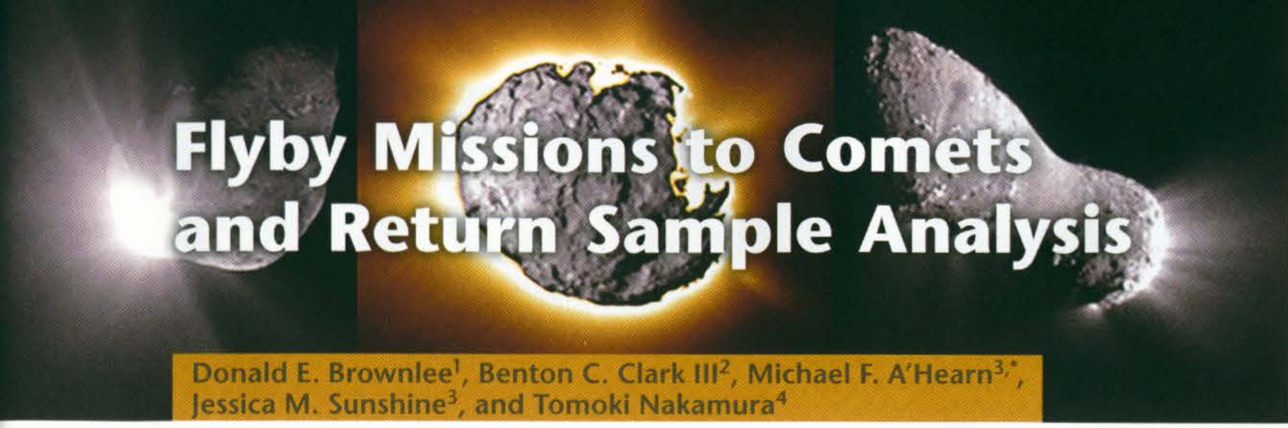

Flyby Missions to Comets and Return Sample Analysis

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Images from flyby missions show comets to be geomorphically diverse bodies that spew jets of gas, dust, and rocks into space. Comet surfaces differ from other small bodies because of their ejection of mass into space. Comet solids >2 µm are similar to primitive meteorite ingredients and include the highest temperature materials made in the early solar system. The presence of these materials in ice-rich comets is strong evidence for large-scale migration of solid grains in the early solar system. Cometary silicates appear to have formed in numerous hot solar system regions. Preserved interstellar grains are rare, unless they have eluded identification by having solar isotopic compositions.

Keywords: comet, meteorite, asteroid, cosmic dust, interstellar, isotope, spacecraft

INTRODUCTION

When they pass through the inner solar system, comets brighten and, with increased heating, they become progressively active with ejection of gas, dust, and rocks into space at rates up to thousands of tons each second. Although an impressive body of information has been obtained from telescopic observations, these observations largely relate to the gas and dust that surrounds active comets, as well as material in comet's tails. Comet tails are the largest visible solar system features. Debris escaping comets is readily seen, but the actual comet nucleus is not. It is a dark body of rocky/icy material, which is typically only a few kilometers across and hidden inside a cloud of dust. Detailed study of actual cometary bodies, what they are made of and how they evolve, requires close-up investigation by spacecraft.

Prior to the investigation of comet 67P/Churyumov–Gerasimenko by the European Space Agency's *Rosetta* mission (Grady et al. 2018 this issue), there had been close encounters with six other comets (Fig. 1). *Rosetta* included both a rendezvous spacecraft for extended measurements near the comet and a lander, whereas all previous missions had been flybys. In addition to the close flybys, the Japanese missions *Suisei* and *Sakigake* completed distant flybys of comet 1P/Halley in 1986. The first spacecraft encounter with a comet was the *International Cometary Explorer (ICE)* that flew through the ion tail of 21P/Giacobini–Zinner in 1985.

The close flyby missions discussed here provided the first direct data on comet nuclei (Table 1). The visited bodies contain ices as volatile as carbon monoxide, and the visited comets are surviving members of a formerly vast population of small icy bodies that formed in cold regions of the early solar system. Some estimates of the total mass of the original population exceed 30 Earth masses (Gomes et al. 2005). With the exception of 1P/Halley, the investigated bodies are Jupiter-family comets that have ~6 year orbital periods. They cannot survive long in these small orbits due to solar heating and gravitational perturbation by Jupiter. Previously, they traveled around the Sun completely beyond Neptune for over four billion years but now they travel on much smaller orbits. The visited comets all appear to be small pristine bodies that are collections of ice and dust particles, not fragments of larger, thermally processed, bodies. Some comets might be collisional fragments of ice-rich bodies as sizable as Pluto, the largest body beyond Neptune. Prior residence inside a large body would likely result in thermal and hydrous alteration of original materials and separation of ice and dust.

