategy of collecting grains that were propelled outward from gas-producing regions enhances the likelihood that the collected sample not only represents an average of multiple regions of the comet but also was not appreciably processed inside the comet. The coma grains most likely come from regions of the comet that are intimate mixes of ice and fine and coarse particulate matter. Although comets are considered primitive bodies, they probably contain regions of processed and sorted material. Comet surfaces could be mantled with layers of fallback material that may be coarser than and unrepresentative of material still packed in the ice-bearing subsurface. Comet Tempel 1 (**Figure 1**) clearly shows evidence for surface regions of smooth, uniform flow–like material that has been deposited by processes that acted on the comet's surface (Belton 2010). Comets probably also contain material that has been modified by internal processes. During and after formation, comets are exposed to impacts, and parts of all comets are likely modified by impact processes.

Even the most primitive comets also likely contain at least some fragments of bodies that underwent substantial thermal modification. Like meteorites, which contain clasts of other meteorite types, comets should be collections of accreted materials. These materials are likely to include debris released from bodies large enough to have had internal thermal modification. The Kuiper belt region, where Wild 2 is believed to have been stored, has many more >500-km bodies than are present in the asteroid belt and also contains Pluto and Eris, bodies that are nearly half the size of Mercury. The original population of ice-bearing bodies must have included a significant number with sufficient internal heating to alter original components, analogous to the various degrees of alteration in meteorites that ranged from melting of silicates and metal to melting of ice and hydrous alteration. Evidence for large-body fragmentation in the Kuiper belt includes the 2,000-km-long Haumea, which appears to be the parent of a collisional family of bodies that include high-albedo icy and low-albedo rocky materials (Brown et al. 2007, Leinhardt et al. 2010). Haumea appears to have differentiated into ice crust and rock-dominated interior before it was partly disrupted, and water must have altered silicates it came into contact with. Most bodies in the Kuiper belt region probably contain collisional debris of other large and thermally altered bodies. Comets are usually assumed to be pristine because of their volatile contents, but portions of them may nonetheless have been heated far beyond nebular or blackbody temperatures at trans-Neptunian distances. Luu & Jewitt (2002) suggest that typical comets may be fragments of larger bodies, and Davis & Farinella (1997) suggest that the Kuiper belt has undergone considerable collisional evolution.

COMET PARTICLE PROPERTIES

During the first year after the sample return, more than 200 investigators were involved in the preliminary examinations, and their group reports were published in a special issue of *Science* (McKeegan et al. 2006, Flynn et al. 2006, Sandford et al. 2006, Horz et al. 2006, Zolensky et al. 2006, Keller et al. 2006, Brownlee et al. 2006). The January 2008 and April 2012 issues of *Meteoritics & Planetary Science* are also dedicated issues; they contain papers from the Timber Cove workshops held on the northern California coast. The thousands of collected Wild 2 particles provide a unique information source on the first-generation solids used to assemble bodies beyond the ice condensation line of the solar nebula. Although particles larger than ~100 μm are too rare for collection and those smaller than 1 μm are biased by capture effects, the returned particles provide sample-derived information on outer Solar System materials at a level of detail that probably could never be obtained by remote sensing or in situ methods.

Wild 2 is a remarkable mix of different components that include fragments of type I, type II, and refractory chondrules; refractory inclusions; condensates such as low-iron Mn-enriched (LIME) forsterite, ^{16}O-rich forsterite, a fayalite/tridymite assemblage, FeNi metal, pyrrhotite, and pentlandite; and a wealth of interesting minor meteoritic phases including osbornite, platinum group nuggets, kosmochloric high-Ca pyroxene, schreibersite, cubanite, whitlockite, and merrillite. Some of these materials may be primary nebular materials; some, such as chondrules, were reprocessed in the nebula; and some, such as merrillite and cubanite, may be debris from previous parent bodies. The ensemble of Wild 2's ingredients provides an invaluable tool for comparing Solar System bodies. Even a simple property such as primary metal content can serve as an important tracer of materials derived from different nebular reservoirs. Some of the most interesting particles are multiphase solid rocks (not accretional aggregates) that provide information on their origin by igneous, metamorphic, aqueous, condensation, or other processes and provide a very strong basis for comparison with well-studied meteorite components. Among the interesting rocks is a particle containing highly reduced silicates that has been associated with aubrites—a very rare meteorite group that is believed to be related to E asteroids and that may have dominated the inner part of the original asteroid belt (Frank et al. 2013c). Because of the limited total sample mass, it is challenging to compare Wild 2 with other types of extraterrestrial materials, but even the tiniest grains can provide precious clues because they were located in the comet formation region at the time of Wild 2's accretion.

PRESOLAR GRAINS IN WILD 2

One of the reasons why the mission was named Stardust was because of the commonly held expectation that the rocky portions of comets would be predominantly composed of presolar interstellar grains (Greenberg & Li 1999). Such grains, formed in gaseous outflows of stars and processed in the interstellar medium, were the initial carriers of heavy elements in the infant Solar System, and it was expected that they would be preserved in comets that formed in remote low-temperature environments. Isotopically anomalous presolar grains are found inside primitive meteorites with matrix-normalized abundances as high as 150–200 ppm (Floss et al. 2013). Their abundance varies among different primitive meteorite types, but presolar grains are never more than a trace constituent. Their low abundance in meteorites is due to a combination of destructive

