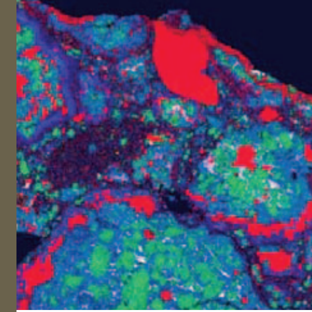

The Asteroid–Comet Continuum: In Search of Lost Primitivity

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Recent results from the Stardust comet sample-return mission have confirmed the idea that there is a continuum between primitive small bodies in the outer main asteroid belt and comets. Indeed, the mineralogy as well as the chemical and oxygen isotope compositions of the dust from comet Wild 2 are very similar to those of carbonaceous chondrites, a class of meteorites allegedly derived from primitive, dark asteroids. Comets no longer represent extremely primitive samples of the early Solar System that are radically different from dark asteroids. We enter a new era in which comets and their siblings, the dark asteroids, are seen as a collection of individual objects whose geology can be studied. The most primitive of these objects, i.e. the ones that escaped thermal metamorphism or hydrothermal alteration, can help us decipher physicochemical processes in the interstellar medium and in the protoplanetary disk from which our Solar System formed.

Keywords: comets, asteroids, chondrites, micrometeorites, Stardust, primitivity

EXTRATERRESTRIAL MATTER ON EARTH

Meteorites are rocky bodies with sizes larger than 1 mm. At present, roughly 10 tonnes of meteorites larger than 1 kg fall on Earth each year. Among meteorites, chondrites represent 86% of the falls, 80% of these being the so-called ordinary chondrites. Chondrites are rocks made of coarse-grained components such as chondrules and calcium–aluminum inclusions (CAIs) embedded in a fine-grained matrix (Fig. 1). CAIs are an assemblage of calcium–aluminum oxides and silicates such as spinel ($MgAl_2O_4$) and anorthite ($CaAl_2Si_2O_8$). They are the oldest recognizable rock fragments in the Solar System, with high-precision absolute Pb–Pb ages of ~4568 million years. Chondrules consist of olivine, pyroxenes, metals, sulfides, oxides, and a glassy mesostasis. Their igneous textures indicate that they were at some point fully or partly melted (Fig. 1). Our current understanding is that chondrules formed over a time period of 1.2–4 million years (My) after CAIs (Villeneuve et al. 2009; Kleine and Rudge 2011 this issue). Both CAIs and chondrules formed in the protoplanetary disk that dissipated ~5 My after the condensation of CAIs.

Carbonaceous chondrites, a subset of chondrites, are divided into 8 groups (CI, CM, CO, CV, CK, CR, CH, and CB) and account for ~4% of meteorite falls. Compared to other chondrites, they have a higher content of CAIs, are enriched in refractory lithophile elements such as Ca and Al relative to the solar photosphere composition, and plot below the terrestrial fractionation line on an oxygen three-isotope plot (see Rumble et al. 2011 this issue). Despite the name *carbonaceous* chondrites, only the CM, CR, and CI groups are significantly enriched in carbon (up to a few percent as organic matter) and water relative to ordinary chondrites. Most carbonaceous chondrites are dark, having an albedo lower than 6%.

Though relatively pristine, carbonaceous chondrites have endured some geological processing on their parent bodies. Most groups have experienced mild thermal metamorphism (e.g. CV and CO chondrites), while others have been subjected to severe hydrothermal alteration (e.g. CM and CI chondrites).

The matrix of carbonaceous chondrites has a highly variable chemical composition and mineralogy, specific to each chondrite group. In the CM and CI chondrites, most primary matrix minerals have been transformed by hydrothermal alteration into secondary minerals, such as clays, carbonates, and magnetite. In many cases, the matrix contains a significant amount of presolar grains—submicron-sized oxides and silicates isotopically anomalous relative to the Solar System composition (Nguyen and Messenger 2011 this issue).

Micrometeorites represent the dust fraction (<1 mm) of extraterrestrial matter falling on Earth. About 7000 tonnes of micrometeorites land annually on our planet (Duprat et al. 2007), the vast majority of them being ~200 µm diameter objects. Among micrometeorites, one distinguishes between Antarctic micrometeorites (AMMs) and interplanetary dust particles (IDPs). The former are collected in Antarctic ice or snow and range in size from 20 to 1000 µm. The latter are collected by aircraft in the Earth's stratosphere and have sizes ranging from 1 to 40 µm (Bradley 2004). Most micrometeorites are rich in organic carbon and are related to carbonaceous chondrites.

