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Connection between micrometeorites and Wild 2 particles: From Antarctic snow to cometary ices

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Abstract–We discuss the relationship between large cosmic dust that represents the main source of extraterrestrial matter presently accreted by the Earth and samples from comet 81P/Wild 2 returned by the Stardust mission in January 2006. Prior examinations of the Stardust samples have shown that Wild 2 cometary dust particles contain a large diversity of components, formed at various heliocentric distances. These analyses suggest large-scale radial mixing mechanism(s) in the early solar nebula and the existence of a continuum between primitive asteroidal and cometary matter. The recent collection of CONCORDIA Antarctic micrometeorites recovered from ultra-clean snow close to Dome C provides the most unbiased collection of large cosmic dust available for analyses in the laboratory. Many similarities can be found between Antarctic micrometeorites and Wild 2 samples, in terms of chemical, mineralogical, and isotopic compositions, and in the structure and composition of their carbonaceous matter. Cosmic dust in the form of CONCORDIA Antarctic micrometeorites and primitive IDPs are preferred samples to study the asteroid-comet continuum.

INTRODUCTION

Microscopic-size particles travel toward the Sun in interplanetary space by Poynting-Robertson light drag (Dohnanyi 1976). Thousands of tons of them are captured by the Earth's gravity each year, sampling material from asteroids and comets (Love and Brownlee 1993). A small portion of them survive the impact with the Earth's atmosphere without being volatilized or completely melted. These particles are collected either on the Earth's surface as micrometeorites (MMs) (see Maurette 2006a) or in the lower stratosphere as interplanetary dust particles (IDPs) by NASA aircrafts (Brownlee et al. 1977; Brownlee 1985). The main difference between these two populations resides in their sizes, with micrometeorites being larger (~20 μm to 500 μm) than IDPs (<50 μm, Bradley 1988).

Micrometeorites are generally collected in clean, isolated environment, far away from both natural and anthropogenic contaminants (see Taylor and Lever 2001). Cosmic dust particles have been extracted from deep sea sediments (Blanchard et al. 1980; Brownlee et al. 1984), terrestrial sand (Harvey and Maurette 1991; Rochette et al. 2008), sedimentary rocks (Taylor and Brownlee 1991), Greenland lake sediments (Maurette et al. 1986, 1987), and Antarctic ice and snow (Maurette et al. 1991; Taylor et al. 1998; Nakamura et al. 1999; Terada et al. 2001; Duprat et al. 2007). Since January 2000, the CSNSM group launched a program to recover micrometeorites from ultra-clean snow in central Antarctica near the CONCORDIA Station at Dome C (73°S 123°E, see Duprat et al. 2007). In January 2006, the Stardust spacecraft returned to Earth after a seven-year mission bringing back thousands of solid particles (<30 μm) from comet 81P/Wild 2 (Brownlee et al. 2006). 81P/Wild 2 is a Jupiter family comet (JFC) formed in regions of the Kuiper belt, that was perturbed in 1974 by Jupiter and transferred to its current orbit. The cometary grains collided with the Stardust collector surface at 6.1 km s^{-1}, producing hypervelocity craters in the aluminum foils and deep penetration tracks in the highly porous, low-density collecting aerogel (e.g., Hörz et al. 2006). The examination of Wild 2 samples makes it now possible to explore the connection between micrometeorites, cometary, and asteroidal objects.

SAMPLES

Antarctic Micrometeorites (AMMs)

Unmelted micrometeorites (MMs) were first recovered in 1984 and 1987 by collecting sediments from the bottom of blue lakes in Greenland (Maurette et al. 1986, 1987). To collect less weathered micrometeorites, the CSNSM team first moved to Cap-Prudhomme, Antarctica in December 1987 where large (25–500 µm) micrometeorites were recovered by filtering melt ice water from blue ice fields, at ~2 km from the margin of the Antarctic ice sheet (Maurette et al. 1987, 1991). Since 2000, a new collection program started in central Antarctica near the French-Italian station CONCORDIA at Dome C to recover pristine dust particles from snow (e.g., Duprat et al. 2007). Since 1995, micrometeorites are also collected in Antarctica by Japanese and American teams using different ways and locations (e.g., Taylor et al. 1998, 2000; Yada and Kojima 2000; Nakamura et al. 2001).

In this study, we will discuss the results obtained from AMMs collected from blue ice fields at Cap-Prudhomme (Maurette et al. 1991) and from pristine CONCORDIA micrometeorites recovered from snow (e.g., Duprat et al. 2007).

Details for AMMs from Cap-Prudhomme can be found elsewhere (e.g., Kurat et al. 1994; Engrand and Maurette 1998). CONCORDIA micrometeorites were extracted from clean snow trenches at Dome C at ~4 m depth (snow layers from 1950–1960) to avoid anthropogenic contamination. The snow was melted in a dedicated stainless steel smelter and the water was filtered without any mechanical pumping (Duprat et al. 2007). All samples found on the filter were hand-picked and analyzed to identify and classify the extraterrestrial particles. In a single day of collection at Dome C (23/01/2006, snow volume of 3 m^3), we identified 411 extraterrestrial particles out of 515 grains (i.e., 80% of extraterrestrial dust) by scanning electron microscopy equipped with energy dispersive X-ray detector (SEM-EDX), based on their textures and chondritic EDX spectra. Assuming an average density of 2.5 for unmelted AMMs and of 3 for cosmic spherules, and using a spheroid approximation, the total mass of extraterrestrial material recovered during that day is ~330 µg.

Two new families of grains (FgF and UCAMM) have been identified in the CONCORDIA collection. Fine-grained fluffy (FgF) samples are unmelted micrometeorites dominated by a fine-grained porous groundmass presenting textures similar to chondritic porous IDPs (Figs. 1a and 1b). Ultracarbonaceous Antarctic micrometeorites (UCAMMs) are fluffy, fragile particles, exceptionally rich in carbon (Fig. 1c). This type of particles is similar to those described by Nakamura et al. (2005). CONCORDIA UCAMMs are dominated by carbonaceous material, with a proportion of carbonaceous matter ranging from ~50% to ~85% in volume.

Using the classification defined by Genge et al. (2008) depending on the extent of thermal reprocessing during atmospheric entry, 28% of the extraterrestrial grains from that day of CONCORDIA collection are fine-grained (Fg); 8% are crystalline micrometeorites (Xtal), 35% scoriaceous particles (Sc) and 29% cosmic spherules (CS). Among the Fg particles, 8% are fine-grained fluffy—FgF (including 4% of UCAMMs) and 20% are fine-grained compact—FgC.

Stardust Samples

Stardust samples were collected in SiO_2-based aerogel and aluminum foils (Brownlee et al. 2006; Hörz et al. 2006). The aluminum foils were initially installed with the intention to facilitate the eventual extraction of aerogel tiles (Tsou et al. 2004). The estimated number of particles bigger than 1 µm captured in aerogel is approximately 1200 (Burchell et al. 2008). The impact features of aerogel were classified into three types based on their morphology (Burchell et al. 2008). The type A tracks are carrot-like, type B tracks have more bulbous cavities and type C consist only of a bulbous rather stubby cavity (Hörz et al. 2006). Burchell et al. (2008) suggest that the cometary dust consisted of some cohesive, relatively strong particles as well as particles with a more friable or low cohesion matrix containing smaller solid grains. Craters residues include grains of sub-micrometer size of silicates, Fe-Ni sulfides and possibly both alkali-rich and mafic glass (Kearsley et al. 2008). The craters in the Stardust aluminum foils present the advantage that the residues were not mixed with silica aerogel allowing determining the silicate compositions (Kearsley et al. 2008; Leroux et al. 2008c).

POSSIBLE COLLECTION BIASES

Antarctic Micrometeorites

Collection biases for Cap-Prudhomme Antarctic micrometeorites collected at the margin of the Antarctic ice sheet include freezing/thawing processes at the surface of the blue ice field and pumping effects during collection (loss of friable grains, e.g., Duprat et al. 2003), potential terrestrial contamination (e.g., by marine aerosols), aqueous alteration (leaching of soluble phases like carbonates and Fe-Ni sulfides that results in bulk depletions of Ca, S and Ni, e.g., Kurat et al. 1994; Engrand and Maurette 1998). Further hand-picking of the dust particles in the laboratory is also required, as only ~20% of the grains are extraterrestrial, and this result in a biased selection of the samples.

These biases are drastically reduced for CONCORDIA micrometeorites: i) the collection procedure preserves the most friable grains; ii) they are protected from terrestrial contamination as the collection site is isolated from the marine coast and from the bedrock; iii) they are well

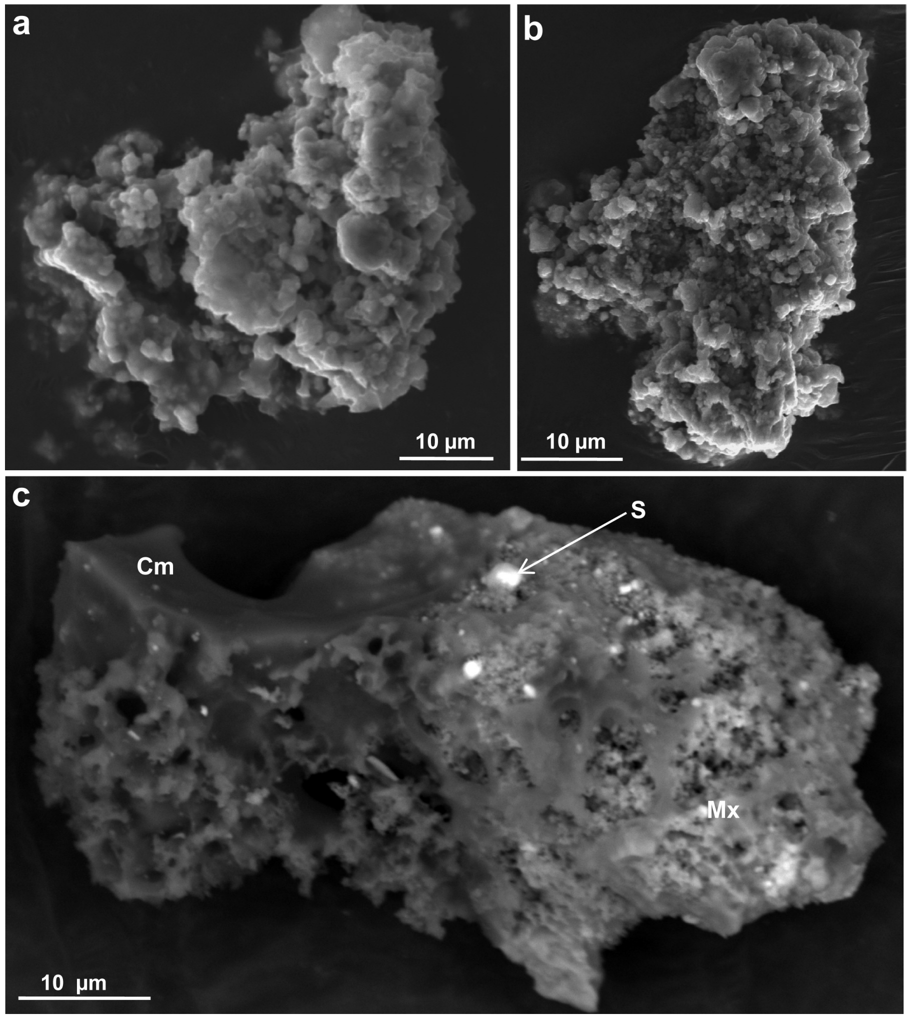

Fig. 1. a and b) External surfaces (secondary electron images) of two fluffy fine-grained (FgF) Antarctic micrometeorites from the 2006 CONCORDIA collection (DC06-09-194 and DC06-09-203). c) Backscattered electron image of an individual fragment of an ultracarbonaceous Antarctic micrometeorite (UCAMM–DC06-09-45) showing a large abundance of carbonaceous matter on the left side (dark phase—Cm) associated with chondritic matrix on the right side (granular light-grey phase—Mx) containing Fe-Ni sulfides (S).

preserved from terrestrial weathering, as they exhibit easily weathered minerals (carbonates and Fe-Ni sulfides) that were rare in previous micrometeorite collections from the blue ice fields (Duprat et al. 2007); iv) no presorting is required before examination of the particles since ~80% of the samples are extraterrestrial. The CONCORDIA collection is the most unbiased and uncontaminated micrometeorite collection. In the 2006 collection, the samples were carefully monitored in the field and brought back under dry nitrogen to be further handled in the laboratory clean room.

Micrometeorites suffer different degrees of heating during atmospheric entry as a function of velocity, entry angle and mass (e.g., Toppani et al. [2001] and references therein). The atmospheric deceleration in the Earth's atmosphere can change the texture, mineralogy and chemistry of AMMs. The most important modifications of AMMs during the atmospheric entry heating are the loss of volatile species, formation of a magnetite shell, recrystallization of olivines with higher iron contents and the occurrence of a Fe-rich glassy mesostasis (Toppani et al. 2001). However, some micrometeorites (~35%) are recovered with no evidence of having been heated above a few hundred degrees for more than a few seconds, as they still contain phyllosilicates (Noguchi et al. 2002), and/or volatile elements like sulfur and phases like Fe-Ni sulfides and carbonates (Duprat et al. 2007; Engrand et al. 2007).