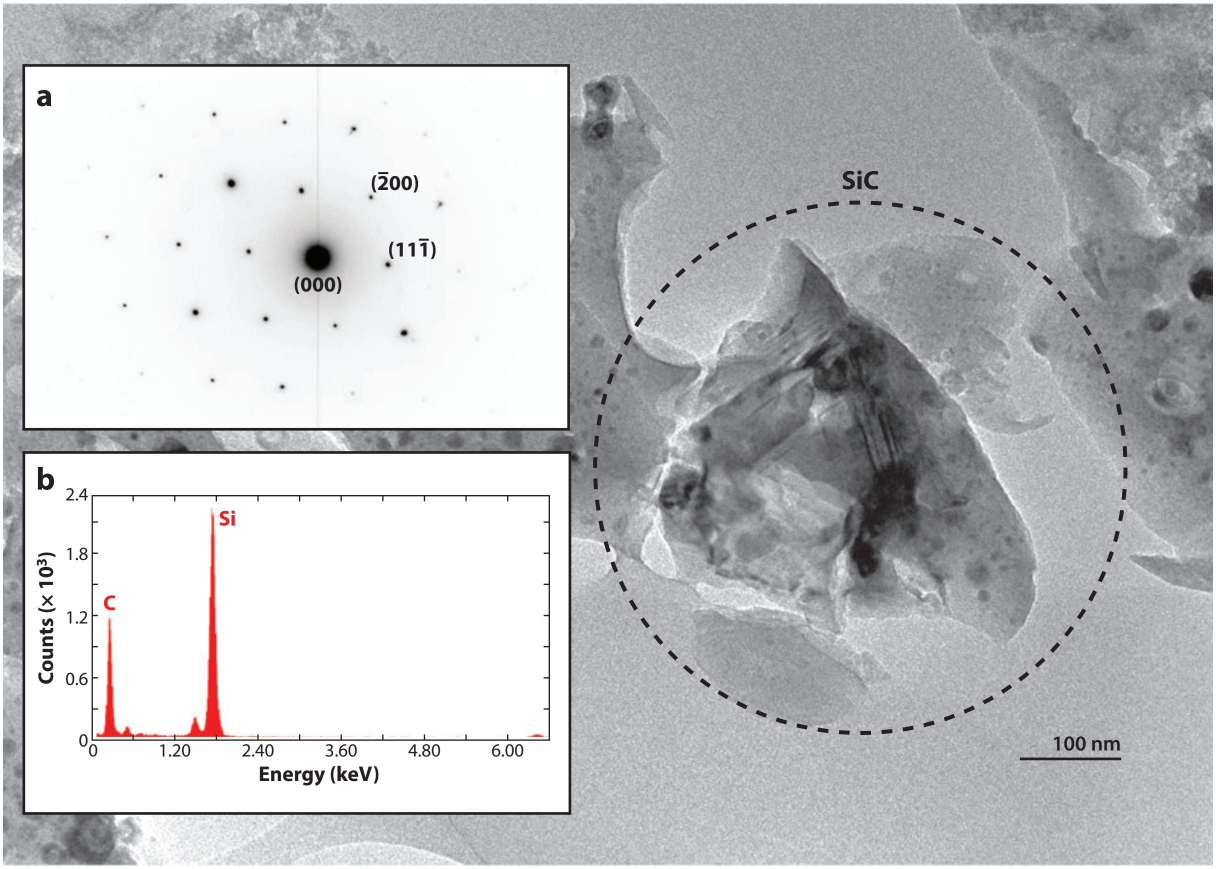

Figure 3

An isotopically anomalous presolar ^{13}C-rich SiC grain found on the wall of the track in **Figure 2*c***. The 001 zone axis diffraction pattern (*inset a*) was indexed to 3C, β-SiC; this polytype, as well as the isotopic composition, matches the most common (mainstream) presolar SiC grains found in chondrites (Messenger et al. 2009). The X-ray spectrum (*inset b*) shows the elemental composition.

processes that occurred in the nebula and thermal and aqueous alteration processes that occurred inside meteorite parent bodies.

The major surprise with the Wild 2 comet samples has been that all of the micron and larger grains that have been analyzed have isotopic compositions consistent with formation inside the Solar System. Six submicron isotopically anomalous (inorganic) presolar grains have been observed (McKeegan et al. 2006; Messenger et al. 2009; Stadermann et al. 2009; Hoppe 2010; Leitner et al. 2010, 2012; Floss et al. 2013). Five of these were found in aluminum foil craters and one, a well-preserved 0.4-μm SiC grain, in an aerogel track (**Figure 3**) (Messenger et al. 2009, Brownlee et al. 2009). The range of isotopic compositions of the isotopically anomalous presolar grains found in Wild 2 is consistent with those found in meteorites.

Taking into account sample degradation during capture, Floss et al. (2013) estimate that the bulk presolar grain abundance of Wild 2 is 600–830 ppm for oxygen-rich grains, a value consistent with the estimate by Leitner et al. (2012) from very small impact craters. This is similar to the average abundance of ~375 ppm measured in a suite of primitive IDPs analyzed by Floss et al. (2013) but higher than the presolar grain abundances in all analyzed meteorites. When capture degradation effects are corrected for, Wild 2 appears to contain a moderately higher abundance of presolar grains than is found in chondrites that accreted in the inner Solar System. This is also the case for IDPs of likely cometary origin, and enhanced abundance of presolar grains, even though they are still a minor component, may be a hallmark property of comets. The highest abundance of isotopically anomalous presolar grains ever found in extraterrestrial samples is ~1%, reported in a portion of an IDP that is thought to be cometary material (Busemann et al. 2009).

The results from the Wild 2 studies imply that preserved isotopically anomalous interstellar grains are not a major component of this comet, at least for grains larger than a micron. That no IDP—many of which must be comet samples—has ever been found to be dominated by such grains suggests that other comets also lack major abundances of isotopically anomalous presolar grains, even of submicron size. In this regard, Wild 2 is surely not an unusual comet. Although comets assembled in cold regions, their rocky materials apparently formed in severe nebular environments that destroyed most presolar solids. This finding implies that the Solar System did not have any refugia where original presolar solids could abundantly survive. The nebular processes that destroyed most presolar oxides and silicates presumably also destroyed less robust presolar compounds such as organics and ices.

The low abundance of isotopically anomalous presolar grains in Wild 2 is a major finding that has profound implications for the origin of grains observed in disks around other stars. One possibility that could soften the conclusion about the scarcity of preserved presolar grains is that comets might contain presolar grains that do not have distinctive isotopic compositions. The Solar System is a mixture of materials with differing nucleosynthetic histories that isotopically equilibrated to generally give fixed isotopic compositions. Solids made from material condensed from outflows of other stars have different isotopic compositions, but processes in the interstellar medium, such as cycles of sputtering and redisposition, could lead to the formation of more isotopically homogenized material. Such material would presumably be amorphous, as the shape of the 10-μm infrared silicate adsorption feature in the interstellar medium indicates that almost all interstellar silicates are amorphous materials (Kemper et al. 2005), in contrast with the appreciable crystalline silicate component of circumstellar environments and comets. Primary amorphous material is not common in captured micron and larger Wild 2 samples, but it could have existed in the submicron fraction and been preferentially destroyed during capture because of its lower melting point.