Interplanetary dust particles are divided into hydrous and anhydrous subtypes (Bradley 2004). Hydrous IDPs contain a significant amount of hydrated minerals such as clays. Minor minerals include sulfides and magnetite. Hydrous IDPs may be related to the CI and CM hydrated carbonaceous chondrites. Anhydrous IDPs are made of amorphous silicates, olivine, and pyroxene, and contain up to a few weight percent of organic matter. They contain peculiar aggregates, called GEMS (glass with embedded metal and sulfide), that could be of interstellar origin (Bradley 2004). Some anhydrous IDPs have a porous and fluffy texture. Rare, refractory IDPs made of minerals similar to those found in CAIs have been identified in stratospheric collectors (Zolensky 1987).

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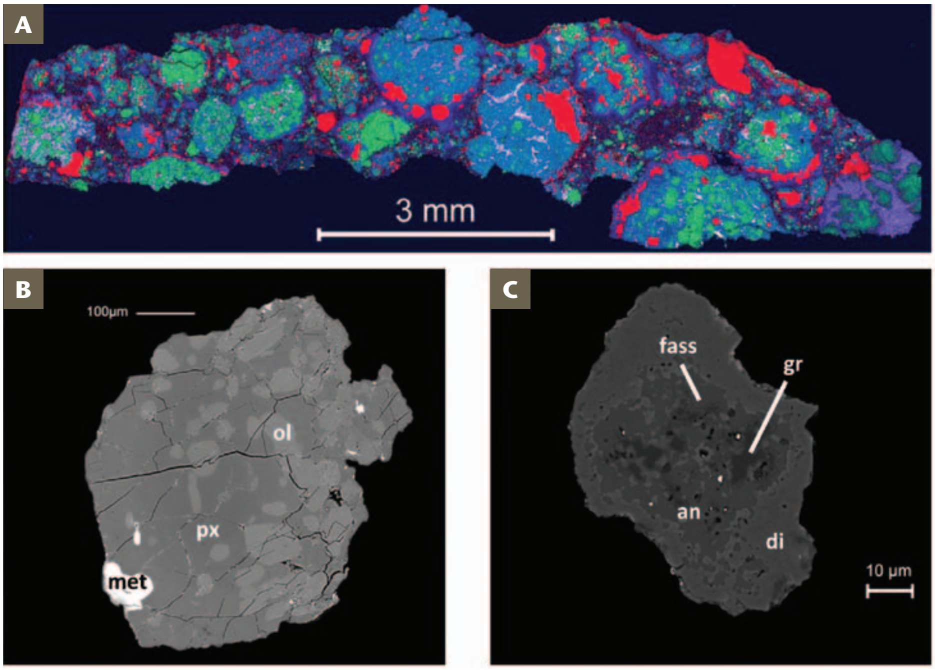

Figure 1 A chondrite meteorite and its components. (**A**) False-color map of a CR chondrite (Mg: green; Si: blue; Ca: yellow; Al: white, Fe: red). This rock is dominated by chondrules—round, iron–magnesium-rich objects—some of which are rimmed by metal. Image courtesy of Anton Kearsley, NHM, London (**B**) Backscattered-electron image of an individual chondrule from the chondrite Bishunpur, composed of olivine (Fo_{75}) (ol), pyroxene ($En_{80}Fs_{20}$) (px), and Fe–Ni metal (met). Image courtesy of Emmanuel Jacquet, MNHN, Paris (**C**) Backscattered-electron image of a CAI from the chondrite Acfer094; the CAI is composed of anorthite (an), grossite (gr), diopside (calcium-rich pyroxene; di), and Al–Ti-rich pyroxene (fass).

AMMs contain clays, olivine, pyroxene, sulfides, and magnetite (Engrand and Maurette 1998). CAIs, though rare, have also been reported in AMMs. For many years, the fluffy objects found in IDPs were lacking from the AMM collection, dominated by compact objects. Duprat et al. (2007) demonstrated, however, that this absence was due to an incomplete sampling of the micrometeorite flux in Terre Adélie blue ice fields. The unbiased micrometeorite collection from central Antarctica snow contains objects of the same nature as IDPs, though significantly larger (Duprat et al. 2010).