Table 1 CLOSE-FLYBY COMET MISSIONS IN WHICH DIRECT DATA ON COMET NUCLEI WERE COLLECTED

Comet	Mission/ Spacecraft	Flyby Date	Orbital Period (years)	Comet Diameter (km)
1P/Halley	*Vega 1, Vega 2, Giotto*	1986	75	11
26P/ Grigg–Skjellerup	*Giotto*	1992	5.3	2.6*
19P/Borrelly	*Deep Space 1*	2001	6.8	5
81P/Wild 2	*Stardust*	2004	6.4	4.5
9P/Tempel 1	*Deep Impact*	2005	5.5	6
103P/Hartley 2	*Deep Impact (EPOXI)*	2010	6.5	2.3
9P/Tempel 1	*Stardust NExT*	2011	5.5	6

* estimated

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Figure 1 Images collected by flyby missions to five comets. The comet surfaces – 1P/Halley, 19P/Borrelly, 81P/Wild 2, 103P/Hartley 2, and 9P/Tempel 1 – show remarkable diversity in morphologies. Long photographic exposures showed jets of escaping dust from all five comets. A sixth comet, 26P/Grigg–Skjellerup, was visited by *Giotto* in 1992 but many of *Giotto*'s instruments, including the camera, were damaged and no flyby images were collected. Credit: NASA and ESA.

COMETS VISITED BY FLYBY MISSIONS

1P/Halley

The Soviet *Vega* and European *Giotto* flybys of 1P/Halley (commonly called "Halley's Comet") in 1986 provided images along with gas/dust composition, plasma, and magnetic-field measurements. The images, the first of a comet nucleus, revealed Halley to be an elongated body silhouetted against a background of escaping dust illuminated by sunlight. The images showed prominent jets of escaping dust but only limited information on surface features. Dust flux and particle size distribution were measured by impact sensors, and elemental compositions of individual particles were measured by time-of-flight mass spectrometers detecting ions produced by the ~70 km/s impact of comet dust on metal targets. The data provided the first direct measurements of the composition of cometary dust (Kissel et al. 1986). Particle compositions ranged in a somewhat continuous manner from pure organic materials to silicate components. The organic components were called CHON because of their high abundances of carbon, hydrogen, oxygen, and nitrogen (Clark et al. 1987).

Although the time-of-flight mass spectrometers could not be calibrated by laboratory methods that duplicated flyby conditions, the bulk mean elemental composition of rock-forming elements in the impacting particles were consistent with the bulk composition of primitive meteorites (Schulze et al. 1997). The broad scatter of elemental compositions of micron-sized particles could be due to the presence of amorphous materials, blending of submicron components, or instrumental factors related to ion production by very high-speed impacts of micron-size particles.

26P/Grigg–Skjellerup

26P/Grigg–Skjellerup was visited by *Giotto* in 1992 but many of the spacecraft's instruments, including the camera, were inoperable due to damage during its previous encounter with 1P/Halley. Measurements made included dust impacts and particle and magnetic field data.

19P/Borrelly

NASA's *Deep Space 1* was built to test ion propulsion and a dozen other new technologies. It flew past an asteroid and then completed a highly successful 2,200 km flyby of comet 19P/Borrelly in 2001. Returned images of the "chicken leg"-shaped comet provided unprecedented spatial resolution of the comet's surface. The images showed linear features that appeared to be ridges and fractures, dark areas, mesas, smooth terrain, and mottled terrain. The mission images were used to produce a detailed geological map of the comet's surface. Spectra (1.3–2.6 μm) of the surface revealed possible nitrogen-bearing organic molecules, but no evidence for water ice (Soderblom et al. 2004). Comet 19P/Borelly is particularly interesting because it is the prototype of a class of comets whose spectra show depletion of C_2, C_3 and longer-chain hydrocarbons relative to comet 1P/Halley but have abundances of NH_2 that are similar to 1P/Halley (A'Hearn et al. 1995). All of the comets that have been visited, except 1P/Halley, are like 19P/Borrelly and are considered "carbon depleted".

81P/Wild 2

In 2004, comet 81P/Wild 2 (commonly called "Wild 2") was visited by *Stardust*, a mission that was strongly focused on collecting solid samples and returning these to Earth for laboratory analysis. The particulate samples were collected at 6.1 km/s by impact into ultra-low-density silica aerogel, a nanoporous material that can decelerate micron and larger silicate grains without heating them to their melting points. The *Stardust* mission collected rocky and organic material, but it could not collect ice. Besides collection of thousands of particles in aerogel, *Stardust* also included a time-of-flight particle impact mass spectrometer and dust counters, which demonstrated in-flight disaggregation of slow-moving particles that were released from the nucleus and then fragmented into lumpy coma streams (Clark et al. 2004). During the 234 km flyby, stereo images having a resolution up to 12 m/pixel were taken. The surface was exceedingly rough, with ridges, cliffs, spires, and deep depressions with flat floors and near vertical walls. Unlike the other imaged comets, 81P/Wild 2 did not have major smooth regions. Although the nucleus was covered with depressions up to a kilometer in size, all features appeared to be the products of cometary activity rather than impacts by external bodies.

