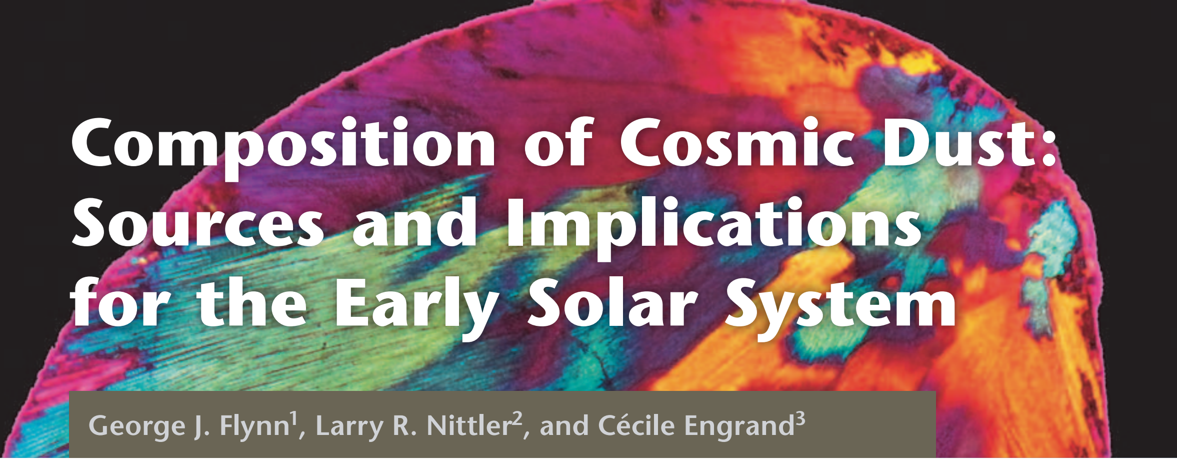

Composition of Cosmic Dust: Sources and Implications for the Early Solar System

George J. Flynn[1], Larry R. Nittler[2], and Cécile Engrand[3]

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Many cosmic dust particles have escaped the aqueous and thermal processing, the gravitational compaction, and the impact shocks that often overprint the record, in most larger samples, of how Solar System materials formed. The least-altered types of cosmic dust can, therefore, act as probes into the conditions of the solar protoplanetary disk when the first solids formed. Analyses of these "primitive" particles indicate that the protoplanetary disk was well mixed, that it contained submicron grains formed in a diversity of environments, that these grains were aerodynamically transported prior to aggregation, which was likely aided by organic grain coatings, and that some minerals that condensed directly from the disk are not found in other materials. These protoplanetary aggregates are not represented in any type of meteorite or terrestrial rock. They can only be studied from cosmic dust.

Keywords: interplanetary dust particles, micrometeorites, cosmic dust, zodiacal cloud, protoplanetary disk, grain condensation, grain aggregation

INTRODUCTION

Our Solar System began as a rotating disk of gas surrounding the forming Sun. The combined effects of gravitational infall, viscosity, and solar radiation heated the gas, doing do most severely (>>1,000 K) within a few astronomical units of the Sun [one astronomical unit is the distance between the Earth and the Sun], while the outer regions of the disk remained cold. The formation of solids from this protoplanetary disk is modeled using thermodynamic properties of a suite of minerals to determine the distribution of major elements between vapor and solid as the gas cools. These models indicate that Ca-, Al-, and Ti-oxides are the first minerals to condense at temperatures around 1,800 K, with Mg-silicates condensing around 1,350 K. Sulfides condense at a much lower temperature, around 700 K. Thus, any object with a solar-like ("chondritic") elemental composition must be an aggregate of minerals that formed at different temperatures, i.e. either at different times in the same location or at different locations.

Because the record of disk conditions has been erased in terrestrial materials (Earth rocks) by planetary processes, extraterrestrial materials are valuable resources for understanding the earliest stages of Solar System and planetary formation. Meteorite analyses constrain some disk conditions, but meteorites only sample narrow zones of the asteroid belt where gravitational resonances from giant planets perturb them into Earth-crossing orbits, and they only sample material strong enough to survive atmospheric deceleration. Cosmic dust, on the other hand, offers samples from all potential dust-producing bodies of the Solar System (predominantly comets and asteroids) and, because dust decelerates higher in the atmosphere, much weaker particles can survive and be collected and analyzed. Thus, characterizing interplanetary dust particles (IDPs) and micrometeorites (MMs), though challenging because of their small size (<1 ng for many IDPs), is most rewarding. The elemental, mineralogical, and isotopic contents of cosmic dust provide evidence of their sources, formation conditions, and any alteration processes they have experienced since their formation.