COMETS AND ASTEROIDS

Classification

Comets and asteroids have historically been distinguished on an observational basis. Comets are active bodies that develop an extended coma (tail) when they approach the Sun close enough to sublimate water and other volatile compounds at their surface. Asteroids do not develop comae and remain an astronomical point source. The inactivity of asteroids is due either to the absence of volatile compounds at their surface or to the fact that they never get close enough to the Sun to cause volatile sublimation.

Comets and asteroids can also be distinguished on the basis of their orbital properties (Fig. 2). In general, asteroids have roughly circular orbits lying inside the orbit of Jupiter. In contrast, comets have elliptical orbits that extend beyond Jupiter. Most asteroids have a low inclination relative to the ecliptic plane (the plane of the Earth's orbit), while many comets are highly inclined.

While the orbits of most asteroids are stable over the lifetime of the Solar System, cometary orbits are unstable. Comets originate from two main reservoirs (Fig. 3). Long-period comets come from the Oort cloud, a spherical reservoir of ice-rich bodies that ranges from a few to tens of thousands of astronomical units (AU) from the Sun. Jupiter family comets (JFCs) probably come from the Kuiper belt, a more proximal toroidal reservoir of ice-rich bodies located beyond the orbit of Neptune. Though both reservoirs are populated with large bodies (up to Earth mass for the Oort cloud), *observed* comets are objects that are small enough to be gravitationally perturbed by close encounters with distant stars (long-period comets) or giant planets (JFCs) and placed on unstable orbits.

Properties of Asteroids and Comets

A comet is made of a nucleus, which represents the bulk of the comet's mass, and a coma, which is an atmosphere made of sublimated gas and dust. Until spacecraft missions could get close enough to comets (see page 32), most of our knowledge about comets came from the remote analysis of the coma, which obscures the nucleus. Because, the dust and gas making up the tenuous coma come directly from the nucleus, they offer an indirect way to probe it.

Comets are thought to contain equal amounts of dust and ice. The ice composition, observed mainly via radio spectroscopy, varies from object to object but is often dominated by water (H_2O) and carbon monoxide (CO). Minor icy species include carbon dioxide (CO_2) and hydrogen cyanide (HCN). The dust component, observed by infrared spectroscopy, is mainly composed of submicron-sized iron–magnesium silicates (olivine and pyroxene). The dust structure is that of a porous aggregate. Cometary nuclei have diameters up to 80 km (Hale-Bopp) and are dark objects with albedos lower than 6%. They have featureless visible-light and infrared reflectance spectra.

By definition, asteroids do not have a coma. In the main asteroid belt, there are 26 asteroids with diameters larger than 200 km and over a million with diameters larger than 1 km. Ceres, the largest asteroid, has a diameter of ~1000 km. There is a great diversity among asteroids, which are classified into taxonomic types according to their visible-light and infrared reflectance spectra, albedos, and orbital properties. S-type asteroids, the most abundant type in the inner asteroid belt (which extends from beyond Mars's orbit to 2.8 AU), have high albedo and complex spectra that are radically different from those of comets. C-, D-, and P-type asteroids have low albedo and featureless spectra resembling those of comets. These dark asteroids dominate the outer asteroid belt (from 2.8 AU to Jupiter's orbit).

The Blurred Line between Dark Asteroids and Comets

None of the definitions presented above are entirely satisfying. The dynamical distinction between comets and asteroids refers ultimately to their reservoirs (asteroid belt, Kuiper belt, Oort cloud), which are implicitly associated with their loci of formation. However, it has recently been shown that large-scale transport of celestial bodies was the rule during the first billion years of Solar System evolution, and that bodies migrated many astronomical units from the location of their formation. For example, D-type asteroids may be JFCs captured in the outer asteroid belt 3.8 billion years ago (Levison et al. 2009).

The definition based on activity strongly depends on astronomers' observational capabilities to detect a coma. Recently, Hsieh and Jewitt (2006) reported objects in the asteroid belt that exhibit periodic cometary activity. These objects had evaded detection until then because of their distance and the faintness of their comae. These "main-belt" comets may be numerous in the asteroid belt. Campins et al. (2010), in a recent spectroscopic study of dark asteroids, found previously unseen water ice and organic material on their surfaces.