The thousands of returned comet particles provided a unique means of studying comets. The analyses began with an international team of 200 investigators using state-of-the-art laboratory capabilities that had evolved from a long heritage of investigating extraterrestrial materials, including lunar samples, meteorites, and cosmic dust. One of the very first findings was that the shape of the aerogel capture-track cavities indicated that cometary particles ranged from strong solid rock fragments at least as large as 50 μm to delicate clusters of fine components that disaggregated during capture (Burchell et al. 2008). Strong solid particles produced thin carrot-shaped tracks as they decelerated, whereas aggregate materials fragmented and produced wider tracks that ranged from the shape of beets to ginseng.

With expectations that comets contained high abundances of interstellar grains (Greenberg 1986), it was a surprise that essentially all of the components that traveled to deep levels in capture tracks were closely related to solar system materials found in primitive meteorites. Nearly all of the cometary silicates have solar system oxygen isotope compositions. Oxygen isotopes in some 81P/Wild 2 components show ^{16}O enrichments that link them to rare ^{16}O-rich reservoirs present during the early solar system (Defouilloy et al. 2017). Detailed analyses of minor elements in 81P/Wild 2 olivine imply formation over a wider range of conditions than those in any particular meteorite class (Frank et al. 2014; Brownlee and Joswiak 2017).

9P/Tempel 1

The comet 9P/Tempel 1 (commonly called "Tempel 1") was literally the target of the *Deep Impact* mission. Before the flyby, the main spacecraft released a "smart" 370 kg impactor. Hitting at 10.2 km/s, it delivered the energy of 5 tons of TNT. The main spacecraft observed the light flash, which lasted less than a second. Great amounts of subsurface material were lifted and where observed with Earth- and with space-based telescopes. The ejected debris prevented imaging of the crater, but that crater was observed six years later when the extended *Stardust* mission (*Stardust NExT*) flew past 9P/Tempel 1. Over the first two weeks after impact, the comet was observed to lose 5,000 tons of water and up to 25,000 tons of dust, a surprisingly high dust/ice ratio. The best information on the composition of the dust came from infrared observations using the space-based Spitzer infrared telescope. Before impact, the 5–35 mm infrared emission contained a weak silicate feature typical of other Jupiter-family comets (Kelley and Wooden 2009) and was best-fitted by amorphous-type pyroxene (Harker et al. 2007). After impact, this region dramatically showed strong spectral features. The post impact spectra showed clear evidence for crystalline silicate components, unlike interstellar silicates that are largely amorphous. The transformation of the infrared spectrum is likely a result of liberation of very small particles. During the three hours post impact, ground-based high spatial resolution imaging, spectroscopy, and visible polarimetry (Harker et al. 2007) revealed rapidly changing dust compositions.

103P/Hartley 2

The comet 103P/Hartley 2 (commonly called "Hartley 2") was visited in 2010 during extension of the *Deep Impact* mission (*Deep Impact EPOXI*). The 2.2 km long comet is dramatically shaped like a bowling pin. Its thin waist is smooth, but its bulbous ends contain large blocks up to 50 m in size. The surface does not appear to have the prominent depressions seen on some of the other comets. For its size, the comet is hyperactive: spacecraft measurements showed that much of the activity is driven by CO_2, a more volatile ice than H_2O. Typically, cometary activity is driven by water sublimation, but gas jets leaving the ends of 103P/Hartley 2 were largely CO_2. Gas coming from the waist region was rich in water. Escape of CO_2 appears to be responsible for ejecting water ice/dust particles that are up to ~30 cm in diameter and that were imaged streaming away from the comet. Comet 103P/Hartley 2 is of particular interest in that it has a more Earth-like D/H than comets whose elevated D/H suggests that they were not major contributors of Earth's water.

HOW COMETS RELEASE SOLIDS TO SPACE

The classical view of released comet dust was that most grains were in the range of tens of microns or less, as observed at comet 1P/Halley with *Giotto*'s DIDSY (dust impact detector system) (McDonnell et al. 1986). Simpson et al. (1986) noted groupings in particles detected by *Vega*'s DUCMA (dust counter and mass analyzer), while the DIDSY detected variations in particle size distribution with distance from 1P/Halley. With the 81P/Wild 2 flyby, the higher spatial sampling of its dust flux monitor instrument (DFMI) could resolve extreme fluctuations in particle density and size distribution. This was interpreted as the release of abundant smaller particles from much larger aggregates (Clark et al. 2004). During the 9P/Tempel 1 flyby, DFMI again detected extreme variations in particle-number densities, inferring subsequent fragmentation of larger aggregates. Large coma objects were also often observed by the *Rosetta* spacecraft at comet 67P/Churyumov–Gerasimenko, and images from an onboard microscope showed that collected mm-size particles were fragile porous aggregates (Langevin et al. 2016).