INTERPLANETARY DUST PARTICLES AND MICROMETEORITES: REMNANTS OF THE SOLAR SYSTEM'S BUILDING BLOCKS

Chemical and Mineralogical Compositions of IDPs

Chondritic meteorites, which sampled undifferentiated parent bodies, have solar-like major element abundances, quite distinct from those of differentiated bodies like the Earth, the Moon, or Mars. For example, Ni, which became concentrated in Earth's core during differentiation, is present in significantly higher concentrations in chondritic meteorites than in most terrestrial samples. The chondritic elemental compositions of IDPs and MMs provided an early indication that they were, indeed, the long-sought interplanetary dust (Fig. 1). Definitive proof of their extraterrestrial origin came via identification of deuterium enrichments relative to terrestrial D/H (Zinner et al. 1983), as well as solar flare tracks, which are linear damage tracks to the crystalline structure and visible in transmission electron microscope images, that are caused by the passage of a solar flare ions, seen in many IDPs, and the presence of noble gases implanted by the solar wind in MMs (Olinger et al. 1990) and IDPs.

Individual IDPs experience different peak temperatures during atmospheric deceleration depending on their size, density, and entry angle. This heating pulse can erase

1 Dept. of Physics, SUNY-Plattsburgh
Plattsburgh, NY 12901, USA
E-mail: george.flynn@plattsburgh.edu

2 Department of Terrestrial Magnetism
Carnegie Institution of Washington
Washington, DC 20015, USA
E-mail: lnittler@carnegiescience.edu

3 Centre de Sciences Nucléaires et de Sciences de la Matière
CNRS/IN2P3-Univ. Paris Sud – UMR8609, Université Paris-Saclay
Batiment 104, 91405 Orsay Campus, France
E-mail: cecile.engrand@csnsm.in2p3.fr

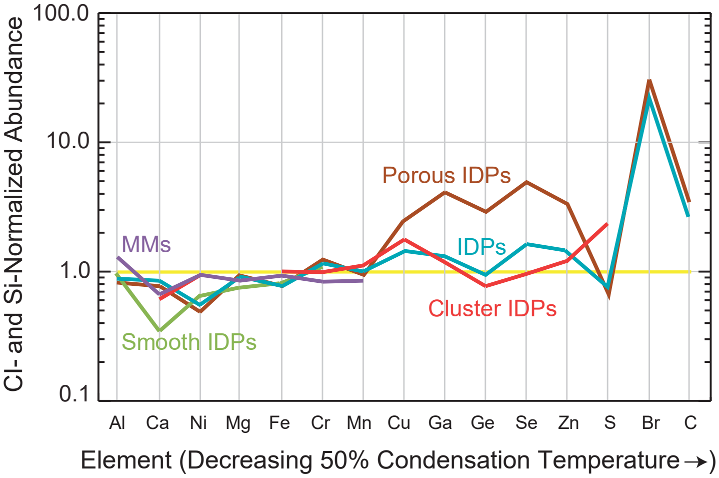


FIGURE 1 Silicon-normalized and CI-normalized element abundances in 200 interplanetary dust particles (IDPs, in blue), a subset of 91 porous (mostly anhydrous) IDPs (brown), a subset of 73 smooth (mostly hydrous) IDPs (green), a set of 100 unmelted MMs from Antarctic snow (purple), and five cluster IDPs (red), ordered such that decreasing condensation temperature goes to the right. The chondritic composition plots on the horizontal line at 1 (yellow). The mean values for all 200 IDPs, the porous IDPs, the cluster IDPs and the primitive MMs each plot within +30% of the CI line for each of the refractory major elements (Al, Ca, Ni, Mg, Fe, and Cr), with Ca showing an ~50% depletion in the smooth IDPs. The moderately volatile elements are enriched in the porous IDPs but not in the larger cluster IDPs (as discussed in the text).

solar flare flare tracks in silicates and result in the loss of solar wind noble gases and some moderately volatile trace elements, such as Zn and S. In extreme cases, some minerals are altered. By measuring one or more of these properties, we can identify those IDPs that have experienced minimal thermal alteration.

The IDPs are generally divided into two groups: anhydrous and hydrous. Anhydrous particles include the highly-porous, fine-grained aggregates, called the chondritic porous (CP) IDPs (Fig. 2A), as well as individual, nonchondritic crystalline grains, mostly silicates or sulfides (Fig. 2B). The hydrous particles contain phyllosilicates and, generally, are more compact with smooth surfaces.

Anhydrous Interplanetary Dust Particles

A single ~10 µm CP IDP generally consists of tens to hundreds of thousands of individual, mostly submicron, grains (Fig. 2A). Detailed characterization of CP IDPs indicates that many never experienced significant hydrous or thermal parent body processing, nor gravitational compaction, nor impact shock. Furthermore, many were only minimally heated during atmospheric deceleration. These CP IDPs are "primitive" and could represent the best-preserved samples of the solid materials that formed from our protoplanetary disk (Ishii et al. 2008).

Although ~10 µm (~1 ng) CP IDPs show significant compositional scatter, averaging over only tens of particles gives a chondritic abundance pattern for the refractory major elements (Fig. 1). However, Schramm et al. (1989) noted a factor-of-four overabundance of carbon in IDPs compared to chondritic. Much of this carbon is macromolecular organic matter, often exhibiting isotopically anomalous H and N, perhaps pointing to exotic chemistry occurring at very low temperatures in the protoplanetary disk or in the protosolar molecular cloud (Sandford et al. 2016 this issue). Minor element measurements show that CP IDPs have chondritic abundances of refractory elements, but there is a factor-of-three or higher enrichment over chondritic for the moderately volatile elements such as K, Mn, Zn, Ge, Se, and Br (Flynn et al. 1996). Some IDPs are contaminated with stratospheric sulfate aerosols, but at amounts insufficient to significantly alter their bulk S content. Other anhydrous IDPs are generally chondritic but have large depletions in S and Zn, suggesting that they lost these moderately volatile elements during atmospheric entry.