Furthermore, the distinction based on activity is tightly linked to the surface state of the observed body, which does not provide any information about the composition of its interior but rather informs us about the locus of its residence during the last 4.6 billion years. Indeed, cometary activity exists because, before being sent close to the Sun, comets remained for billions of years in the cold outer Solar System where volatile compounds remained frozen. It is well known that after a number of passages close to the Sun, comets become dormant and show no further activity. Reciprocally, comet-like activity can be activated on an asteroid-like body following a collision, when fragmentation brings up hidden ice from its interior.

PRIMITIVITY CONTEST: COMETS VERSUS ASTEROIDS – THE PRE-STARDUST SITUATION

Identifying the source of extraterrestrial samples has long been one of the primary goals of cosmochemistry. It was only a few years after meteorites were recognized as extraterrestrial samples that Jean-Baptiste Biot (1774–1862) proposed they came from the Moon. We now know that because chondrites did not endure planetary differentiation, they must have originated from small bodies, such as asteroids or comets. For example, the Tagish Lake carbonaceous chondrite came from a body placed into an asteroidal orbit (Fig. 2). An asteroidal origin is therefore usually attributed to this C2 chondrite and to the rest of the carbonaceous chondrites.

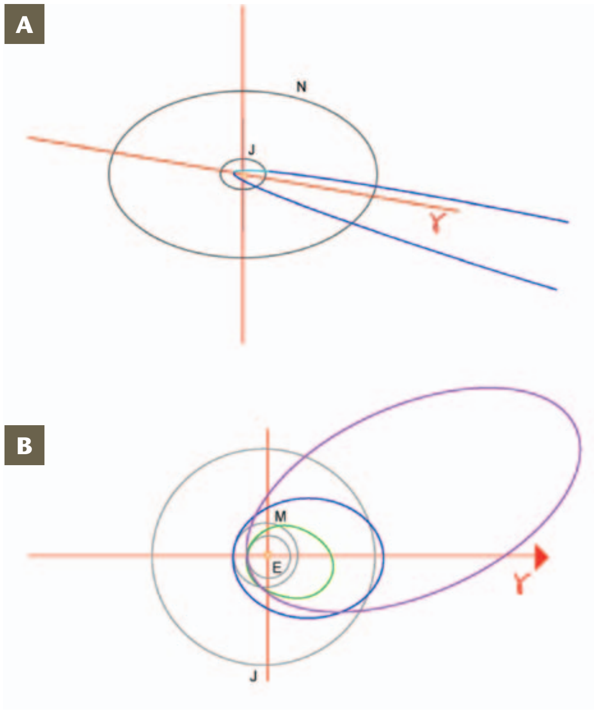

FIGURE 2 Orbits of some celestial bodies. (**A**) The orbit of the long-period comet Hyakutake, which extends to the Oort cloud. (**B**) Orbits of the Wild 2 Jupiter family comet (blue) and the Tagish Lake meteorite (green), as well as the preferred orbit for the Orgueil meteorite (adopting an entry velocity of 18 km/s for the Orgueil meteor; Gounelle et al. 2006) (purple). Note that the scales of the two illustrations, given by Jupiter's orbit, are different. J, N, E, and M stand for Jupiter, Neptune, Earth, and Mars, respectively. ϒ indicates the direction of the vernal point. FIGURE PREPARED BY MICHEL SERRANO

This quest for meteorite parent bodies has always been intimately linked to the preconception that comets and asteroids are two radically different kinds of bodies and that comets are more primitive than asteroids. The supposed primitivity of comets was mainly based on (1) the assumption that comets' components formed farther away in the protoplanetary disk than those of asteroids, in a region where high-temperature processing was virtually absent; (2) the observation that cometary water is enriched in deuterium (D) relative to hydrogen (H), yielding a D/H ratio greater then the terrestrial value by a factor of 2 – these enrichments are reminiscent of those observed in the ISM (Fig. 4); and (3) the surmise that comets did not endure secondary processing such as hydrothermal alteration or thermal metamorphism.