Given the great diversity in surface geomorphology, activity, and volatile compositions among these particular cometary nuclei, it may be surprising that not a single one has a coma that is homogeneously populated by the fine particles of which comets are made. Rather, the dominant process for mass loss seems to be release of large aggregates, which then fragment down to dust. The finer fractions fan out from the comet's orbit, due to the effects of sunlight pressure, and form spectacular dust tails. Some larger "dust clod aggregates" remain intact, stay close to the comet orbital path, and are sometimes seen as dust trails. In infrared sky images these are visible as thin lines: the thermal emission from large particles along a comet's orbit. When Earth passes through these trails we see the famous annual cometary meteor showers. The fragile nature of these small comet rocks is well known because they fragment at exceedingly low aerodynamic ram pressure as they enter the top of the atmosphere.

The escape of material from comets is driven by solar heating, which may be amplified by the buildup of gas from the mobilization of volatile components into quasi-trapped macroscopic voids. Other sources of energy include the enthalpy of solid–solid phase transitions of certain ices; the release of energy from kinetically inhibited chemical reactions; or the reaction of radiation-induced free radicals and ions. Much remains to be learned of these putative processes, which affect coma formation and behavior, as well as surface sculpting and regolith formation.

COMET MINERALOGY

The most secure assessment of cometary mineralogy comes from laboratory analyses of 81P/Wild 2 samples returned by the *Stardust* mission, although the total mass analyzed is less than a milligram. Additional mineralogical constraints come from the infrared spectra of the massive quantity of micron and smaller particles ejected from the 150 meter deep impact crater.

Telescopic Observations

Initial analysis of the Spitzer 5–35 mm observations of the *Deep Impact* event was based on the linear fitting of over 80 candidate mineral species (Lisse et al. 2006). This procedure resulted in identification of a wealth of crystalline, amorphous, and even hydrated minerals that could mathematically recreate the spectrum. Subsequent analysis of Spitzer and other ground-based emission spectra are consistent with forsterite, amorphous-type olivine, and pyroxene, plus a highly absorbing spectrally featureless material that was found using optical constants of amorphous carbon (Harker et al. 2007). Limitations in the data and their interpretation remain. However, the detection of amorphous materials in comets is notable. While it is expected that comets, like asteroids, contain amorphous silicates, the common use of "amorphous olivine and pyroxene end members" by the astronomical community is problematic in that it is not clear how appropriate they are as proxies for naturally occurring amorphous silicates. Furthermore, initial analyses suggest an appreciable abundance of secondary phases (> 20% phyllosilicates and carbonates) (Lisse 2006), which would require that 9P/Tempel 1 had experienced interior temperatures and pressures sufficient to retain liquid water. Phyllosilicates were not found in the 81P/Wild 2 samples nor were they detected in the reflectance spectra of 9P/Tempel 1, 103P/Hartley, or 67P/Churyumov–Gerasimenko (Davidsson et al. 2016).

Sample Analyses

The 81P/Wild 2 samples were investigated in laboratories with a long heritage of quantitative microanalysis of extraterrestrial materials. The captured particles include an impressive range of compositionally and isotopically unequilibrated materials. The apparent lack of significant diffusion between adjacent grains is evidence against the level of heating that commonly altered meteorite parent bodies. Many of the collected particles are solid microrocks whose coexisting phases provide important capabilities to compare comet solids with meteoritic materials.

Chondrules and Calcium–Aluminum Inclusions

Among the first comet particles studied in detail were fragments of chondrules (Fig. 2) and calcium–aluminum inclusions (Fig. 3). Chondrules are millimeter-scale igneous spheroids formed at temperatures in the 1,750–2,150 K range by nebular melting of silicates, metal, and sulfides. Chondrules individually melted in space followed by rapid cooling that quenched mixes of glass and crystalline silicates. After decades of investigation, the origin of chondrules remains controversial. Because their abundance exceeds 80% in some primitive meteorites, it is clear they were the dominant rocky material in some regions of the solar system at the time of planet-building planetesimals. The chondrule olivine fragments from 81P/Wild 2 range from Fe-poor (e. g. Nakamura et al. 2008) that formed in reducing conditions to Fe-rich that formed in more oxidizing conditions (Frank et al. 2014; Gainsforth et al. 2015).

Calcium–aluminum inclusions (CAIs) are the oldest solar system solids and usually predate chondrules by a few million years (Russel 2018 this issue). They are distinctively dominated by refractory minerals that formed above 1,400 K. Unlike most solar system solids, the oxygen isotopic composition of CAIs is like the Sun, enriched in ^{16}O by approximately 5% compared to Earth and bulk meteorites. The exotic mineral contents, age, and isotopic composition have been used as arguments that CAIs formed in high-temperature environments close to the Sun and over a very short period of time. Unlike chondrules, CAIs are rare: their abundance ranges from several percent to less than 0.01% in different classes of primitive meteorites.