A common submicron component in IDPs that contains abundant amorphous silicate is GEMS—glass with embedded 10-nm blebs of metal and sulfide, two immiscible phases. Decades after their discovery in IDPs, the origin and even the properties of GEMS remain controversial. Bradley & Dai (2004) and Bradley (2013) maintained that their nominal solar isotopic compositions, size, shape, superparamagnetic inclusion content, and evidence for irradiation are consistent with irradiated interstellar silicates but that their origin is uncertain, whereas Keller & Messenger (2011, 2013) implied that the isotopic and elemental compositions of GEMS show that most originated in the Solar System by nonequilibrium processes. GEMS are abundant in many anhydrous IDPs, but they are rare or nonexistent in meteorites. Keller & Messenger (2012) and Leroux et al. (2013) reported what appear to be altered GEMS-like features in the chondrite Acfer 094 and the CM chondrite Paris. Zolensky et al. (2003) also reported GEMS in an inclusion in the Ningqiang meteorite. Keller & Messenger (2012) suggested that GEMS were widely distributed in the nebula but were destroyed by parent body alteration processes in all but the least processed bodies. Unfortunately, the possible presence of GEMS in Wild 2 remains enigmatic because the projectile/aerogel melt that lines capture track walls has morphology and composition nearly identical to those of GEMS (Ishii et al. 2008). It is likely that Wild 2 does contain submicron GEMS, even though they have not been definitively identified in the collected samples. Determining whether this comet accreted GEMS is an important goal of future sample work. This effort is challenging

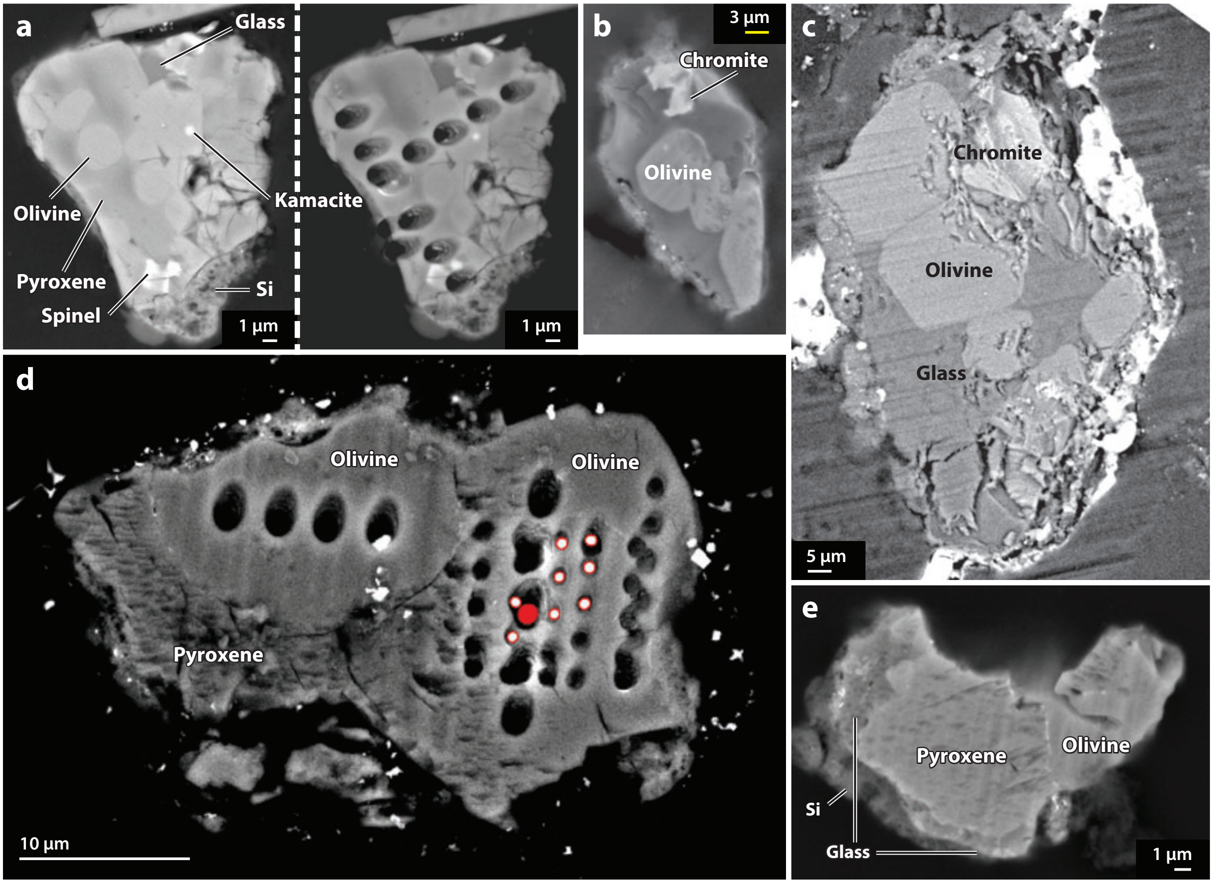

Figure 4

Electron backscattered images of cut faces of Wild 2 components that are thought to be chondrule fragments. Panels *a*, *d*, and *e* are from Nakamura et al. (2008a), panel *b* is from Butterworth et al. (2010), and panel *c* is from Ogliore et al. (2012). The white boundary between olivine and pyroxene in panel *e* is chromite. The holes seen in panels *a* and *d* were made with the ion probe during isotopic measurements. The formation temperature of the component in panel *d* is estimated on the basis of mineral chemistry to be ~1,800 K (Nakamura et al. 2008b), and the olivine grain on the right is extremely ^{16}O-rich compared with the olivine on the left and the rest of the particle.

because GEMS can melt during capture and because they are difficult to distinguish from impact melt lining track walls.

CHONDRULE FRAGMENTS

A significant fraction of the larger Wild 2 particles have properties consistent with being chondrule fragments (**Figure 4**) (Nakamura et al. 2008a,b, 2009; Jacob et al. 2009; Butterworth et al. 2010; Gainsforth et al. 2010; Joswiak et al. 2010; Bridges et al. 2012). Chondrules are the dominant component of some of the most primitive meteorites, and most of the mass of solids at least in local regions of the solar nebula was turned into chondrules by high-temperature processes. Chondrules are spheroidal components that are commonly about a millimeter across with igneous textures composed of crystalline components and interstitial glass. They were at least partially molten and formed by short-term heating to temperatures in the 1,700–2,050 K range (Hewins & Radomsky 1990). Chondrules often contain relict components that did not melt when the chondrule formed and clearly predate the chondrule. The first chondrule fragment described from Wild 2 contained such a relict grain (Nakamura et al. 2008a). It was an olivine grain that was ^{16}O-rich compared with its host material and could not have formed by crystallization of the chondrule. As is seen in meteoritic chondrules, this grain did not melt and did not isotopically equilibrate with the comparatively ^{16}O-poor gas that most of the chondrule melted in.

Wild 2 contains examples of a wide range of chondrule types, including Fe-rich, Fe-poor, and Al-rich refractory chondrules. Importantly, chondrules from different meteorite groups differ in their minor element and oxygen isotopic composition. Such differences suggest that a major fraction of chondrules in some chondrite groups were produced in specific nebular environments or were influenced by specific processes. These are likely regional properties or processes, and accretion of abundant locally made materials is presumably the reason why chondrites have diagnostically distinctive properties. A dramatic example is the Fe and Mn abundances in ferrous olivine in chondrules from different chondrite groups. Berlin et al. (2011) and others have shown a strong correlation of Mn and Fe (Mn^{2+} substituting for Fe^{2+}) in ferrous chondrule olivine from different primitive chondrite groups, although this is not seen in Fe-poor olivine. They suggest that the iron-rich type IIA chondrules in different chondrite classes formed in different reservoirs that influenced their Mn/Fe ratios. In their extensive study of primitive chondrites, they showed that the Mn/Fe ratio in ordinary chondrite (OC) ferrous olivine is more than twice that in CO olivine and that CR olivines usually have an Mn/Fe ratio intermediate between those of OC and CO olivines. The Berlin data are for chondrules, whereas the Wild 2 samples are much smaller than typical chondrules and many of the Wild 2 olivine grains are isolated, probably analogous to the anhydrous portion of the fine-grained matrix of primitive meteorites (Joswiak et al. 2012). Recent data indicate that olivine fragments in primitive chondrite matrices show the same trends as chondrules (Frank et al. 2012a,b, 2013b), supporting suggestions that much of the matrix olivine is derived from fragmented chondrules.