Stardust Samples

All Stardust samples of comet Wild 2 were modified at different degrees by heating effects because of their capture at high velocity (6.1 km s^{-1}) in silica aerogel and aluminum foils (see Brownlee et al. 2006). The particles reached high peak temperatures, up to several thousand Kelvin. For strongly altered particles, mineralogical studies based on the diffusion of MgO and SiO_2 have shown that the duration of heating

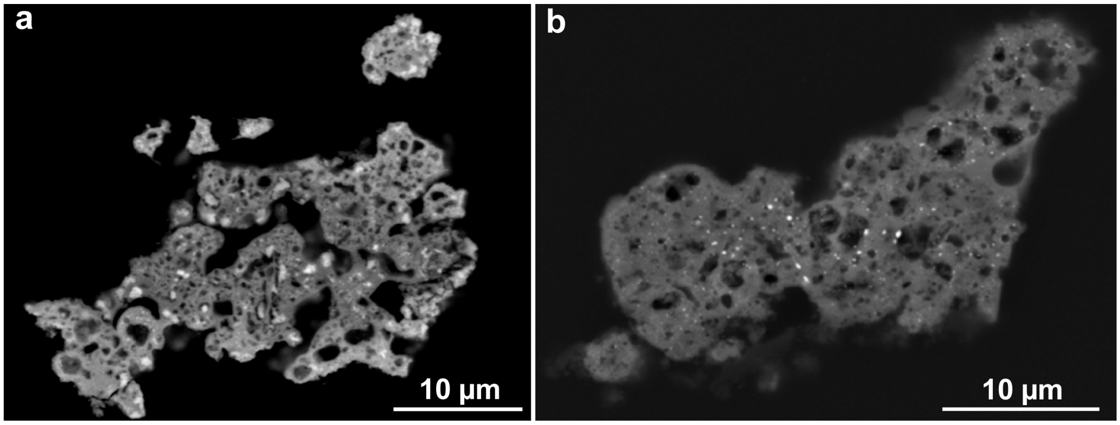

Fig. 2. a) Backscattered electron images of a polished section of a scoriaceous Antarctic micrometeorite (AMM—DC06-09-122). b) An amorphous-rich type particle from Wild 2 samples (Nakamura et al. 2008b). The internal texture of the partially melted AMMs resembles that of the cometary Wild 2 sample captured in aerogel.

(~1800 °C for 0.1 ms, Roskosz et al. 2008) is longer than thought from laboratory experiments on large analogues (~2500 °C/µm near the surface and >300 °C at the center of >4 µm, for heating duration of about 0.1–1.8 µs, Noguchi et al. 2007). In these conditions, small fine-grained (submicron) friable materials could be severely damaged (Roskosz et al. 2008). Particles from Wild 2 comet were classified into two groups based on silicate crystallinity: crystalline type and amorphous-rich type (Nakamura et al. 2008b). This last group presents some textural similarities with the partially melted micrometeorites (scoriaceous AMMs) (see Fig. 2).

METHODS

Antarctic Micrometeorites

The first textural classification of Antarctic micrometeorites (AMMs) is determined according to their external aspect and their apparent content in low-Z material (i.e., carbonaceous matter), by analytical scanning electron microscopy (SEM associated with energy dispersive X-ray spectroscopy—EDX). The bulk chemical composition of CONCORDIA AMM matrix was determined from 80 AMMs with a Cameca SX100 electron microprobe (EMPA) at Univ. Paris VI Jussieu (CAMPARIS) using a defocused beam (~5 µm) at 15 kV and 10 nA. The compositions of large (>2 µm) olivines (54 grains), pyroxenes (56 grains), and Fe-Ni sulfides (43 grains) were measured in CONCORDIA AMMs with a focused beam (~1–2 µm) on polished sections with the electron microprobe at 15 kV and 10 nA (4 to 10 nA for the sulfides). One fragment of a fine-grained fluffy micrometeorite (DC06-08-26) was mounted in epoxy (EMBed-812) and ultramicrotomed for analytical transmission electron microscopy (TEM) using Tecnai G2-20 TEMs equipped with EDX (200 kV, at LSPES Lille and CSNSM Orsay). We also performed high-resolution TEM characterization of MM carbonaceous phases using a Jeol 2011 (200 kV, at Univ. Paris VI Jussieu) on two powdered samples (UCAMMs—DC06-09-45 and DC06-09-119) transferred onto C-lacey TEM support grids (Cu).

The carbon content of AMMs was measured with the 3f ion microprobe at CRPG Nancy simultaneously to D/H measurements (see Engrand et al. [1999a] and Maurette et al. [2000]). Orgueil and Murchison crushed fragments were used as carbon abundance standards for these measurements. The carbonaceous matter of micrometeorites was also studied by Raman micro-spectroscopy (Dobrică et al. 2009b), an analytical technique sensitive to the degree of structural order of the carbonaceous matter (Quirico et al. 2005a, 2005b; Bonal et al. 2006; Dobrică et al. 2009b). Raman spectra were obtained with a Labram micro-spectrometer, at 514 nm excitation. The laser power at the sample's surface was set as low as 300 µW to avoid thermal alteration. No effect of sample damaging by laser irradiation as a function of acquisition time was observed. The microscope optics provided a spot diameter estimated at 2–3 µm. The experiments were performed in an inert atmosphere (argon) to reduce and stabilize the variations of the Raman parameters (Quirico et al. 2005a; Dobrică et al. 2009b).

The hydrogen isotopic composition was measured by ion microprobe (SIMS) in 26 AMMs and 15 cosmic spherules from the Cap-Prudhomme collection (Engrand et al. 1999a). Oxygen isotopes were analyzed by SIMS in anhydrous minerals from 18 AMMs (12 olivines, 11 pyroxenes, one melilite, one spinel and mixed refractory phases) (Lorin et al. 1989; Greshake et al. 1996; Engrand et al. 1999b). Complementary data is also available on cosmic spherules from deep sea sediments (Clayton et al. 1986; Herzog et al. 1999; Engrand et al. 2005) and Antarctic cosmic spherules (Engrand et al. 2005; Taylor et al. 2005; Yada et al. 2005).

Stardust Samples

Comet 81P/Wild 2 (hereafter Wild 2) samples brought back by the Stardust mission were analyzed by a variety of analytical techniques. In this paper where we focus on the

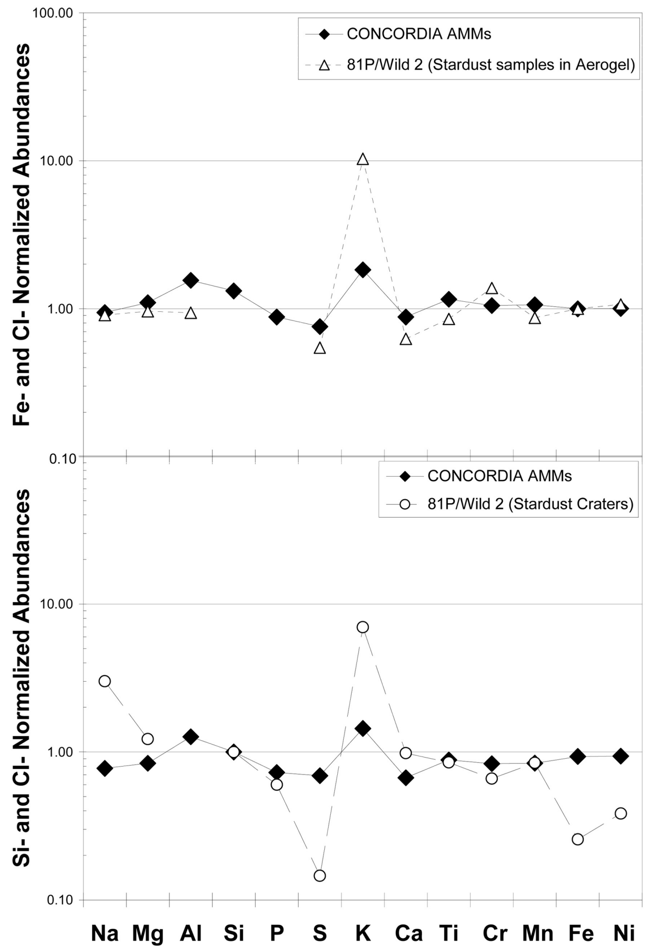

Fig. 3. Fe- and CI-, and Si and CI-normalized abundances of the average composition of CONCORDIA micrometeorites (black diamonds) compared to the abundances of Wild 2 samples taken from the aerogel (open triangles in top diagram, data from Flynn et al. 2006; Ishii et al. 2008b; Lanzirotti et al. 2008; Leroux et al. 2008b; Stephan et al. 2008b) and from crater residues (open circles in lower diagram, data from Flynn et al. 2006; Kearsley et al. 2008; Leitner et al. 2008; Leroux et al. 2008c).

comparison of AMMs with Wild 2 samples, we will use previously published Wild 2 data (Flynn et al. 2006; McKeegan et al. 2006; Sandford et al. 2006; Zolensky et al. 2006; Cody et al. 2008; Gallien et al. 2008; Glavin et al. 2008; Ishii et al. 2008b, Lanzirotti et al. 2008; Leitner et al. 2008; Leroux et al. 2008b, 2008c; Matrajt et al. 2008; Nakamura et al. 2008a; Nakamura et al. 2008b; Simon et al. 2008; Stephan et al. 2008a, 2008b; Tomeoka et al. 2008; Zolensky et al. 2008).

RESULTS

Chemical Composition

Figure 3 compares the average major and minor element contents of CONCORDIA AMMs with that of comet Wild 2 for samples collected both in aerogel and in crater residues. In an attempt to reduce analytical and sampling limitations, we have compiled and averaged all available compositional data for Wild 2 samples. Figure 3 (top) compares the Fe- and CI-normalized compositions of AMMs and Wild 2 samples in aerogel (CI data from Lodders 2003; Wild 2 data from Flynn et al. 2006; Ishii et al. 2008b; Lanzirotti et al. 2008; Leroux et al. 2008b; Stephan et al. 2008b). All compositions in Fig. 3 bottom for AMMs and Wild 2 crater residues are normalized to Si and to CI (data for Wild 2 was taken from Flynn et al. 2006; Kearsley et al. 2008; Leitner et al. 2008; Leroux et al. 2008c).

The AMM fine-grained materials exhibit a major and minor element composition pattern comparable within a factor of 2 to the bulk CI composition (Fig. 3). It shows a good agreement with the abundance pattern of Wild 2 samples measured in aerogel except for a K enrichment observed in one Wild 2 sample by Ishii et al. (2008b, see Fig. 3 top). Sulfur and calcium are only slightly depleted in Wild 2 aerogel tracks compared to CI and to AMMs (Fig. 3 top). The Si content of Wild 2 particles is not reported in Fig. 3 (top) because of its large observed enrichment over the CI abundance, showing that Wild 2 samples and silica aerogel are often intimately mixed (e.g., Leroux et al. 2008b; Nakamura et al. 2008b).

Data for Wild 2 particles in crater residues show a chondritic abundance within a factor of 2, with the exception of Na and K enrichments, and S and Fe slight depletions.

Mineralogical Properties

Refractory Minerals/Inclusions and Chondrules

Twenty-nine Antarctic micrometeorites containing refractory mineral phases (spinel, anorthite, melilite, hibonite, Ca-Al-rich pyroxene, and perovskite) have been identified so far (e.g., Hoppe et al. 1995; Engrand et al. 1999b and unpublished data). These minerals are typical components of calcium-aluminum-rich inclusions (CAIs) found in meteorites. The relative abundance of AMMs-bearing refractory mineral in their matrix (13 AMMs) or of refractory minerals assemblages resembling miniature CAIs (16 AMMs, see Fig. 4a) is less than 1%.

Remarkably, comet Wild 2 samples contain rare refractory minerals like anorthite, Ca-Al-Ti-rich clinopyroxene, gehlenite, spinel, corundum, V-bearing osbornite, and a phase that is probably perovskite (Zolensky et al. 2006; Simon et al. 2008).

Unmelted AMMs contain rare fragments that once belonged to chondrules, including one fragment (~80%) of a radial pyroxene chondrule (~120 μm in diameter) that was first classified by error in the Antarctic cosmic spherule population due to its overall rounded shape. Only a few assemblages showing a porphyritic texture have been found in AMMs up to now (Walter et al. 1995a; Kurat et al. 1996).

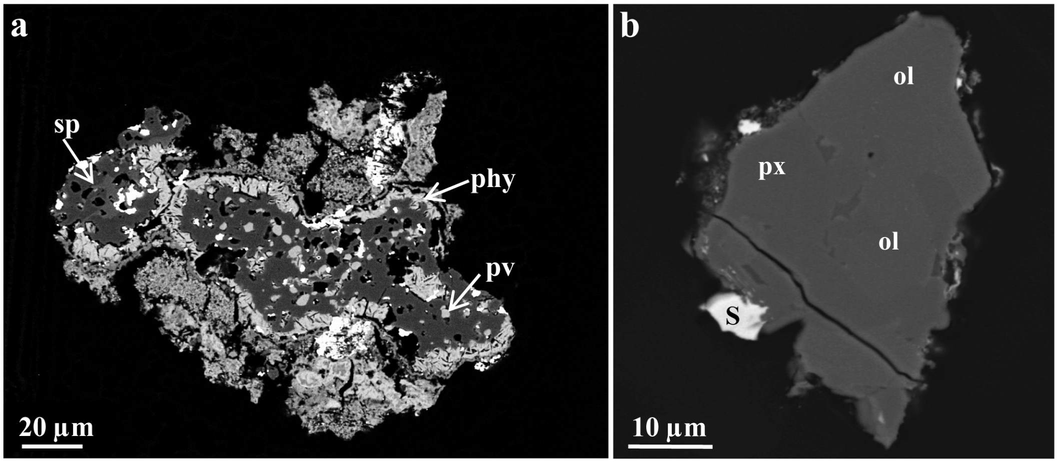

Fig. 4. Backscattered electron images of a) a CAI present in MM 94-4-36 containing spinel (sp) and perovskite (pv) surrounded by Fe-rich dehydrated phyllosilicates (phy). Brights specks are remnants of gold coating used for ion microprobe measurements (some ion probe pits are still visible despite re-polishing of the section). b) A coarse-grained MM (DC06-09-125) containing olivines (ol), pyroxenes (px) and Fe-Nisulfide (S), with a porphyritic texture, possibly representing a chondrule fragment.

