Meteoritics & Planetary Science 47, Nr 4, 453–470 (2012)
doi: 10.1111/j.1945-5100.2012.01339.x

Overview of the rocky component of Wild 2 comet samples: Insight into the early solar system, relationship with meteoritic materials and the differences between comets and asteroids

Don BROWNLEE*, Dave JOSWIAK, and Graciela MATRAJT

Department of Astronomy, University of Washington, Seattle, Washington 98195, USA
*Corresponding author. E-mail: brownlee@astro.washington.edu

(Received 28 June 2011; revision accepted 17 January 2012)

Abstract–The solid 2–10 μm samples of comet Wild 2 provide a limited but direct view of the solar nebula solids that accreted to form Jupiter family comets. The samples collected by the Stardust mission are dominated by high-temperature materials that are closely analogous to meteoritic components. These materials include chondrule and CAI-like fragments. Five presolar grains have been discovered, but it is clear that isotopically anomalous presolar grains are only a minor fraction of the comet. Although uncertain, the presolar grain content is perhaps higher than found in chondrites and most interplanetary dust particles. It appears that the majority of the analyzed Wild 2 solids were produced in high-temperature "rock forming" environments, and they were then transported past the orbit of Neptune, where they accreted along with ice and organic components to form comet Wild 2. We hypothesize that Wild 2 rocky components are a sample of a ubiquitously distributed flow of nebular solids that was accreted by all bodies including planets and meteorite parent bodies. A primary difference between asteroids and the rocky content of comets is that comets are dominated by this widely distributed component. Asteroids contain this component, but are dominated by locally made materials that give chondrite groups their distinctive properties. Because of the large radial mixing in this scenario, it seems likely that most comets contain a similar mix of rocky materials. If this hypothesis is correct, then properties such as oxygen isotopes and minor element abundances in olivine, should have a wider dispersion than in any chondrite group, and this may be a characteristic property of primitive outer solar system bodies made from widely transported components.

INTRODUCTION

The Stardust mission to comet Wild 2 and the Hayabusa mission to the near-Earth asteroid Itokawa (Yurimoto et al. 2011) provided the only samples that we have from specifically known (named) primitive solar system bodies. The Wild 2 samples are the only proven samples from a comet, and they are a unique source of information on the solid components that accreted to form planetismals beyond Neptune. Comet samples must also exist in the interplanetary dust (IDP) and micrometeorite collections. In the case of IDP collections targeted on meteor streams, they may be associated with specific comets (Messenger 2002), but unfortunately, it is not presently possible to prove that any particular meteoritic sample is positively from a comet. The comparison of the Wild 2 samples with inner solar system materials found in chondrites provides a means to directly compare inner and outer solar nebula materials and constrain models for the origin and mixing of nebular solids. The direct sample of the rocky materials that formed comets at the edge of the solar system provides a level of sample-derived knowledge, analogous to ground truth for remote sensing. This information is particularly insightful for interpreting astronomical data on dust around comets as well as dust around other stars. This overview is focused on a subset of results on the rocky materials in Wild 2, and is not intended to be a comprehensive review. It also does not cover the very important results on Wild 2 organics, but good overviews of Wild 2 organics can be found elsewhere (Sandford et al. 2006; Elsila et al. 2009; Cody et al. 2011; De Gregorio et al. 2011).

COMET WILD 2 HISTORY

Wild 2 is an active Jupiter family comet (JFC) that was observed to have at least 20 active jets during the 2004 Stardust flyby (Sekanina et al. 2004). Ground- and space-based measurements indicated a water sublimation rate of ~20,000 tons/day (Farnham and Schleicher 2005, De Val-Borro et al. 2010) and active emission of CN (Knight and Schleicher 2010). The spectral emissions of Wild 2 classify it as a Borrelly-type comet depleted in C_2, but with average to slightly high NH_2 abundance (Fink et al. 1999). This relative depletion of C_2 is characteristic for comets that are believed to have been derived from the Kuiper Belt (A'Hearn et al. 1995). The behavior of Wild 2 seems to be typical for JFCs, and this comet has an activity level that is much higher than what is likely to be the average activity level of main belt comets that appear to have formed in the asteroid belt and have resided there since their origin (Hsieh and Jewitt 2006). The surface of Wild 2 contains km-sized depressions, some with steep walls and flat floors (Kirk et al. 2005, Brownlee et al. 2004). Assuming that these are erosional features, it is evident that some of the material released by Wild 2 has come from original depths of several hundred meters. Wild 2 also has mesas, pinnacles, and roughness on all measurable spatial scales with the exception of its overall shape that gives the body a smoothly rounded limb profile. The unusual surface features (Basilevsky and Keller 2006) indicate that Wild 2 has clearly had a dramatically different evolutionary history from other imaged comets or asteroids. If the surface depressions relate to sites of past or present gas and dust emission, then the ubiquitous presence of depressions suggest that essentially all of the Wild 2 surface has emitted dust and rocks into space.

The collected Wild 2 samples were released from an active comet that is presently on a ~6-yr orbit with perihelion near the orbit of Mars and aphelion near Jupiter's orbit. Prior to 1974, when it made a close flyby of Jupiter, it was on a ~43-year orbit that ranged from Jupiter to beyond Uranus. If Wild 2 is a typical JFC, it should spend $\sim 3 \times 10^5$ yr on orbits that pass near Jupiter before it is ultimately ejected from the solar system (Duncan et al. 2004). Typical JFCs spend only about 7% of this inner solar system time on orbits with perihelia < 2.5 AU when they are active enough to be generally observable comets (Duncan et al. 2004). During the JFC phase, a typical comet may switch about ten times between orbital periods longer and shorter than 20 yrs (Levison and Duncan 1997). Prior to becoming a JFC, Wild 2 probably experienced multiple outer planet perturbations that led to a planet-to-planet meander that transferred Wild 2 from beyond Neptune to JFC orbits. This migration period typically lasts a few million years (Levison and Duncan 1997). During the active period of such comets, they typically lose about a quarter of their radius (Thomas 2009). If Wild 2 is roughly halfway through its JFC lifetime in the inner solar system, it should have lost over 200 m of its original surface of rocks, dust, and ice. Before this final phase in the life of Wild 2, when it passed interior to Neptune's orbit, it is nearly certain that Wild 2 was stored beyond Neptune below 50 K for most of the history of the solar system.

An interesting complication to understanding the accretion region of comets is the possibility that planets and planetismals might have undergone substantial migration in the early solar system. Both the Nice Hypothesis (Levison et al. 2011) and the Grand Tack Hypothesis (Walsh et al. 2011) propose that the solar system's planets were originally packed into a region roughly half the size of the Neptune's final orbit and that their redistribution led to major planetismal scattering. A recent study by Nesvorný (2011) even suggests that a major planet may have been lost from the early solar system. In light of these ideas, the outer solar system ice-bearing planetismals may have had a more complex origin than traditionally envisioned.

WILD 2 SAMPLE COLLECTION AND LIMITATIONS

Most of the Wild particles were collected by 6.1 km s^{-1} impact into low-density silica aerogel, but some were captured by cratering into aluminum foil. The sample-derived inferences on the nature of comet Wild 2 are influenced by the sizes of well-preserved particles that can be studied. Due to the size distribution of emitted particles and the size-dependent effects of capture, much of the information on Wild 2 solids comes from a restricted set of materials. Some of the best data come from components in the ~2 μm to a few 10 μm in diameter that were sufficiently strong that they did not fragment during capture in aerogel. Larger components are rare, and the smaller ones were selectively degraded during capture due to the combined effects of low thermal inertia and intimate contact with molten silica. Most submicron particles were degraded or even dissolved in molten aerogel during the aerogel capture process, but a fraction did survive. During impact in aerogel, weakly bonded materials disaggregated and the separated components were somewhat size-sorted with depth. Small components, with large area-to-mass ratios, tended to stop high in the tracks, while larger components penetrated more deeply before losing their

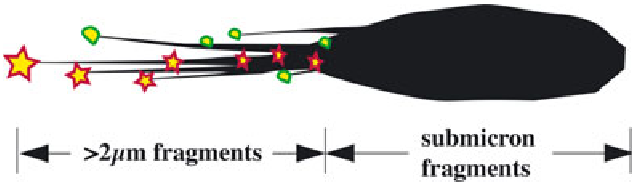

Fig. 1. An idealized view of a bulbous entry track caused by a comet particle entering 0.01 g cm^{-3} silica aerogel flown on the Stardust mission. The particle entered on the right at 6.1 km s^{-1} and the "terminal particles" are on the left. Most of the submicron components stopped in the hollow bulbous region, a hollow void partly lined by melted silica + projectile. The larger particles that penetrated below the bulb are usually the best-preserved comet samples. The track acts as a sieve size sorting particle components.

initial momentum (Fig. 1). The complex process involved in aerogel capture has been discussed elsewhere (Brownlee et al. 2006; Trigo-Rodríguez et al. 2008; Niimi et al. 2011). Generally, small isolated components were captured in the upper "bulb" regions of tracks where most of the impact power and aerogel melt were generated. The instantaneous power generated in tracks varies as the cube of the projectile velocity and most of the energy that melts silica aerogel is generated in the upper track regions when the velocity is still high. In most cases, the largest and deepest penetrating components, extending below the bulb, were competent strong materials, either mineral grains or solid rocks made of multiple phases.

The hollow upper bulb regions of tracks are lined with melted silica glass that was heated to the silica melting point of ~1700 °C. The thickness of melt lining the track should scale with the track diameter and the very largest tracks should have equivalent silica glass track liners that are 10 μm thick. Many of the submicron components were in direct contact with micron or larger masses of molten silica. The solid components larger than about 2 μm were generally captured in excellent condition and were essentially protected by their thermal inertia (Fig. 2). The effect of this transient heat source is somewhat analogous to meteorites, where the high temperatures generated during atmospheric entry only penetrate the thickness of the fusion crust. Sometimes compressed aerogel also forms a protective cap that insulates a particle during capture, and this process is most effective on large particles because the cap is thicker. The thermal penetration skin-depth for silicates collected by Stardust appears to be less than a micron for the collected samples, although thicker layers of material may have been lost by melting or vaporization. The alteration depth is estimated by observation of the perimeter of microtomed particles that show very sharp contact with compressed or aerogel melt. In polyphase materials, the integrity of adjacent phases is seen to be within a micron of the particle surface. Surfaces were abraded and lost, but the interiors were preserved in excellent state, usually with no discernable thermal alteration.