Wild 2 contains abundant ferrous olivine grains; their compositions (Zolensky et al. 2008; Frank et al. 2012a,b, 2013b; Joswiak et al. 2012; Brownlee et al. 2013) appear to show that both small and large Wild 2 ferrous olivines have a distinctly different distribution of Fe and Mn than is seen in chondrule olivines from specific chondrite groups (**Figure 5**). The Mn/Fe range is large, and there are no correlation trends between Mn and Fe, unlike the clear correlations seen in both primitive and equilibrated chondrites. The data provide evidence that the Wild 2 ferrous olivines could not have come from the constrained source regions that produced chondrule ferrous olivine from any specific chondrite class; they suggest that materials accumulated by Wild 2 come from a broader range of locations than the bulk of the material that accreted onto specific classes of meteorite parent bodies. This observation alone demonstrates that the assembly of comets differs from the assembly of asteroids.

OXYGEN ISOTOPES

Wild 2 olivine and pyroxene $\Delta^{17}O$ compositions span the range from −27‰ to +2.5‰ (where $\Delta^{17}O \equiv \delta^{17}O - 0.52\delta^{18}O$, and the δ notations refer to $^{17}O/^{16}O$ or $^{18}O/^{16}O$ ratios relative to standard mean ocean water, SMOW, in parts per thousand) (Nakamura et al. 2008a, Nakamura-Messenger et al. 2011, Nakashima et al. 2012) and lie close to the carbonaceous chondrite anhydrous mineral (CCAM) or Young & Russell (1998) lines on the standard three-isotope oxygen diagram (**Figure 6**). Even fragments from a single track span this full range (Nakashima et al. 2012). Many of the forsterites and all of the Mn-rich forsterites are quite ^{16}O-rich, similar

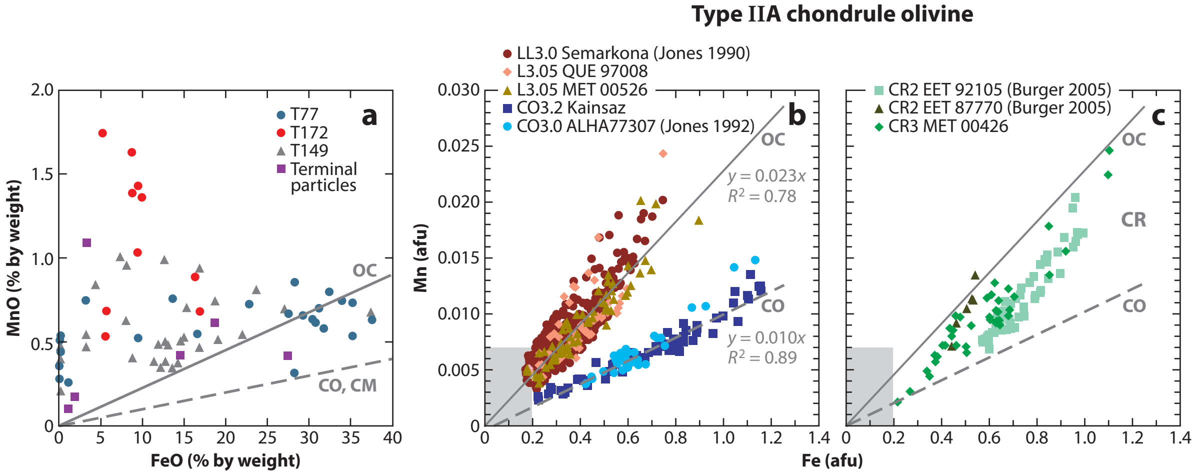

Figure 5

(*a*) MnO and FeO weight percent for ferrous olivine grains in three Wild 2 capture tracks (Brownlee et al. 2013). The largest terminal grain is 30 μm; most are smaller. The MnO distribution values do not show the Fe correlation trends observed in chondrule olivine from CO, OC, and CR chondrite data from Berlin et al. (2011) and Paris (CM) and Semarkona (OC) data from Hewins et al. (2011). The dotted and solid lines marked OC, CO, and CM are meteorite trend lines. Wild 2 olivine could not have come exclusively from chondrule fragments from any of these specific chondrites types but could have been derived from a mix of chondrule fragments from other sources. The Berlin chondrule olivine data in panels *b* and *c* are in atomic formula units (afu; O = 4).