To explain the observed low concentration of chondrules in AMMs, it has been proposed that coarse-grained AMMs may be related to fragments of chondrules (Walter et al. 1995a; Genge et al. 2005) (see Fig. 4b). Genge (2008) also proposes that the parent bodies of AMMs linked to ordinary chondrites (from a few % to ~15% of the AMMs, according to Walter et al. 1995b; or Genge 2008, respectively) would belong to the Koronis asteroid family.

Among the crystalline particles examined so far in comet Wild 2, Nakamura et al. (2008b) have identified four particles that are texturally, mineralogically, and compositionally similar to carbonaceous chondrite chondrules.

Silicates

Mg-rich crystalline silicates (olivine and low-Ca pyroxenes) are the most commonly encountered minerals in AMMs. The pyroxene/olivine numerical abundance ratio in Antarctic micrometeorites is about 1 (184 pyroxenes for 201 olivines analyzed in Cap-Prudhomme micrometeorites, 56 pyroxenes, and 54 olivines in the CONCORDIA collection). This value is larger than in CM chondrites (pyroxene/olivine ~0.2), which have been proposed as the closest meteoritic analogue of micrometeorites (Kurat et al. 1994; Engrand and Maurette 1998). The best match for this pyroxene/olivine criterion in carbonaceous chondrites is represented by the CR chondrite group (Kurat et al. 1994; Engrand and Maurette 1998; Gounelle et al. 2003).

The compositions of olivines and low-Ca pyroxenes from the CONCORDIA collection have been measured in coarse-grained AMMs and in isolated minerals embedded in fine-grained, scoriaceous MMs and in cosmic spherule relict minerals. We present here the compositions of olivines and pyroxenes from CONCORDIA micrometeorites as they are more pristine than Cap Prudhomme AMMs, but no significant differences are observed for anhydrous minerals in AMMs between these two collections (Engrand et al. 2006). Olivines in CONCORDIA AMMs (N = 54) show a wide compositional range, from Fo_{100} to Fo_{48}, with a pronounced frequency peak at Fo_{99} (Fig. 5). Low-Ca pyroxene compositions (N = 56) vary from $En_{98.5}Fs_{1.4}$ to $En_{64.9}Fs_{34.6}$, with Wo_{0-5} and present a pronounced peak at En_{98} (Fig. 5). Micrometeorite Ca-rich pyroxenes have compositions that range from $En_{98.7}$ to $En_{41.9}$ and from Wo_5 to Wo_{44} (pigeonite and augite) (Fig. 6).

Three AMMs exhibit low-iron, manganese-enriched (LIME) pyroxenes and olivines with elevated MnO (1.7 wt%) and Cr_2O_3 (2.1 wt%) (see Fig. 7). One olivine and one pyroxene grains contain 4.5 wt% and 3.5 wt% MnO, respectively, but they are also rich in FeO (7.9 wt% and 8.5 wt% FeO).

The best preserved comet Wild 2 samples are dominated by olivine and pyroxene grains (Nakamura et al. 2008b), with a pyroxene/olivine numerical ratio of about one. Nakamura et al. (2008b) estimate the proportion of low-Ca pyroxenes to olivines in one track to ~1.1 and compositional data from (Zolensky et al. 2006; Leroux et al. 2008a, 2008b, 2008c; Tomeoka et al. 2008; Zolensky et al. 2008) yield a total of 84 low-Ca pyroxenes for 85 olivine grains. The sizes of these minerals range from submicrometer to over 10 µm (e.g., Zolensky et al. 2008).

Wild 2 olivines have a wide compositional range (Fo_{100-4}), with a pronounced frequency peak at Fo_{99} (Zolensky et al. 2006; Leroux et al. 2008a, 2008b; Tomeoka et al. 2008; Zolensky et al. 2008). Some Wild 2 LIME olivines also contain very elevated MnO, Al_2O_3 and Cr_2O_3, up to 6.45 wt%, 0.71 wt% and 1.46 wt%, respectively (Zolensky et al. 2006). Low-Ca pyroxenes present a large compositional range En_{100-52}, presenting a peak centered at En_{95} (Zolensky et al. 2006; Leroux et al. 2008b; Tomeoka et al. 2008; Zolensky et al. 2008). Ca-rich pyroxenes are also present in comet

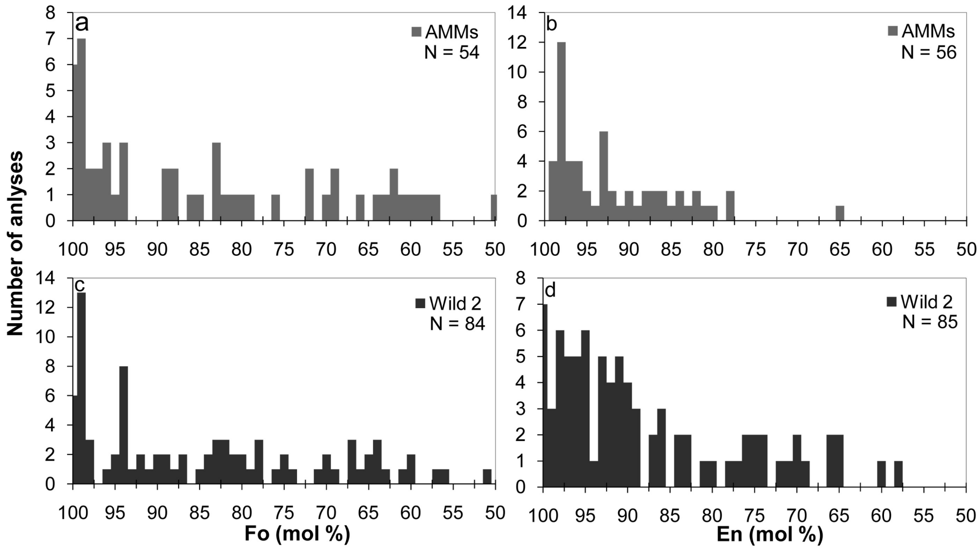

Fig. 5. Histograms showing the compositions Mg/(Fe + Mg) of olivines (a, c) and pyroxenes (b, d) in CONCORDIA micrometeorites (a, b) and Wild 2 samples (c, d). (Data for Wild 2 samples are taken from Zolensky et al. 2006; Leroux et al. 2008b, 2008c; Tomeoka et al. 2008).

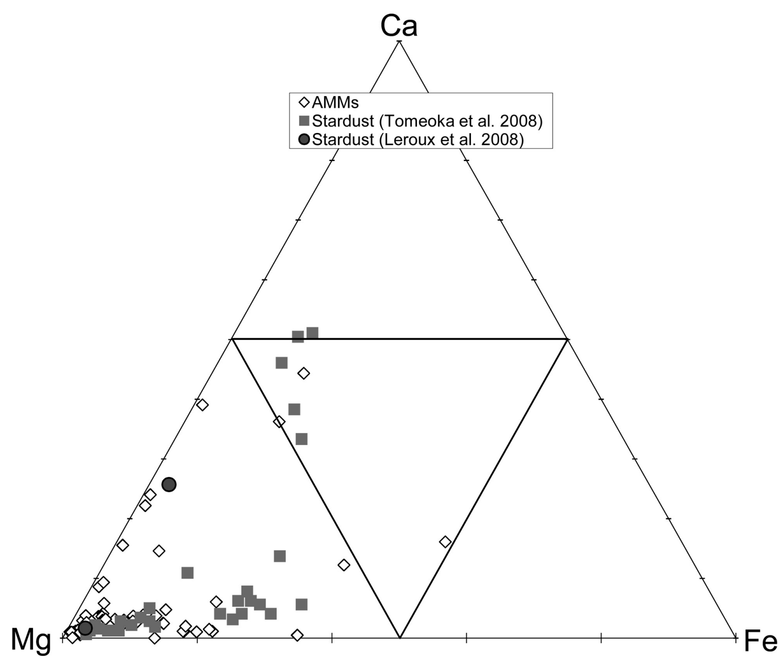

Fig. 6. Ternary Mg-Ca-Fe diagram (at%) of orthopyroxenes and Ca-rich clinopyroxenes in AMMs (open diamonds) and Wild 2 samples (data for Wild 2 samples from Leroux et al. 2008a; Tomeoka et al. 2008; Jacob et al. 2009 filled grey squares, circles and triangles, respectively).

Wild 2 (Leroux et al. 2008a, 2008b; Tomeoka et al. 2008; Jacob et al. 2009) (see Fig. 6). Several analyses plot in the "forbidden zone" of the Mg-Fe-Ca ternary diagram (in which pyroxenes are not stable at low pressure, Lindsley 1983), probably because of their overlap with other mineral phases. Leroux et al. (2008a) point out the presence in Wild 2 samples of a diopside grain with an exsolution microstructure of pigeonite, suggesting a crystallization from a melt and a cooling rate within the range 10–100 °C/h.

Fe-Ni Sulfides

Fe-Ni sulfides are present in all types of extraterrestrial samples, and thus represent a pertinent tool for comparison purpose. Troilite (FeS), pyrrhotite ($Fe_{1-x}S$) and pentlandite ($\{Fe,Ni\}_9S_8$) have been identified both in micrometeorites and in comet Wild 2.

Large Fe-Ni sulfides (from >1 µm to ~15 µm) present in AMMs of different textural types (from unmelted fine-grained to partially melted scoriaceous particles) have been analyzed by electron microprobe (see Engrand et al. 2007).

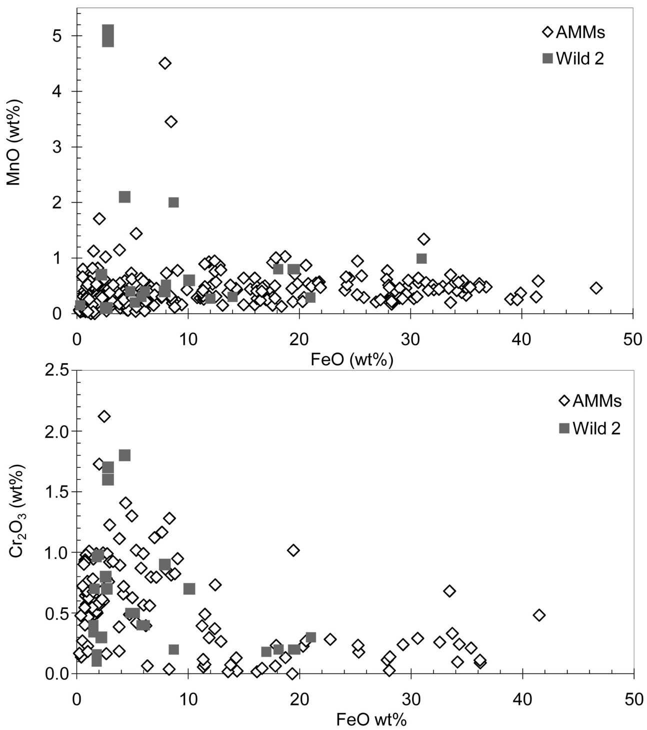

Fig. 7. Minor element contents MnO and Cr_2O_3 as a function of FeO (wt%) in pyroxenes and olivines from Antarctic micrometeorites (open diamonds) compared to Wild 2 measurements (filled grey squares) (data for Wild 2 samples from Zolensky et al. 2006; Nakamura et al. 2008b).

Smaller sulfides with submicron sizes (<1 µm) were also observed by transmission electron microscopy and their compositions measured by EDX analysis. These compositions measured by TEM-EDX analysis are similar to that of micron-sized crystals measured by electron microprobe (Fig. 8) (Engrand et al. 2007; Dobrică et al. 2009a). Most Fe-Ni sulfides have homogeneous compositions close to that of troilite with less than 3 at% Ni. Only rare pentlandite grains are detected, mainly in scoriaceous AMMs.

Comet Wild 2 samples contain abundant Fe-Ni sulfides. A number of them have been thermally decomposed during their entry in the aerogel (Zolensky et al. 2006; Ishii et al. 2008a; Leroux et al. 2008b, 2009), but some of them are thought to have retained their initial composition and structure (Zolensky et al. 2008). Wild 2 Fe-Ni sulfides plot close to the troilite-pyrrhotite composition in the Fe-S-Ni ternary diagram and have generally less than 2 at% Ni (Zolensky et al. 2006). So far, only rare pentlandite minerals are noticed among Wild 2 cometary particles (Zolensky et al. 2006; Leroux et al. 2008b; Zolensky et al. 2008).