The mineralogy of the CP IDPs confirms that each has sampled a wide range of disk conditions. The most abundant crystalline phases are silicates, mainly olivine and low-Ca pyroxene, with lesser amounts of high-Ca pyroxene, feldspar, and melilite, as well as Fe- and Zn-sulfides. The olivine compositions range from almost pure forsterite (Mg-olivine) to relatively high Fe-olivine, some with Fe/Mg ~1 (Fig. 3A), which is a compositional range inconsistent with equilibrium condensation at a single temperature and gas composition. The pyroxenes show a similar range of Fe contents (Fig. 3C).

Low Fe- and Mn-enriched (LIME) olivines, commonly observed in CP IDPs and sometimes found in unequilibrated ordinary chondrite meteorites, may be high-temperature condensates of the protoplanetary disk. Enstatite whiskers, elongated along the [100] crystallographic axis, exhibit axial screw dislocations (Fig. 2A), which strongly suggests growth from a vapor phase.

Most CP IDPs also contain glass with embedded metal and sulfide (called "GEMS"), having some characteristics similar to interstellar amorphous silicates. Some GEMS could be survivors from the protosolar molecular cloud, although their connection to interstellar silicates is debated.

Some of the minerals found in CP IDPs provide evidence of formation by nonequilibrium processes. For example, equilibrium cooling of an Fe-, Zn-, and S-bearing gas should produce two minerals: an Fe-sulfide, whose compact structure is the lowest energy state for Fe and S, and a

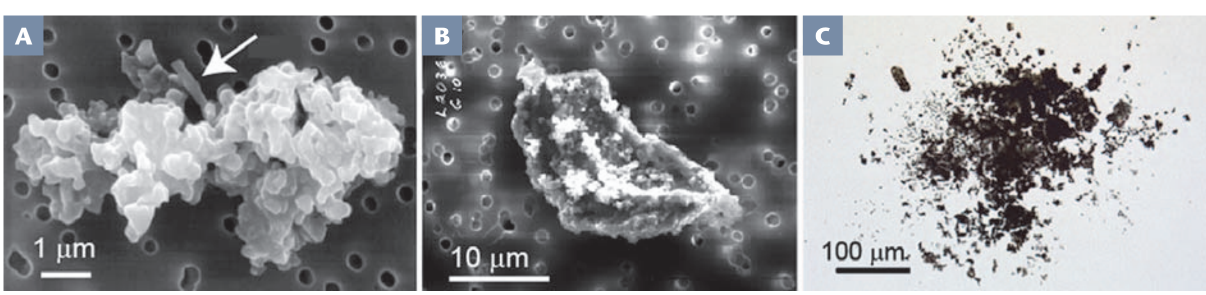


FIGURE 2 (**A**) Scanning electron microscope (SEM) image of a chondritic porous interplanetary dust particle (CP IDP) containing an enstatite whisker (arrow). The texture indicates the size of the individual grains. (**B**) SEM image of Fe-sulfide particle, with adhering CP IDP material. Image courtesy of NASA (**C**) Optical microscope image of a large cluster IDP in the silicone oil in which it was collected. Each visible fragment is comparable to or larger than either of the particles shown in 2A and 2B. Image courtesy of D. Joswiak.