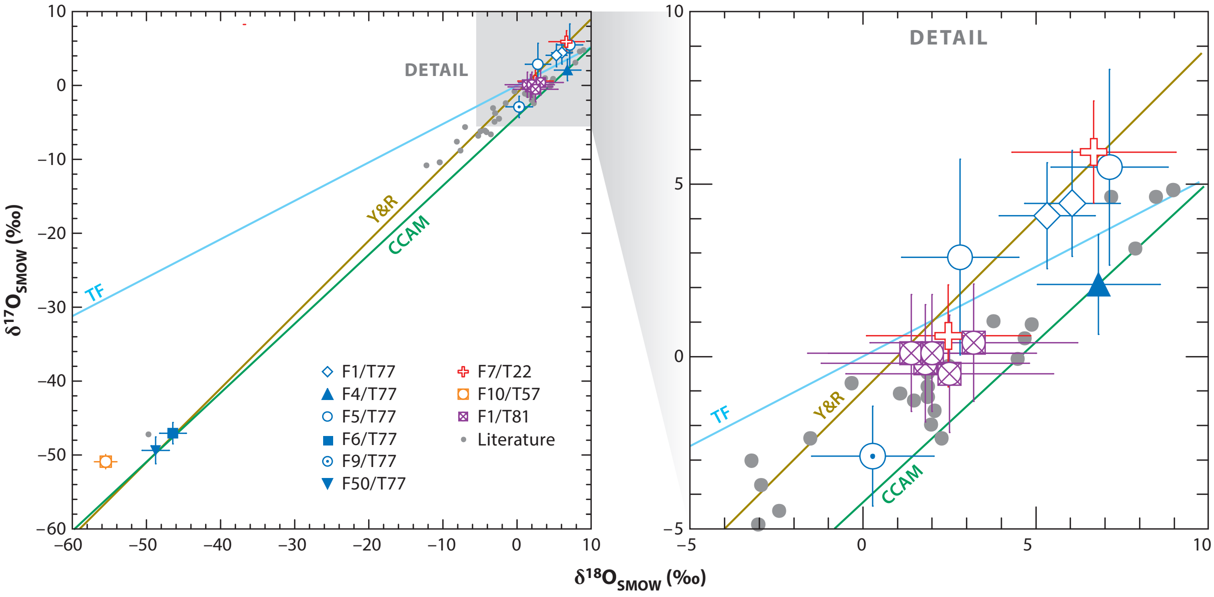

Figure 6

Oxygen three-isotope ratios of nine Wild 2 particles. The terrestrial fractionation line (TF, *light blue*), the Young & Russell (1998) line (Y&R, *dark yellow*), and the carbonaceous chondrite anhydrous mineral line (CCAM, *green*) are shown. Literature data of ferromagnesian Wild 2 particles (from McKeegan et al. 2006, Nakamura et al. 2008a, Nakashima et al. 2011, Ogliore et al. 2012) are shown for comparison. Modified with permission from Nakashima et al. (2012).

to refractory inclusions; these grains may have formed in a related environment, possibly near the Sun (Nakashima et al. 2012). They seem to show an association of oxygen isotope values, with Mg/(Mg + Fe) ratios similar to those seen in CR chondrites (Nakashima et al. 2012). Work on chondrules (Ushikubo et al. 2013) from very primitive chondrites has shown that their $\Delta^{17}O$ values cluster in three groups centered on −5‰, −2‰, and 0‰, which indicates that there were at least three nebular regions with differing $\Delta^{17}O$ that existed during the period of chondrule formation. The Wild 2 data span this entire range.

CALCIUM-ALUMINUM INCLUSIONS

Calcium-aluminum inclusions (CAIs) found in primitive meteorites are the oldest Solar System materials. They are predominantly composed of refractory materials; they are ^{16}O-rich, similar to the Sun; and it appears that they formed in a restricted time and space in the early Solar System (Dauphas & Chaussidon 2011). Three proven CAI fragments have been found in Wild 2 tracks, and a CAI candidate was reported by Schmitz et al. (2009). Nakamura-Messenger et al. (2011) reported finding an amoeboid olivine aggregate, another type of refractory inclusion that is also usually ^{16}O-rich.

The three Wild 2 CAIs (discovered at the University of Washington; the first, Inti, was reported by Zolensky et al. 2006) are mineralogically similar and appear comparable to precursor materials to type C CAIs proposed by Lin & Kimura (1998) and Krot et al. (2004). These CAIs, from three different tracks, are all composed of nodules a few microns across that have a mix of diopside and Al,Ti-bearing diopside rimming interiors composed of spinel, anorthite, and sometimes melilite, perovskite, and other refractory phases (**Figure 7**) (Simon et al. 2008, Matzel et al. 2009,

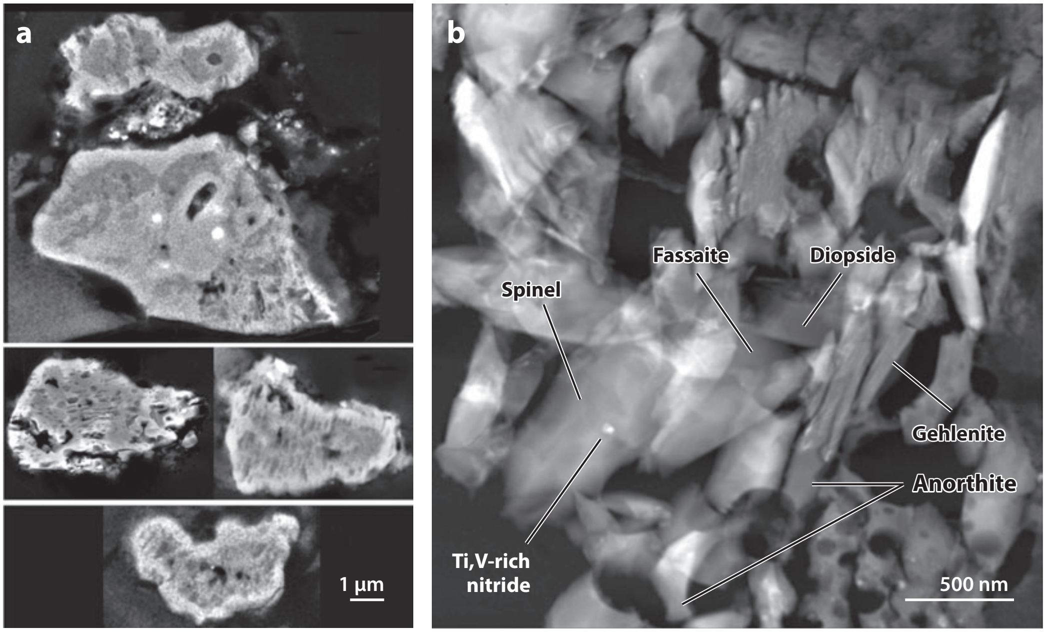

Figure 7

Fragments of the >20-μm calcium-aluminum inclusion (Inti) that produced track 25. (*a*) Backscattered electron images of cut faces show diopside (including Al,Ti-rich fassaite) rims enclosing interiors that contain spinel, anorthite, and other refractory phases. (*b*) A high-angle annular dark-field transmission electron image of shards in a 70-nm microtome section with prominent phases noted.

Joswiak et al. 2013). Although poorly determined, the abundance of refractory inclusions in Wild 2 appears to be on the order of 1%. This is lower than the ~10% abundance in CV chondrites but higher than that found in most meteorites.

The discovery of ^{16}O-rich CAIs in a comet was a major finding of the Stardust mission (Simon et al. 2008) because of the possibility that CAIs formed close to the Sun during the earliest stage of disk evolution and hence the possibility that material had to travel a great distance to reach the comet accretion regions. ^{26}Mg measurements on two Wild 2 CAIs (Krot et al. 2012) and one chondrule fragment (Ogliore et al. 2012) did not find evidence for the former presence of the short-lived radioisotope ^{26}Al. This limits the initial ^{26}Al/^{27}Al ratio to below the canonical $\sim 5 \times 10^{-5}$ value often seen in meteoritic CAIs (Young & Russell 1998) and suggests formation either after ^{26}Al (half-life of 0.7 million years) decayed or before it was injected into the Solar System. Krot et al. (2012), Kita et al. (2013), and Makide et al. (2013) noted that there were ^{26}Al-poor early nebular materials, such as Al_2O_3 grains and FUN inclusions (rare CAIs with large isotopic fractionation and unknown nuclear effects), and that ^{26}Al distribution was not initially homogeneous. They suggested that addition of ^{26}Al to the nebular disk may have occurred after the first generation of solids formed.