Hydrated Silicates

Phyllosilicates such as saponite or serpentine were detected in unmelted micrometeorites (Maurette et al. 1990; Kurat et al. 1994; Genge et al. 1997; Nakamura et al. 2001; Noguchi et al. 2002). Their total abundance in the AMMs investigated so far, do not exceed 1% (Noguchi et al. 2002). The occurrence of phyllosilicates in close association with anhydrous phases in micrometeorites is also typical of CM and CR meteorites. Up to now, no phyllosilicate-bearing AMMs have been found in the CONCORDIA collection, yet only a few particles have been recently investigated by TEM.

At this stage, no phyllosilicates were found in the cometary Wild 2 samples. These fragile phases could have been destroyed during the impact in the aerogel, or be simply absent from Wild 2 material.

Carbonates

Carbonates are very rare in Cap Prudhomme AMMs, due to terrestrial weathering in the ice. Several calcite ($CaCO_3$) and one dolomite ($CaMg(CO_3)_2$) grains have been identified in CONCORDIA AMMs so far (e.g., Duprat et al. 2007 and unpublished data). These carbonates are mostly found in fine-grained fluffy and ultracarbonaceous AMMs. No systematic mineralogical study of carbonates in AMMs is currently available. However, the average calcium content of the fine-grained matrix of CONCORDIA micrometeorites (Ca = 0.54 at%) is no longer depleted compared to CI (Ca = 0.5 at%, see Lodders, 2003 and Fig. 3) and CM (Ca = 0.62 at%), like what was observed in Cap-Prudhomme AMMs.

Carbonates (calcite, dolomite and possibly breunnerite) are also found in comet Wild 2 samples, with sizes varying from 0.1 µm to 0.7 µm (Mikouchi et al. 2007; Wirick et al. 2007; Flynn et al. 2008; Tomeoka et al. 2008). It is difficult to estimate the abundance of carbonates in Wild 2 samples so far and to fully exclude the possibility of carbonate contamination in the Stardust aerogel (Wirick et al. 2007).

Isotopic Compositions

Hydrogen Isotopic Composition

The hydrogen isotopic compositions of the hydrous component of 26 Cap-Prudhomme micrometeorites reveal a distribution centered on the terrestrial SMOW value (see Fig. 5 in Engrand et al. 1999a). This distribution of D/H ratios found for hydrated minerals in Cap-Prudhomme AMMs is roughly compatible with that of carbonaceous chondrites (e.g., Engrand et al. 1999a; Robert 2003). Similar values were measured for fossil micrometeorites found in HED meteorites (Gounelle et al. 2005a). Recently, extreme deuterium enrichments have been found in the carbonaceous matter of ultracarbonaceous micrometeorites (Duprat et al. 2009).

The D/H ratios of Stardust samples are not easy to assess, as the aerogel is highly hygroscopic, but values measured so far do not reveal large deuterium excesses (McKeegan et al. 2006).

Oxygen Isotopic Composition

The oxygen isotopic compositions of anhydrous minerals measured in a variety of AMMs show similarities with that of

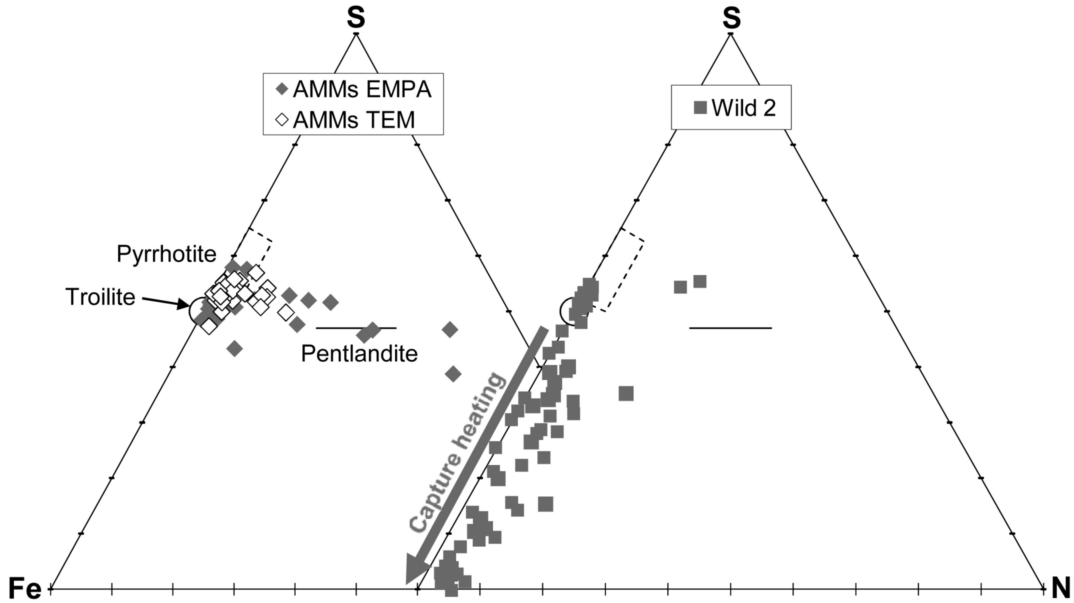

Fig. 8. Fe-Ni-S ternary diagram (at%) of Fe-Ni sulfides in Antarctic micrometeorites (MMs) (left diagram) and in Wild 2 samples (right diagram, data from Zolensky et al. 2006; Leroux et al. 2008b). In the left diagram, the transmission electron microscopy (TEM) data (open diamonds) of AMMs are compared to electron microprobe measurements of Fe-Ni sulfides in polished sections (filled grey diamonds, data from Engrand et al. 2007).

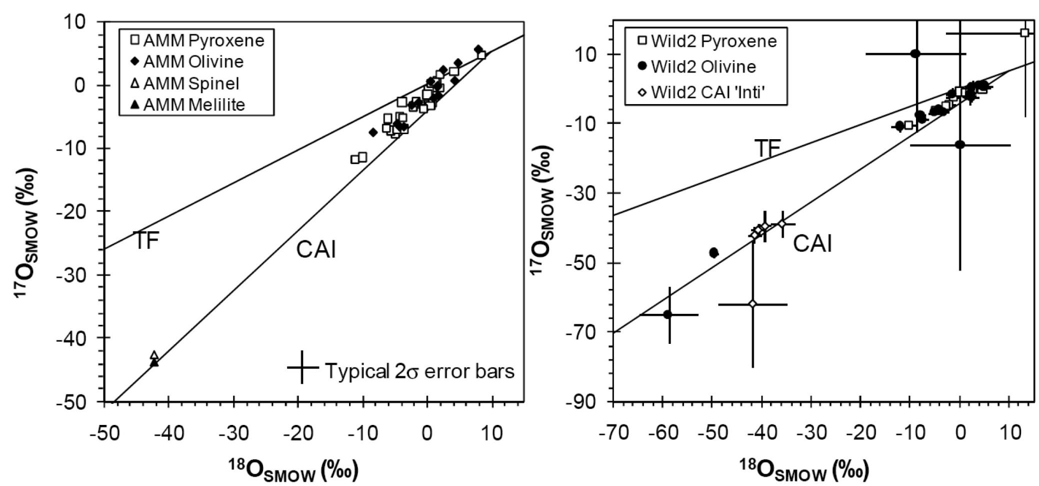

Fig. 9. Comparison of the oxygen isotopic compositions of anhydrous minerals in Antarctic micrometeorites (data from Engrand et al. 1999b) and in Wild 2 samples (data from McKeegan et al. 2006; Messenger et al. 2008a; Nakamura et al. 2008a; Simon et al. 2008; Nakamura-Messenger et al. 2009). Two sigma error bars are displayed for AMMs data sets. The terrestrial fractionation line (TF) and the line defined by carbonaceous chondrites anhydrous minerals (CCAM—data from Clayton 1993) are shown for reference.

isolated minerals and chondrules from carbonaceous chondrite minerals (Engrand et al. 1999b). Isotopic data for stony cosmic spherules (i.e., melted micrometeorites initially entering the atmosphere with higher velocities than unmelted ones) are also compatible with carbonaceous chondrite precursors (Clayton et al. 1986; Herzog et al. 1999; Engrand et al. 2005; Taylor et al. 2005; Yada et al. 2005).

Oxygen isotope data of Stardust samples are available for several minerals (enstatites and forsterites), a refractory inclusion (Inti) and chondrule-like objects found in the aerogel tracks (McKeegan et al. 2006; Messenger et al. 2008a; Nakamura et al. 2008a; Simon et al. 2008; Nakamura-Messenger et al. 2009). Figure 9 shows that oxygen isotopes are comparable in AMMs and in Stardust anhydrous minerals. These data are compatible with that of analogous material (olivines, pyroxenes and refractory minerals) in carbonaceous chondrites (e.g., Clayton 1993).

Carbonaceous Matter

The carbon content of Antarctic micrometeorites (except ultracarbonaceous micrometeorites—UCAMMs) measured with an ion microprobe yielded an average carbon content of ~2.5 wt% for Cap-Prudhomme AMMs (e.g., Maurette et al. 2000). Independent measurements of the C contents using a nuclear microprobe gave abundances from 0.2 to 2.8 wt% (Matrajt et al. 2003). The carbon content of UCAMMs discovered in the CONCORDIA collection was estimated from the volume of carbonaceous matter identified in SEM micrographs. UCAMMs contain from 50 vol% to 85 vol% of carbonaceous material. To calculate the corresponding C content, we took the insoluble organic matter (IOM) formula of Murchison ($C_{100}H_{48}N_{1.8}O_{12}S_2$, Gilmour 2005) as a proxy for the composition of the UCAMM carbonaceous matter. Assuming an average density of 2.5 for the MM silicates and of 1.2 for its carbonaceous matter, we obtain C contents ranging from ~35 wt% to ~55 wt%, comparable or larger than that of anhydrous IDPs (Thomas et al. 1993). The average carbon content of carbonaceous chondrites is <2.3 wt%, and C is less than 0.4 wt% in ordinary chondrites and C <0.3 wt% for enstatite chondrites (Alexander et al. 2007). Tagish Lake (CI) presents an elevated carbon abundances (5.81 wt%), larger than any other chondrite (Grady et al. 2002), but still much less than UCAMMs or C-rich anhydrous IDPs.

Micrometeorites Raman spectra exhibit the first-order carbon bands G and D, which point to the presence of polyaromatic carbonaceous matter. The high degree of disorder of this material revealed by the width and position of these bands definitely evidences the lack of significant thermal process (Dobrică et al. 2008, 2009b, unpublished data).

High-resolution TEM investigations of the carbonaceous matter in UCAMMs are coherent with the Raman measurements (e.g., Dobrică et al. 2009b). They show that the carbonaceous matter is highly disorganized but not stricto sensu amorphous since it is made of nanometer sized misoriented graphene layers (Rouzaud et al. 2005). Graphitic nanodomains with total sizes of ~1000 nm^2 have been observed as inclusions in amorphous-like carbonaceous material (~15 μm^2), but their abundance (<0.01%) is insignificant with regard to the disorganized carbonaceous material (Dobrică et al. 2009a).

Since the 1960s, rounded micron-size C-rich particles have been mentioned in meteorites and seem to be widespread constituents of carbonaceous chondrites (e.g., Briggs and Kitto 1962). Hollow organic globules have also been previously described in micrometeorites (Maurette et al. 1995, 1996) (see also Fig. 10) but no isotopic measurements have been performed on these globules so far. No organic globules have been observed in UCAMMs so far.

The abundance of carbon in Wild 2 samples, after correction for the presence of aerogel, is comparable or larger (from 1 wt% to 37 wt% C) to values obtained for carbonaceous meteorites (Gallien et al. 2008).

The cometary carbonaceous phases captured in aerogel by the Stardust spacecraft are rare and often intimately associated with silicates. From 14 particles analyzed, only two of them contain small (~100–200 nm) amounts of highly disorganized, organic material (Matrajt et al. 2008). Raman spectroscopy performed on Wild 2 samples shows the presence of an organic component with characteristics comparable to that of IDPs and very primitive meteorites (Sandford et al. 2006; Rotundi et al. 2008).

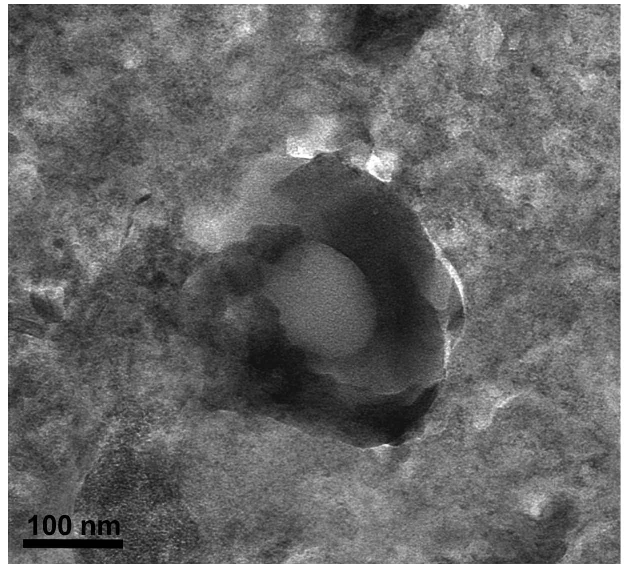

Fig. 10. Bright-field transmission electron microscopy (TEM) image of an organic globule from a fine-grained Cap Prudhomme Antarctic micrometeorite (CP99-02-09).