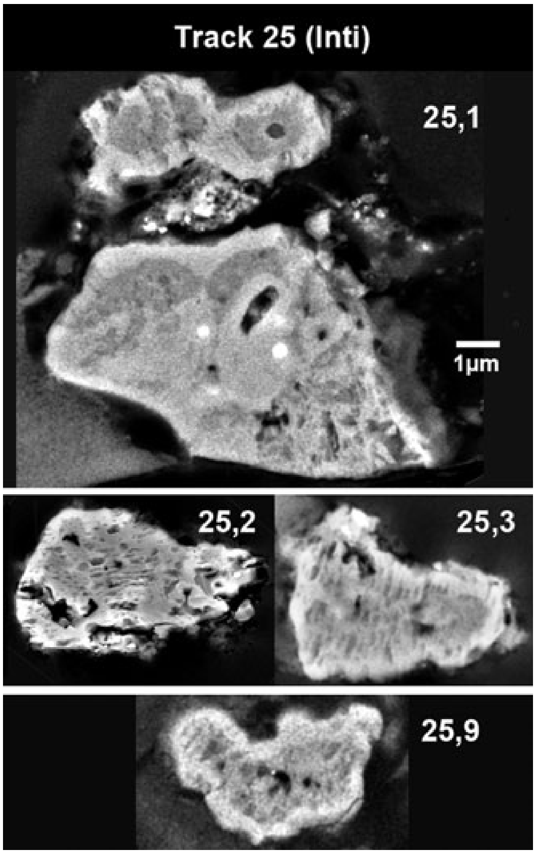

Fig. 2. SEM backscattered electron images of the potted butts of five fragments in track 25 made by the CAI-like particle nicknamed Inti. All images have the same scale and the fragments that form different parts of the track all have the same basic structure. They are nodules with spinel cores with ~1 μm rims of Al-Ti diopside. The entire impacting particle was composed of these nodules whose internal structures beautifully preserved during the aerogel capture process.

The bias in the collection is that much of the finest size fraction and all of the coarsest size fraction were missed, and this hampers comparison of Wild 2 with other meteoritic materials. While hundreds of submicron grains have been studied, the majority of grains in this size were not preserved, and there is no way of determining how representative the survivors are. As a result, the full nature of the submicron fraction remains quite uncertain. This is particularly acute for components such as presolar grains and organic materials that are expected to be small. The large components in Wild 2 are also uncertain because few particles >100 μm were collected and the largest samples have yet to be analyzed.

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 millimeter particles was too small to be sampled by the 0.1 m^2 collector. 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 over 90% of the impacting mass of particles smaller than 700 μm diameter was in particles larger than 100 μm.

The seriousness of this sampling bias depends on the nature of cometary materials. If larger comet particles are just aggregates of many smaller components, then missing the large particles is not a problem. If most of the large particles are solid components such as chondrules, then it is a major problem. If Wild 2 was composed of materials that generally resembled a primitive ordinary chondrite like Semarkona, the sampling bias would yield a quite misleading view of the Semarkona parent body because of the dichotomy between chondrules and fine matrix. Semarkona is dominated by tightly packed millimeter chondrules with fine matrix filling the narrow spaces between them. Most of the analyzed particles would be matrix, and the best preserved would be those larger than 2 μm. Over 75% of the mass of Semarkona is in millimeter chondrules that would be too rare to impact the Stardust collector. An additional sample consideration is the possibility that comets may contain components that are systematically retained as surface lag deposits and not be ejected into space. The presence of depressions on Wild 2 that are over 100 m deep suggests that the development of inert lag deposits may not be common on this comet and that particles released into space may well be representative of the comet's interior inventory of rocky components.

The abundance of the larger Wild 2 particles that are solid competent materials relative to those that are just aggregates of smaller materials is unknown, although analysis of solid grains in Stardust tracks has shown a remarkable abundance of competent grains up to at least 50 μm size. 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 about half of the 1 mm long tracks were bulbous-shaped and half were thin. The shorter tracks were made by micron-sized particles and the longest ones were made by particles in the 10 μm up to a few 100 μm size range. The track shapes suggest that the micron-sized particles that made the shorter tracks were coherent, while about half of the 10 μm or larger sized particles that produced the larger tracks were fragmenting materials and presumably were either aggregates or otherwise weak or unstable materials. The nature of the millimeter grains remains unknown, and it is possible that Wild 2 could in fact contain a substantial abundance of full-size chondrules and we would not know it because, as previously mentioned, millimeter-sized particles are too rare by number to have been sampled even if they do dominate the mass of particles in the comet's coma. The size distribution of Wild 2 particles (Price et al. 2010) does not seem to indicate the degree of bimodality that would occur from the disintegration of a chondrule-rich material similar to Semarkona.

COMET SAMPLES AND PRESOLAR GRAINS

A major surprise of the analysis of Wild 2 samples has been how "meteoritic" the collected samples are (Ishii et al. 2008). Reasonable pre-mission predictions were that comet solids would be either dominated by well-preserved interstellar grains or by presolar grains that had only been modestly changed by thermal processes in the solar nebula. A common expectation, as described by Greenberg and Li (1999), was that comet dust should be made of core-mantle interstellar grains composed of silicate cores surrounded by organic mantles. The silicate portion of such grains should be amorphous because the shape of the 10 μm interstellar silicate infrared feature is consistent with almost pure amorphous silicates (Kemper et al. 2005). Another expectation was that comet dust might contain appreciable secondary crystalline phases that formed in the nebula by subsolidus annealing of amorphous silicates at ~1000 K. This is the most common explanation for the presence of crystalline silicates observed in young circumstellar disks (Poteet et al. 2011). It is generally envisioned that the annealing process could occur in disks either in stable warm disk regions (Poteet et al. 2011) or in colder regions, where transient heating can occur due to shocks (Harker and Desch 2002; Wooden et al. 2007).

Instead of a comet dominated by submicron interstellar dust, most of the analyzed Wild 2 materials that have been examined have been coarser grained and appear to be closely related to common meteoritic materials. For the Stardust comet samples described here, we will use the relative term "coarse" to refer to grains that are larger than a micron or so and much larger than the size of typical interstellar grains. Most Wild 2 materials formed at high temperature (greater than the 1000 K temperature proposed for the annealing of interstellar amorphous silicates) and, like the major meteoritic components, they presumably formed in the inner solar system. With only a few exceptions, the studied particles are not primary isotopically anomalous interstellar grains similar to presolar grains (Hoppe 2010) that have been identified in chondrites (McKeegan et al. 2006, Leitner et al. 2010). To date, five isotopically anomalous presolar grains have been found in the Stardust samples, four in aluminum foil craters (Leitner et al. 2010), and one in an aerogel track (Messenger et al. 2009). One of these is a SiC grain and the others are silicates or oxides. The isotopic compositions of the grains fall in the range of similar presolar grains in chondrites. The abundance of these grains in Wild 2 is difficult to estimate because particles of the size of interstellar grains (Hoppe 2010) are often degraded during capture. Early findings (Stadermann and Floss 2008) indicated that the presolar grain abundance in Wild 2 might be lower than in primitive chondrites. Later work has shown that thermal degradation during collection has destroyed small grains, and the measured presolar grain abundance is now considered to be a lower limit (Stadermann et al. 2009). With considerable uncertainty, the current best estimate is ~1400 ppm (Leitner et al. 2010), a value that is higher than the 44–66 ppm found in the most presolar grain-rich meteorites and micrometeorites. It is also higher than the ~375 ppm abundance commonly seen in primitive IDPs (Leitner et al. 2010). This is, however, less than the ~1% presolar grain abundance reported for part of a cluster IDP that is thought to be cometary material (Busemann et al. 2009). While isotopically anomalous grain abundances may or may not be relatively high in Wild 2 compared with chondrites, these presolar grains are still only a very minor fraction of the comet's rocky materials.

The isotopic compositions of most of the Stardust samples that have been measured do not support a presolar origin. It also does not appear that annealed presolar grains are abundant in Wild 2, at least in the larger than micron size range. In general, most of the larger than micron particles are too large and too mineralogically complex to be produced by simple ~1000 K subsolidus annealing of presolar amorphous silicates or clusters of presolar grains (Joswiak et al. 2012). The Wild 2 samples contain many components that could not plausibly have formed by solid-state annealing of presolar material that had roughly solar composition for the rock forming elements. Such components include pure forsterite; refractory forsterite with high Ca; nearly pure fayalite; LIME olivine with Mn > Fe; sulfides; and minerals such as osbornite, perovskite, Cr-rich augite, refractory metal inclusions, schreibersite, Ti and V-rich pyroxene, and V-rich spinel that contain elevated abundances of rather cosmically rare elements (Hanner and Zolensky 2010, Joswiak et al. 2012). These materials are also found in chondrites, but their origin is not commonly attributed to annealing of presolar materials, a simple solid-state process with limited potential for producing diverse phases from amorphous interstellar grains. While devitrification does not seem to play an important role in making larger than micron comet dust, this process did occur in the solar nebula. In addition to devitrified chondrule glass, there is a component in meteoritic samples that does have a suggested annealing origin. Equilibrated olivine/glass aggregates are a minor component of interplanetary dust and their properties are consistent with formation by subsolidus annealing of an amorphous silicate precursor (Bradley 1994; Keller and Messenger 2009).

CHONDRULES, CAIS, AND MIXING IN THE SOLAR NEBULA

Most of the analyzed Wild 2 particles are either mineral grains or "rocks" composed of multiple phases in the few to 50 μm size range. Many of the Wild 2 rocks are similar to common components in primitive meteorites, although they are usually finer-grained than their meteoritic counterparts (Hanner and Zolensky 2010). However, as mentioned previously, these components are coarse relative to presolar grains, and in some cases, they are a million times more massive than typical interstellar grains. Numerous Wild 2 particles have been shown to be either chondrule fragments or chondrule-like fragments (Nakamura et al. 2008, 2009; Jacob et al. 2009; Bridges and Changela 2010; Butterworth et al. 2010; Gainsforth et al. 2010; Joswiak et al. 2010, 2012; Ogliore et al. 2012). One of these particles even contains a relict ^{16}O-rich olivine grain previously made in a ^{16}O-rich reservoir (Nakamura et al. 2008).

One of the very first Stardust tracks analyzed was made by a ~20 μm CAI-like particle composed of spinel rimmed pyroxene nodules (Simon et al. 2008). This particle is ^{16}O-rich like common CAIs and the Sun, and it contains a host of refractory minerals including Al-rich, Ti-bearing and Ti-free clinopyroxene, Mg-Al spinel, anorthite, melilite, perovskite, refractory metal, and osbornite (TiN) grains. Other tracks also contain refractory materials, but the abundance of CAIs or even CAI-like particles has not been well determined. It is probably in the range of 1–10%, an abundance that is lower than CAI-rich chondrites such as Allende, but much higher than in unequilibrated ordinary chondrites.

Wild 2 is a potpourri of such remarkably diverse meteoritic materials that it seems unlikely that the comet can be matched to any given chondrite class. The diversity of mineral compositions even within individual particles suggests that the Wild 2 samples are at least as primitive as the most primitive type 3.0 chondrites. The high Cr content of some Wild 2 olivine grains indicates a lack of parent body heating beyond what was experienced by type 3.0 chondrites (Grossman and Brearley 2005). This evidence for the general lack of substantial parent body heating is consistent with the scenario that most of the components released by Wild 2 were simply materials that accreted along with ice and organics, were stored in ice for the age of the solar system, and then released to space from subsurface regions due to ice sublimation. The presence of abundant freely released submicron particles in the Wild 2 dust coma, that were both detected (Green et al. 2007) and collected (Price et al. 2010), practically guarantees that this comet, or at least its portions released to space, did not suffer pervasive internal aqueous or other thermal alteration that would have caused consolidation of fines into more strongly bonded composites. Although phyllosilicates have not been seen in Wild 2 samples, there are a number of reports of small amounts of secondary phases that are generally associated with aqueous alteration and these will be discussed later in this article.