As fluffy anhydrous IDPs are also enriched in deuterium relative to hydrogen and the terrestrial value, it has long been thought that they had a cometary origin. Some researchers argued that their high atmospheric entry velocity coupled with their low density/high porosity was an indication of cometary origin. The absence of evidence for hydrothermal alteration was also used as an argument in favor of a cometary origin for fluffy anhydrous IDPs.

The cometary origin of fluffy IDPs is, however, not supported by new observations. Elevated D/H ratios can no longer be taken as evidence for a cometary origin as they are also found in asteroidal materials (Busemann et al. 2006). The atmospheric entry velocity of cometary dust is similar to that of asteroidal dust (Nesvorný et al. 2010).

GLOSSARY

Astronomical Unit (AU) – By definition, 1 AU is equal to the Sun–Earth distance (150 million kilometers). This is the characteristic distance between objects in the Solar System.

Albedo – The amount of sunlight reflected by a solid body. It varies between 0% (a totally absorbing body) and 100% (a perfect mirror). For example, the albedo of the Moon is 12%.

Primitive body – A body in the Solar System whose components have not been substantially modified by high-temperature events occurring in the protoplanetary disk during the earliest phases of Solar System formation nor by secondary geological processes such as metamorphism or hydrothermal alteration. Primitive bodies have best retained the properties of the interstellar medium (ISM).

Interstellar medium (ISM) – This term refers to the molecular clouds from which stars form. Though there are different phases within molecular clouds, all are characterized by elevated D/H ratios compared to the Earth value.

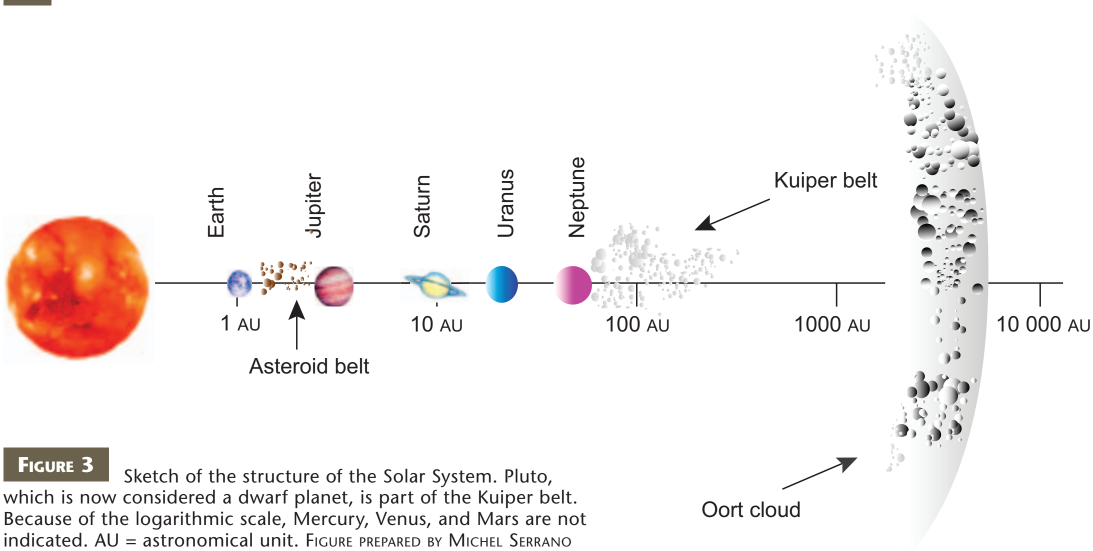

FIGURE 3 Sketch of the structure of the Solar System. Pluto, which is now considered a dwarf planet, is part of the Kuiper belt. Because of the logarithmic scale, Mercury, Venus, and Mars are not indicated. AU = astronomical unit. FIGURE PREPARED BY MICHEL SERRANO

The density of dust from dark asteroids has never been measured; it could well be as low as that of cometary dust. More importantly, recent results are leading us to question the assumption that comets did not undergo hydrothermal alteration. The emblematic Orgueil CI chondrite, made entirely of clays and heavily altered, was shown to come from an object on a cometary orbit (FIG. 2) (Gounelle et al. 2006). Hydration features, possibly due to clays, were also reported in Kuiper belt objects (KBOs), the source of JFCs (Barucci et al. 2008).