Cometary Wild 2 samples contain areas rich in carbon, shaped like doughnuts that resemble the organic globules initially described in Tagish Lake meteorite and found since then in many carbonaceous chondrites (Nakamura-Messenger et al. 2006; Matrajt et al. 2008; Messenger et al. 2008b).

Complex Organics

Extraterrestrial non-biogenic amino acids are molecules that are extremely rare on Earth but reach levels of hundreds of ppm in meteorites (e.g., Cronin and Moore 1971; Cronin and Pizzarello 1983; Pizzarello et al. 1991; Pizzarello and Cronin 2000; Pizzarello et al. 2001; Martins et al. 2007). The tentative detection of the amino acid α-aminoisobutyric acid (AIB) in Antarctic micrometeorites from Cap-Prudhomme (Brinton et al. 1998) was confirmed by a complementary study on South Pole Water Well AMMs (Matrajt et al. 2004). These studies show that AIB is present in about 15% of the AMMs, in concentrations much higher than in CM meteorites (Brinton et al. 1998; Matrajt et al. 2004).

Preliminary results of the cometary samples captured by the Stardust Mission indicate the presence of at least two volatile amine compounds (methylamine—MA and ethylamine—EA) and possibly one amino acid (Sandford et al. 2006; Glavin et al. 2008).

Table 1. Summary of the similarities and differences between micrometeorites and Wild 2 particles.

		AMMs	Stardust samples
Parent body		Asteroids and comets	Comet 81P/Wild 2
Bulk composition		~CI abundance	~CI abundance
Refractory minerals		In 29 AMMs Abundance < 1%	1 CAI Abundance?
Chondrules		Yes Low abundance	Yes Abundance?
	Olivine (Fo mol%)	$Fo_{48–100}$ (N = 54)	$Fo_{51–100}$ (N =84)
	Low-Ca pyroxene (mol%)	$En_{65–99}$; Wo<5 (N = 56)	$En_{58–100}$ (N = 85)
	Ca-rich pyroxene (mol%)	$Wo_{<44}$	$Wo_{<51}$
Silicates	LIME	Rare	Rare
	Phyllosilicate	Yes	No
	Pyroxene/olivine ratio	~1	~1
Carbonates	Sizes (µm)	0.5–7	0.1–0.7
Fe-Ni sulfides		All 3 types of sulfides, dominated by troilite	All 3 types of sulfides, dominated by troilite
Carbonaceous matter		Amorphous-like organic globules	Amorphous-like organic globules
Complex organics	Amino acids PAHs	Yes Yes	Yes? Yes
Isotopic compositions	D/H ratios	1 to 2×10^{-4}	1.2 to 5×10^{-4}
	Oxygen	CC-like	CC-like

Micrometeorites and particles from comet Wild 2 both contain polycyclic aromatic hydrocarbons (PAHs) (Clemett et al. 1998; Sandford et al. 2006). Comet Wild 2 organic particles contain low concentrations of aromatic and/or olefinic carbon relative to aliphatic and heteroatom-containing functional groups, e.g., amide, carboxyl and alcohol/ethers. The carbonaceous matter of Wild 2 samples shows a wide range in chemistry, both in elemental abundances and specific organic functional groups, with atomic ratios N/C and O/C being higher than that of primitive organic meteoritic matter (Cody et al. 2008).

DISCUSSION

Connection between Micrometeorites and Wild 2 Cometary Samples

We observe strong relationships between AMMs and Wild 2 cometary samples, in terms of chemical, mineralogical and isotopic compositions (Table 1).

Micrometeorites and Wild 2 samples have broadly the same bulk compositions matching the solar system abundances for rock forming elements. The K enrichment observed in one Wild 2 sample might be a sampling or contamination effect. The Fe depletion observed in Wild 2 crater residues may be the only significant indigenous deviation of Wild 2 composition from the CI value, as was already observed in comet 1P/Halley by the impact-ionization mass spectrometers on the Giotto and VEGA spacecraft (Jessberger 1999).

Refractory minerals are found in both Antarctic micrometeorites and Wild 2 samples. They are fragments of CAIs which are the oldest and most primitive objects formed in the solar system and are generally ubiquitous in chondritic meteorites (MacPherson 2005). These refractory minerals are predicted by thermodynamic calculations to condense from a gas of solar composition (Lord 1965; Grossman 1972). Their presence among Wild 2 samples requires radial transport of material from short distances from the protosun to the outer regions of the protoplanetary disk (Zolensky et al. 2006; Simon et al. 2008).

Chondrule-like materials are found in AMMs and Wild 2 samples (Genge et al. 2005; Nakamura et al. 2008a). Recent results confirmed that chondrules from meteorites formed ~2 Ma after CAIs (Amelin et al. 2002; Connelly et al. 2008). The finding of chondrule-like objects in comet Wild 2 strongly suggests that the transport mechanism(s) mentioned heretofore occurred in the early solar nebula for at least a few million years.

Mg-rich crystalline silicates (olivine and low-Ca pyroxenes) are the most commonly encountered minerals in AMMs. Unexpectedly, cometary samples from Wild 2 also present a high abundance of crystalline minerals with olivine and pyroxene as the most dominant phases (Brownlee et al. 2006; Zolensky et al. 2006). Pyroxenes are about as abundant as olivines in AMMs and in Wild 2 samples, as was also found in the Deep Impact ejecta of comet 9P/Tempel 1 (Lisse et al. 2006). The pyroxene/olivine numerical ratio of about unity could thus to be a useful indication for a cometary origin. Other authors have also proposed the possibility for chondrites from the CR group (with a high pyroxene/olivine ratio) to originate from cometary-like bodies (Weisberg and Connolly 2008). Although the size ranges of olivines and pyroxenes in micrometeorites (measured in this study) are larger than those measured in Wild 2, they present similar variation ranges in Mg/(Mg + Fe). One exception is the presence in comet Wild 2 of a pyroxene with lamellar intergrowths of pigeonite and diopside indicating that some of the cometary materials have been subject to igneous processes (Leroux et al. 2008a). Minerals such as LIME olivines and pyroxenes could form by condensation from a gas of solar composition (Klöck et al. 1989). We have shown here that AMMs contain rare LIME olivines and pyroxenes. Such minerals are also present in small quantities in Wild 2 particles (Zolensky et al. 2006, 2008).

Amorphous silicates are not present in high proportion in AMMs. This configuration contrasts with chondritic porous IDPs in which amorphous silicates are abundant in form of glass with embedded metal and sulfides (GEMS) (e.g., Bradley 1994; Keller and Messenger 2005). Amorphous silicate material is also present in very primitive meteorites (Brearley 1993; Greshake 1997). In Stardust samples, the abundance of indigenous amorphous silicates is not well constrained because of the thermally induced modifications during the capture (Leroux et al. 2008b, 2009). A significant part of the fine-grained component has been melted and mixed with the aerogel, leading to a microstructure close to that of GEMS in IDPs, thus preventing a clear identification of indigenous amorphous silicate component in Wild 2.

The presence of abundant Fe-Ni sulfides in micrometeorites indicates that a significant fraction of the samples (about 1/3) are not strongly heated during their deceleration at the atmospheric entry. The Fe-Ni sulfides of comet Wild 2 that have not been transformed during capture exhibit compositions similar to that of AMM Fe-Ni sulfides. In AMMs, the Fe-Ni sulfides are dominated by troilite, with some Fe-Ni sulfides plotting on a mixing trend between the troilite-pyrrhotite and pentlandite stability fields (see Fig. 8). In Wild 2 samples, the Fe-Ni sulfide compositions plot from the troilite-pyrrhotite fields directly toward the Fe apex (Zolensky et al. 2006), or toward the pentlandite composition. The Wild 2 data toward the Fe apex strongly suggest a capture effect of material which suffered thermal decomposition during the impact heating (Leroux et al. 2008b). As Ni-rich sulfides are only observed in partially melted (scoriaceous) micrometeorites (Engrand et al. 2007), the trend toward pentlandite suggests a formation of secondary pentlandite during the flash heating event in the atmospheric entry for AMMs or in the aerogel for Wild 2 samples. The primary Fe-Ni sulfides from AMMs and Wild 2 samples are dominated by troilite, which is thought to be the first sulfur containing mineral to form in the solar nebula from the sulfurization of Fe-Ni metal grains by H_2S, S_2, or other S-bearing gas species (Lauretta and Fegley 1994).

Formed in cold regions of the solar system, comets are believed to preserve pristine materials that are not expected to have suffered aqueous alteration. No phyllosilicates have been found in CONCORDIA micrometeorites so far, but only a few samples were examined by TEM. Phyllosilicates are absent from comet Wild 2 samples (Zolensky et al. 2008), although they might have been observed in comet 9P/Tempel 1 Deep Impact ejecta (Lisse et al. 2006). Carbonates are generally associated with aqueous alteration in meteorites. They are present in the CONCORDIA micrometeorites (Duprat et al. 2007) and in Wild 2 particles (Mikouchi et al. 2007; Wirick et al. 2007; Flynn et al. 2008; Tomeoka et al. 2008). They have also been observed in 1986 in the coma of comet 1P/Halley (Bregman et al. 1987), were ~5% of the carbonaceous compounds could belong to carbonates (Fomenkova et al. 1992; Fomenkova 1999). In comet, carbonates could form in the absence of liquid water by non-equilibrium condensation in circumstellar environments in the presence of water vapor (Toppani et al. 2005; Wooden 2008).

The good agreement between the oxygen isotopic compositions of Antarctic micrometeorites and Wild 2 samples reinforces the similarities observed in their chemical and mineralogical compositions. The situation is more complicated for the hydrogen isotopic composition of AMMs and Wild 2 samples, as the data sets are incomplete for both populations: in AMMs, only the hydrous component has been systematically studied so far (Engrand et al. 1999a); in Wild 2 samples, moderate D enrichments are only associated with carbonaceous matter and the D/H ratios are probably perturbed by the aerogel (McKeegan et al. 2006).

The high abundance of the amino-acid AIB found in some AMMs (Brinton et al. 1998; Matrajt et al. 2004) suggests that AIB may have been synthesized in an HCN-rich environment typical of comets, by a process different from the Strecker-type synthesis of amino acids in CM chondrites during an aqueous alteration of their parent asteroids. Although no amino-acids have been positively identified in Wild 2 samples so far, the presence of amines was shown to be indigenous of the cometary samples (Sandford et al. 2006; Glavin et al. 2008). The identification of organics with a wide range in chemistry, both in elemental abundances and specific organic functional groups, suggests that comet Wild 2 organics may have multiple origins (Cody et al. 2008).

Comets have long been proposed as a source of biogenic molecules for the origin of life on Earth (e.g., Chyba 1987, 1990). Some issues with this scenario include the possibly destructive high impact velocity of comets onto the early Earth, and the amount of biogenic material brought by comets. Micrometeorites represent the main source of extraterrestrial matter accreted by the Earth nowadays, and they contain carbonaceous matter and complex organics. They could have delivered complex organics and biogenic elements such as carbon, nitrogen and amino-acids and could have played a role in the emergence of life on the early Earth (e.g., Maurette 2006b).

An Unbiased Sampling of Primitive Interplanetary Matter?

Cosmic dust in the size range of micrometeorites currently represents the dominant input of extraterrestrial matter accreted by the Earth, about 1000 times more than meteorites (Love and Brownlee 1993; Bland et al. 1996; Taylor et al. 1998). The dynamical evolution of micrometeorites in interplanetary space is dominated by non-gravitational forces like Poynting-Robertson drag (Burns et al. 1979) whereas meteorites are delivered to Earth as a result of interactions with resonances, and their accretion is biased through gravitational focusing by the Earth (Vokrouhlický and Farinella 2000). Cosmic dust particles may thus be more representative of interplanetary bodies than meteorites do. Moreover, fragile meteorites like carbonaceous chondrites, may also be preferentially destroyed during atmospheric entry and by terrestrial weathering with regard to other meteorite classes (only 4% of meteorites are carbonaceous chondrites). Micrometeorites are related to carbonaceous chondrites (e.g., Kurat et al. 1994; Engrand and Maurette 1998), and the good match observed between this observation and the abundance of C-type over S-type asteroids (e.g., Meibom and Clark 1999) had led to the proposition that micrometeorites are the best representatives on Earth of the matter present in interplanetary space (e.g., Kurat et al. 1994; Gounelle et al. 2003). There are also evidences that the flux of micrometeorites did not change in composition as a function of time (Gounelle et al. 2003, 2005a) or toward smaller sizes (Gounelle et al. 2005b; Aléon et al. 2008). Very large micrometeorites (>400 µm) recently collected in Antarctica (e.g., Rochette et al. 2008; van Ginneken et al. 2008) show evidence for a larger contribution of ordinary chondrite-like objects than in AMMs from the 25–400 µm size range (Suavet et al. 2009). These large micrometeorites most probably sample the low mass tail of the meteoritic flux, representing “mini-meteorites” rather than “macro-micrometeorites.”