The solar nebula contained multiple regions that could be considered to be "rock factories," regions that made many of the coarse materials in primitive chondrites such as chondrules and CAIs. The millimeter products of these factories are typically a billion times more massive than typical interstellar dust grains that initially delivered rock-forming elements in the early solar system. The nebular rock factories did not produce meteoritic components by mild processes such as subsolidus annealing of presolar grains. They formed new generations of materials under much more extreme conditions that involved melting, vaporization, and condensation. The most common rock product in the solar nebula appears to have been chondrules, nebular components that commonly formed by episodes of brief heating in the 1400–1750 °C range (Hewins and Radomsky 1990). The majority of the well-preserved Wild 2 materials appear to be products of the rock factories that made the bulk of the materials in chondrites. The initial nebular rock-forming episodes began with CAI formation and ended a few million years later when the last chondrules formed or were reworked. Rocks were also made inside strongly heated parent bodies. Impact debris from aqueous altered, strongly heated and differentiated parent bodies must have joined the ensemble of orbiting debris that could spread across the solar nebula and reach the regions where comets accreted.

LONG DISTANCE PARTICLE TRANSPORT

The results from the Stardust mission provide fundamental information on the mixing of solids larger than 2 μm in the solar nebula. It appears that the 2–50 μm size range of Wild 2 rocky materials is dominated by materials that formed in 1000–2000 K nebular environments. They are samples of materials made by the high-temperature processes that made chondrules and refractory materials. If the source region of the Wild 2 grains was in the inner solar system, then the grains must have been transported over distances of 10 AU to reach the region where JFCs accreted. In this scenario, the vast majority of cometary rocky materials, and in fact the majority of cometary mass, formed in distant locales and not the Kuiper belt region where the JFCs accreted. This strongly suggests that the cold region of the solar nebula was a collection site of materials that were made or severely transformed in hot rock-forming nebular regions. In light of the transportation distances involved, it seems likely that the materials reaching the JFC formation region should have been well mixed. As both chondrule and CAI materials were found in the comet, Wild 2 must have accreted materials that were formed during the time interval when both CAIs and chondrules formed or at least existed in the early solar system. The only Wild 2 sample data that relate to formation ages are the lack of detection of ^{26}Mg excesses in a CAI fragment (Matzel et al. 2010) and an Fe-rich chondrule fragment (Ogliore et al. 2012). This measurement implies that these two components formed late, after ^{26}Al had decayed or perhaps early, before ^{26}Al was injected into the solar nebula.

The Wild 2 data imply that particles at least as large as 50 μm were transported radially across the full width of the solar nebula. This transport could have occurred ballistically above the disk or it may have occurred within the plane of the disk. Shu et al. (1996, 2001) predicted that such transport would occur out of the plane due to ejection near the Sun by the X-wind. In the X-wind model, particles as large as CAIs are ejected to the edge of the solar nebula and beyond by a magnetically driven wind that begins just a few radii from the Sun. Outward transport in the plane has been modeled by processes involving turbulent diffusion and instabilities (Bockelee-Morvan et al. 2002; Keller and Gail 2004; Ciesla 2007, 2009, 2010; Boss 2008; and Cuzzi et al. 2008).

COMETS AND ASTEROIDS

It appears that the Wild 2 rocky components are largely and perhaps entirely composed of material made in distant locales. This situation is totally different from the case of chondrites. Typical chondrite parent bodies are dominated by local materials whose properties give chondrite classes their distinctive chemical, mineralogical, and isotopic properties. Chondrites do, however, contain wayfaring materials that did not form locally. These materials include presolar grains and CAIs, but they are minor components that are highly diluted by locally made materials. We suggest that a major difference between the rocky materials in asteroids and comets is

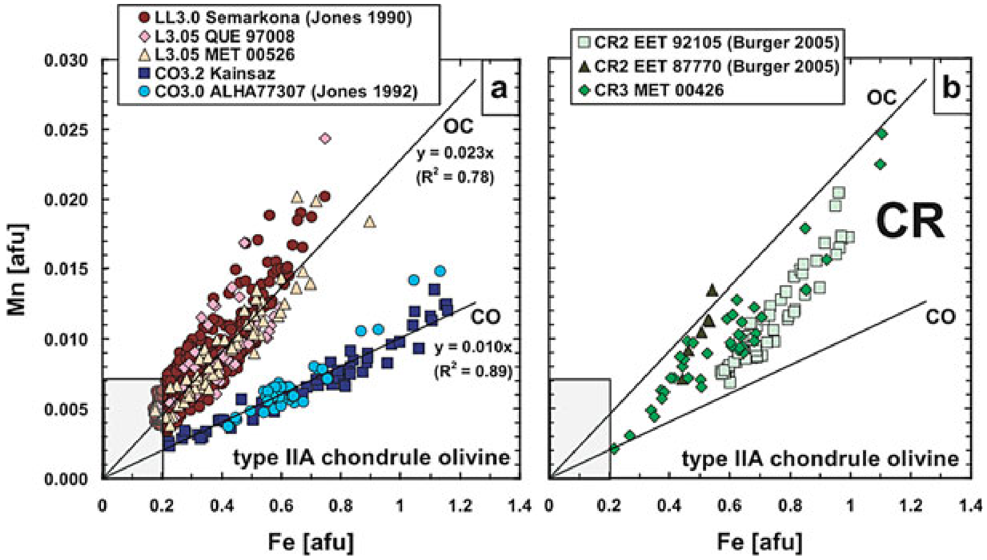

Fig. 3. Fe-Mn systematics of olivine in type IIA chondrules from Berlin et al. (2011). The CO ferrous olivines have the most correlated Mn and Fe abundances with a Mn/Fe less than half of the mean value for primitive ordinary chondrites. The ordinary chondrites (OC) and CR olivines have more complex Mn/Fe associations, but with distinctive abundance patterns. afu = atomic formula, so Fe in fayalite = 2.

that asteroids are dominated by local materials, while rocky material in comets is dominated by material from distant sources. The materials from distant sources are somewhat analogous to glacial erratics because their formation region is unrelated to the location where they are found.

Asteroids were close to the rock-forming regions of the solar nebula, and their accretion times were short because of the higher material density and orbital angular velocities in the inner solar system. If the rocky contents of comets were derived from distant nebular materials and transported 10 AU to comet-forming regions, it is likely that they are a broad and perhaps representative sampling of early nebular solids. At a very minimum, they should be a representative sampling of the nebular component that was widely distributed across the width of the disk. In addition, being the dominant source of Kuiper belt rocky materials, this population is likely to have been accreted on all solar system bodies, although in the inner solar system it may only have contributed a very minor fraction because of dilution by locally made materials.

There is a simple way to test the hypothesis that comets contain a broad mix of nebular materials. If comets were made from a broader mix of rocky materials than those that made individual asteroids, then the difference should be detectable as a broader dispersion of component properties. Comet solids should contain a broader range of components than found in meteorites from mainbelt asteroids. Specific tracers that could be used to investigate this difference include minor element concentrations in olivine and high-precision oxygen isotope compositions of olivine. Olivine is particularly important because it has distinctive properties in primitive chondrites, and there is a substantial database of meteoritic data.

The work of Berlin et al. (2011), Hewins et al. (2011), Zanda et al. (2010), and others has shown that the Mn/Fe ratios in ferrous olivine (magnesian olivine behaves differently) in several chondrite groups are distinctive, as shown in Fig. 3 from Berlin et al. (2011). The ferrous olivine in unequilibrated ordinary chondrites and CO chondrites has well correlated Fe and Mn abundances, but these two groups show distinctively different Mn/Fe ratios. The differences may be related to condensation, but they can differ among chondrule reservoirs due to loss or gain of either Fe or Mn. CR chondrite ferrous olivines have variable Mn/Fe ratios, but distinctive distribution pattern with ratios between OC and CO chondrites. Unaltered cometary olivine or olivine from any meteoritic source that showed such distinctive patterns even for these two elements could not possibly be a broad sampling of the solar nebula disk. While distinctive properties of chondritic olivine often indicate formation from regional or at least restricted environments, the Wild 2 olivines appear to contain a broader mix of Mn and other minor element contents consistent with formation across a broad range of the early solar system. Wild 2 olivine has a truly broad range of Mn values (Zolensky et al. 2006; Frank and Zolensky 2010; Joswiak et al. 2012) and fortunately, the comet contains abundant Fe-rich olivines that can be meaningfully compared with existing meteoritic and IDP data. Ferrous olivines are important because Mn/Fe is not generally correlated in forsteritic olivines. The growing number of minor element analyses of Wild 2 olivines will provide a way to quantitatively determine how the range of olivine grains accreted by Wild 2 compare to those that were incorporated into the various chondrite types. Principal component analyses of such data and comparison with meteoritic data such as that shown in Fig. 3 will shed light on how components from different reservoirs were distributed across the solar system. The broad range of properties of specific comet phases, produced in wide ranging nebular environments, may be the identifying hallmark property of rocky cometary matter.

Another means of distinguishing different populations of olivine grains is oxygen isotopic composition measured at ~1 per mil precision. The high-precision oxygen isotope data on Mg-rich meteoritic olivine from Libourel and Chaussidon (2011) indicate that there are remarkably distinctive differences at the few per mil level between chondrite types, as shown in Fig. 4 from Libourel and Chaussidon (2011). The implication from this work is that the early solar system had distinctive nebular or even planetary reservoirs of material with somewhat discrete oxygen compositions. Different chondrite types sampled one or more of these reservoirs. If this interpretation is correct, then high-precision oxygen data might be a straightforward way to detect material with contributions from the whole disk and not just localized sources. Like minor elements, we would expect O isotopic compositions of a suite of cometary olivine to show broader dispersion than found in any chondrite group and should in fact encompass the full range of common meteoritic compositions.

In addition to measuring the dispersion of properties of olivine and other phases it is also possible that comets may contain unique components that are not found in inner solar system materials. If they exist, such components could be considered distinctive markers (smoking guns), whose mere presence would denote cometary or outer solar system origin. For example, we have found at least two materials in both Wild 2 samples and IDPs that have not been reported in chondrites. One is an assemblage of Na,Cr-rich augite, ferrous olivine, and sometimes albite and spinel (Joswiak et al. 2009), and the other is a fine-grained assemblage of pyrrhotite, pentlandite, and sphalerite (Joswiak et al. 2012). Other distinctive markers might be organic residue from sublimed ice or the presence of GEMS, glass with embedded metal and sulfides. GEMS are an important component in primitive carbon-rich IDPs (Bradley 1994; Bradley et al. 1999), but their presence has not been positively confirmed in other meteoritic samples. Unfortunately, trying to positively identify GEMS in the Stardust collection is difficult because GEMS are always less than a micron across and such small particles were usually strongly heated during capture (Ishii et al. 2008). Greatly complicating the problem is that the high-speed aerogel–projectile interaction produces melt glass (Rietmeijer 2009) with nanometer-sized beads of metal and sulfide that mimic the fundamental interior structure of GEMS.

AQUEOUS ALTERATION IN COMETS?

Evidence for aqueous alteration is found in the majority of compositionally primitive chondrites. Except for possible cases of formation by thin layers of "unfrozen water" below 0 °C, aqueous alteration processes are most likely to occur in environments with temperatures above freezing and water vapor partial pressure above 0.006 atm (0.6 kPa), the triple point of water. In early solar system history, such environments must have been common in the interiors of chondrite parent bodies even when their blackbody surface temperatures were <200 K. Heat sources included impacts, heat of hydration, and heat from the decay of ^{26}Al. Internal energy generation from impacts on kilometer-sized bodies and radiogenic heating from short-lived radionuclides should have been lower in the outer solar system because bodies that formed beyond Neptune have lower collision velocities and their accretion times should be longer. It is likely that comet assembly did not occur until ^{26}Al had largely decayed.