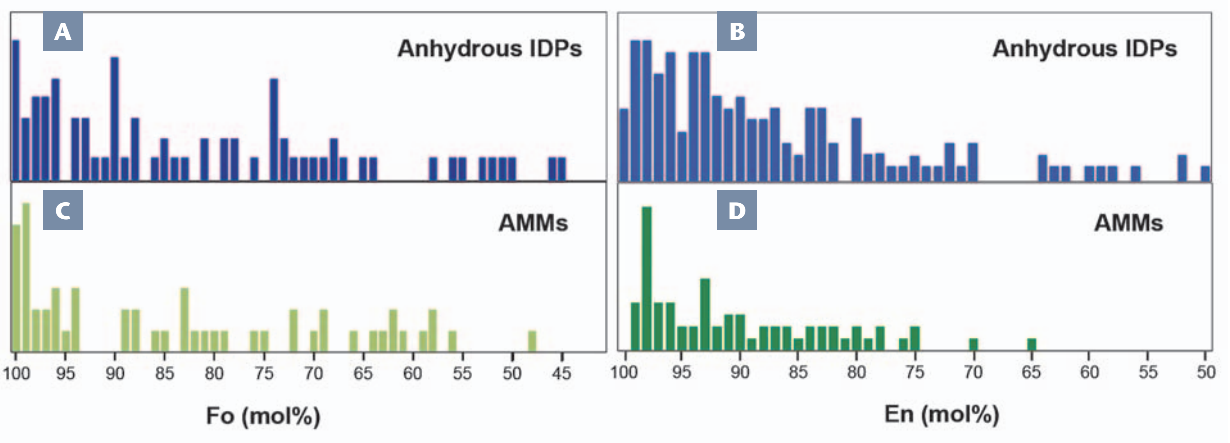


FIGURE 3 (**A**) Compositional range of olivines in anhydrous interplanetary dust particles (IDPs). (**B**) Compositional range of olivines in Antarctic micrometeorites (AMMs). (**C**) Compositional range of low-calcium pyroxenes in anhydrous IDPs. (**D**) Compositional range of low-calcium pyroxenes in AMMs. The forsterite (Fo) or enstatite (En) numbers represent the mole fraction of forsterite (Mg_2SiO_4) versus fayalite (Fe_2SiO_4) for olivines, and enstatite ($MgSiO_3$) versus ferrosilite ($FeSiO_3$) for pyroxenes [Fo or En = Mg/(Mg + Fe) in mol%]. Data for the anhydrous IDPs from Zolensky et al. (2008); data for the Antarctic micrometeorites from Dobrică et al. (2009).

separate Zn-sulfide, sphalerite, because Zn is too large to fit in the Fe-sulfide structure. In CP IDPs, the dominant Zn-bearing mineral has a sphalerite structure, but contains similar amounts of Zn and Fe, indicating nonequilibrium formation.

A comparative study of the sizes of the Mg-rich silicates and Fe-sulfides, which are the most abundant minerals, shows the mean grain size varies from one CP IDP to another, the size–density relationship being consistent with aerodynamic sorting before grain aggregation (Wozniakiewicz et al. 2013). In many CP IDPs, the individual mineral grains are coated with a ~100 nm layer of organic carbon, which likely aided in the grain aggregation (Flynn et al. 2013) because uncoated crystalline grains stick together only when collisions occur at extremely slow speeds.

Fine-grained CP IDP-like material adhering to the surfaces of many of the individual crystalline grains (Fig. 2B), some >10 µm in size, on cosmic dust particle collectors indicates these larger crystalline minerals are derived from the same parent bodies as the CP IDPs. Also found are cluster IDPs, which are aggregates consisting of a fine-grained matrix (<30% by mass) and larger crystalline grains (>70% by mass), mostly olivine, pyroxene, and sulfides. Cluster IDPs, each >50 times the volume of an ~10 µm CP IDP, allow us to examine the anhydrous IDP parent body at a larger size scale. The mean composition of five anhydrous cluster IDPs that have experienced minimal atmospheric heating is chondritic (Fig. 2), with most measured refractory and moderately volatile elements deviating by <30% from chondritic. The chondritic composition of the cluster IDPs, as well as the presence of reduced, oxidized and occasionally metallic Fe, demonstrates that the region of the disk sampled by cluster IDPs was well-mixed, containing grains that formed at a wide range of temperatures and redox conditions.

A few anhydrous IDPs have nonchondritic compositions. One group, highly enriched in Ca and Al, has mineralogies similar to those predicted for high-temperature condensates from the protoplanetary disk (e.g. McKeegan 1987). These Ca- and Al-enriched IDPs are similar to Ca–Al inclusions found in primitive meteorites, inclusions that are the oldest dated objects in the Solar System. A few of the anhydrous IDPs have very low Ni contents, similar to achondrites, possibly sampling a differentiated parent body, although detailed mineralogical comparisons are lacking.

Hydrous Interplanetary Dust Particles

The hydrous IDPs show depletions in Ca, suggesting leaching of Ca during parent body aqueous alteration (Schramm et al. 1989), yet the other refractory major elements show a chondritic pattern (Fig. 1).

Phyllosilicates and carbonates are major hydrous phases in these IDPs, and Fe sulfides, especially Ni-rich ones like pentlandite, are commonly present. However, many hydrous IDPs are mineralogically different from the hydrous CM meteorites, being dominated by smectite, instead of serpentine. Generally, hydrous IDPs are not completely hydrated: they contain anhydrous minerals, including Mg–Fe-silicates. It is, therefore, possible that hydrous IDPs are hydration products of anhydrous IDPs. This is consistent with the finding that isotopically anomalous organic matter in hydrous IDPs is similar to that in both chondrites and CP IDPs.

Chemical and Mineralogical Composition of Micrometeorites from Deep-Sea Sediments and Polar Regions

The polar regions are the cleanest places on Earth to collect micrometeorites (MMs), with collections having been made in Greenland and a variety of locations in Antarctica (Table 1 in Taylor et al. 2016 this issue). The larger MMs, typically 50–400 µm in size, are classified by the increasing degree of thermal transformation that they have experienced during atmospheric entry: unmelted (fine-grained and compact), scoriaceous, and spherules (with or without relict minerals). Only spherules, which are most resistant to terrestrial weathering, are recovered from deep-sea sediments.