Despite these hints that comets might not be as primitive as once thought, most researchers expected that cometary samples brought back by the Stardust spacecraft would be similar to fluffy anhydrous IDPs, and would be rich in unprocessed solids and organic matter with an isotopic composition radically different from that of the Solar System.

THE STARDUST MISSION: TALES OF THE UNEXPECTED

The Stardust mission brought back to Earth several hundred micrograms of dust collected in the coma of the JFC Wild 2 using an aerogel tile (FIG. 5A). After a preliminary study phase that involved about 200 selected investigators (Brownlee et al. 2006), these precious samples are now available to all scientists for dedicated investigations. Individual grains with sizes up to 40 µm were collected. CAIs and chondrules similar in composition and mineralogy to those found in carbonaceous chondrites were discovered (FIG. 6). In addition, these objects have the same oxygen isotope composition as their counterparts in carbonaceous chondrites (McKeegan et al. 2006; Nakamura et al. 2008). A copper sulfide, cubanite, was also found within Wild 2 samples. This type of sulfide was previously known to occur in CI chondrites as a product of hydrothermal alteration. The observed olivine and low-Ca pyroxene compositions best match those of the hydrothermally altered CI chondrites (Zolensky et al. 2008) rather than those of anhydrous IDPs. Only a handful of presolar grains have been found, and these occur in lower abundances than in carbonaceous chondrites. The structure of cometary organic matter from Wild 2 is reminiscent of that found in carbonaceous chondrites (Sandford et al. 2006); its enrichment in deuterium relative to hydrogen is comparable, though smaller, than enrichments observed in carbonaceous chondrites and micrometeorites (McKeegan et al. 2006).

Four important conclusions emerged from these surprising results. (1) Cometary solids are not unmodified, pristine interstellar matter. (2) Cometary solids were processed in the solar protoplanetary disk. (3) Given that CAIs are thought to have formed close to the Sun, solid transport between the inner and outer Solar System (where comets agglomerated) was efficient within the protoplanetary disk. (4) The differences between cometary solids and carbonaceous chondrites are comparable to the differences among the different groups of carbonaceous chondrites.

The last finding strengthens the hypothesis that a continuum exists between dark asteroids and comets, as suggested by Gounelle et al. (2008). The continuum does not extend to S asteroids sampled by ordinary chondrites, whose composition indicates they formed at a different time and/or location than dark asteroids and comets.

THE ASTEROID–COMET CONTINUUM

Other recent results support the idea that there is no fundamental difference between dark asteroids and comets. Dynamical studies showed that AMMs originate either from D-type asteroids (Levison et al. 2009) or from JFCs (Nesvorný et al. 2010). Because D asteroids are probably KBOs captured in the asteroid belt some 3.8 billion years ago (Levison et al. 2009), and because KBOs are the source

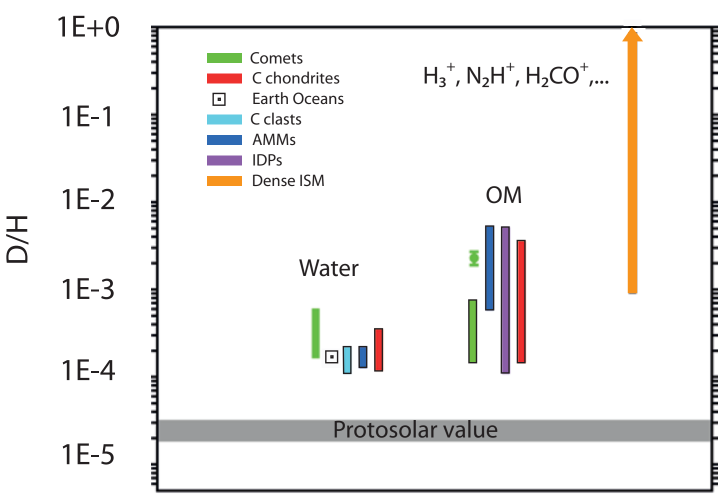

FIGURE 4 Range of D/H ratios in selected objects. The protosolar value is that of Jupiter. Black-contoured ranges correspond to data obtained in the laboratory, while others correspond to astronomical measurements. As far as cometary OM is concerned, the single point refers to the HCN molecule detected in the comet Hale-Bopp coma, and the range to Wild 2 dust brought back by the Stardust spacecraft. Data from literature (see text). C stands for carbonaceous and OM for organic matter. Other abbreviations are given in the text.

of JFCs, whether AMMs come from D asteroids or JFCs does not make any difference as far as their primordial origin and composition are concerned. Since the mineralogy and the chemical and isotopic compositions of AMMs are very similar to those of carbonaceous chondrites that allegedly came from dark asteroids (Engrand and Maurette 1998), the similarity between cometary solids and dark asteroid solids extends well beyond the case of Wild 2 samples.