Could liquid water have existed inside comets as small as Wild 2? Wickramasinghe et al. (2009) described a scenario where a strong cometary crust could conceivably contain steady-state pressure above the water triple point and retain liquid water in small comets, but this model seems contrived. Impacts on comets can certainly provide transient conditions where water could exist. Contact with liquid water should readily transform a loose mix of fine anhydrous phases into a stronger material containing hydrated silicates, and perhaps secondary phases such as carbonates and magnetite. A strong argument that aqueous alteration has not profoundly altered comets, or at least the materials that they typically release to space, comes from observations of cometary meteor showers. Meteors fragment when their strength is exceeded by the dynamic ram pressure of the atmosphere. Meteors associated with Jupiter Family Comets are the weakest of all meteors because they have measured crushing strengths of less than 1 kPa, the strength of soft snow (Borovička 2007). This is orders of magnitude weaker than carbonaceous chondrites that have strengths in the 0.3–30 MPa range (Tsuchiyama et al. 2009).

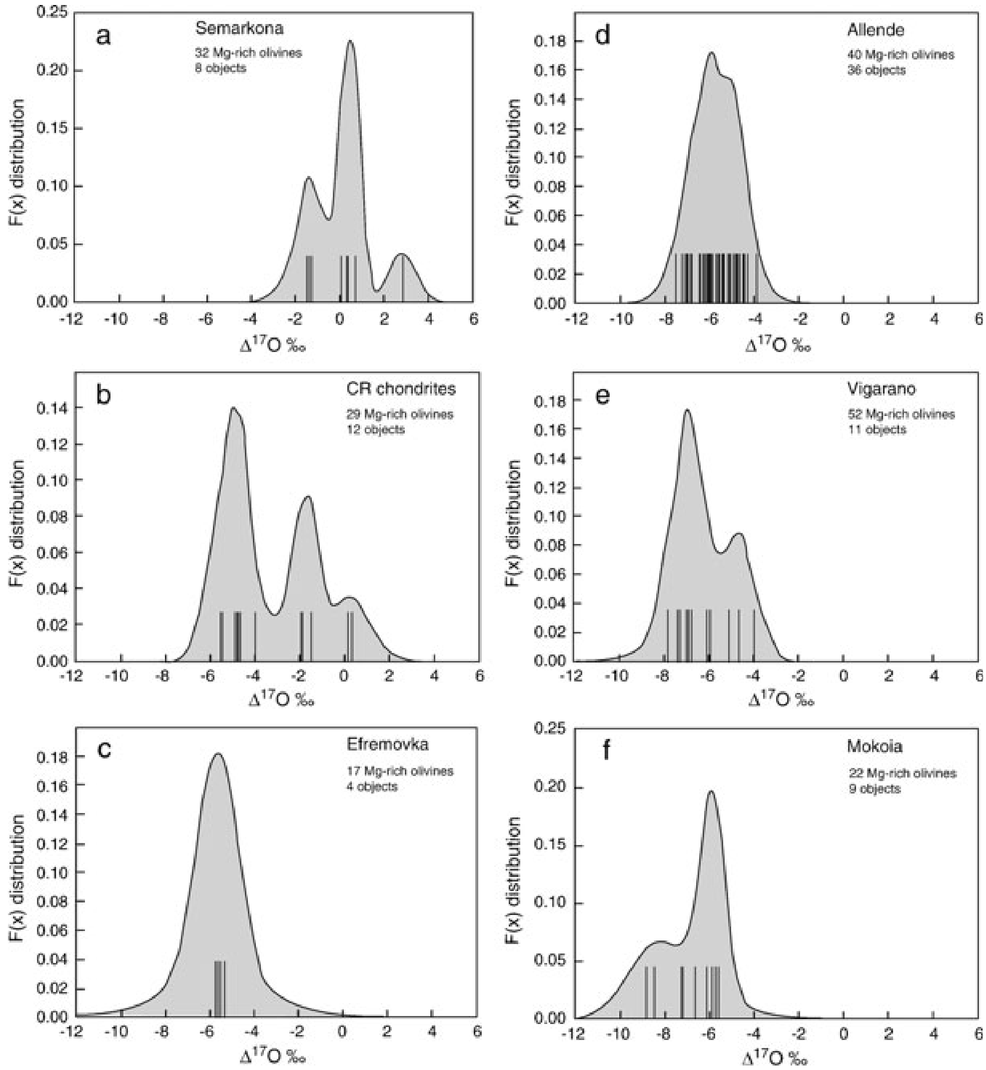

Fig. 4. High-precision oxygen isotope compositions of Mg-rich olivine grains in 6 primitive chondrites. The figure from Libourel and Chaussidon (2011) shows data that are consistent with the chondrite groups incorporating olivine from multiple reservoirs with distinctive isotopic compositions. This remarkable data show that the chondrite groups have distinctively different olivine and most contain grains from multiple sources.

All meteorites must be relatively strong rocks to survive atmospheric entry and they are a biased subset of meteoroids that are strong and have low entry speed. Their physical strength is much higher than the typical cometary materials ejected into space by comets, and no meteorite can be typical of the unprocessed cometary material that produces meteor showers. The only meteoritic analog with the physical strength similar to cometary meteors are the "cluster IDPs" that fragment into thousands of pieces when they are collected in the stratosphere. Meteorites are strong because they were compacted and internally bonded by processes of thermal metamorphism and/or aqueous alteration in their parent bodies. No meteorite is simply a porous loose aggregate of originally accreted material. In contrast, meteors released by comets fragment into fine particles at exceedingly low ram pressures, showing that they are weakly bonded porous aggregates. Retention of its original weakly bonded nature is probably a definitive signature of a truly primitive solar system material that is nearly unmodified since its accretion. Significant aqueous alteration inside a comet would presumably lithify its contents into strong rocks similar to what has happened in chondrites.

While comets could have aqueously altered portions that were formed by processes such as impacts or were accreted from larger bodies, it is reasonable to expect that these materials would be inactive and not be ejected into space by cometary activity. If altered material was ejected, then cometary meteor showers would contain appreciable numbers of strong meteorite-like rocks. Meteor showers do contain a few hard rocks, but they are rare components (Borovička 2007). It is also unlikely that processed rocks would normally be ejected by normal cometary activity. The simultaneous release of submicron to millimeter comet solids, expelled by escaping gas, implies that the components did not develop strong bonds to one another. For example, if a meteorite like Murchison was soaked in water, frozen, and put in a vacuum, it seems unlikely that subliming ice would be capable of propelling debris outwards, particularly submicron particles whose surface forces provide strong adhesion to the other surfaces. The release of submicron materials from comet rock-ice mixtures may require individual ice coatings of rocky components even at the submicron level.

Several studies of Wild 2 materials have provided evidence for phases that are produced by aqueous alteration. Stodolna et al. (2010) found substantial numbers of small magnetite grains in the bulb region of track 80. The abundance of these was on the order of 10% of the surviving crystalline phases in the studied sample. This track is unusual, but it does seem reasonable that the magnetite grains have a similar origin to those found in CI and some CM chondrites, and were produced by aqueous alteration. Berger et al. (2011) found several small cubanite grains associated with pyrrhotite and pentlandite, and suggested that the association formed by low-temperature aqueous alteration. Hanner and Zolensky (2010) suggested that the minor amounts of pentlandite seen in Wild 2 are aqueous alteration products. Small isolated grains of carbonate have been reported (Flynn et al. 2009), but small carbonate grains are contaminants in the silica aerogel and none of the carbonate grains have yet been proven to be related to the comet. All of the above reports are rare components whose origin is consistent with hydrous alteration, but the most common aqueous alteration products in chondrites and hydrated IDPs are phyllosilicate phases that have not been found in aerogel tracks (Joswiak et al. 2012) or in Al foil craters (Wozniakiewicz et al. 2010). All of the larger than 2 μm silicate phases that have been studied are anhydrous and show no evidence of alteration by aqueous processes. The Wild 2 samples also contain large numbers of submicron anhydrous silicates that would have been modified by contact with water, even for short periods of time. If the comet does contain abundant hydrated silicates, they would have to have escaped detection because (1) they were mostly of submicron size, (2) they decomposed during capture, or (3) they remained in the comet and were not ejected into space. While phyllosilicates are often considered to be fine-grained, they are sheet silicates and even poorly ordered phyllosilicates found in chondrites and IDPs usually have coherent regions that are microns across.

Because of the overwhelmingly anhydrous nature of the >2 μm Wild 2 materials, coupled with the meteor strength and the emission of fine solids by comet activity as discussed previously, we do not believe that Wild 2, or at least its portions ejected into space, has experienced pervasive aqueous alteration in the parent body. Wild 2 does not resemble meteorites such as Orgueil and Murchison that were profoundly transformed by water nor does it resemble unequilibrated ordinary chondrites that show only moderate evidence for aqueous alteration. A cautionary note here is that the fine-grained material that is most sensitive to alteration was not well preserved by the aerogel capture process.

If Wild 2 did not experience large-scale aqueous alteration, but if it does contain bona-fide aqueous alteration products, then these materials could have either formed in local regions of the comet or on other bodies. Local sources could be impact sites where ice melted and produced alteration products. Debris from this material could be spread across the comet by regolith-like processes. If they are produced on other bodies and accreted onto Wild 2, they could be fragments of inner solar materials like carbonaceous chondrite parent bodies or they could also be fragments of substantial size bodies that formed beyond Neptune. The Kuiper belt contains more bodies >500 km diameter than exist in the asteroid belt, and it contains planetary-sized bodies such as the dwarf planets Pluto and Eris. There is direct evidence that collisions on these large bodies produce ejected debris that can be accreted by other bodies in the Kuiper belt region. The 2000 km long Haumea appears to be the parent of a collisional family of bodies that include high albedo icy and low albedo rocky materials, evidence of the breakup of a body with a rocky interior and ice crust (Brown et al. 2007; Leinhardt et al. 2010). The interiors of large bodies are likely to contain aqueous alteration products, and fragments ejected from impacts on these bodies are likely to be contained in all comets. Like meteorites, comets are collections of accreted debris and they should contain inclusions of other solar system bodies. Small bodies that form by accretion, and are not strongly processed, should have regolith-like interiors that contain debris from a range of bodies.

DIVERSITY AMONG COMETS?

Assuming that the rocky components of comets are effectively cosmic sediments that were transported to the edge of the solar nebula, we hypothesize that most comets will commonly contain a similar mix of rocky materials, unless they were transported at different times or exposed to differing sorting or modification processes. Our prediction is that the dust and rock inventories in different Jupiter Family Comets may be similar due to the mixing processes associated with transportation over distances of tens of astronomical units. Such homogeneity would be in contrast with the inner solar system, where meteorite parent bodies formed from distinctively different component populations. The great diversity between meteorite groups is probably related to higher gradients of nebular properties in the inner solar system and because meteorite parent bodies formed close to regions where rocky components were formed and reworked by nebular processes. It is also likely that the accretion timescale was shorter in the inner solar system and that shock-related processes were more likely to have occurred in denser gas and in regions where large planets were forming. The asteroid region was a complex region of the solar nebula because it was near the snow line, Jupiter, the Sun, the regions where chondrules formed, and near the boundary between the terrestrial and Jovian planets. Dobrica et al. (2009) and Gounelle (2011) suggest that there is a continuum between comets and asteroids, and this seems likely for the rocky components if comets and asteroids are composed of different mixes of basic nebular materials. A complication to fully exploring this concept is the fact that there are no regions between Jupiter and the Kuiper belt where small bodies could be stored for the life of the solar system. Original planetesimals in this vast zone were all either perturbed elsewhere or were accreted by larger bodies.