Two of the Wild 2 CAIs contain abundant TiN (osbornite), sometimes with high vanadium content, as 10-nm-sized inclusions in anorthite and spinel (Chi et al. 2009). Osbornite is expected to condense as a first condensate from gas with a C/O ratio near twice the solar value (Ebel 2006). Osbornite grains have been rarely found in meteoritic CAIs, but there are no reports either of common nanophase osbornite grains as seen in Wild 2 or of vanadium-bearing osbornite in any meteorite.

KOSMOCHLORIC HIGH-CALCIUM PYROXENE

Comet Wild 2 contains a few materials that have not been seen in chondrites but that have been found in anhydrous IDPs. One of these is a mix of associated phases, termed a Kool assemblage, that contains kosmochloric high-Ca pyroxene and olivine (**Figure 8**) (Joswiak et al. 2009). Half of the Stardust comet tracks contain fragments of this very unusual assemblage of kosmochloric

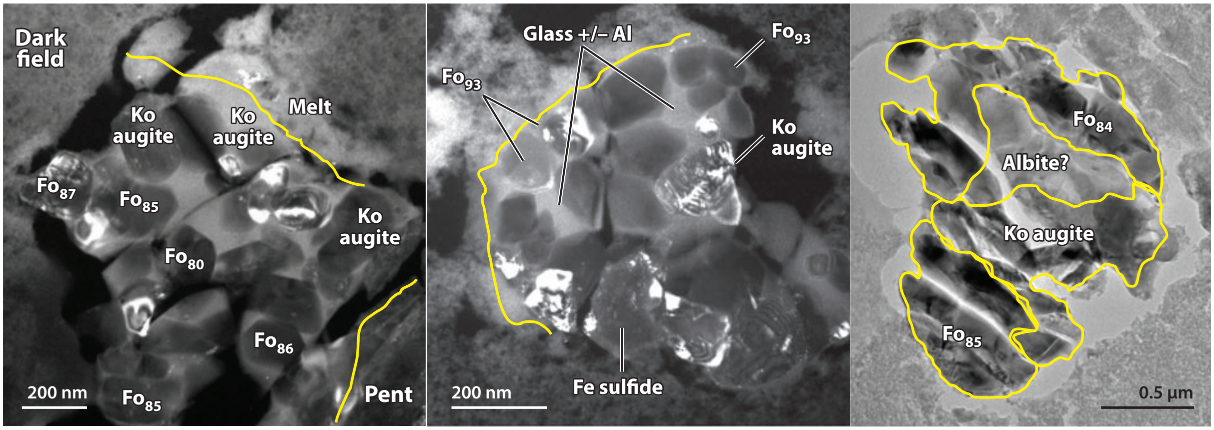

Figure 8

Kool assemblages are commonly found in Wild 2 tracks and interplanetary dust particles. They contain kosmochloric (Ko) diopside or augite that has high Na_2O and Cr_2O_3 content and is always associated with Fe-rich olivine and albite or aluminosilicate glass and sometimes with Cr-rich spinel. Abbreviations: Fo, forsterite; Pent, pentlandite.

diopside or augite that has Na_2O and Cr_2O_3 contents up to 6 wt% and 12 wt%, respectively, and is always associated with Fe-rich olivine and albite or aluminosilicate glass and sometimes with Cr-rich spinel. Kool assemblages have not been reported in meteorites. If they truly do not exist in meteorites, and have not just been overlooked, they may be a nebular material that for some reason was only present or preserved in outer Solar System materials. One possibility is that they are materials that escaped destruction by chondrule-forming processes because they either were not in the chondrule formation region or were ejected from this region before chondrules formed. Why such strange pyroxenes with high Cr and Na content would form in the early Solar System, either before or after chondrule formation, remains an enigma. As with GEMS, the abundance of Kool assemblages in both IDPs and Wild 2 suggests that they were important nebular components, even if they are not abundant in meteorites.

CONDENSATES

The initial high-temperature Solar System solids should have included condensates. Probably the clearest evidence for the presence of condensates in Wild 2 are LIME forsterites, olivines with low iron and enhanced manganese abundances relative to solar composition (Joswiak et al. 2012, Nakashima et al. 2012). LIME forsterites were first discovered in IDPs (Klock et al. 1989) and later found in chondrites. As described by Ebel et al. (2012), their abnormally high Mn/Fe ratios are evidence that they formed by condensation. It is noteworthy that all of the Wild 2 LIME olivines that have been analyzed are ^{16}O-rich, similar to CAIs. Besides LIME olivine, the osbornite grains found in Wild 2 CAIs are almost surely condensates, and they likely represent the first-forming solids in the unusual C/O-enriched nebular region required for their formation (Ebel 2006).

ALTERATION PRODUCTS

Parent body alteration is a process that has modestly to severely affected all meteorite parent bodies. Secondary alteration phases such as smectite, cronstedtite, tochilinite, carbonates, sulfides, and magnetite are common in the most carbon-rich meteorites, and they likely formed in the presence of water. Although most asteroid surface temperatures are <200 K, internal early Solar System heat sources capable of melting ice include ^{26}Al decay, impact or accretion heat, and heat from exothermic reactions such as silicate hydration. The sources that heated asteroids could also plausibly have heated comets if they formed early enough and were large enough. The equilibrium temperatures of solar-heated bodies orbiting beyond Neptune are <50 K. Aqueous alteration processes in parent bodies are most likely to occur where temperatures are above freezing and water vapor partial pressure is above 0.006 atm (0.6 kPa), the triple point of water. In the early Solar System, such environments must have been common in the interiors of the parent bodies that produced carbon-rich and phyllosilicate-rich meteorites. Unlike these meteorites, both anhydrous IDPs and the Wild 2 samples that survived collection are predominantly anhydrous (Zolensky et al. 2006). Strong evidence against significant alteration in comets, of the type that made strong rocks in chondrite parent bodies, is the low strength of cometary materials observed in meteor showers. Meteors associated with JFCs are the weakest of all meteors; they have measured crushing strengths of less than 1 kPa, the strength of fresh snow (Borovicka 2007). Typical cometary matter is much weaker than asteroid material found as even the most fragile meteorites.

Small quantities of possible aqueous alteration phases have been seen in Wild 2. The most abundant of these are magnetite grains found in parts of the bulbs of tracks 80 (Stodolna et al. 2012) and 149 (unpublished observation). The magnetite abundance in one region of track 80 is on the order of 10%, but this track is unusual in this regard. It is reasonable that the observed magnetite grains have an origin analogous to that of similar rounded magnetite grains found in CI and some CM chondrites, and they are considered to have been produced by aqueous alteration (Jedwab 1971). A rare phase in Wild 2 that has been associated with aqueous alteration is cubanite, a copper iron sulfide. Berger et al. (2011) described several small cubanite grains associated with pyrrhotite and pentlandite and implied that the association formed by low-temperature aqueous alteration. Hanner & Zolensky (2010) suggested that the minor amount of the Ni-rich sulfide pentlandite in Wild 2 is also an aqueous alteration product. These minerals are all accessory to layer silicates, which should be considerably more abundant than accessory phases.

