Cosmic Dust: Finding a Needle in a Haystack

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1811-5209/16/0012-0171$2.50 DOI: 10.2113/gselements.12.3.171

Collecting cosmic dust is a tricky business! Despite Earth's surface being showered by thousands of tons of comic dust every year, such dust is quickly lost in a sea of terrestrial particles. Finding the tiny cosmic treasures requires collecting dust from the cleanest environments where the terrestrial particle background is low. The stratosphere can be sampled via high-flying aircraft, whereas sampling cosmic dust from polar regions and the deep sea requires techniques that concentrate the particles. Collection efforts are worth it. Cosmic dust derives from every dust-producing object in the Solar System, including ancient Solar System materials, possibly even interstellar materials, of a type not found in meteorites.

Keywords: micrometeorites, interplanetary dust particles (IDP), polar collections, stratospheric collections

INTRODUCING COSMIC DUST

Planet Earth was essentially formed 4.56 billion years ago. Yet, our planet is still growing by some 40,000 tons (4×10^6 kg) each year due to its continual sweeping up of extraterrestrial materials. To the surprise of many, it is not meteorites that are contributing to the bulk of this mass but "cosmic dust." Most of these dust particles melt or vaporize when they enter Earth's atmosphere at high speed (11–72 km s^{-1}), but around 2,500 tons reaches the Earth's surface intact, 50 times higher than that estimated for meteorites. The larger particles—50 µm to 2 mm (10^{-8}–10^{-2} g) grains termed *micrometeorites* (MMs)—have been found on the Earth's surface in exceptionally clean polar environments, in ancient sediments, and even at the bottom of the ocean. The smallest and most fragile particles—called *interplanetary dust particles* (IDPs), which are 5–50 µm in size (10^{-9}–10^{-8} g)—are collected in the stratosphere by specialized aircraft. Micrometeorites and IDPs are smaller than meteors (shooting stars), which are objects that by definition burn up in the atmosphere.

Cosmic dust particles are invaluable samples from disintegrating comets, asteroid collisions, and any other type of Solar System impacts. They come from hundreds or thousands of bodies—far more than we could ever visit or hope to sample directly by spacecraft. Because the orbits of cosmic dust particles gradually degrade due to interactions with solar radiation, they ultimately strike the Sun or a planet or they are ejected from the Solar System. This orbital evolution makes it possible for cosmic dust from anywhere in the Solar System to reach Earth.

Cosmic dust has great scientific value, a value that more than justifies the considerable efforts required for its collection and analysis. Many of these dust particles are unique samples of bodies that are unlike any meteorite: they include the least processed remnants of the Solar System's starting materials. Some primitive particles contain interstellar dust grains and primordial organic matter, while other particles retain evidence of the inner workings of minor planets and the dynamical evolution of the asteroid belt. Cutting-edge instruments show that these dust particles consist of thousands of still smaller particles, each of which has a unique story to tell about the evolution of stars, the lifecycle of matter in the galaxy, and the first stages of planet formation. It was the poet William Blake (1757–1827) who said that the world could be seen in a grain of sand (*Auguries of Innocence*) but it was our colleague Matt Genge who added "in cosmic dust most of the galaxy is visible."

Cosmic spherules were first collected from abyssal oceanic sediments during the 1873–1876 period of the voyage of HMS *Challenger*. Murray and Renard (1891) found "two groups: first, black magnetic spherules, with or without a metallic nucleus; second, brown-coloured spherules resembling chondr(ul)es, with a crystalline structure". Murray and Renard reasoned that the spherules were extraterrestrial because they were found far from terrestrial particle sources, were most abundant in slowly accumulating sediments, did not resemble magnetic spheres produced in furnaces, and had Ni-bearing metal cores that were compositionally similar to meteoritic metal.