Astronomical data indicate that there are significant differences between outer solar system bodies. KBOs show a spread of spectral reflectance ranging from flat spectral reflectance (albedo not a function of wavelength) to the reddest bodies in the solar system. These color differences may be due to radiation processing of condensed volatiles such as H_2O, CO_2, CH_3OH, and NH_3, compounds whose abundances can vary appreciably with distance in the cold regions of the solar nebula (Brown et al. 2011). Color differences may be related to differences in original volatile contents and not to rocky components. Differences in volatile contents are seen from emission line spectra A'Hearn et al. (1995) and dramatic differences in H_2O and CO_2 were even seen from different regions of a single comet, Hartley 2 (A'Hearn et al. 2011). Comet surface images show a remarkable difference in morphology for Jupiter family comets (Basilevsky and Keller 2006). In spite of all of these observed differences, it is possible that JFCs all eject very similar solid contents.

Evidence against the proposed similarity between rocky contents of comets is the Spitzer IR spectra of comet Tempel 1 debris liberated by the Deep Impact mission. Lisse et al. (2006) interpreted the excellent and feature-rich spectrum as a mix of over a dozen phases. The fit to the comet spectrum included 14% smecite, several percent each of siderite and magnesite, 15% niningerite, 9% fayalite, 31% forsterite, 17% "amorphous olivine," 33% ferrosilite, 11% diopside, and other phases. Taken at face value, this spectral fitting model is a very poor match to the laboratory analytical data on comet Wild 2 samples. There is some overlap, but the Tempel 1 mineralogical interpretation is not consistent with Wild 2 or any type of extraterrestrial material that has been analyzed in the laboratory. The high abundances of ferrosilite, niningerite, and the high fayalite/forsterite ratio, put Tempel 1 in a unique category. Unfortunately, there is no sure way to test how meaningful a spectral match to so many phases is without ground truth, an actual sample return from Tempel 1, or perhaps a landed experiment package that can determine the mineralogy of submicron materials. Comets are complex mixtures of crystalline, amorphous, and organic components with unknown grain sizes, unknown relationship between phases, and unknown influence by processes such as radiation and shock. Modeling of such a complex natural material with spectra from a multicomponent suite of laboratory standards should be viewed with caution until confirming evidence can be obtained. In addition to the presence of highly reduced phases such as niningerite, an issue of major importance is whether or not aqueous alteration products such as smectite, magnesite, and siderite really exist in this comet at significant abundance. They have not been found in Wild 2 components larger than 2 μm. A weakness of the comparison of Wild 2 analysis data using well-understood laboratory analysis techniques and the Tempel 1 infrared spectra is that the infrared spectrum is emitted by submicron particles, the size range that is poorly preserved and not reliably characterized in the Stardust collections. If the submicron mineral contents of both comets are similar to each other as well as the mineral mix modeled for the Tempel 1 spectra, then the submicron fraction of Wild 2 would have to be mineralogically quite different from the micron and larger components recovered by the Stardust mission.

A remarkable aspect of the post-impact Tempel 1 infrared spectrum is that it is nearly identical to that of the bright long period comet Hale Bopp. This implies that the dust liberated by the impact on the short period comet Tempel 1 from the Kuiper belt is similar to the dust released by Hale Bopp, an Oort cloud comet that is generally believed to have accreted interior to Neptune's orbit before being ejected into the Oort cloud. The similarity of Tempel 1 and Hale Bopp IR spectra is notable because short period and long period comets are usually seen to have quite different spectra, indicating a possible difference between these types of comets. Before the impact, Tempel 1 had a typical short period comet spectrum with only a weak silicate feature above continuum. After the impact, the spectra changed dramatically to show a spectrum with very strong features, nearly identical to Hale Bopp. This astonishing transformation from the same comet suggests that the apparent differences between long and short period comets is not a fundamental property of the material inside the comet, but is related to the form of the material that is ejected to space (Hanner and Zolensky 2010). The energetic liberation of fine materials from the impact produced a spectacular long period comet spectrum, rich in silicate spectral features, from a short period comet! It is also conceivable that the difference between the preimpact and postimpact spectra is solely due to profound heterogeneity in the comet.

We have suggested that the rocky components of comets may be similar mixtures of materials made in the inner regions of the solar system, but this might not be true for all comets. Comets like Wild 2 were made when there was a very efficient outward flow, a diffuse "Grand Radial Express," that carried material to the region beyond Neptune. This radial express is no longer in operation and it probably did not occur either in the first or the final stages of nebular evolution. It is possible that the major outflow of dust may have varied with time and may have either diminished or increased during transient events such as FU Orionis outbursts. There may have been times when the outward flow of inner solar nebula material did not dominate the flux of presolar grains falling onto the nebula. At such times, there might have been comets that formed largely from presolar interstellar grains as suggested by Greenberg and Li (1999)—with their ice and organic coatings intact. It will be an interesting challenge for future research and future missions to see if the solar system did produce two kinds of comets with drastically different rocky components.

WILD 2 MATERIAL AND THE PROVINCE OF METEORITIC SAMPLES

Meteoritic materials that have fallen to Earth are our major source of information on the early solar system, but the province of individual samples is usually poorly constrained. The Wild 2 samples, from a known active comet, as well as the Itokawa samples returned from an S type asteroid by the Hayabusa mission (Yurimoto et al. 2011), provide important insight for relating meteoritic materials to parent bodies.

The collected meteoritic materials cover a broad range of sizes, and while the largest provide the most sample mass, the smaller ones provide a sampling of early solar system materials that is differently and less influenced by effects related to delivery to Earth-crossing orbits and survival of atmospheric entry. Conventional meteorites are the larger meteoritic materials, but if they are smaller than a millimeter, they are called micrometeorites. The small particles that are collected before they hit the ground and are numerous enough to be collected in the stratosphere are called IDPs. Most meteorites are too strong to be related to typical cometary meteoroids whose low strength is determined by the high altitude fragmentation of material in cometary meteor showers. Rare cometary meteors, or small fragments of cometary meteors, perhaps hardened by parent body impacts or aqueous alteration, do have strength similar to chondrites (Borovička 2007), but these are uncommon and are not representative of typical material released by comets. Gounelle et al. (2008) discussed the possibility that some fraction of existing meteorites, including Orgueil, could have formed in the outer solar system. Dobrica et al. (2009) provide arguments that micrometeorites are cometary and discuss similarities to Wild 2 samples.

It has long been understood that some of the cosmic dust particles collected in the stratosphere must be from comets, but solar system dust models implied that the majority of collected samples should have asteroidal origins (Dermott et al. 2002). A far-reaching change in this view occurred with the model of Nesvorný et al. (2010) that predicts that 85% of IDPs are cometary! This new and more sophisticated model matches the spatial distribution of infrared emission of the solar system dust cloud observed by the IRAS and other spacecraft. The model also predicts that the long known process of orbital circularization sufficiently reduces the atmospheric entry speed of comet dust, and thus diminishes a bias hampering atmospheric survival of comet dust on elliptical orbits. Circularization is a process that is affected by size, density, optical properties, collisions, resonances, and lifetime as a free orbiting particle. The Nesvorný et al. model is a radical change from the past and implies that the majority of stratospheric IDPs may be cometary samples. If this is true, then it marks a major sea change in IDP and micrometeorite work and implies that we already have in hand thousands of meteoritic comet samples from perhaps a significant number of different comets. This proposition needs to be fully explored and exploited because the meteoritic samples provide a means to investigate the diversity among comets and leverage mission data to a larger number of bodies that can ever be visited by spacecraft. We hope that the wide dispersion of properties of particular phases, the presence of distinctive cometary materials, or other properties can be used to fingerprint comet samples or least provide strong evidence of cometary origin for specific IDP, micrometeorite, and meteorite samples.

An extremely important and relatively new aspect of stratospheric cosmic dust collections is the specific targeting of collections to occur during the dust plane crossings of specific short period comets (Messenger 2002). These targeted collections have been successful and have returned remarkable samples with exceptionally high presolar grain contents (Busemann et al. 2009 and Floss et al. 2010). Targeted stratospheric collections can be effective comet sample return missions and cluster IDPs from these flights retain submicron components of the size that were usually destroyed during aerogel capture on the Stardust mission.

WILD 2 SOLIDS AND IMPLICATIONS FOR THE SURVIVAL OF PRESOLAR ORGANICS

The finding that isotopically anomalous presolar grains are rare in Wild 2 has profound implications for the survival of presolar organics. If nebular processes destroyed most of the presolar silicates, they almost surely destroyed most presolar organic materials. It is highly likely that presolar organic and rocky materials were mixed at fine scale and both components should have experienced the same transport and exposure to destructive environments. The rocky materials in Wild 2 must have been totally devoid of all volatiles after their high temperature origin, and ice and organics must have become associated with them at a later time. The presence of ice and organics in comets implies that these components formed in quite different environments than the rocky components. If vast quantities of refractory solids migrated to cold nebular regions, a reasonable expectation would be that much of ice would have condensed on them when they passed the snow line, the relatively warm and probably dense region when water could first condense to form ice. If this had happened, then much of the ice in comets like Wild 2 could have condensed at the highest possible condensation temperature. If organics coated migrating grains, did they do so before or after ice formation? Ice layers would presumably inhibit organic formation by catalytic reactions with nebular CO. If catalytic reactions occurred, they might have had to occur quickly before grains were transported to the snow line. Again, a great unknown here is the nature of the cometary submicron fines. Because of their poor preservation, it cannot be shown that the submicron fraction was not loaded with both presolar grains and presolar organics. We can only confidently say that these materials were not major materials in the > 2 μm size fraction.

CONCLUSIONS

The laboratory studies of samples from a known comet have provided profound sample-based insight into the nature of solid outer solar system materials and how they formed. Assuming that the sampled comet is a typical Jupiter family comet, the results paint a quite different picture of how planetesimals formed in the outer solar system than was imagined before the Stardust mission was flown. Their rocky components, often the majority of their mass, formed in high-temperature nebular environments that were quite distinct from the environments that produced their icy and organic materials. The materials were apparently transported over long distances to environments where they could accumulate to form ice-rich bodies. The sample results lead to a testable hypothesis that comet Wild 2 solids are a population of rocky materials that were distributed across the full breadth of the solar nebula. The hallmark signature of cometary rocky materials may be that they are a diverse set of materials whose nebular-related properties cover the full range of solids made in the solar nebula. It is reasonable to imagine that the materials that formed comets were derived from all dust-bearing regions of the early solar system. The comet solids are dominated by this component and the same solids are also found in asteroids that have produced meteorites, but they are highly diluted by locally produced materials.

We also predict that the dust and rocks from other comets will be similar to those that formed Wild 2 with the caveat that there might be an additional class of comets that are dominated by presolar grains. Such comets would have had to have been made during time periods when inner solar system materials were not abundantly transported to the edge of the solar system. If the majority of Kuiper belt bodies were made of the same solids that were found in Wild 2, then it is possible that these broadly distributed high-temperature rocky materials were also the basic building blocks of larger bodies such as Pluto, Eris, and even Triton, Neptune's irregular moon that may be a captured Kuiper belt object. An interesting aspect of this speculation is that the total mass of these larger KBOs exceeds that total mass of the asteroid belt by a considerable fraction. The total mass of meteoritic-like materials that formed in the solar nebula's hot "rock factories" and was then ejected into cold regions may have been quite substantial.