Cosmic Spherules

Melted MMs are generally subdivided into three types: I-type spherules, which are mainly composed of Fe and Ni oxides, some with metallic cores; S-type spherules, which have an approximately chondritic elemental composition for Mg, Al, Si, Ca, Fe, and Ni; and G-type spherules, which are generally composed of a dendritic network of magnetite with interstitial glass. At least 75% of the cosmic spherules are believed to derive from fine-grained precursors with compositions similar to CM or CI meteorites (Taylor et al. 2012), with most of the rest being related to ordinary chondrites or chondrules. Less than 1% have achondritic, or differentiated, compositions. Although melted and partially melted MMs have had their chemical and mineralogical compositions altered from their preatmospheric compositions by atmospheric entry, these particles are important because they account for most of the cosmic dust (by mass) that accretes to Earth.

Unmelted Chondritic Micrometeorites

Unmelted MMs, ~20–400 µm in size, are recovered from the ice and snow in Antarctica. More than 80% of the Antarctic MMs with sizes <400 µm are related to carbonaceous chondrites (e.g. Dobrică et al. 2009), with about 15% being related to ordinary chondrites (Genge 2008).

Antarctic MMs collected from blue ice fields at Cap Prud'homme, having a terrestrial age of ~ 50,000 years, show depletions in Ca, S, and Ni with respect to chondritic. This probably arose from preferential leaching of Fe–Ni sulfides and carbonates, which are rare in these MMs. These latter phases are present, however, in MMs collected from snow and ice that have had limited contact with liquid water, as evidenced by the elemental pattern in 100 MMs from Dome C snow (Fig. 1). Chondritic MMs also typically contain a few weight percent of carbonaceous matter (see Sandford et al. 2016 this issue).

Recent snow and ice collections also contain fluffy particles similar in structure to CP IDPs (Fig. 4A). As in meteorites and IDPs, crystalline olivine and Ca-poor pyroxenes are the most abundant minerals in these MMs. Their compositions peak at the Mg-rich end-members but extend over a wide range of Fe-contents (Fig. 3). In contrast to most chondritic meteorites, MMs have about an equal abundance (by number) of pyroxenes compared to olivines, for mineral sizes ranging from submicron to about 10 µm. This equal abundance of pyroxenes compared to olivines has also been observed in CP IDPs and in Wild 2 comet samples collected by *Stardust* (Dobrică et al. 2009). This suggests that about equal abundances of olivine and pyroxene could characterize the outer regions of protoplanetary disks, with the inner regions being dominated by olivines, a supposition compatible with an origin for MMs and CP IDPs in the outer regions of the asteroid belt, or from Jupiter Family comets (Nesvorný et al. 2010).

Calcium-rich pyroxenes are less abundant in MMs, and have compositions close to that of pigeonite and augite. As in CP IDPs, LIME pyroxenes and olivines are also observed in MMs. Amorphous silicates, like the GEMS in CP IDPs, have been found in fine-grained fluffy MMs. Among the primitive MMs, a few percent contain miniature refractory inclusions, or refractory minerals (spinel, Ca–Al-rich pyroxene, anorthite, melilite, hibonite and perovskite) (Dobrică et al. 2009). Rare fragments of chondrules are also found in unmelted MMs, or found as whole particles in the cosmic spherule population (Genge et al. 2005).

As in meteorites, Fe–Ni sulfides are the second most abundant minerals after Fe–Mg silicates in MMs. They range in size from submicrometer to ~ 15 µm. Most Fe–Ni sulfides have compositions close to troilite (FeS), thought to be the first sulfur-bearing mineral formed in the protoplanetary disk from the sulfurization of metallic Fe grains. These contain less than 3 at% Ni.

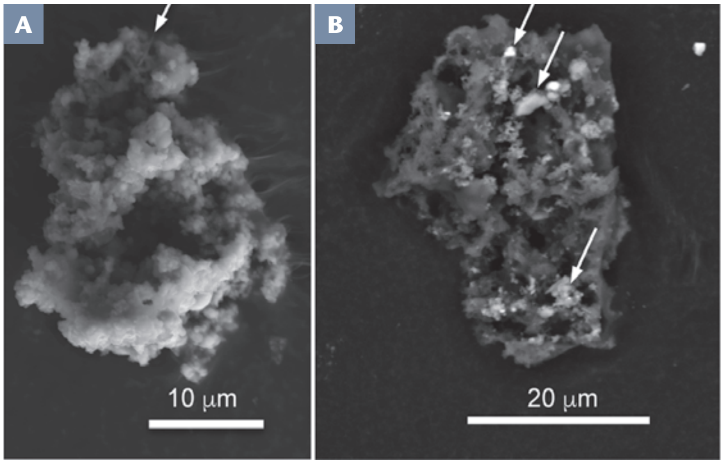


Figure 4 (**A**) Scanning electron microscope (SEM) image of a fragment of a fluffy, fine-grained, unmelted micrometeorite (MM). A pyroxene whisker is arrowed. (**B**) Backscattered electron micrograph of a fragment of an ultracarbonaceous Antarctic MM. The bulk of the particle in dark grey is organic matter. Three arrows point to brighter flakes, which are either silicates or Fe–Ni sulfides.