The most common aqueous alteration products in chondrites and hydrated IDPs are phyllosilicates, but to date, preserved phyllosilicates have not been seen in aerogel tracks (Zolensky et al. 2006, Wooden 2008, Zolensky et al. 2008, Joswiak et al. 2012) or in aluminum foil craters (Wozniakiewicz et al. 2012); however, possible relict phyllosilicates have been reported (Schmitz & Brenker 2011). None of the >2-μm silicate phases that have been studied show evidence of even partial alteration to hydrated silicates. If the comet does contain a substantial abundance of hydrated silicates, they would have to have had escaped detection because (*a*) they were mostly of submicron size, (*b*) they decomposed during capture, or (*c*) they remained in the comet and were not ejected into space. Although phyllosilicates are often considered to be fine grained, in chondrites and IDPs they usually have coherent regions that are microns across, and these regions have textures that are highly distinctive in the transmission electron microscope methods used to study the comet samples, IDPs, and meteorites.

The lack of readily detectable hydrated silicates or commonly occurring secondary minerals suggests that this comet did not experience significant internal heating and alteration of the type that occurred on the parent bodies of carbon-rich meteorites. The presence of trace amounts of possible aqueous alteration products indicates that these materials had a different history than that of the bulk of the comet. This could have happened in local regions of the comet, such as impact sites, or these materials could be accreted debris from larger bodies where aqueous alteration was pervasive. It is also possible that these materials are debris from inner Solar System bodies that were transported to regions where comets accreted. Anhydrous IDPs, many of which are likely of cometary origin, sometimes contain tiny hydrated silicate grains even though almost all the particle mass is composed of anhydrous material that includes water-sensitive phases such as amorphous silicates and nanophase metal beads (Keller & Messenger 2011, Bradley 2013).

COARSE AND FINE MATERIALS

Like primitive meteorites and IDPs, Wild 2 is definitely a mix of coarse and submicron materials. For reasons discussed above, the information on the coarse components is compromised by the collection process, and there is considerable uncertainty in both the nature of the submicron fraction and the ratio of total mass in fine compared with coarse materials. This uncertainty complicates comparison with infrared spectroscopy of comets (Lisse et al. 2007), where spectral signatures are dominated by the submicron component. It also complicates comparison with analyses of typical 10-μm-sized IDPs, where most analytical studies have focused on the numerous submicron components.

ORGANICS

Among Solar System bodies, comets are famed for their organic and ice contents. Mass spectrometer data from the Giotto mission showed that comet Halley contained abundant organic material that was termed CHON, after its major elements (Clark et al. 1987). Anhydrous IDPs, which are widely thought to be samples of comets, have carbon contents that are substantially higher than those of most carbon-rich meteorites (Thomas et al. 1993), but the determination of the abundance and character of carbonaceous matter in Wild 2 is compromised by alteration effects of capture and issues with contamination (Sandford et al. 2010). Carbonaceous material is seen in most capture tracks and has been studied by a wide variety of microbeam techniques including Raman spectroscopy (Wopenka 2012), coordinated electron microscopy/mass spectroscopy (Matrajt et al. 2013a), synchrotron methods (Matrajt et al. 2010), and time-of-flight mass spectroscopy (Stephan et al. 2008). Carbon-rich components are usually less than a micron in size, and their abundance is lower than that typically seen in IDPs. No large carbon components have been found.

The apparent low abundance of organic materials is presumably related to degradation during capture. De Gregorio et al. (2010) found in the samples only two types of organic matter that appeared to be unaltered: (*a*) polyaromatic carbonyl-containing matter, similar to the insoluble organic matter found in primitive meteorites and IDPs, and (*b*) highly refractory organic material, similar to that in nanoglobules that are also found in primitive meteorites and IDPs and that usually have high ^{15}N enrichments. Matrajt et al. (2013b) found that the organic components in Wild 2 tracks could be classified into five morphological categories—graphitic, smooth, dirty, spongy, and globular—that are also observed in carbon-rich meteorites and IDPs. The ^{13}C and ^{15}N excesses in some of these materials are consistent with low-temperature formation (Matrajt et al. 2012). Matrajt et al. (2013a) provided evidence that the aliphatic organics that produce the carbonyl band feature at 3.4 and 5.8 μm in Wild 2 and IDPs differ from the their astronomically observed interstellar analogs, which suggests that they formed in the Solar System and not in the interstellar medium. The most celebrated organic finding in the Wild 2 samples was the definitive discovery of glycine (Elsila et al. 2009), an amino acid that is an important building block of life and was first discovered in meteorites in 1970.

OTHER SAMPLES

The Stardust mission also returned fascinating noble gas contents in the aerogel tracks (Marty et al. 2008) and used the backside of the aerogel collector to collect contemporary interstellar grains currently entering the Solar System. The interstellar side of the collector contained lower-density aerogel and was oriented toward the incoming interstellar dust flux during portions of the spacecraft trajectory when the velocity of impacting grains was minimized. Working on the contemporary interstellar grains is more challenging than working with the comet samples because the particles are smaller and fewer in number. Exciting grains of likely interstellar origin have been recovered, and the first analytical studies of these grains are just now being published (Frank et al. 2013a, Westphal et al. 2013).

CONCLUSIONS

The Wild 2 samples have provided a surprising glimpse into the nature of early Solar System materials and an epiphany on the origin of the initial planetary building blocks of the bulk of the early Solar System. The findings from these samples show that the cold regions of the early Solar System were not isolated and did not provide a refuge where original isotopically anomalous presolar materials could abundantly survive (**Figure 9**). In contrast to expectations, Wild 2 is not dominated by submicron interstellar grains coated with radiation-processed organic mantles. This model is entirely reasonable, and for decades was essentially an entrenched dogma in the astronomical community; however, it is quite at odds with the Stardust mission finding that most