The unexpected observation of a fairly uniform carbonaceous-chondrite-like population in the micrometeorite collection that could not be reconciled with the two distinct sources of dust in interplanetary space, asteroids and comets, had lead to the proposition of an asteroid-comet continuum (see Maurette 2006a for a review). Wild 2 samples and AMMs show many similarities, suggesting a common origin of their major constituents. Regarding the grain size of the individual mineral components, they also display strong resemblance with a wide range of components. The FgF and FgC micrometeorites contain submicron minerals. The rest of the unmelted micrometeorites, the coarse-grained (Cg), contain crystals that cover a wide range of sizes (1~20 µm). A parallel configuration is encountered for the Wild 2 samples, as revealed by the shape of the impact morphologies of tracks in the aerogel and by the petrological studies of the collected grains (Hörz et al. 2006, Zolensky et al. 2006). The Wild 2 dust comprises dense and coarse-grained particles (up to several tens of micrometers) that could be compared to the Cg micrometeorite population. On the other hand, the bulbous-shaped tracks in aerogel also reveal poorly cohesive fine-grained aggregates ranging from tens of nanometers to hundreds of micrometers in size (Hörz et al. 2006; Burchell et al. 2008). Unfortunately, the fragile fine-grained matrix has been severely damaged during heating of the impact process and mixed with aerogel (Leroux et al. 2008b, 2009). At this stage, this configuration precludes a direct accurate comparison of grain size with the FgF and FgC micrometeorites. At the same time, they contain a large variety of primitive components formed at different heliocentric distances, suggesting efficient radial mixing mechanism(s) in the early solar nebula. The analyses of Wild 2 samples show that a continuum exists between primitive asteroidal matter (i.e., carbonaceous chondrites) and comets (see also Gounelle et al. 2008). Bottke et al. (2008) recently suggested a preferential formation of large amounts of dust from outer belt carbonaceous asteroids (extinct comet nuclei?) that could explain the high abundance of carbonaceous-chondrite-like objects in the micrometeorite collections. Cosmic dust particles, in the form of micrometeorites and primitive IDPs (Ishii et al. 2008a) are privileged objects to study this continuum between primitive asteroids and comets.

CONCLUSIONS

Antarctic micrometeorites and comet Wild 2 samples bear significant similarities. Wild 2 samples, the only proven cometary material available for analysis on Earth, are close to carbonaceous chondrites, anhydrous interplanetary dust particles, and micrometeorites, in terms of chemical, mineralogical, and isotopic compositions, thus suggesting a continuum between primitive asteroidal matter and comets.

Micrometeorites collected in Antarctica, and especially those from the CONCORDIA collection, well illustrate this asteroidal-cometary continuum, and together with primitive IDPs could be the best representatives of the most primitive interplanetary matter currently available for analyses in the laboratory. Cosmic dust in the size range of micrometeorites represents the dominant extraterrestrial matter currently accreted by the Earth, and they could have played a role in the early history of the Earth in terms of delivery of volatiles and exobiology.

The presence of chondrules, CAI fragments, and diverse types of organic compounds in both Wild 2 and micrometeorites suggest multiple origins and processes for these compounds, as well as large-scale radial mixing in the early solar nebula that lasted at least a few million years.

A word of caution should be taken as the Stardust mission sampled one comet among a population of several millions or more. Additional evidences about the origin and composition of another comet will be provided by the Rosetta mission that will encounter comet 67P/Churyumov-Gerasimenko in 2014. In addition, the Marco Polo mission proposed to ESA for the Cosmic Vision program would provide a means to investigate the physical and chemical properties of a carbonaceous asteroid and further study the link between asteroids and comets.

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REFERENCES

Aléon J., Engrand C., Leshin L., and McKeegan K. D. 2008. Oxygen isotopic composition of chondritic interplanetary dust particles: A genetic link between carbonaceous chondrites and comets. *Geochimica et Cosmochimica Acta* 73:4558–4575.

Alexander C. M. O. D., Fogel M., Yabuta H., and Cody G. D. 2007. The origin and evolution of chondrites recorded in the elemental and isotopic compositions of their macromolecular organic matter. *Geochimica et Cosmochimica Acta* 71:4380–4403.

Amelin Y., Krot A. N., Hutcheon I. D., and Ulyanov A. A. 2002. Lead isotopic ages of chondrules and calcium-aluminum-rich inclusions. *Science* 297:1678–1683.

Blanchard M. B., Brownlee D. E., Bunch T. E., Hodge P. W., and Kyte F. T. 1980. Meteoroid ablation spheres from deep-sea sediments. *Earth and Planetary Science Letters* 46:179–190.

Bland P. A., Smith T. B., Jull A. J. T., Berry F. J., Bevan A. W. R., Couldt S., and Pillinger C. T. 1996. The flux of meteorites to the Earth over the last 50,000 years. *Monthy Notices of the Royal Astronomical Society* 283:551–565.

Bonal L., Quirico E., Bourot-Denise M., and Montagnac G. 2006. Determination of the petrologic type of CV3 chondrites by Raman spectroscopy of included organic matter. *Geochimica et Cosmochimica Acta* 70:1849–1863.

Bottke W. F., Levison H. F., Nesvorny D., Morbidelli A., and Gounelle M. 2008. The collisional evolution of objects captured in the outer asteroid belt during the late heavy bombardment (abstract #8096). 2008 Asteroids, Comets, Meteors Conference.

Bradley J. P. 1988. Analysis of chondritic interplanetary dust thin-sections. *Geochimica et Cosmochimica Acta* 52:889–900.

Bradley J. P. 1994. Chemically anomalous preaccretionally irradiated grains in interplanetary dust from comets. *Science* 265:925–929.

Brearley A. J. 1993. Matrix and fine-grained rims in the unequilibrated CO3 chondrite, ALHA77307—Origins and evidence for diverse, primitive nebular dust components. *Geochimica et Cosmochimica Acta* 57:1521–1550.

Bregman J. D., Witteborn F. C., Allamandola L. J., Campins H., Wooden D. H., Rank D. M., Cohen M., and Tielens A. G. G. M. 1987. Airborne and ground-based spectrophotometry of comet P/Halley from 5–13 micrometers. *Astronomy and Astrophysics* 187:616–620.

Briggs M. H. and Kitto G. B. 1962. Complex organic microstructures in the Mokoia meteorite. *Nature* 193:1126–1127.

Brinton K. L. F., Engrand C., Glavin D. P., Bada J. L., and Maurette M. 1998. A search for extraterrestrial amino acids in carbonaceous Antarctic micrometeorites. *Origins of Life and Evolution of the Biosphere* 28:413–424.

Brownlee D., Tsou P., Aléon 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., Hörz 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., and Lyon I. 2006. Comet 81P/Wild 2 under a microscope. *Science* 314: 1711–1716.

Brownlee D. E. 1985. Cosmic dust: Collection and research. *Annual Review Earth and Planetary Science* 13:147–173.

Brownlee D. E., Bates B. A., and Wheelock M. M. 1984. Extraterrestrial platinum group nuggets in deep-sea sediments. *Nature* 309:693–695.

Brownlee D. E., Tomandl D. A., and Olszewski E. 1977. Interplanetary dust—A new source of extraterrestrial material for laboratory studies. Proceedings, 8th Lunar Science Conference. pp. 149–160.

Burchell M. J., Fairey S. A. J., Wozniakiewicz P., Brownlee D. E., Hörz 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.

Burns J. A., Lamy P. L., and Soter S. 1979. Radiation forces on small particles in the solar system. *Icarus* 40:1–48.

Chyba C. F. 1987. The cometary contribution to the oceans of primitive Earth. *Nature* 330:632–635.

Chyba C. F., Thomas P. J., Brookshaw L., and Sagan C. 1990. Cometary delivery of organic molecules to the early Earth. *Science* 249:366–373.

Clayton R. N. 1993. Oxygen isotopes in meteorites. *Annual Review Earth and Planetary Science* 21:115–149.

Clayton R. N., Mayeda T. M., and Brownlee D. E. 1986. Oxygen isotopes in deep-sea spherules. *Earth and Planetary Science Letters* 79:235–240.

Clemett S. J., Chillier X. D. F., Gillette S., Zare R. N., Maurette M., Engrand C., and Kurat G. 1998. Observation of indigeneous polycyclic aromatic hydrocarbons in 'giant' carbonaceous Antarctic micrometeorites. *Origins of Life and Evolution of the Biosphere* 28:425–448.

Cody G. D., Ade H., Alexander C. M. O., Araki T., Butterworth A., Fleckenstein H., Flynn G., Gilles M. K., Jacobsen C., Kilcoyne A. L. D., Messenger K., Sandford S. A., Tyliszczak T., Westphal A. J., Wirick S., and Yabuta H. 2008. Quantitative organic and light-element analysis of comet 81P/Wild 2 particles using C-, N-, and O-μ-XANES. *Meteoritics & Planetary Science* 43:353–365.

Connelly J. N., Amelin Y., Krot A. N., and Bizzarro M. 2008. Chronology of the solar system's oldest solids. *The Astrophysical Journal* 675:L121–L124.

Cronin J. R. and Moore C. B. 1971. Amino acid analyses of the Murchison, Murray, and Allende carbonaceous chondrites. *Science* 172:1327–1329.

Cronin J. R. and Pizzarello S. 1983. Amino acids in meteorites. *Advances in Space Research* 3:5–18.

Dobrică E., Engrand C., Leroux H., Rouzaud J.-N., and Duprat J. 2009a. Transmission electron microscopy of ultracarbonaceous Antarctic micrometeorites of possible cometary origin (abstract #1534). 40th Lunar and Planetary Science Conference. CD-ROM.

Dobrică E., Engrand C., Quirico E., Montagnac G., and Duprat J. 2008. New clues on composition and structure of carbonaceous matter in Antarctic micrometeorites. *Meteoritics & Planetary Science* 43:A38–A38.

Dobrică E., Engrand C., Quirico E., Montagnac G., and Duprat J. 2009b. Immature carbonaceous matter in CONCORDIA Antarctic micrometeorites (abstract #1688). 40th Lunar and Planetary Science Conference. CD-ROM.

Dohnanyi J. 1976. Sources of interplanetary dust: Asteroids. In *Interplanetary dust and zodiacal light.* Berlin/Heidelberg: Springer. pp. 187–205.

Duprat J., Dobrică E., Engrand C., Aléon J., Gounelle M., Leroux H., Marrocchi Y., Meibom A., Mostefaoui S., Quirico E., Rouzaud J.-N., Slodzian G., and Robert F. 2009. Extreme deuterium enrichment in organic matter from cometary Antarctic micrometeorites (abstract #1724). 40th Lunar and Planetary Science Conference. CD-ROM.

Duprat J., Engrand C., Maurette M., Gounelle M., Hammer C., and Kurat G. 2003. The CONCORDIA-collection : Pristine contemporary micrometeorites from central Antarctica surface snow (abstract #1727). 34th Lunar and Planetary Science Conference. CD-ROM.

Duprat J., Engrand C., Maurette M., Kurat G., Gounelle M., and Hammer C. 2007. Micrometeorites from central Antarctic snow: The CONCORDIA collection. *Advances in Space Research* 39: 605–611.

Engrand C., Deloule E., Robert F., Maurette M., and Kurat G. 1999a. Extraterrestrial water in micrometeorites and cosmic spherules from Antarctica: An ion microprobe study. *Meteoritics & Planetary Science* 34:773–787.

Engrand C., Duprat J., Maurette M., and Gounelle M. 2007. Fe-Ni sulfides in Concordia Antarctic micrometeorites (abstract #1668). 38th Lunar and Planetary Science Conference. CD-ROM.

Engrand C., Duprat J., Maurette M., Kurat G., and Gounelle M. 2006. Comparison of anhydrous minerals of Concordia and Cap-Prudhomme Antarctic micrometeorites. Predictions for Wild-2 cometary particles. *Meteoritics & Planetary Science* 41:A51.

Engrand C. and Maurette M. 1998. Carbonaceous micrometeorites from Antarctica. *Meteoritics & Planetary Science* 33:565–580.

Engrand C., McKeegan K. D., and Leshin L. A. 1999b. Oxygen isotopic compositions of individual minerals in Antarctic micrometeorites: Further links to carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 63:2623–2636.

Engrand C., McKeegan K. D., Leshin L. A., Herzog G. F., Schnabel C., Nyquist L. E., and Brownlee D. E. 2005. Isotopic compositions of oxygen, iron, chromium, and nickel in cosmic spherules: Toward a better comprehension of atmospheric entry heating effects. *Geochimica et Cosmochimica Acta* 69:5365–5385.

Flynn G. J., Bleuet P., Borg J., Bradley J. P., Brenker F. E., Brennan S., Bridges J., Brownlee D. E., Bullock E. S., Burghammer M., Clark B. C., Dai Z. R., Daghlian C. P., Djouadi Z., Fakra S., Ferroir T., Floss C., Franchi I. A., Gainsforth Z., Gallien J.-P., Gillet P., Grant P. G., Graham G. A., Green S. F., Grossemy F., Heck P. R., Herzog G. F., Hoppe P., Hörz F., Huth J., Ignatyev K., Ishii H. A., Janssens K., Joswiak D., Kearsley A. T., Khodja H., Lanzirotti A., Leitner J., Lemelle L., Leroux H., Luening K., MacPherson G. J., Marhas K. K., Marcus M. A., Matrajt G., Nakamura T., Nakamura-Messenger K., Nakano T., Newville M., Papanastassiou D. A., Pianetta P., Rao W., Riekel C., Rietmeijer F. J. M., Rost D., Schwandt C. S., See T. H., Sheffield-Parker J., Simionovici A., Sitnitsky I., Snead C. J., Stadermann F. J., Stephan T., Stroud R. M., Susini J., Suzuki Y., Sutton S. R., Taylor S., Teslich N., Troadec D., Tsou P., Tsuchiyama A., Uesugi K., Vekemans B., Vicenzi E. P., Vincze L., Westphal A. J., Wozniakiewicz P., Zinner E., and Zolensky M. E. 2006. Elemental compositions of comet 81P/Wild 2 samples collected by Stardust. *Science* 314:1731–1735.