Ultracarbonaceous Antarctic Micrometeorites

A few percent of the primitive MMs are dominated by organic matter, and these are called ultracarbonaceous Antarctic micrometeorites (UCAMMs) (Fig. 4B) (Duprat et al. 2010). These particles contain up to 85% organic matter by volume, ten times higher than most C-rich meteorites. The composition of UCAMMs appears compatible with that of the carbon-rich "CHON" grains (named after the elements C, H, O and N) detected in comet Halley by the *Giotto* and *Vega* spacecraft missions in 1986.

The organic matter of UCAMMs, which is nitrogen-rich and shows extreme deuterium enrichments, could have formed by cosmic ray irradiation of the N_2–CH_4-rich surfaces of icy bodies in the outer Solar System (Dartois et al. 2013). A minor fraction of minerals are embedded in the carbonaceous matter. They are small, complex assemblages of fine-grained olivine, pyroxenes, Fe–Ni sulfides, and glassy phases similar to GEMS. Exotic phases such as Mn- and Zn-rich sulfides and perryite have also been found as accessory minerals. The variety of high-temperature minerals in UCAMMs is similar to those in CP IDPs.

Isotopic Composition of Cosmic Dust

Variations in isotopic compositions of the elements are crucial to understanding the origin and evolution of geological materials. Measurements of isotopic compositions, for example H, N, O and noble gases, provide key information about a wide range of the physical and chemical processes that may have affected these tiny samples. Isotopic anomalies associated with organic matter have been discussed above and by Sandford et al. (2016 this issue).

Noble Gases

Because of their low chemical reactivity, the noble gases are exceedingly rare in planetary materials, but their abundances and isotopic compositions provide important constraints on the origin and history of extraterrestrial materials. Solar wind ions directly implant solar noble gases into dust grains and can also generate noble gas isotopes by nuclear reactions with atoms of the dust grains. Detection of diagnostic solar-implanted noble gases (e.g. ^{3}He) in cosmic dust serves both to prove an extraterrestrial origin and to help constrain how long each dust grain has

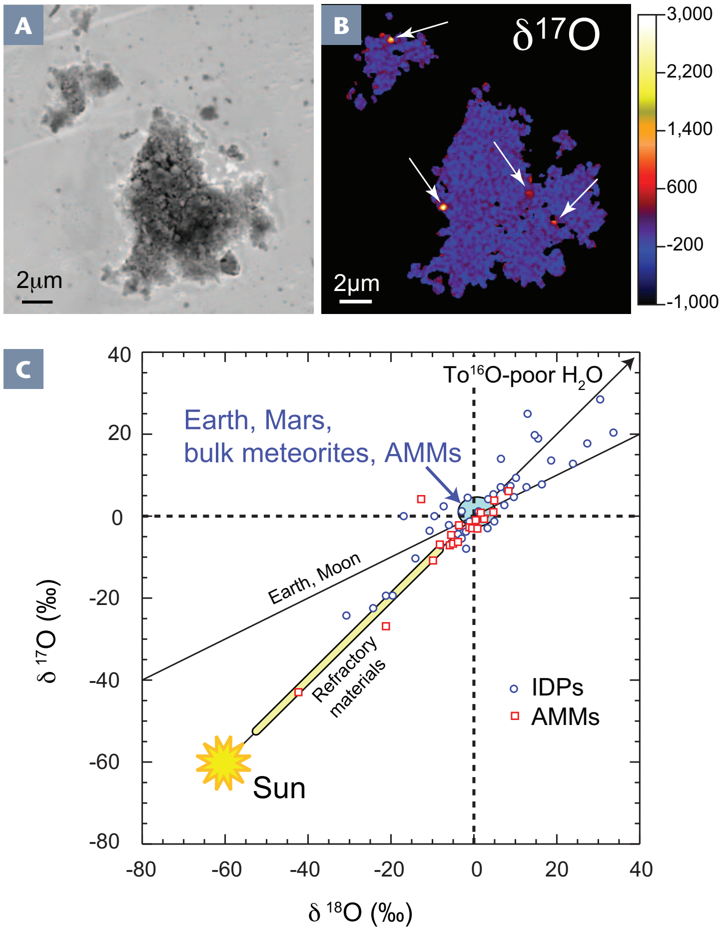


FIGURE 5 (**A**) Secondary electron image of an interplanetary dust particle (IDP). (**B**) Image of the $^{17}O/^{16}O$ ratio across the same IDP as in 5A. Four submicron presolar grains with extreme ^{17}O enrichments are visible (arrows). (**C**) Oxygen isotopic composition of the Solar System. Ratios of $^{17}O/^{16}O$ and $^{18}O/^{16}O$ are expressed as δ-values: parts-per-thousand deviations from terrestrial ocean water. Bulk planets and asteroids are depleted in ^{16}O, relative to the Sun. IDPs and micrometeorites show similar ranges and average compositions to meteoritical materials. Some ^{16}O-rich cosmic dust grains are similar to refractory materials (e.g. Ca–Al-rich inclusions) in meteorites. Very rare materials in primitive meteorites and IDPs have been identified with $\delta^{17}O$ values about the same as $\delta^{18}O$ values, both being about +200 ‰, which is thought to represent ^{16}O-poor water in the early Solar System (black arrow). ADAPTED FROM BUSEMANN ET AL. (2009).

been exposed as a small particle in space. The presence of ^{3}He in cosmic dust is also used to probe the past flux of cosmic dust onto the Earth by measuring ^{3}He in terrestrial sediments (Peucker-Ehrenbrink and Ravizza 2016 this issue). Noble gases may also have been incorporated into dust particles when they originally formed. Such "trapped" gases in meteorites, believed to represent primordial noble gases from the protoplanetary disk, seem to be carried in yet-to-be-identified phase(s).