MICROMETEORITES

Micrometeorites (MMs) were discovered over a century ago in abyssal oceanic sediments collected during the voyage of the HMS *Challenger* (1873–1876) (see side bar). These MMs were termed "cosmic spherules" because they were round and appeared to have melted. Since then, MMs have been recovered from ocean sediments using cores, box cores, clamshell grabbers, and magnetic sleds (Table 1). MMs have also been found in sediments that have low accumulation rates (such as claystones), sediments that are easily dissolved (such as salt deposits and limestones),

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and sediments that have been mass sorted (such as heavy mineral concentrates found in desert and beach sands). Micrometeorites can be preserved for hundreds of millions of years within sedimentary strata, and examples of fossil MMs include iron spherules found in 180–140 Ma (Early Jurassic to Early Cretaceous) oceanic sediments, and those found in 240 Ma (Middle Triassic) chert. The best-preserved MMs, however, are those collected in polar snow and ice. Polar MM collection sites include snow and cryoconite (deposits of dust on ice) from Greenland; from blue ice, aeolian debris, and ice cores from the Antarctic; and from material gleaned from drinking waters wells at the South Pole, as well as from sediment traps and present day snow (Table 1).

Micrometeorites are generally strong, solid particles composed of micrometer-sized mineral grains, and they can be separated from terrestrial particles using magnets, density contrasts, or manually. The particles are first embedded in epoxy or resin and then sectioned and analyzed in polished section (Fig. 1). Cross-sections reveal coarse mineralogy and vesicles formed by partial melting during atmospheric entry (Fig. 1). Micrometeorites range from unmelted particles that retain their original mineralogy, to partially melted particles, to totally melted cosmic spherules. Even some melted ones contain large relict grains of high-temperature phases such as Mg-rich olivine (forsterite) and chromite. The degree of heating undergone by a MM is determined by its speed, density, and angle of entry into the atmosphere. A low entry velocity and a shallow angle will largely preserve the particles' chemical composition and texture, whereas a high angle and entry velocity will destroy the MM.

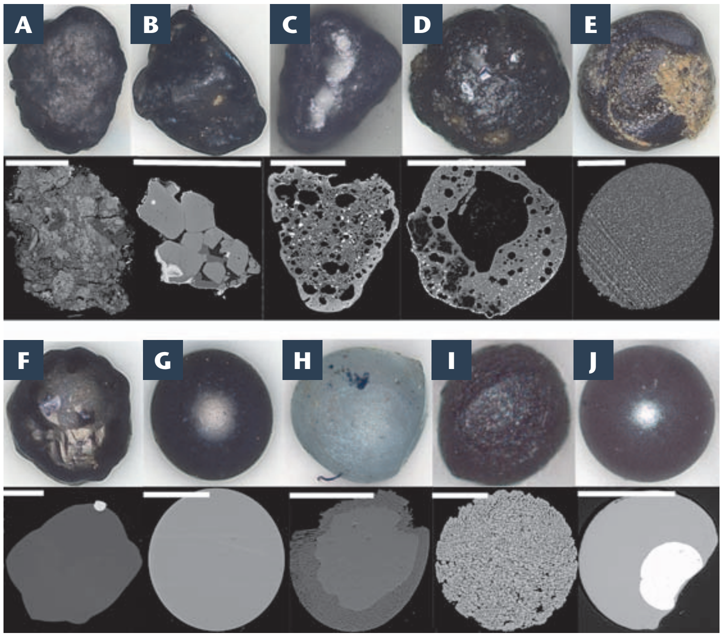

Figure 1 Ten micrometeorite classes, labeled A–J, each class having two representative images; (**above**) optical image and (**below**) scanning electron microscope cross section image. The classes themselves are as follows: (**A**) Fine-grained unmelted. (**B**) Coarse-grained unmelted. (**C**) Scoriaceous. (**D**) Porphyritic. (**E**) Barred Olivine. (**F**) Cryptocrystalline. (**G**) Glass. (**H**) Ca–Al–Ti-rich (CAT). (**I**) G-type. (**J**) I-type. Scale bars are 100 µm. Image credit: S. Taylor and L. Sachs

Table 1 METHODS USED TO COLLECT COSMIC DUST FROM TERRESTRIAL ENVIRONMENTS. All known methods are listed but, in the interest of brevity, not all collections are included.