Flynn G. J., Leroux H., Tomeoka K., Tomioka N., Ohnishi I., Mikouchi T., Wirick S., Keller L. P., Jacobsen C., and Sandford S. A. 2008. Carbonate in comets: A comparison of comets 1P/Halley, 9P/Temple 1, and 81P/Wild 2 (abstract #1979). 39th Lunar and Planetary Science Conference. CD-ROM.

Fomenkova M. N. 1999. On the Organic Refractory Component of Cometary Dust. *Space Science Reviews* 90:109–114.

Fomenkova M. N., Kerridge J. F., Marti K., and McFadden L. A. 1992. Compositional trends in rock-forming elements of comet halley dust. *Science* 258:266–269.

Gallien J. P., Khodja H., Herzog G. F., Taylor S., Koepsell E., Daghlian C. P., Flynn G. J., Sitnitsky I., Lanzirotti A., Sutton S. R., and Keller L. P. 2008. Characterization of carbon- and nitrogen-rich particle fragments captured from comet 81P/Wild 2. *Meteoritics & Planetary Science* 43:335–351.

Genge M. J. 2008. Koronis asteroid dust within Antarctic ice. *Geology* 36:687–690.

Genge M. J., Engrand C., Gounelle M., and Taylor S. 2008. The classification of micrometeorites. *Meteoritics & Planetary Science* 43:497–515.

Genge M. J., Gileski A., and Grady M. M. 2005. Chondrules in Antarctic micrometeorites. *Meteoritics & Planetary Science* 40: 225–238.

Genge M. J., Grady M. M., and Hutchison R. 1997. The textures and compositions of fine-grained Antarctic micrometeorites; implications for comparisons with meteorites. *Geochimica et Cosmochimica Acta* 61:5149–5162.

Gilmour I. 2005. Structural and isotopic analysis of organic matter in carbonaceous chondrites. In *Meteorites, comets and planets*, edited by Davis A. Treatise on Geochemistry, vol. 1. Oxford: Elsevier-Pergamon. p. 269.

Glavin D. P., Dworkin J. P., and Sandford S. A. 2008. Detection of cometary amines in samples returned by Stardust. *Meteoritics & Planetary Science* 43:399–413.

Gounelle M., Engrand C., Alard O., Bland P. A., Zolensky M. E., Russell S. S. and Duprat J. 2005a. Hydrogen isotopic composition of water from fossil micrometeorites in howardites. *Geochimica et Cosmochimica Acta* 69:3431–3443.

Gounelle M., Engrand C., Maurette M., Kurat G., McKeegan K. D., and Brandstätter F. 2005b. Small Antarctic micrometeorites (25–50 µm): A mineralogical and in situ oxygen isotopic study. *Meteoritics & Planetary Science* 40:917–932.

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

Gounelle M., Zolensky M. E., Liou J.-C., Bland P. A., and Alard O. 2003. Mineralogy of carbonaceous chondritic microclasts in howardites: identification of C2 fossil micrometeorites. *Geochimica et Cosmochimica Acta* 67:507–527.

Grady M. M., Verchovsky A. B., Franchi I. A., Wright I. P., and Pillinger C. T. 2002. Light element geochemistry of the Tagish Lake CI2 chondrite: Comparison with CI1 and CM2 chondrites. *Meteoritics & Planetary Science* 37:713–735.

Greshake A. 1997. The primitive matrix components of the unique carbonaceous chondrite ACFER 094: A TEM study. *Geochimica et Cosmochimica Acta* 61:437–452.

Greshake A., Hoppe P., and Bischoff A. 1996. Mineralogy, chemistry, and oxygen isotopes of refractory inclusions from stratospheric interplanetary dust particles and micrometeorites. *Meteoritics & Planetary Science* 31:739–748.

Grossman L. 1972. Condensation in the primitive solar nebula. *Geochimica et Cosmochimica Acta* 36:597–619.

Harvey R. P. and Maurette M. 1991. The origin and significance of cosmic dust from the Walcott Neve, Antarctica. Proceedings, 21st Lunar and Planetary Science Conference. pp. 569–578.

Herzog G. F., Xue S., Hall G. S., Nyquist L. E., Shih C. Y., Wiesmann H., and Brownlee D. E. 1999. Isotopic and elemental composition of iron, nickel, and chromium in type I deep-sea spherules: Implications for origin and composition of the parent micrometeoroids. *Geochimica et Cosmochimica Acta* 63:1443–1457.

Hoppe P., Kurat G., Walter J., and Maurette M. 1995. Trace elements and oxygen isotopes in a CAI-bearing micrometeorite from Antarctica. 26th Lunar and Planetary Science Conference. pp. 623–624.

Hörz F., Bastien R., Borg J., Bradley J. P., Bridges J. C., Brownlee D. E., Burchell M. J., Chi M., Cintala M. J., Dai Z. R., Djouadi Z., Dominguez G., Economou T. E., Fairey S. A. J., Floss C., Franchi I. A., Graham G. A., Green S. F., Heck P., Hoppe P., Huth J., Ishii H., Kearsley A. T., Kissel J., Leitner J., Leroux H., Marhas K., Messenger K., Schwandt C. S., See T. H., Snead C., Stadermann F. J., Stephan T., Stroud R., Teslich N., Trigo-Rodríguez J. M., Tuzzolino A. J., Troadec D., Tsou P., Warren J., Westphal A., Wozniakiewicz P., Wright I., and Zinner E. 2006. Impact features on Stardust: Implications for comet 81P/Wild 2 dust. *Science* 314:1716–1719.

Ishii H. A., Bradley J. P., Dai Z. R., Chi M., Kearsley A. T., Burchell M. J., Browning N. D., and Molster F. 2008a. Comparison of comet 81P/Wild 2 dust with interplanetary dust from comets. *Science* 319:447.

Ishii H. A., Brennan S., Bradley J. P., Luening K., Ignatyev K., and Pianetta P. 2008b. Recovering the elemental composition of comet Wild 2 dust in five Stardust impact tracks and terminal particles in aerogel. *Meteoritics & Planetary Science* 43:215–231.

Jacob D., Stodolna J., Leroux H., Langenhorst F., and Houdellier F. 2009. Pyroxene microstructures in comet 81P/wild 2 terminal dust particles. *Meteoritics & Planetary Science* 44. This issue.

Jessberger E. K. 1999. Rocky cometary particulates: Their elemental, isotopic and mineralogical ingredients. *Space Science Reviews* 90:91–97.

Kearsley A. T., Borg J., Graham G. A., Burchell M. J., Cole M. J., Leroux H., Bridges J. C., Hörz F., Wozniakiewicz P. J., Bland P. A., Bradley J. P., Dai Z. R., Teslich N., See T., Hoppe P., Heck P. R., Huth J., Stadermann F. J., Floss C., Marhas K., Stephan T., and Leitner J. 2008. Dust from comet Wild 2: Interpreting particle size, shape, structure, and composition from impact features on the Stardust aluminum foils. *Meteoritics & Planetary Science* 43:41–73.

Keller L. P. and Messenger S. 2005. The nature and origin of interplanetary dust: High-temperature components. In *Chondrites and the Protoplanetary Disk.* ASP Conference Series. 657 p.

Klöck W., Thomas K. L., McKay D. S., and Palme H. 1989. Unusual olivine and pyroxene composition in interplanetary dust and unequilibrated ordinary chondrite. *Nature* 339:126–128.

Kurat G., Hoppe P., and Engrand C. 1996. A chondrule micrometeorite from Antarctica with vapor fractionated trace element abundances (abstract). *Meteoritics & Planetary Science* 31:A75.

Kurat G., Koeberl C., Presper T., Brandstätter F., and Maurette M. 1994. Petrology and geochemistry of Antarctic micrometeorites. *Geochimica et Cosmochimica Acta* 58:3879–3904.

Lanzirotti A., Sutton S. R., Flynn G. J., Newville A., and Rao W. 2008. Chemical composition and heterogeneity of Wild 2 cometary particles determined by synchrotron X-ray fluorescence. *Meteoritics & Planetary Science* 43:187–213.

Lauretta D. S. and Fegley B., Jr. 1994. Troilite formation kinetics and growth mechanism in the solar nebula. *Meteoritics* 29:490.

Leitner J., Stephan T., Kearsley A. T., Hörz F., Flynn G. J., and Sandford S. A. 2008. TOF-SIMS analysis of crater residues from Wild 2 cometary particles on Stardust aluminum foil. *Meteoritics & Planetary Science* 43:161–185.

Leroux H., Jacob D., Stodolna J., Nakamura-Messenger K., and Zolensky M. E. 2008a. Igneous Ca-rich pyroxene in comet 81P/Wild 2. *American Mineralogist* 93:1933–1936.

Leroux H., Rietmeijer F. J. M., Velbel M. A., Brearley A. J., Jacob D., Langenhorst F., Bridges J. C., Zega T. J., Stroud R. M., Cordier P., Harvey R. P., Lee M., Gounelle M., and Zolensky M. E. 2008b. A TEM study of thermally modified comet 81P/Wild 2 dust particles by interactions with the aerogel matrix during the Stardust capture process. *Meteoritics & Planetary Science* 43: 97–120.

Leroux H., Roskosz M., and Jacob D. 2009. Oxidation state of iron and extensive redistribution of sulfur in thermally modified Stardust particles. *Geochimica et Cosmochimica Acta* 73:767–777.

Leroux H., Stroud R. M., Dai Z. R., Graham G. A., Troadec D., Bradley J. P., Teslich N., Borg J., Kearsley A. T., and Hoerz F. 2008c. Transmission electron microscopy of cometary residues from micron-sized craters in the Stardust Al foils. *Meteoritics & Planetary Science* 43:143–160.

Lindsley D. H. 1983. Pyroxene thermometry. *American Mineralogist* 68:477–493.

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.

Lodders K. 2003. Solar system abundances and condensation temperatures of the elements. *The Astrophysical Journal* 591: 1220–1247.

Lord H. C., III 1965. Molecular equilibria and condensation in a solar nebula and cool stellar atmospheres. *Icarus* 4:279.

Lorin J. C., Christophe Michel-Lévy M., Slodzian G., Dennebouy R. and Bourot-Denise M. 1989. Isotopic and minor elements signature of coarse-grained micrometeorites from Greenland blue ice lakes. *Meteoritics* 24:295.

Love S. G. and Brownlee D. E. 1993. A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science* 262:550–553.

MacPherson G. J. 2005. Calcium-aluminum-rich inclusions in chondritic meteorites. In *Meteorites, comets and planets*, edited by Davis A. Treatise on Geochemistry, vol. 1. Oxford: Elsevier-Pergamon. pp. 201–246.

Martins Z., Alexander C. M. O., Orzechowska G. E., Fogel M. L., and Ehrenfreund P. 2007. Indigenous amino acids in primitive CR meteorites. *Meteoritics & Planetary Science* 42:2125–2136.

Matrajt G., Ito M., Wirick S., Messenger S., Brownlee D. E., Joswiak D., Flynn G., Sandford S., Snead C., and Westphal A. 2008. Carbon investigation of two Stardust particles: A TEM, NanoSIMS, and XANES study. *Meteoritics & Planetary Science* 43:315–334.

Matrajt G., Pizzarello S., Taylor S., and Brownlee D. 2004. Concentration and variability of the AIB amino acid in polar micrometeorites: Implications for the exogenous delivery of amino acids to the primitive Earth. *Meteoritics & Planetary Science* 39:1849–1858.

Matrajt G., Taylor S., Flynn G., Brownlee D. E., and Joswiak D. 2003. A nuclear microprobe study of the distribution and concentration of carbon and nitrogen in Murchison and Tagish Lake meteorites, Antarctic micrometeorites, and IDPs: implications for astrobiology. *Meteoritics & Planetary Science* 38:1585–1600.

Maurette M. 1996. Carbonaceous micrometeorites and the origin of life. *Origins of Life and Evolution of Biospheres* 28:385–412.

Maurette M. 2006a. Cometary micrometeorites in planetology, exobiology, and early climatology. In *Comets and the origin and evolution of life*. pp. 69–111.

Maurette M. 2006b. *Micrometeorites and the mysteries of our origins*. Berlin: Springer. 330 p.

Maurette M., Beccard B., Bonny P., Brack A., Christophe M., and Veyssière P. 1990. C-rich micrometeorites on the early earth and icy planetary bodies. In *Formation of stars and planets, and the evolution of the solar system*. pp. 167–172.

Maurette M., Duprat J., Engrand C., Gounelle M., Kurat G., Matrajt G., and Toppani A. 2000. Accretion of neon, organics, CO_2, nitrogen and water from large interplanetary dust particles on the early Earth. *Planetary and Space Science* 48:1117–1137.