Noble gas studies of IDPs and MMs revealed multiple components with distinct elemental and isotopic compositions. IDPs and MMs are typically dominated by solar-derived gases, but also include isotopes produced by interactions with galactic cosmic rays, trapped gases and, especially in larger melted particles, noble gases from Earth's atmosphere. Higher noble gas concentrations are typically seen in IDPs rather than in the larger MMs (Marty et al. 2005), probably because of the higher surface-to-volume ratio of smaller particles (implantation of the solar wind occurs very close to the surface) and the preferential loss of noble gases from larger particles due to stronger atmospheric entry heating. Exposure ages inferred from noble gas measurements of IDPs span a wide range, supporting the idea that IDPs originate from asteroids, comets, and possibly even objects in the Kuiper Belt (Kehm et al. 2006), though specific interpretations depend on assumptions about dust transport mechanisms.

Atmospheric heating complicates the interpretation of noble gas signatures from cosmic dust, but it is also a valuable tool. Helium-release patterns upon step-wise heating of individual IDPs reveal the peak temperature experienced by each particle. High entry speeds, producing high peak temperatures, indicate some IDPs originated in comets (Kehm et al. 2006). However, the perturbation of cometary orbits by the giant planets permits lower entry speeds for some cometary particles (Nesvorný et al. 2010), making these latter types indistinguishable from main-belt asteroidal dust. Isotopic effects from entry heating can also be probed using other elements. For example, studies of isotopic fractionation of O, Fe, K, Mg and Si in melted micrometeorites constrain the composition and sizes of the objects prior to atmospheric entry, as well as the degree of vaporization during entry (e.g. Taylor et al. 2005).

Oxygen

Oxygen, the most abundant element in most planetary materials, varies in isotopic composition throughout the Solar System (FIG. 5C), with bulk planets and asteroids being depleted by about 6% in the predominant isotope ^{16}O relative to the rare isotopes ^{17}O and ^{18}O as compared to the Sun (McKeegan et al. 2011). This "planetary" isotope signature is thought to represent mixing between ^{16}O-rich bulk solar composition and an ^{16}O-depleted reservoir, whose nature and origin is debated. Some models postulate a reservoir of ^{16}O-poor water ice in the outer Solar System, which was mixed into the inner part of the protoplanetary disk to produce the compositions observed in meteoritic materials. Regardless of origin, the overall spread in oxygen isotopic compositions is a very useful classification tool because small differences in ^{16}O are observed among various meteorite groups.

The first oxygen isotopic analyses of IDPs confirmed the extraterrestrial origin of several Ca–Al-rich IDPs (McKeegan 1987). Since then, O-isotope measurements have been reported on all types of cosmic dust, from resolved micrometer-scale measurements of subcomponents of IDPs to higher-precision measurements of bulk IDPs, MMs, and cosmic spherules (Engrand et al. 1999a; Starkey et al. 2014).

Isotopic imaging (FIG. 5A, B) identified submicron grains with O-isotopic ratios falling far outside the range for materials formed in the Solar System (Messenger et al. 2003). These "presolar" silicate grains formed in outflows and explosions of previous generations of stars and were part of the mix of starting materials from which the Sun formed. Presolar silicates, while rare, are on average more abundant in IDPs and some MMs than in even the least processed meteorites (Busemann et al. 2009). Beyond rare presolar grains, O-isotopes in cosmic dust at both bulk and micron scales show remarkable similarity to those in primitive meteorites, i.e. on average, most particles are isotopically similar to the Earth, not to the Sun (FIG. 5C). High-precision O-isotope measurements of large melted MMs confirm the dominant connection of MMs to carbonaceous chondrites (Suavet et al. 2010). The isotopic similarity between CP IDPs and UCAMMs (both thought to be largely cometary in origin) to asteroidal meteorites suggests that this "planetary" signature was ubiquitous throughout the protoplanetary disk, indicating the O-isotopic difference between the bulk Sun and planetary materials was most likely established very early in Solar System history or possibly even before, in the Sun's own parental molecular cloud.

Deuterium to Hydrogen (D/H) ratio

In IDPs and unmelted MMs, hydrogen is present in organic molecules and, in some of the particles, in hydrous silicates. Isotopic anomalies in H, C, and N in organic matter provide important clues to the chemistry of the protosolar cloud and the nascent Solar System (Sandford et al. 2016 this issue). Less is known about the D/H composition of the water that was incorporated into hydrous phases. Terrestrial water has D/H about eight times higher than the protosolar value. Earth's D/H ratio is comparable to, or higher than, that of water in chondritic meteorites, but lower than that typically measured remotely in cometary water. Thus, D/H ratios in IDP and MM water could help constrain the origin of the particles as well as the original origin of Earth's water. Engrand et al. (1999b) showed that water in MMs has D/H similar to carbonaceous chondrites, further supporting a link between these primitive meteorites and many types of cosmic dust particles.