If comets that formed at the edge of the solar system are a reasonable proxy for the cold dust seen around other stars, then the lessons from Wild 2 provide intriguing insight into the general nature and origin of circumstellar dust. Formation of silicate materials in hot rock-forming regions close to stars may be the dominant source of circumstellar silicates that are observed to orbit stars similar to the Sun. Circumstellar crystalline silicates around stars (Takeuchi and Lin 2002; Van Boeckel et al. 2004; Oliveira et al. 2011) may have formed by high-temperature nebular processes and then carried outwards by a massive flow of a second generation of solids made by total transformation of the initial prestellar solid materials accreted from the interstellar medium. Instead of formation of crystalline material by mild subsolidius thermal annealing, these solids may have formed by processes related to condensation and chondrule formation. These were the major processes that formed solids in the Sun's asteroid region and were the major processes that produced the rocky materials that existed in the Kuiper belt region beyond Neptune.

The cumulative results of this mission reiterate the importance of sample return to primitive bodies. Without laboratory studies, often done at the micron and submicron scale, such complex materials could not possibly reveal key information such as the abundance of presolar grains and detailed records of early solar system processes. Stardust was limited because of restraints on submicron components that complicated the study of organics, presolar grains, and other fine components. The lack of millimeter size components complicates the comparison with meteoritic components such as chondrules and CAIs. The data from well-preserved samples clearly show that Wild 2 is an unequilibrated object at least as unaltered as type 3.0 chondrites. Wild 2 contains abundant materials that formed at high temperature, but the comet is a very primitive body in the sense that it appears to have excellently preserved its originally accreted solids. The evidence that comets are deep-frozen storage facilities of solids formed across the full width of the nebula supports the importance of future comet sample return missions. Future missions, with more capability than the Stardust flyby sample return mission, could collect many orders of magnitude more mass and collect it in a largely nondestructive manner. Such collections, even done at room temperature, would provide information on organics and fines and components in the chondrule to CAI size range. Detailed studies of these samples could provide unprecedented information on the chronology of nebular materials, their properties, and how they were transported across the solar nebula. They would also provide vital information on comet diversity and the origin of organic matter in comets.

Acknowledgments—We are indebted to NASA for funding the Stardust mission and its sample analysis program. We are eternally grateful for the efforts put into this endeavor by the entire Stardust mission team and the global team of researchers who are analyzing these unique samples. This contribution greatly benefited from detailed reviews by Scott Sandford and Brad DeGregorio.

Editorial Handling—Dr. Bradley De Gregorio

REFERENCES

A'Hearn M. F., Millis R. L., Schleicher D. G., Osip D. J., and Birch P. V. 1995. The ensemble properties of comets: Results from narrowband photometry of 85 comets, 19761992. *Icarus* 118:223–270.

A'Hearn M. F., Belton M. J. S., Delamere W. A., Feaga L. M., Hampton D, Kissel J., Klaasen K. P., McFadden L. A., Meech K. J., Melosh H. J., Schultz P. H., Sunshine J. M., Thomas P. C., Veverka J., Wellnitz D. D., Yeomans D. K., Besse S., Bodewits D., Bowling T. J., Carcich B. T., Collins S. M., Farnham T. L., Olivier G., Brendan H., Kelley M. S., Li J.-Y., Lindler D. J., Lisse C. M., McLaughlin S. A., Merlin F., Protopapa S., Richardson J. E., and Williams J. L. 2011. EPOXI at comet Hartley 2. *Science* 332:1396–1400.

Basilevsky A. T. and Keller H. U. 2006. Comet nuclei: Morphology and implied processes of surface modification. *Planetary and Space Science* 54:808–829.

Berger E. L., Zega T. J., Keller L. P., and Lauretta D. S. 2011. Evidence for aqueous activity on comet 81P/Wild 2 from sulfide mineral assemblages in Stardust samples and CI chondrites. *Geochimica et Cosmochimica Acta* 75:3501–3513.

Berlin J., Jones R. H., and Brearley A. J. 2011. Fe-Mn systematics of type IIA chondrules in unequilibrated CO, CR and ordinary chondrites. *Meteoritics & Planetary Science* 46:513–533.

Bockelee-Morvan D., Gautier D., Hersant F., Hure J.-M., and Robert F. 2002. Turbulent radial mixing in the solar nebula as the source of crystalline silicates in comets. *Astronomy & Astrophysics* 384:1107–1118.

Borovička J. 2007. Properties of meteoroids from different classes of parent bodies. In *Near earth objects, our celestial neighbors: opportunity and risk*, *Proceedings of IAU Symposium 236*, edited by Valsecchi G. B., Vokrouhlický D., and Milani A. Cambridge, UK: Cambridge University Press. pp. 107–120.

Boss A. P. 2008. Mixing in the solar nebula: Implications for isotopic heterogeneity and large-scale transport of refractory grains. *Earth and Planetary Science Letters* 268:102–109.

Bradley J. P. 1994. Nanometer-scale mineralogy and petrography of fine-grained aggregates in anhydrous interplanetary dust particles. *Geochimica et Cosmochimica Acta* 58:2123–2134.

Bradley J. P., Keller L. P., Snow T. P., Hanner M. S., Flynn G. J., Gezo J. C., Clemett S. J., Brownlee D. E., and Bowey J. E. 1999. An infrared spectral match between GEMS and interstellar grains. *Science* 285:1716–1718.

Bridges J. C. and Changela H. G. 2010. Chondrule fragments in Stardust tracks 113 and 154 (abstract #5280). *Meteoritics & Planetary Science* 45.

Brown M. E., Barkume K. M., Ragozzine D., and Schaller E. L. 2007. A collisional family of icy objects in the Kuiper belt. *Nature* 446:294–296.

Brown M. E., Schaller E. L., and Fraser W. C. 2011. A hypothesis for the color diversity of the Kuiper belt. *The Astrophysical Journal* 739:L60.

Brownlee D. E., Hörz F., Newburn R. L., Zolensky M., Duxbury T. C., Sandford S., Sekanina Z., Tsou P., Hanner M. S., Clark B. C., Green S. F., and Kissel J. 2004. Surface of young Jupiter family comet 81 P/Wild 2: View from the Stardust spacecraft. *Science* 304:1764–1769.

Brownlee D., Tsou P., Aleon J., Alexander C. M. O'D., Araki T., Bajt S., Baratta G. A., Bastien R., Bland P., Bleuet P., Borg J., Bradley J. P., Brearley A., Brenker F., Brennan S., Bridges J. C., Browning N. D., Brucato J. R., Bullock E., Burchell M. J., Busemann H., Butterworth A., Chaussidon M., Cheuvront A., Chi M., Cintala M. J., Clark B. C., Clemett S. J., Cody G., Colangeli L., Cooper G., Cordier P., Daghlian C., Dai Z., D'Hendecourt L., Djouadi Z., Dominguez G., Duxbury T., Dworkin J. P., Ebel D. S., Economou T. E., Fakra S., Fairey S. A.J., Fallon S., Ferrini G., Ferroir T., Fleckenstein H., Floss C., Flynn G., Franchi I. A., Fries M., Gainsforth Z., Gallien J.-P., Genge M., Gilles M. K., Gillet P., Gilmour J., Glavin D. P., Gounelle M., Grady M. M., Graham G. A., Grant P. G., Green S. F., Grossemy F., Grossman L., Grossman J. N., Guan Y., Hagiya K., Harvey R., Heck P., Herzog G. F., Hoppe P., Horz F., Huth J., Hutcheon I. D., Ignatyev K., Ishii H., Ito M., Jacob D., Jacobsen C., Jacobsen S., Jones S., Joswiak D., Jurewicz A., Kearsley A. T., Keller L. P., Khodja H., Kilcoyne A. L. D., Kissel J., Krot A., Langenhorst F., Lanzirotti A., Le L., Leshin L. A., Leitner J., Lemelle L., Leroux H., Liu M.-C., Luening K., Lyon I., MacPherson G., Marcus M. A., Marhas K., Marty B., Matrajt G., McKeegan K., Meibom A., Mennella V., Messenger K., Messenger S., Mikouchi T., Mostefaoui S., Nakamura T., Nakano T., Newville M., Nittler L. R., Ohnishi I., Ohsumi K., Okudaira K., Papanastassiou D. A., Palma R., Palumbo M. E., Pepin R. O., Perkins D., Perronnet M., Pianetta P., Rao W., Rietmeijer F. J. M., Robert F., Rost D., Rotundi A., Ryan R., Sandford S. A., Schwandt C. S., See T. H., Schlutter D., Sheffield-Parker J., Simionovici A., Simon S., Sitnitsky I., Snead C. J., Spencer M. K., Stadermann F. J., Steele A., Stephan T., Stroud R., Susini J., Sutton S. R., Suzuki Y., Taheri M., Taylor S., Teslich N., Tomeoka K., Tomioka N., Toppani A., Trigo-Rodríguez J. M., Troadec D., Tsuchiyama A., Tuzzolino A. J., Tyliszczak T., Uesugi K., Velbel M., Vellenga J., Vicenzi E., Vincze L., Warren J., Weber I., Weisberg M., Westphal A. J., Wirick S., Wooden D., Wopenka B., Wozniakiewicz P., Wright I., Yabuta H., Yano H., Young E. D., Zare R. N., Zega T., Ziegler K., Zimmerman L., Zinner E., and Zolensky M. 2006. Comet 81P/Wild 2 under a microscope. *Science* 314:1711–1716.

Burchell M. J., Fairey S. A. J., Wozniakiewicz P., Brownlee D. E., Horz F., Kearsley A. T., See T. H., Tsou P., Westphal A., Green S. F., Trigo-Rodríguez J. M., and Dominguez G. 2008. Characteristics of cometary dust tracks in Stardust aerogel and laboratory calibrations. *Meteoritics & Planetary Science* 43:23–40.

Busemann H., Nguyen A. N., Cody G. D., Hoppe P., Kilcoyne A. L. D., Stroud R. M., Zega T. J., and Nittler L. R. 2009. Ultra-primitive interplanetary dust particles from the comet 26P/Grigg-Skjellerup dust stream collection. *Earth and Planetary Science Letters* 288:44–57.

Butterworth A. L., Gainsforth Z., Bauville A., Bonal L., Brownlee D. E., Fakra S. C., Huss G. R., Joswiak D., Kunz M., Marcus M. A., Nagashima K., Ogliore R. C., Tamura N., Telus M., Tyliszczak T., and Westphal A. J. 2010. A Type IIA chondrule fragment from comet 81P/Wild 2 in stardust track C2052,2,74 (abstract #2446). 41st Lunar and Planetary Institute Science Conference. CD-ROM.

Ciesla F. J. 2007. Outward transport of high-temperature materials around the midplane of the solar nebula. *Science* 318:613–615.

Ciesla F. J. 2009. Two-dimensional transport of solids in viscous protoplanetary disks. *Icarus* 200:655–671.

Ciesla F. J. 2010. Residence times of particles in diffusive protoplanetary disk environments. I. Vertical motions. *The Astrophysical Journal* 723:514–529.