In the 81P/Wild 2 samples, chondrule fragments are common and CAI fragments occur near 1% abundance. The presence of these two high-temperature components in a comet was a major surprise. It provided powerful sample-based evidence for large-scale transport of inner solar system materials outwards to ice-bearing regions of the early solar system. Similar abundance levels of chondrule fragments and CAIs are also found in interplanetary dust particle types that are believed to be of cometary origin. This is evidence that the rocky materials in 81P/Wild 2 are not unusual for Jupiter-family comets. The high-temperature environments that formed chondrules and CAIs would have destroyed previously existing ices and organic materials.

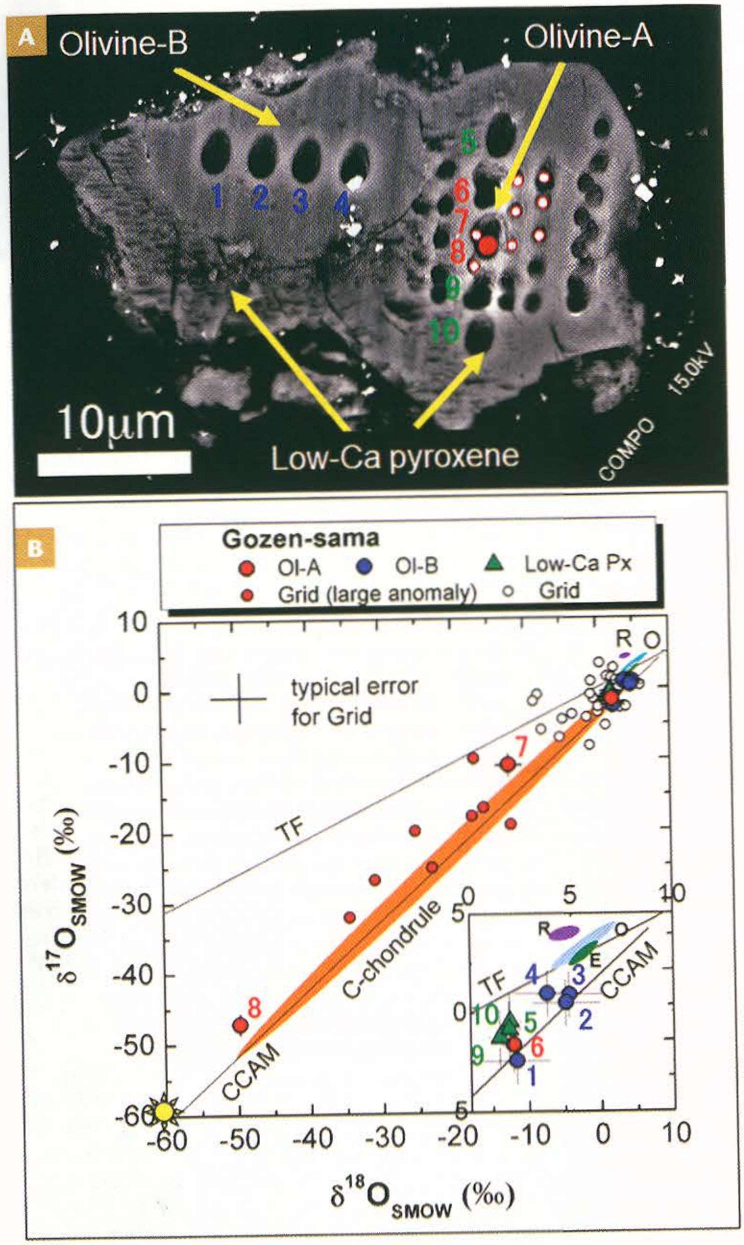

Figure 2 (**A**) Section of a large chondrule fragment (Gozen-sama) from the comet 81P/Wild 2 showing ion probe analysis pits. This fragment contains two olivine grains (Ol-A, red; Ol-B, blue) and a pyroxene (Low-Ca Px; green). Adapted from Nakamura et al. (2008). The Ol-A olivine grain (red points) is rich in ^{16}O, making it a relict grain that predates the other phases, which formed during crystallization of the molten chondrule. (**B**) Oxygen isotope plots for the data from the ion probe analyses of the Gozen-sama grain in 2A. TF is the mass dependent fractionation line where terrestrial materials plot; CCAM is the unity slope line where anhydrous minerals in carbonaceous chondrites plot. CCAM is a mixing line between solar composition (yellow dot) and the region where Earth and most meteoritic values plot. SMOW is standard mean ocean water. The orange, purple, light blue, and green elliptical regions—labeled as C, R, O, and E— are compositional fields of chondrules in carbonaceous, rumuruti, ordinary, and enstatite chondrites, respectively.