Thus far, the small grain sizes have precluded any study of the radiogenic isotopic systems present in cosmic dust, e.g. for chronology purposes.

SUMMARY AND IMPLICATIONS FOR THE EARLY SOLAR SYSTEM

Cosmic dust particles in the size range of MMs (~200 µm) dominate the current mass flux accreting onto the Earth. Early in Solar System history and over time scales of millions of years the extraterrestrial mass flux was dominated by rare, but large, impacts. Nevertheless, the constant, gentle accretion of cosmic dust onto the early, differentiated Earth could have provided significant amounts of organics, water, and minerals to its surface.

The chondritic porous interplanetary dust particles (CP IDPs) and ultracarbonaceous Antarctic micrometeorites (UCAMMs) are important classes of extraterrestrial material because they are not represented in any type of meteorite. They show no evidence of significant parent body alteration, so are thought to preserve a record of grain formation, transport, and aggregation in the solar protoplanetary disk. Their mineral fractions sample the original condensates of the disk, making them the building blocks of the terrestrial planets, asteroids, and the rocky component of comets.

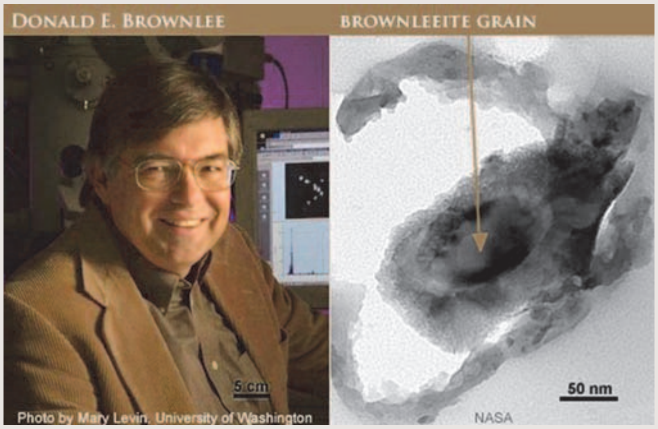
The compositions of CP IDPs indicate that, even at the scale of only a few hundred μm^3 (a few cluster IDPs), the site where they aggregated contained a well-mixed sample of grains spanning a diversity of formation temperatures and redox conditions. The grains were aerodynamically transported from their formation site(s) to the region where they aggregated, where organic coatings on the individual grains likely aided aggregation.

Minerals including LIME olivine and brownleeite (see SIDEBAR), both thought to be high-temperature condensates from the protoplanetary disk, were first identified in CP IDPs. A small fraction of the silicate minerals, glass, organic matter, and water have isotopic compositions identifying them as preserved extrasolar material. The organic matter of CP IDPs and UCAMMs shows isotopic anomalies indicating formation at very cold temperature, possibly in the outer regions of the protoplanetary disk. The nitrogen-rich organic matter of UCAMMs could have formed by cosmic ray irradiation of icy bodies in the outer Solar System.

New Minerals from a Unique Formation Environment

Direct condensation from the gaseous solar protoplanetary disk is a remarkably different environment from most of the mineral formation environments on the Earth, the Moon, and the asteroids. On Earth, most minerals are formed from melts or in aqueous or biogenic environments. Only mineral formation from cooling volcanic gases is even crudely similar to condensation from the nebula. But terrestrial gas compositions are significantly different from those of the protoplanetary disk, which results in the formation of a different suite of minerals. Thus, chondritic porous interplanetary dust particles (CP IDPs), which are believed to sample products from protoplanetary disk condensation, are likely to contain new, naturally occurring minerals.

One 4 µm diameter IDP was found to host three grains of a new mineral, named brownleeite (after Dr. Donald Brownlee, who pioneered the collection and characterization of IDPs from the Earth's stratosphere). The particle, L2055 I3, was collected on a NASA collection flight timed to coincide with Earth's passage through a dust stream from comet Grigg–Skjellerup. The absence of solar flare tracks in the silicate minerals suggests that the particle was recently released from comet Grigg–Skjellerup, rather than being a typical IDP which spends tens of thousands of years in space before encountering Earth.



Brownleeite grain indicated by arrow.

Brownleeite is a Mn-silicide mineral that had been theoretically predicted then manufactured synthetically (as pure MnSi) by materials scientists, but had never been previously identified in nature. Three submicron-sized grains of brownleeite, having a composition of $(Mn_{0.77}Fe_{0.18}Cr_{0.05})Si$ and maximum dimensions of 100 nm, 250 nm, and 600 nm, respectively, were identified in fourteen 70 nm thick ultramicrotome slices of L2055 I3 by Nakamura-Messenger et al. (2010). The mineral name was approved by the International Mineralogical Association as the first natural manganese-dominant fersilicite, making it the first new mineral identified in an IDP.

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