Cody G., Heying E., Alexander C. M. O'D., Nittler L. R., Kilcoyne A. L. D., Sandford S. A., and Stroud R. M. 2011. Establishing a molecular relationship between chondritic and cometary organic solids. *Proceedings of the National Academy of Sciences* 108:19171–19176.

Cuzzi J. N., Hogan R. C., and Shariff K. 2008. Toward planetesimals: Dense chondrule clumps in the protoplanetary nebula. *The Astrophysical Journal* 687:1432–1447.

De Gregorio B. T., Stroud R. M., Cody G. D., Nittler L. R., Kilcoyne A. L. D., and Wirick S. 2011. Correlated microanalysis of cometary organic grains returned by Stardust. *Meteoritics & Planetary Science* 46:1376–1396.

Dermott S. F., Durda D. D., Grogan K., and Kehoe T. J. J. 2002. Asteroidal Dust. In *Asteroids III*, edited by Bottke W. F. Jr., Cellino A., Paolicchi P., and Binzel R. P. Tucson, AZ: The University of Arizona Press. pp. 423–442.

De Val-Borro M., Hartogh P., Crovisier J., Bockelee-Morvan D., Biver N., Lis D. C., Moreno R., Jarchow C., Rengel M., Szutowicz S., Banaszkiewicz M., Bensch F., Blecka M. I., Emprechtinger M., Encrenaz T., Jehin E., Kuppers M., Lara L.-M., Lellouch E., Swinyard B. M., Vandenbussche B., Bergin E. A., Blake G. A., Blommaert J. A. D. L., Cernicharo J., Decin L., Encrenaz P., de Graauw T., Hutsemekers D., Kidger M., Manfroid J., Medvedev A. S., Naylor D. A., Schieder R., Stam D., Thomas N., Waelkens C., Szczerba R., Saraceno P., di Giorgio A. M., Philipp S., Klein T., Ossenkopf V., Zaal P., and Shipman R. 2010. Water production in comet 81P/Wild 2 as determined by Herschel/HIFI. *Astronomy & Astrophysics* 521:L50–L50.

Dobrica E., Engrand C., Duprat J., Gounelle M., Leroux H., Quirico E., and Rouzaud J. N. 2009. Connection between micrometeorites and Wild 2 particles: From Antarctic snow to cometary ices. *Meteoritics & Planetary Science* 44:1643–1661.

Duncan M., Levison H., and Dones L. 2004. Dynamical evolution of ecliptic comets. In *Comets II*, edited by Festou M. C., Keller H. U., Weaver H. Tucson, AZ: The University of Arizona Press. pp. 193–204.

Elsila J. E., Glavin D. P., and Dworkin J. P. 2009. Cometary glycine detected in samples returned by Stardust. *Meteoritics & Planetary Science* 44:1323–1330.

Farnham T. L. and Schleicher D. G. 2005. Physical and compositional studies of Comet 81P/Wild 2 at multiple apparitions. *Icarus* 173:533–558.

Fink U., Hicks M. P., and Fevig R. A. 1999. Production rates for the Stardust mission target: 81P/Wild 2. *Icarus* 141:331–340.

Floss C., Stadermann F. J., Mertz A. F., and Bernatowicz T. J. 2010. A NanoSIMS and Auger Nanoprobe investigation of an isotopically primitive interplanetary dust particle from the 55P/Tempel-Tuttle targeted stratospheric dust collector. *Meteoritics & Planetary Science* 45:1889–1905.

Flynn G. J., Wirick S., Keller L. P., and Jacobsen C. 2009. STXM search for carbonate in samples of Comet 81P/Wild 2. *Journal of Physics Conference Series* 186:012085.

Frank D. and Zolensky M. 2010. A mineralogical comparison of Stardust Wild 2 grains and carbonaceous chondrites (abstract #5411). *Meteoritics & Planetary Science* 45.

Gainsforth Z., Butterworth A. L., Bonal L., Brownlee D. E., Huss G. R., Joswiak D., Ogliore R. C., Telus M., Tyliczszak T., and Westphal A. J. 2010. Coordinated TEM/STXM/IMS analysis of a type IIA chondrule fragment from Comet 81P/Wild 2 Stardust track C2052,2,74. *Meteoritics & Planetary Science Supplement* 73:5428.

Gounelle M. 2011. The asteroid comet continuum: In search of lost primitivity. *Elements* 7:29–34.

Gounelle M., Morbidelli A., Bland P. A., Spurný P., Young E. D., and Sephton M. 2008. Meteorites from the outer solar system? The solar system beyond Neptune. In *The solar system beyond Neptune*, edited by Barucci M.A., Boehnhardt H., Cruikshank D. P., and Morbidelli A. Tucson, AZ: The University of Arizona Press. pp. 525–541.

Green S. F., McBride N., Colwell M. T. S. H., McDonnell J. A. M., Tuzzolino A. J., Economou T. E., Clark B. C., Sekanina Z., Tsou P., and Brownlee D. E. 2007. Stardust Wild 2 dust measurements.In *Dust in planetary systems*, edited by Krueger H. and Graps A. Workshop on Dust in Planetary Systems (ESA SP-643). September 26–30 2005. Kauai, Hawaii. Noordwijk, The Netherlands: ESTEC. pp. 35–44.

Greenberg J. M. and Li A. 1999. All comets are born equal: Infrared emission by dust as a key to comet nucleus composition. *Planetary and Space Science* 47:787–795.

Grossman J. N. and Brearley A. J. 2005. The onset of metamorphism in ordinary and carbonaceous chondrites. *Meteoritics & Planetary Science* 40:87–122.

Hanner M. S., and Zolensky M. E. 2010. The mineralogy of cometary dust. In *Lecture notes in physics*, vol. 815, edited by Henning T. Berlin: Springer Verlag. pp. 203–232.

Harker D. E. and Desch S. J. 2002. Annealing of silicate dust by nebular shocks at 10 AU. *The Astrophysical Journal* 565:L109–L112.

Hewins R. H. and Radomsky P. M. 1990. Temperature conditions for chondrule formation. *Meteoritics* 25:309–318.

Hewins R. H., Zanda B., and Bourot-Denise M. 2011. The formation of Type II chondrules in CM chondrites (abstract #1914). 42nd Lunar and Planetary Science Conference. CD-ROM.

Hoppe P. 2010. *Stardust in primitive solar system materials*. Proceedings, American Institute of Physics Conference Series 1213, pp. 84–94.

Hsieh H. H. and Jewitt D. 2006. A population of comets in the main asteroid belt. *Science* 312:561–563.

Ishii H. A., Bradley J. P., Dai Z. R., Chi M., Kearsley A. T., Burchell M. J., Browning N. D., and Molster F. 2008. Comparison of comet 81P/Wild 2 dust with interplanetary dust from comets, *Science* 25:447–450.

Jacob D., Stodolna J., Leroux H., Langenhorst F., and Houdellier F. 2009. Pyroxenes microstructure in comet 81P/Wild 2 terminal Stardust particles. *Meteoritics & Planetary Science* 44:1475–1488.

Joswiak D. J., Brownlee D. E., Matrajt G., Westphal A. J., and Snead C. J. 2009. Kosmochloric Ca-rich pyroxenes and FeO-rich olivines (Kool grains) and associated phases in Stardust tracks and chondritic porous interplanetary dust particles: Possible precursors to FeO-rich type II chondrules in ordinary chondrites. *Meteoritics & Planetary Science* 44:1561–1588.

Joswiak D. J., Brownlee D. E., Matrajt G., Messenger S. M., and Ito M. 2010. Stardust track 130 terminal particle: Possible Al-rich chondrule fragment or altered amoeboid olivine aggregate (abstract #2119). 41st Lunar and Planetary Science Conference. CD-ROM.

Joswiak D. J., Brownlee D. E., and Matrajt G. 2012. Comprehensive examination of large mineral and rock fragments in Stardust tracks: Mineralogy, analog extraterrestrial materials and source regions. *Meteoritics & Planetary Science* 47:1–52.

Keller C. and Gail H.-P. 2004. Radial mixing in protoplanetary accretion disks. VI. Mixing by large-scale radial flows. *Astronomy & Astrophysics* 415:1177–1185.

Keller L. P. and Messenger S. 2009. Equilibrated aggregates in cometary IDPs: Insights into the crystallization process in protoplanetary disks (abstract #2121). 40th Lunar and Planetary Institute Science Conference. CD-ROM.

Kemper F., Vriend W. J., and Tielens A. G. G. M. 2005. Erratum: "The Absence of Crystalline Silicates in the Diffuse Interstellar Medium." *The Astrophysical Journal* 633:534–534.

Kirk R. L., Duxbury T. C., Horz F., Brownlee D. E., Newburn R. L., and Tsou P. The Stardust Team. 2005. Topography of the 81/P Wild 2 nucleus derived from Stardust stereoimages (abstract #2244). Proceedings, 36th Lunar and Planetary Science Conference. CD-ROM.

Knight M. M. and Schleicher D. G. 2010. Dust and gas morphology of Comets 81P/Wild 2, 10P/Tempel 2, and 103P/Hartley 2. *Bulletin of the American Astronomical Society* 42:965.

Leinhardt Z. M., Marcus R. A., and Stewart S. T. 2010. The Formation of the collisional family around the dwarf planet Haumea. *The Astrophysical Journal* 714:1789–1799.

Leitner J., Hoppe P., and Heck P. R. 2010. First discovery of presolar material of possible supernova origin in impact residues from Comet 81P/Wild 2 (abstract #1607). 41st Lunar and Planetary Science Conference. CD-ROM.

Levison H. F. and Duncan M. J. 1997. From the Kuiper belt to Jupiter-family comets: The spatial distribution of ecliptic comets. *Icarus* 127:13–32.

Levison H. F., Morbidelli A., Tsiganis K., Nesvorne D., and Gomes R. 2011. Late orbital instabilities in the outer planets induced by interaction with a self-gravitating planetesimal disk. *The Astronomical Journal* 142:152–163.

Libourel G. and Chaussidon M. 2011. Oxygen isotopic constraints on the origin of Mg-rich olivines from chondritic meteorites. *Earth and Planetary Science Letters* 301:9–21.

Lisse C. M., VanCleve J., Adams A. C., A'Hearn M. F., Fernandez Y. R., Farnham T. L., Armus L., Grillmair C. J., Ingalls J., Belton M. J. S., Groussin O., McFadden L. A., Meech K. J., Schultz P. H., Clark B. C., Feaga L. M., and Sunshine J. M. 2006. Spitzer spectral observations of the deep impact ejecta. *Science* 313:635–640.

Matzel J. E. P., Ishii H. A., Joswiak D., Hutcheon I. D., Bradley J. P., Brownlee D., Weber P. K., Teslich N., Matrajt G., McKeegan K. D., and MacPherson G. J. 2010. Constraints on the formation age of cometary material from the NASA Stardust mission. *Science* 328:483–486.

McKeegan K. D., Aleon J., Bradley J., Brownlee D., Busemann H., Butterworth A., Chaussidon M., Fallon S., Floss C., Gilmour J., Gounelle M., Graham G., Guan Y., Heck P. R., Hoppe P., Hutcheon I. D., Huth J., Ishii H., Ito M., Jacobsen S. B., Kearsley A., Leshin L. A., Liu

M.-C., Lyon I., Marhas K., Marty B., Matrajt G., Meibom A., Messenger S., Mostefaoui S., Mukhopadhyay S., Nakamura-Messenger K., Nittler L., Palma R., Pepin R. O., Papanastassiou D. A., Robert F., Schlutter D., Snead C. J., Stadermann F. J., Stroud R., Tsou P., Westphal A., Young E. D., Ziegler K., Zimmermann L., and Zinner E. 2006. Isotopic compositions of cometary matter returned by Stardust. *Science* 314:1724–1728.