In a similar vein, Briani et al. (2010) demonstrated dynamically that dust trapped in asteroid Vesta (in the form of carbonaceous clasts) is expected to be a mixture of asteroidal and cometary dust. Given that two clear-cut populations are not observed within carbonaceous clasts embedded in HED meteorites (thought to originate from asteroid Vesta) (Gounelle et al. 2005), there is no positive way to tell the difference between asteroidal and cometary dust.

As far as the volatile fraction is concerned, there is no evidence (at present) of any similarity or dissimilarity between asteroids and comets. This is mainly because the ice composition of asteroids is virtually unknown (Campins et al. 2010). Since icy solids were subjected to transport and mixing in the protoplanetary disk as much as rocky solids, the ice composition of asteroids is expected to fall within the wide range of ice compositions observed in comets (Crovisier et al. 2009). In addition, the density of dark asteroids varies between 1.3 and 0.8 g/cm^3 (Marchis et al. 2008), a range comparable to that of KBOs and compatible within error bars with that of comets, 0.6 ± 0.2 g/cm^3 (Weissman and Lowry 2008). Because of their smaller size, the macroscopic porosity of observed comets is probably larger than that of dark asteroids (Weissman and Lowry 2008); therefore, some dark asteroids probably have an ice/rock ratio as high as the cometary value (~1).

Though the hypothesis of a dark asteroid–comet continuum is supported by many observations, summarized above, we still face an unsolved problem. The D/H ratio measured in water from four long-period comets (Jehin et al. 2009) is roughly twice the D/H ratio measured in clays from carbonaceous chondrites (Robert 2003), indicating a fundamental difference between some comets and dark asteroids. This problem would be solved if JFCs (the potential source of some carbonaceous chondrites, AMMs, and IDPs) had a D/H ratio half that of Oort cloud comets. This difference between JFCs and long-period comets could be due to the extra–Solar System origin of Oort cloud comets, as suggested by Levison et al. (2010).

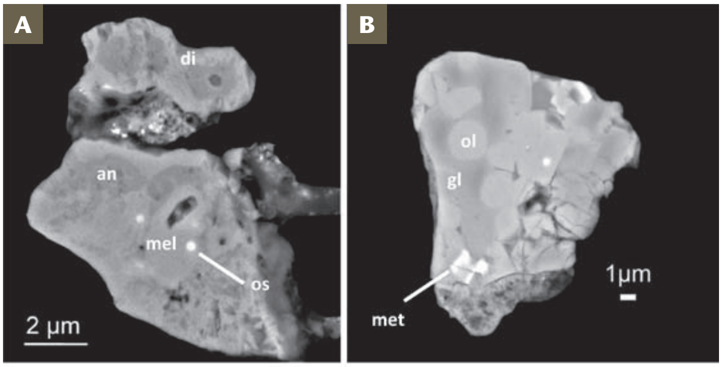

Figure 6 High-temperature assemblages discovered in Wild 2 dust. (**A**) Calcium–aluminum inclusion discovered in Wild 2 dust brought back by the Stardust spacecraft. The inclusion is made of an assemblage of very refractory minerals, such as diopside, gehlenitic melilite, anorthite, and osbornite (Zolensky et al. 2006). Image courtesy of Hope Ishii (LLNL) (**B**) Chondrule found in Wild 2 dust sampled by the Stardust spacecraft. The chondrule is composed of olivine, glass, pyroxene, and metal. Image courtesy of T. Nakamura