Inferring Formation Temperatures from Mineralogy

Linking crystalline silicates in a comet to high-temperature processes that made millimeter to centimeter high-temperature materials in meteorites is a significantly different result from predictions based on astronomical infrared observations. A common view for the origin of crystalline silicates in comets and the dust disks around young stars is

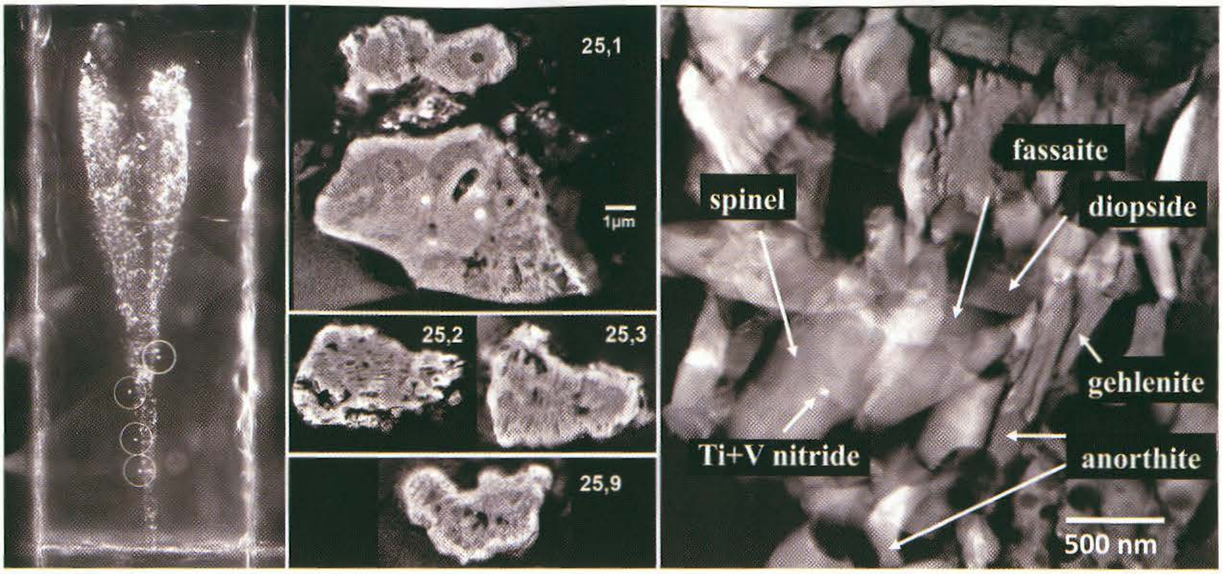

FIGURE 3 Fragments of the comet 81P/Wild 2 particle named Inti, a calcium–aluminum inclusion. (**LEFT**) A 2 millimeter long hollow track made by compression and melting of silica aerogel during the top to bottom deceleration of the 6 km/s particle. Circles mark larger fragments among hundreds of smaller ones in the track. (**MIDDLE**) Electron backscatter images of five of the grains taken from the aerogel and sectioned with a diamond microtome. The bright rims of nodules in the grains are Al,Ti,Mg–rich pyroxene (fassaite) enclosing interiors of spinel, anorthite, and other phases. (**RIGHT**) A high-angular dark-field transmission electron microscope image of one of the grains showing the phases present, including vanadium-rich TiN (osbornite) – an extremely rare mineral that condenses from solar composition gas at 1,600 K under C/O that is nearly twice the solar ratio.

hat they form by low-temperature (≤ 1,000 K) processing of amorphous interstellar silicates (Kimura et al. 2011). Such a subsolidus origin is at odds with the much higher temperature and much more complex formation processes needed to make particles related to chondrules and CAIs. While it is possible that some cometary materials could be made by low-temperature processing of clusters of amorphous silicates, it is clear that most of the crystalline cometary silicates and sulfides collected by the *Stardust* mission could not have formed in this manner. Subsolidius processing of submicron amorphous interstellar grains could not account for the size and mineral assemblages of 81P/Wild 2 particles.

The Low Abundance of Pre-solar Grains

A major surprise with the laboratory analyses of cometary grains was that isotopically identifiable pre-solar grains are rare, having an abundance of ~0.1% (Floss et al. 2013). This small fraction is similar to what is found in interplanetary dust but higher than found in meteorites. It had long been promoted that comets formed in isolation from the inner parts of the solar system and had retained major amounts of preserved interstellar solids (Greenberg 1986). Nearly all of the 81P/Wild 2 grains analyzed have the oxygen isotopic compositions of solar system materials and not the highly anomalous compositions used to identify pre-solar (older than the Sun) grains in meteorites. In addition to 81P/Wild 2, no meteorite or interplanetary dust has been found that contains more than trace amounts of isotopically anomalous grains. A straightforward conclusion from this finding is that 99.9% of the interstellar solids involved in forming the solar system were destroyed by processes that broke chemical bonds in silicates, oxides, and sulfides. In contrast to expectations, it does not appear that there were any regions of the solar system where interstellar solids could abundantly survive, at least for competent materials >2 µm.