Messenger S. 2002. Opportunities for the stratospheric collection of dust from short-period comets. *Meteoritics & Planetary Science* 37:1491–1506.

Messenger S., Joswiak D., Ito M., Matrajt G., and Brownlee D. E. 2009. Discovery of presolar SiC from Comet Wild 2 (abstract #1790). 40th Lunar and Planetary Science Conference. CD-ROM.

Nakamura T., Noguchi T., Tsuchiyama A., Ushikubo T., Kita N. T., Valley J. W., Zolensky M. E., Kakazu Y., Sakamoto K., Mashio E., Uesugi K., and Nakano T. 2008. Chondrule-like objects in short-period comet 81P/Wild 2. *Science* 321:1664–1667.

Nakamura T., Noguchi T., Tsuchiyama A., Ushikubo T., Kita N. T., Valley J. W., Takahata N., Sano Y., Zolensky M. E., Kakazu Y., Uesugi K., and Nakano T. 2009. Additional evidence for the presence of chondrules in comet 81P/Wild 2. (abstract #5304). *Meteoritics & Planetary Science* 44.

Nesvorný D. 2011. Young solar system's fifth giant planet? *The Astrophysical Journal* 742:L22.

Nesvorný D., Jenniskens P., Levison H. F., Bottke W. F., Vokrouhlicky D., and Gounelle M. 2010. Cometary origin of the zodiacal cloud and carbonaceous micrometeorites, implications for hot debris disks. *The Astrophysical Journal* 713:816–836.

Niimi R., Kadono T., Arakawa M., Yasui M., Dohi K., Nakamura A.M., Iida Y., and Tsuchiyama A. 2011. In situ observation of penetration process in silica aerogel: Deceleration mechanism of hard spherical projectiles. *Icarus* 211:986–992.

Ogliore R. C., Huss G. R., Nagashima K., Butterworth A. L., Gainsforth Z., Stodolna Z. J., Westphal A. J., Joswiak D., and Tyliszczak T. 2012. Incorporation of a late-forming chondrule into Comet Wild 2. *Astrophysical Journal Letters* 745:L19.

Oliveira I., Olofsson J., Pontoppidan K. M., Van Dishoeck E. F., Augereau J.-C., and Mern B. 2011. On the evolution of dust mineralogy, from protoplanetary disks to planetary systems. *The Astrophysical Journal* 734:51.

Poteet C. A., Megeath S. T., Watson D. M., Calvet N., Remming I. S., McClure M. K., Sargent B. A., Fischer W. J., Furlan E., Allen L. E., Bjorkman J. E., Hartmann L., Muzerolle J., Tobin J. J., and Ali B. 2011. A Spitzer infrared spectrograph detection of crystalline silicates in a protostellar envelope. *The Astrophysical Journal* 733: L32.

Price M. C., Kearsley A. T., Burchell M. J., Horz F., Borg J., Bridges J. C., Cole M. J., Floss C., Graham G., Green S. F., Hoppe P., Leroux H., Marhas K. K., Park N., Stroud R., Stadermann F. J., Telisch N., and Wozniakiewicz P. J. 2010. Comet 81P/Wild 2: The size distribution of finer (sub-10 μm) dust collected by the Stardust spacecraft. *Meteoritics & Planetary Science* 45:1409–1428.

Rietmeijer F. J. M. 2009. Stardust glass: Indigenous and modified comet Wild 2 particles. *Meteoritics & Planetary Science* 44:1707–1715.

Sandford S. A., Aleon J., Alexander C. M. O'D., Araki T., Bajt S., Baratta G. A., Borg J., Bradley J. P., Brownlee D. E., Brucato J. R., Burchell M. J., Busemann H., Butterworth A., Clemett S. J., Cody G., Colangeli L., Cooper G., D'Hendecourt L., Djouadi Z., Dworkin J. P., Ferrini G., Fleckenstein H., Flynn G. J., Franchi I. A., Fries M., Gilles M. K., Glavin D. P., Gounelle M., Grossemy F., Jacobsen C., Keller L. P., Kilcoyne A. L. D., Leitner J., Matrajt G., Meibom A., Mennella V., Mostefaoui S., Nittler L. R., Palumbo M. E., Papanastassiou D. A., Robert F., Rotundi A., Snead C. J., Spencer M. K., Stadermann F. J., Steele A., Stephan T., Tsou P., Tyliszczak T., Westphal A. J., Wirick S., Wopenka B., Yabuta H., Zare R. N., and Zolensky M. E. 2006. Organics captured from comet 81P/Wild 2 by the Stardust spacecraft. *Science* 314:1720.

Sekanina Z., Brownlee D. E., Economou T. E., Tuzzolino A. J., and Green S. F. 2004. Modeling the nucleus and jets of comet 81P/Wild 2 based on the Stardust encounter data. *Science* 304:1769–1774.

Shu F. H., Shang H., and Lee T. 1996. Toward an astrophysical theory of chondrites. *Science* 271:1545–1552.

Shu F. H., Shang H., Gounelle M., Glassgold A. E., and Lee T. 2001. The origin of chondrules and refractory inclusions in chondritic meteorites. *The Astrophysical Journal* 548:1029–1050.

Simon S. B., Joswiak D. J., Ishii H. A., Bradley J. P., Chi M., Grossman L., Aleon J., Brownlee D. E., Fallon S., Hutcheon I. D., Matrajt G., and McKeegan K. D. 2008. A refractory inclusion returned by Stardust from comet 81P/Wild 2. *Meteoritics & Planetary Science* 43:1861–1877.

Stadermann F. J. and Floss C. 2008. Abundance of presolar grains in comet Wild 2 and implications for transport and mixing in the solar nebula (abstract #1889). 39th Lunar and Planetary Science Conference. CD-ROM.

Stadermann F. J., Floss C., Gavinsky A., Kearsley A. T., and Burchell M. J. 2009a. Calibrating the abundance determinations of presolar grains in Wild 2 cometary matter (abstract #1188). 40th Lunar and Planetary Science Conference. CD-ROM.

Stadermann F. J., Floss C., Kearsley A. T., and Burchell M. J. 2009b. Why are there so few presolar grains in samples from comet Wild 2? *Geochimica et Cosmochimica Acta Supplement* 73:1262.

Stodolna J., Jacob D., and Leroux H. 2010. Mineralogy of Stardust Track 80: Evidences for aqueous alteration and igneous process (abstract #1657). 41st Lunar and Planetary Science Conference. CD-ROM.

Takeuchi T. and Lin D. N. C. 2002. Radial flow of dust particles in accretion disks. *The Astrophysical Journal* 581:1344–1355.

Thomas N. 2009. The nuclei of Jupiter family comets: A critical review of our present knowledge. *Planetary and Space Science* 57:1106–1117.

Trigo-Rodríguez J. M., Dominguez G., Burchell M. J., Horz F., and Llorca J. 2008. Bulbous tracks arising from hypervelocity capture in aerogel. *Meteoritics & Planetary Science* 43:75–86.

Tsuchiyama A., Mashio E., Imai Y., Noguchi T., Miura Y., Yano H., and Nakamura T. 2009. Strength measurement of carbonaceous chondrites and micrometeorites using micro compression testing machine. *Meteoritics & Planetary Science Supplement* 72:5189.

Van Boekel R., Min M., Leinert C., Waters L. B. F. M., Richichi A., Chesneau O., Dominik C., Jaffe W., Dutrey A., Graser U., Henning T., de Jong J., Köhler R., de Koter A., Lopez B., Malbet F., Morel S., Paresce F., Perrin G., Preibisch T., Przygodda F., Scholler M., and Wittkowski M. 2004. The building blocks of planets within the "terrestrial" region of protoplanetary disks. *Nature* 432:479–482.

Walsh K. J., Morbidelli A., Raymond S. N., O'Brien D. P., and Mandell A. M. 2011. A low mass for Mars from Jupiter's early gas-driven migration. *Nature* 475:206–209.

Wickramasinghe J. T., Wickramasinghe N. C., and Wallis M. K. 2009. Liquid water and organics in comets: Implications for exobiology. *International Journal of Astrobiology* 8:281–290.

Wooden D., Desch S., Harker D., Gail H.-P., and Keller L. 2007. Comet grains and implications for heating and radial mixing in the protoplanetary disk. In *Protostars and planets V*, edited by Reipurth V. B., Jewitt D., and Keil K. Tucson, AZ: University of Arizona Press. pp. 815–833.

Wozniakiewicz P. J., Ishii H. A., Kearsley A. T., Burchell M. J., Bradley J. P., Teslich N., and Cole M. J. 2010. Survivability of Cometary Phyllosilicates in Stardust Collections and Implications for the Nature of Comets (abstract #2357). 41st Lunar and Planetary Science Conference. CD-ROM.

Yurimoto H., Abe K., Abe M., Ebihara M., Fujimura A., Hashiguchi M., Hashizume K., Ireland T. R., Itoh S., Katayama J., Kato C., Kawaguchi J., Kawasaki N., Kitajima F., Kobayashi S., Meike T., Mukai T., Nagao K., Nakamura T., Naraoka H., Noguchi T., Okazaki R., Park C., Sakamoto N., Seto Y., Takei M., Tsuchiyama A., Uesugi M., Wakaki S., Yada T., Yamamoto K., Yoshikawa M., and Zolensky M. E. 2011. Oxygen isotopic compositions of asteroidal materials returned from Itokawa by the Hayabusa mission. *Science* 333:1116–1119.

Zanda B., Bourot-Denise M., Hewins R. H., Barrat J. A., and Gattacceca J. 2010. The Paris CM chondrite yields new insights on the onset of parent body alteration (abstract #5312). *Meteoritics & Planetary Science* 45.

Zolensky M. E., Zega T. J., Yano H., Wirick S., Westphal A. J., Weisberg M. K., Weber I., Warren J. L., Velbel M. A., Tsuchiyama A., Tsou P., Toppani A., Tomioka N., Tomeoka K., Teslich N., Taheri M., Susini J., Stroud R., Stephan T., Stadermann F. J., Snead C. J., Simon S. B., Simionovici A., See T. H., Robert F., Rietmeijer F. J. M., Rao W., Perronnet M. C., Papanastassiou D. A., Okudaira K., Ohsumi K., Ohnishi I., Nakamura-Messenger K., Nakamura T., Mostefaoui S., Mikouchi T., Meibom A., Matrajt G., Marcus M. A., Leroux H., Lemelle L., Le L., Lanzirotti A., Langenhorst F., Krot A. N., Keller L. P., Kearsley A. T., Joswiak D., Jacob D., Ishii H., Harvey R., Hagiya K., Grossman L., Grossman J. N., Graham G. A., Gounelle M., Gillet P., Genge M. J., Flynn G., Ferroir T., Fallon S., Ebel D. S., Dai Z. R., Cordier P., Clark B., Chi M., Butterworth A. L., Brownlee D. E., Bridges J. C., Brennan S., Brearley A., Bradley J. P., Bleuet P., Bland P. A., and Bastien R. 2006. Mineralogy and petrology of comet 81P/Wild 2 nucleus samples. *Science* 314:1735–1739.