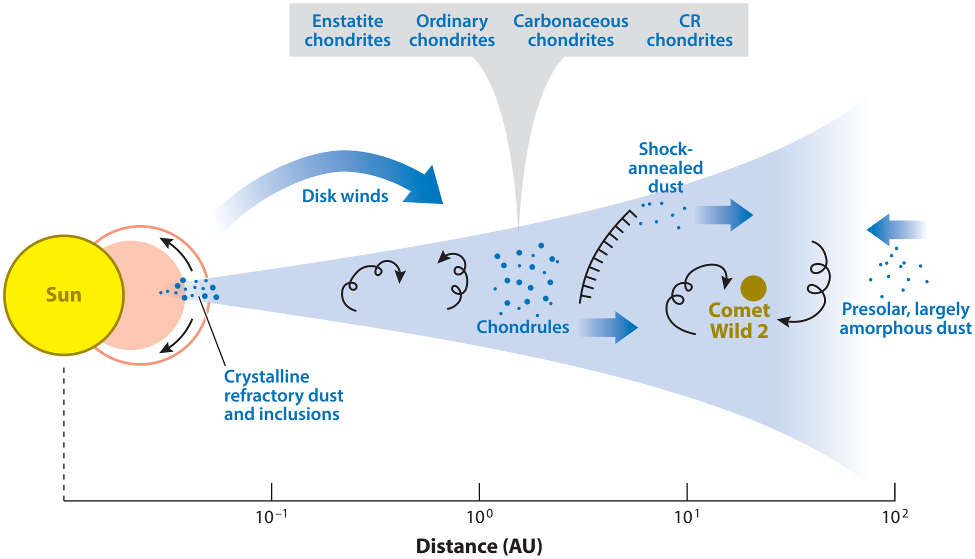

Figure 9

A schematic illustrating outward radial transport in and above the solar nebula plane relative to the comet formation regions. The outward flow contained a range of nebular materials, including calcium-aluminum inclusion and chondrule fragments and possible debris from disrupted parent bodies that experienced parent body alteration. During transport, grains can be influenced by a variety of processes, including heating from shocks. The presolar component is present but minor, presumably because of the high dilution with outwardly transported solids from the inner Solar System. This figure and its description are based on Nakashima et al. (2012), who adapted the graphic from Scott & Krot (2005).

of the analyzed materials are isotopically normal materials that appear to have formed in the Solar System by the same set of complex high-temperature processes that produced the bulk of the nebular components found in primitive meteorites. The efficient destruction of presolar silicates casts serious doubt on the long-held notion that interstellar molecules play a role in the formation of habitable planets in the Solar System or in other planetary systems. If silicates are destroyed, presolar organics are surely also destroyed by cycling through destructive disk environments.

The Wild 2 findings are also at odds with the popular model for the presence of crystalline silicates observed in disks around young stars and in comets. It is commonly envisioned that crystalline silicates formed by 1,000 K annealing (devitrification) of presolar amorphous solids in disks either in stable warm disk regions (Poteet et al. 2011) or in cold regions where transient heating could occur due to shocks (Harker & Desch 2002, Wooden et al. 2007). It is unimaginable that most of the collected Wild 2 materials could have formed by simple subsolidus transformation of clusters of submicron amorphous silicates. The remarkably complex Wild 2 materials (Joswiak et al. 2012), such as chondrule fragments, CAI grains, LIME forsterites, Kool assemblages, and osbornite grains, require much more involved formation scenarios. The largest Wild 2 crystals are a million times more massive than typical interstellar grains, and their mineralogical, chemical, and isotopic compositions imply that they formed in the Solar System by the same complex and high-temperature nebular processes that made the materials that formed primitive meteorites. These materials did not form by mild thermal transformation but are the result of processing, sometimes cycles of processing, in severe high-temperature environments where material temperatures can exceed 2,000 K.

Although Wild 2 is just a single comet, its similarity to IDPs that sample many comets suggests that the Stardust mission findings can be generalized, at least to first order, to other comets. If there were a major diversity among the solids of different comets—for instance, those dominated by interstellar grains—it would have been found in the extensive study of IDPs. Many IDPs are thought to be samples of comets (Nesvorny et al. 2010), and until the next sample return mission, they will be our main access to laboratory samples that have a likely cometary origin (Bradley et al. 1988, Rietmeijer 1999). Aircraft collections targeted to cometary dust streams may have already returned samples from comet Grigg–Skjellerup (Busemann et al. 2009).

The simplest interpretation of finding complex high-temperature materials in a comet from the Solar System's frozen attic is that the cometary rocky materials were transported and mixed over distances of tens of astronomical units to regions where they could accumulate ices and organic materials. The high abundance of high-temperature nebular solids at the edge of the Solar System is compelling evidence for massive outward transport of inner Solar System materials by a variety of possible in- and above-plane processes (Shu et al. 2001, Bocklee-Morvan et al. 2002, Cuzzi et al. 2008, Ciesla 2010, Boss 2012). An alternative view is that the high-temperature components formed in atypical outer Solar System environments such as transient Jupiter mass embryos (Bridges et al. 2012, Nayakshin et al. 2011).

It is significant that Wild 2 appears to contain a mix of materials more diverse than that found in specific chondrite groups. Chondrite groups have distinctive properties presumably because much of a chondrite's mass comes from local materials that often have restricted ranges of properties such as oxygen isotopic composition and olivine minor-element composition, as well as characteristic oxidation states, Fe/Si ratios, volatile contents, and other classic discriminators of meteorite types. Meteorites are samples of asteroids that formed close to the nebular source regions where rocky materials could be formed and then reworked in the solar nebula. In contrast, comets formed in cold regions where rock-forming elements were already totally condensed and probably not easily influenced by nebular gas-grain interactions or high-temperature processes such as CAI or chondrule formation. The outer Solar System rocky solids were brought in from distant sources. Analogous to glacial erratics, the outer Solar System rocky components are not related to the location where they are found. Although asteroids contain distantly made components such as presolar grains and CAIs, they are dominated by regional materials. Comet Wild 2's rocky components appear to originate exclusively from distant locales and probably represent a good sampling of the outward flow of inner Solar System materials.

Other than volatile content, the issue of local versus global source region is probably the major difference between comets and asteroids. Gounelle (2012) and others have suggested that there is a continuum between the asteroid and comet populations. Because of mixing during long-distance transport, it seems reasonable that all outer Solar System bodies accreted a similar mix of materials transported from the rock factories of the inner Solar System. If this is true, then the rocky components of Pluto, Eris, Triton, comets, and vast numbers of planetesimals that formed planets or were ejected from the Solar System could all have started with the same inventory of initial rocky components. Because inner Solar System planetesimals accreted close to the nebular grain formation regions and because they accreted faster than grains could be efficiently transported from elsewhere, it is reasonable that their rocky components show the diversity seen in meteorite classes.

The Stardust mission, as well as the Hayabusa asteroid mission, proved that critically important information on the early Solar System can be obtained with modest sample return missions. Stardust demonstrated that samples from the Solar System's frozen attic carry paradigm-changing information on early Solar System materials. Future, more sophisticated missions that return kilograms of well-preserved rocky, organic, and icy material from a comet could provide refined insight into the nature of nebular solids and their nebula-wide transport as well as direct information on the issue of how high-temperature rocky materials became associated with organic materials and ices. The isotopic compositions of substantial numbers of modestly sized cometary chondrule and refractory inclusion fragments could provide invaluable chronological information on the evolution of the high-temperature materials and their transport to the cold regions of the early Solar System.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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