These implications on pre-solar grain survival are based on the perception that interstellar grains have isotopically anomalous compositions. If there were isotopically normal pre-solar grains, homogenized in the interstellar medium, then they would be difficult to identify. Interplanetary dust particles contain submicron grains composed of glass with embedded metal and sulfides (GEMS). Most, but not all, of these have solar system oxygen isotope compositions, but there is vigorous debate about their solar system or pre-solar origin (Keller and Messenger 2011; Bradley 2013). Mineral grains larger than 2 microns were well preserved during high-speed capture in the *Stardust* mission but submicron glassy materials could be easily altered and confused with debris created by the capture process (Ishii et al. 2008).

Aqueous Alteration

Carbon-rich meteorites contain abundant phyllosilicates and other hydrous alteration phases formed in asteroid interiors that were warm, wet, and under pressure. This extensive alteration probably occurred when asteroidal ice was melted by heat from the decay of ^{26}Al present in the early solar system. In contrast, 81P/Wild 2 samples are dominated by anhydrous silicates, an important similarity to the most porous class of interplanetary dust, anhydrous chondritic porous interplanetary dust particles, commonly believed to be comet samples. Chondritic porous dust particles are uncompacted fine aggregates of unequilibrated anhydrous components and are made up of >10% organic material. No phyllosilicates or carbonates were found in 81P/Wild 2 samples, but it is possible that some small grains may have been present and did not survive capture. The presence of glass and metal in 81P/Wild 2 chondrule fragments is inconsistent with significant exposure to liquid water. The presence of magnetite (Hicks et al. 2017) and trace amounts of cubanite ($CuFe_2S_3$) (Berger et al. 2015) in some tracks indicate that secondary minerals are present in minor amounts.

The fact that unaltered and altered materials can coexist presents an enigma. It is possible that hydrous alteration may have occurred in specific regions of the comet, such as at impact sites. It is also possible that altered materials are fragments of larger bodies where liquid water prevailed. Comets, like asteroids, are collections of materials that include collisional debris from larger bodies. It is likely that even the smallest comets contain fragments of larger ice-bearing bodies that formed in the outer or inner solar system.

WHAT MINERALOGY TELLS US ABOUT THE FORMATION OF COMETS

The minerals identified in comets are common, or at least exist, in primitive asteroids. The finding of chondrules and CAIs in comets is strong evidence that the highest temperature solids made in the solar system were transported to the coldest regions of the disk of gas and dust from which the planets formed. There have been suggestions of how such materials might have been made far from the Sun. However, it seems probable they were made in the same inner solar system extreme environments that produced chondrules and destroyed nearly all interstellar silicates. The presence of rare olivine and CAIs with solar isotopic composition oxygen suggests that the high-temperature minerals formed very close to the Sun. In comparison to the Sun and CAIs, most solar system solids are enhanced in the rare oxygen isotopes ^{17}O and ^{18}O. This enrichment is most commonly attributed to self-shielding effects of photo-dissociation of nebular carbon monoxide gas that, except for regions close to the Sun, systematically liberated ^{17}O and ^{18}O to form silicates and other phases.

It is clear that the minerals found in comets could not have formed in the same environments where cometary ices and organics formed. The most likely scenario is that the rocky components were transported from hot, perhaps transient, rock-forming regions of the inner solar system to cold outer regions where ices and organic materials formed around them. If this is the case, then the rocky components and volatile components of comets are totally unrelated.

Laboratory studies of collected cometary samples have revealed a surprising relationship between the rocky ingredients of comets and the asteroidal parents of primitive meteorites. This suggests that primitive solar system bodies might have been a continuum, varying mainly with content of ices and organics that increase in proportion with solar distance. This seems to be partly true, and some asteroids appear to have contained ice whose melting resulted in the aqueous alteration seen in primitive meteorites.

There is, however, a fundamental difference between the mix of solids in comets and the mix of solids in asteroids: it relates to the way that they were assembled. The difference between the rocky materials in the two body types may be due to the provenance of their components. Meteorites contain rare components, such as pre-solar grains and CAIs, that formed in distant locales. But most of their contents appear to have local origins. Pre-solar grains predate the solar system and CAIs probably formed very close to the Sun. Meteorite classes have distinctive properties because many components formed under constrained local conditions. In contrast, comets probably don't contain any rocky components that were made where the comets were assembled. The rocky materials in comets formed in numerous distant locations and were transported and mixed over billions of kilometers. It is well established that the volatile contents of comets vary, but if the rocky contents were transported over great distances it is possible that most comets contain similar mixes of rocky materials, less diverse than asteroids.