In any case, the question of whether a primitive meteorite or micrometeorite comes from a comet or a dark asteroid is somehow irrelevant. What matters for cosmochemistry is the origin and history of the material that constitutes asteroids and comets, namely, high-temperature phases such as the ones making up CAIs and chondrules, as well as organic matter and ices. What do their properties and associations at the mineral scale tell us about the physicochemical processes in the protoplanetary disk? This interrogation is irrespective of (1) where primitive meteorites and micrometeorites agglomerated and (2) where they were stored during the last 4.5 billion years. Keeping such an approach in mind, new primitive samples from either dark asteroids or comets will help us build a more complete map of processes that happened in the ISM and in the protoplanetary disk. Examples of recently identified key samples are xenoliths embedded in meteorites (Briani et al. 2009) exhibiting the largest known enrichments in ^{15}N, a new class of AMMs with extreme enrichments in D (Duprat et al. 2010), and some porous IDPs enriched in GEMs (Ishii et al. 2008).

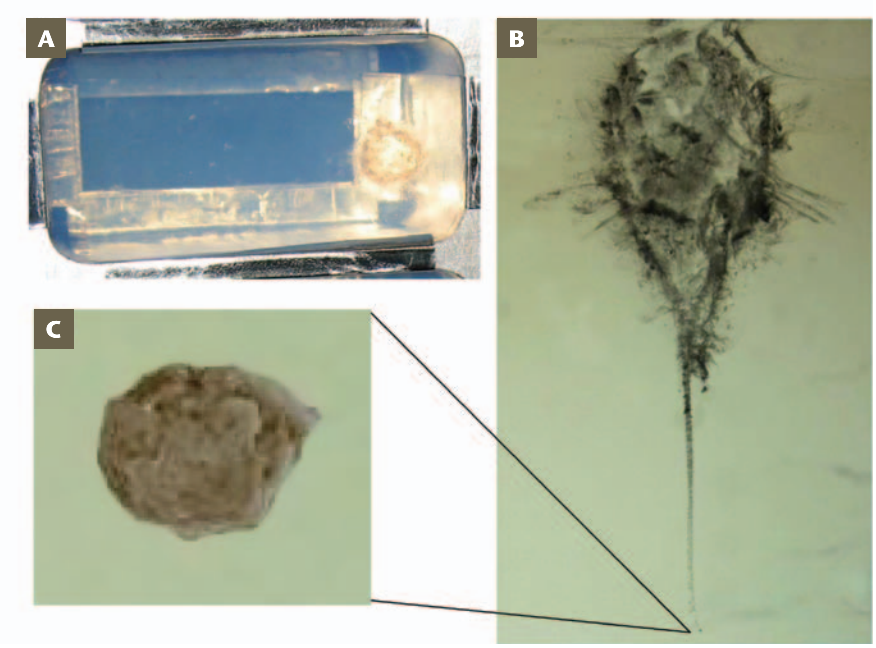

Figure 5 (**A**) Aerogel tile (2 × 4 cm) from the Stardust spacecraft showing an impact crater made by a solid grain from comet Wild 2. (**B**) Track created in the aerogel by a Wild 2 dust grain impacting at a relative velocity of ~6 km/s. The dust grain entered at the top and created an explosion cavity before being stopped ~5 mm farther. (**C**) Individual terminal grain with a size of ~1 μm. Images courtesy of M. Zolensky (NASA JSC)

As the idea of a continuum between comets and dark asteroids emerges, we realize that comets are geologically processed in the same way as asteroids are. Comets are probably subjected to hydrothermal alteration and possibly thermal metamorphism (Prialnik et al. 2008). This should not be a surprise given that they contain much ice and that the solids carrying the radionuclide ^{26}Al (half-life = 0.7 My)—the probable heat source for melting water ice—can be transported from the inner to the outer Solar System. There might be as much or more geological variability within comets as within asteroids, as indicated by space missions that have approached cometary nuclei (Britt et al. 2004). In other words, while some comets might have been extensively hydrothermally altered, others might have been preserved from the effects of fluid circulation. Because *observed* comets are small objects, they are unlikely to have recorded much hydrothermal alteration, which occurs preferentially in large bodies (Gounelle et al. 2008).

Finally, to overcome the limitations of telescopic observations, which only probe the surface of primitive bodies, and of meteoritics, which studies samples deprived of any geological context, sample-return missions that provide us with samples of the surface and interior of known primitive bodies are greatly needed. We look forward to such missions, which, no doubt, will rejuvenate our thoughts about Solar System formation and evolution as much as the Stardust mission did.

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