Maurette M., Engrand C., Brack A., Kurat G., Leach S., and Perreau M. 1995. Carbonaceous phases in Antarctic micrometeorites and their mineralogical environment. Their contribution to the possible role of micrometeorites as “chondritic chemical reactors” in atmospheres, waters and/or ices. 26th Lunar and Planetary Science Conference. pp. 913–914.

Maurette M., Hammer C., Brownlee D. E., Reeh N., and Thomsen H. H. 1986. Placers of cosmic dust in the blue ice lakes of Greenland. *Science* 233:869–872.

Maurette M., Jéhano C., Robin E., and Hammer C. 1987. Characteristics and mass distribution of extraterrestrial dust from the Greenland ice cap. *Nature* 328:699–702.

Maurette M., Olinger C., Christophe M., Kurat G., Pourchet M., Brandstätter F., and Bourot-Denise M. 1991. A collection of diverse micrometeorites recovered from 100 tons of Antarctic blue ice. *Nature* 351:44–47.

McKeegan K. D., Aléon 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.

Meibom A. and Clark B. E. 1999. Invited review: Evidence for the insignificance of ordinary chondritic material in the asteroid belt. *Meteoritics & Planetary Science* 34:7–24.

Messenger S., Ito M., Joswiak D. J., Keller L. P., Stroud R. M., Nakamura-Messenger K., Matrajt G., and Brownlee D. E. 2008a. Oxygen isotopic compositions of Wild 2 silicates (abstract #5308). *Meteoritics & Planetary Science* 43:A97.

Messenger S., Nakamura-Messenger K., and Keller L. P. 2008b. 15N-rich organic globules in a cluster IDP and the Bells CM2 chondrite (abstract #2391). 39th Lunar and Planetary Science Conference. CD-ROM.

Mikouchi T., Tachikawa O., Hagiya K., Ohsumi K., Suzuki Y., Uesugi K., Takeuchi A., and Zolensky M. E. 2007. Mineralogy and crystallography of comet 81P/Wild 2 particles (abstract #1946). 38th Lunar and Planetary Science Conference. CD-ROM.

Nakamura-Messenger K., Keller L. P., Clemett S. J., and Messenger S. 2009. NM-Scale Anatomy of an entire Stardust carrot track (abstract #1989). In 40th Lunar and Planetary Science Conference. CD-ROM.

Nakamura-Messenger K., Messenger S., Keller L. P., Clemett S. J., and Zolensky M. E. 2006. Organic globules in the Tagish Lake meteorite: Remnants of the protosolar disk. *Science* 314:1439–1442.

Nakamura T., Imae N., Nakai I., Noguchi T., Yano H., Terada K., Murakami T., Fukuoka T., Nogami K.-I., Ohashi H., Nozaki W., Hashimoto M., Kondo N., Matsuzaki H., Ichikawa O., and Ohmori R. 1999. Antarctic micrometeorites collected at the Dome Fuji Station. *Antarctic Meteorite Research* 12:183–198.

Nakamura T., Noguchi T., Ozono Y., Osawa T., and Nagao K. 2005. Mineralogy of ultracarbonaceous large micrometeorites (abstract #5046). *Meteoritics & Planetary Science* 40:A110.

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. 2008a. Chondrule-like objects in short-period comet 81P/Wild 2. *Science* 321:1664–1667.

Nakamura T., Noguchi T., Yada T., Nakamuta Y., and Takaoka N. 2001. Bulk mineralogy of individual micrometeorites determined by X-ray diffraction analysis and transmission microscopy. *Geochimica et Cosmochimica Acta* 65:4385–4397.

Nakamura T., Tsuchiyama A., Akaki T., Uesugi K., Nakano T., Takeuchi A., Suzuki Y., and Noguchi T. 2008b. Bulk mineralogy and three-dimensional structures of individual Stardust particles deduced from synchrotron X-ray diffraction and microtomography analysis. *Meteoritics & Planetary Science* 43: 247–259.

Noguchi T., Nakamura T., and Nozaki W. 2002. Mineralogy of phyllosilicate-rich micrometeorites and comparison with Tagish Lake and Sayama meteorites. *Earth and Planetary Science Letters* 202:229–246.

Noguchi T., Nakamura T., Okudaira K., Yano H., Sugita S., and Burchell M. J. 2007. Thermal alteration of hydrated minerals during hypervelocity capture to silica aerogel at the flyby speed of Stardust. *Meteoritics & Planetary Science* 42:357–372.

Pizzarello S. and Cronin J. R. 2000. Non-racemic amino acids in the Murray and Murchison meteorites. *Geochimica et Cosmochimica Acta* 64:329–338.

Pizzarello S., Huang Y., Becker L., Poreda R. J., Nieman R. A., Cooper G., and Williams M. 2001. The organic content of the Tagish Lake meteorite. *Science* 293:2236–2239.

Pizzarello S., Krishnamurthy R. V., Epstein S., and Cronin J. R. 1991. Isotopic analysis of amino acids from the Murchison meteorite. *Geochimica et Cosmochimica Acta* 55:905–910.

Quirico E., Borg J., Raynal P.-I., Montagnac G., and D'Hendecourt L. 2005a. A micro-Raman survey of 10 IDPs and 6 carbonaceous chondrites. *Planetary and Space Science* 53:1443–1448.

Quirico E., Rouzaud J.-N., Bonal L., and Montagnac G. 2005b. Maturation grade of coals as revealed by Raman spectroscopy: Progress and problems. *Spectrochimica Acta Part A* 61:2368–2377.

Robert F. 2003. The D/H ratio in chondrites. *Space Science Reviews* 106:87–101.

Rochette P., Folco L., Suavet C., van Ginneken M., Gattacceca J., Perchiazzi N., Braucher R., and Harvey R. 2008. Micrometeorites from the Transantarctic Mountains. *Proceedings of the National Academy of Sciences* 105:18,206–18,211.

Roskosz M., Leroux H., and Watson H. C. 2008. Thermal history, partial preservation and sampling bias recorded by Stardust cometary grains during their capture. *Earth and Planetary Science Letters* 273:195–202.

Rotundi A., Baratta G. A., Borg J., Brucato J. R., Busemann H., Colangeli L., D'Hendecourt L., Djouadi Z., Ferrini G., Franchi I. A., Fries M., Grossemy F., Keller L. P., Mennella V., Nakamura K., Nittler L. R., Palumbo M. E., Sandford S. A., Steele A., and Wopenka B. 2008. Combined micro-Raman, micro-infrared, and field emission scanning electron microscope analyses of comet 81P/Wild 2 particles collected by Stardust. *Meteoritics & Planetary Science* 43:367–397.

Rouzaud J. N., Skrzypczak A., Bonal L., Derenne S., Quirico E., and Robert F. 2005. The high resolution transmission electron microscopy: A powerful tool for studying the organization of terrestrial and extra-terrestrial carbons (#1322). 36th Lunar and Planetary Science Conference. CD-ROM.

Sandford S. A., Aléon 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* 314:1720–1724.

Simon S. B., Joswiak D. J., Ishii H. A., Bradley J. P., Chi M., Grossman L., Aléon 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.

Stephan T., Flynn G. J., Sandford S. A., and Zolensky M. E. 2008a. TOF-SIMS analysis of cometary particles extracted from Stardust aerogel. *Meteoritics & Planetary Science* 43:285–298.

Stephan T., Rost D., Vicenzi E. P., Bullock E. S., Macpherson G. J., Westphal A. J., Snead C. J., Flynn G. J., Sandford S. A., and Zolensky M. E. 2008b. TOF-SIMS analysis of cometary matter in Stardust aerogel tracks. *Meteoritics & Planetary Science* 43: 233–246.

Suavet C., Alexandre A., Franchi I. A., Gattacceca J., Sonzogni C., Folco L., Greenwood R. C., and Rochette P. 2009. Oxygen isotope ratios of large cosmic spherules: Carbonaceous and ordinary chondrite parent bodies (abstract #1776). 40th Lunar and Planetary Science Conference. CD-ROM.

Taylor S., Alexander C. M. O. D., Delaney J., Ma P., Herzog G. F., and Engrand C. 2005. Isotopic fractionation of iron, potassium, and oxygen in stony cosmic spherules: Implications for heating histories and sources. *Geochimica et Cosmochimica Acta* 69: 2647–2662.

Taylor S. and Brownlee D. E. 1991. Cosmic spherules in the geologic record. *Meteoritics* 26:203–211.

Taylor S. and Lever J. H. 2001. Seeking unbiased collections of modern and ancient micrometeorites. In *Accretion of extraterrestrial matter throughout Earth's history*, edited by Peucker-Ehrenbrink B. and Schmitz B. New York: Kluwer Academic/Plenum Publishers. pp. 205–219.

Taylor S., Lever J. H., and Harvey R. P. 1998. Accretion rate of cosmic spherules measured at the South Pole. *Nature* 392:899–903.

Taylor S., Lever J. H., and Harvey R. P. 2000. Numbers, types and compositions of an unbiased collection of cosmic spherules. *Meteoritics & Planetary Science* 35:651–666.

Terada K., Yada T., Kojima H., Noguchi T., Nakamura T., Murakami T., Yano H., Nozaki W., Nakamuta Y., Matsumoto N., Kamata J., Mori T., Nakai I., Sasaki M., Itabashi M., Setoyanagi T., Nagao K., Osawa T., Hiyagon H., Mizutani S., Fukuoka T., Nogami K.-I., Ohmori R., and Ohashi H. 2001. General characterization of Antarctic micrometeorites collected by the 39th Japanese Antarctic Research Expedition: Consortium studies of JARE AMMs (III). *Antarctic Meteorite Research* 14:89.

Thomas K. L., Blanford G. E., Keller L. P., Klöck W., and McKay D. 1993. Carbon abundance and silicate mineralogy of anhydrous interplanetary dust particles. *Geochimica et Cosmochimica Acta* 57:1551–1566.

Tomeoka K., Tomioka N., and Ohnishi I. 2008. Silicate minerals and Si-O glass in comet Wild 2 samples: Transmission electron microscopy. *Meteoritics & Planetary Science* 43:273–284.

Toppani A., Libourel G., Engrand C., and Maurette M. 2001. Experimental simulation of atmospheric entry of micrometeorites. *Meteoritics & Planetary Science* 36:1377–1396.

Toppani A., Robert F., Libourel G., de Donato P., Barres O., D'Hendecourt L., and Ghanbaja J. 2005. A 'dry' condensation origin for circumstellar carbonates. *Nature* 437:1121–1124.

Tsou P., Brownlee D. E., Hörz F., Newburn R. L., Sandford S. A., Sekanina Z., and Zolensky M. E. 2004. STARDUST sample collection at Wild 2 and its preliminary examination (abstract #1898). 35th Lunar and Planetary Science Conference. CD-ROM.

Van Ginneken M., Folco L., and Rochette P. 2008. Micrometeorites in the 400–1100 μm size range from the Transantarctic Mountains (abstract #5084). *Meteoritics & Planetary Science* 43:A161.

Vokrouhlický D. and Farinella P. 2000. Efficient delivery of meteorites to the Earth from a wide range of asteroid parent bodies. *Nature* 407:606–608.

Walter J., Brandstätter F., Kurat G., Koeberl C., and Maurette M. 1995a. Cosmic spherules, micrometeorites and chondrules (abstract). 26th Lunar and Planetary Science Conference. pp. 1457–1458.

Walter J., Kurat G., Brandstätter F., Koeberl C., and Maurette M. 1995b. The abundance of ordinary chondrite debris among Antarctic micrometeorites. *Meteoritics* 30:592–593.

Weisberg M. K. and Connolly H. C. 2008. On the relationship between chondrites, comets, and asteroids, a petrologic perspective (abstract #1981). 39th Lunar and Planetary Science Conference. CD-ROM.

Wirick S., Leroux H., Tomeoka K., Zolensky M., Flynn G. J., Tyliszczak T., Butterworth A., Tomioka N., Ohnishi I., Nakamura-Messenger K., Sandford S., Keller L., and Jacobsen C. 2007. Carbonates found in Stardust aerogel tracks (abstract #1534). 38th Lunar and Planetary Science Conference. CD-ROM.

Wooden D. H. 2008. Cometary refractory grains: Interstellar and nebular sources. *Space Science Reviews* 138:75–108.

Yada T. and Kojima H. 2000. The collection of micrometeorites in the Yamato meteorite ice field of Antarctica in 1998. *Antarctic Meteorite Research* 13:9–18.

Yada T., Nakamura T., Noguchi T., Matsumoto N., Kusakabe M., Hiyagon H., Ushikubo T., Sugiura N., Kojima H., and Takaoka N. 2005. Oxygen isotopic and chemical compositions of cosmic spherules collected from the Antarctic ice sheet: Implications for their precursor materials. *Geochimica et Cosmochimica Acta* 69:5789–5804.

Zolensky M., Nakamura-Messenger K., Rietmeijer F., Leroux H., Mikouchi T., Ohsumi K., Simon S., Grossman L., Stephan T., Weisberg M., Velbel M., Zega T., Stroud R., Tomeoka K., Ohnishi I., Tomioka N., Nakamura T., Matrajt G., Joswiak D., Brownlee D., Langenhorst F., Krot A., Kearsley A., Ishii H., Graham G., Da Z. R., Ch M., Bradley J., Hagiya K., Gounelle M., Keller L., and Bridges J. 2008. Comparing Wild 2 particles to chondrites and IDPs. *Meteoritics & Planetary Science* 43:261–272.

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.