The comet samples contain rocky materials from the inner solar system, but they seem to have a broader range of materials than found in specific meteorite classes. This is illustrated by the Mn contents of cometary ferrous olivines. Figure 4A shows the Mn and Fe contents of ferrous chondrule olivine from the most common type of meteorites (OC, or ordinary chondrite) and CO, a type of carbonaceous chondrite. The CO chondrite abundances match the solar Mn/Fe ratio, while the OC chondrite ratio is enhanced by a factor 2.3. Not shown on the figure are CR (carbonaceous Renazzo type) chondrite olivines that plot between the CO and OC distributions. Cometary olivine compositions, shown in Figure 4B, are broadly spread and not dominated by CO, OC, or CR. The comet olivine distribution could be made by mixing materials from different nebular regions, supporting the notion that the rocky portion of comets came from diverse regions.

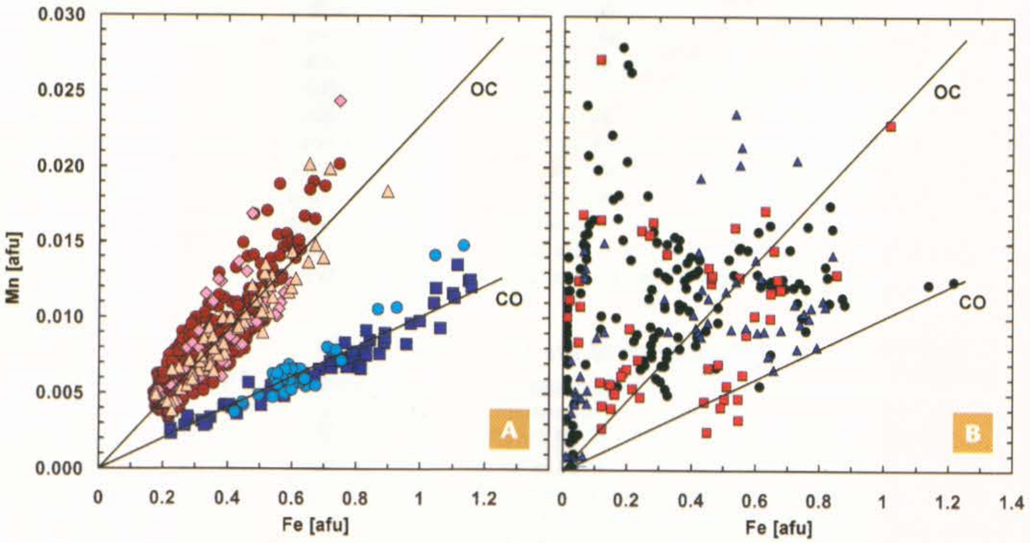

Figure 4 Plots of Mn and Fe atomic formula units (afu abundances) in meteoritic and cometary olivine. **(A)** Meteorite chondrule Mn/Fe data from OC (ordinary carbonaceous chondrite) and CO (Ornans type of carbonaceous chondrite) types. Data from Berlin et al. (2011). **(B)** Comet Mn/Fe data includes analyses from comet 81P/Wild 2 olivines (circles and triangles), as well as grains (squares) from an interplanetary dust particle that is thought to have a cometary origin. The OC and CO lines from (A) are given for reference. The broad spread in the comet data is evidence that comets incorporated olivine from multiple early solar system regions. From Frank et al. (2014) and Brownlee and Joswiak (2017).

SUMMARY

Flyby missions to comets have yielded remarkable insights into the nature of the small ice-rich bodies that formed at the edge of the solar system. The images alone have dramatically revealed a fantastic diversity of morphologies and surface features. Unlike asteroids and moons, comet surfaces are greatly influenced by large-scale loss of dust, rocks, and gas into space. Their surfaces are quite different from those of bodies shaped by impacts. Ground-based studies and missions have shown that comets contain different mixes of volatiles that, in some cases, are not evenly distributed on global scales. The long-term survival of volatiles is proof that comets were not heated like other similar-sized solar system bodies, yet the heterogeneity of volatiles in comets suggests that comet formation and evolution was complex. The presence of high-temperature rocky components is evidence that the formation of ice, organics, and rocks occurred in different places. The inferred large-scale transport and mixing of rocky materials suggests that outer solar system bodies may have received a similar mix of materials as inner solar system bodies. Many, and perhaps nearly all, of the rocky materials formed in hot locales, while the ices, and also probably the organics, formed in low-temperature environments. A few pre-solar grains do survive in comets, but only in minor amounts (unless they happen not to have distinctive isotopic compositions).

Although much has been learned, comets remain mysterious complex bodies that preserve information on the origin of planets and on how volatiles might have been delivered to planets. Astronomical observations of disks around other stars indicate that comets are common products of star formation. The direct study of comets in our solar system provides important insight and a degree of ground truth for the interpretation of the infrared spectra of silicates in protoplanetary disks.

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