Environment	Collection Method	Size Range (mm)	Metric Tons/yr	Reference
Deep-sea sediment cores	Magnetic separation	60–500		[1]
Deep-sea sediments	Magnetic rake	100–500	30	[2]
Deep-sea sediment cores	Magnetic separation	10–230	125	[3]
Desert sands	Magnetic separation	30–300		[4]
Greenland snow	Melt, magnetic separation	5–160		[5]
Salt deposits	Dissolve and magnetically sieve	5–70		[6]
Beach sand	Heavy mineral separates	80–650		[7]
Stratosphere	Balloon-borne vacuum	>3		[8]
Stratosphere (1981–present)	Aircraft, silicone oil	>5		[9]
Deep-sea sediments	Magnetic sled, Cosmic Muck Rake	<5,000		[10]
Jurassic ocean sediments	Dissolve and sieve	100–300		[11]
Greenland cryoconite	Vacuum and sieve	<50–300	3200	[12]
Antarctic air	Electrostatic precipitation	<1		[13]
Antarctic ice cores	Melt and sieve	50–160	1,500	[14]
Antarctic glacial sediment	Dry sieve	125–500		[15]
Antarctic blue ice	Melt, vacuum, and sieve	>5		[16]
Limestones	Dissolve and sieve	>50		[17]
Antarctic water well	Vacuum and sieve	50–2,000	2,700±1,400	[18]
Antarctic snow	Melt and sieve	>25		[19]
Antarctic sediment traps	Dry sieve	>200		[20]
Deep-sea sediments	Magnetic rake	55–600		[21]
Triassic chert deposits	Crush, sieve, magnetically separate	<125	25±8 (I-type)	[22]
Deep-sea sediments	Grab sampler	>200	160±70	[23]
Antarctic snow and ice	Melt and sieve	>10		[24]
Pacific Ocean air	Nucleopore air filters	>5		[25]
Stratosphere	Aircraft, polyurethane	>5		[26]

References [1] Murray and Renard (1891); [2] Brunn et al. (1955); [3] Laevastu and Mellis (1955); [4] Fredriksson and Gowdy (1963); [5] Langway (1963); [6] Mutch (1966); [7] Marvin and Einaudi (1967); [8] Brownlee et al. (1973); [9] Brownlee and Hodge (1973); [10] Brownlee et al. (1979); [11] Czajkowski et al. (1983); [12] Maurette et al. (1987); [13] Witkowski (1988); [14] Yiou and Reisbeck (1989); [15] Koeberl and Hagen (1989); [16] Maurette et al. (1991); [17] Taylor and Brownlee (1991); [18] Taylor et al. (1998); [19] Duprat et al. (2007); [20] Rochette et al. (2008); [21] Parashar et al. (2010); [22] Onoue et al. (2011); [23] Prasad et al. (2013); [24] Noguchi et al. (2015); [25] Wozniakiewicz et al. (2014); [26] Messenger et al. (2015)

Melted micrometeorites are classified by their compositions and textures. Most cosmic spherules are stony (type S) and contain micron-sized olivine and magnetite in a quenched glass matrix. Most stony spherules are magnetic although ~10% are Fe-free and nonmagnetic. Rare iron-type (I-type) and glassy-type (G-type) spherules account for ~2% of micrometeorites and are high in iron. I-type spherules often have an Fe–Ni metal core surrounded by a thick oxide shell composed of magnetite and wüstite ($Fe_{(1-x)}O$), while G-type spherules contain skeletal magnetite grains in a glass matrix. Rarer still are the Ca–Al–Ti-rich (CAT) spherules. These are isotopically fractionated, which suggests that a large fraction of their mass vaporized while they were still molten.

Unmelted micrometeorites are more difficult to optically recognize in sediments yet are valuable because they retain original Solar System minerals and components, such as organics and trapped gasses. The unmelted particles are irregular and often black. Some of these particles are totally unmelted, but there is a continuum between totally unmelted and those that are cosmic spheres. As shown in Figure 1, some particles are vesicular and represent a transition between those least melted to those more strongly heated.

EXTRATERRESTRIAL ORIGIN

Demonstrating that these tiny particles were extraterrestrial was a formidable challenge to early workers. The presence of metal inside the iron spheres from deep-sea sediments was the first clue that the spherules were not terrestrial (Murray and Renard 1891). It was, however, the use of the electron microprobe that finally demonstrated their extraterrestrial nature. For type I cosmic spheres it was their meteoritic proportions of Ni and Co (Castaing and Fredriksson 1958). For stony spherules, their major and minor elements were found to be "chondritic," meaning that their proportions matched those for rock-forming elements found in the Sun. Only the elements of Na, S, and C—those that can be lost during atmospheric heating—fail to follow this rule. The abundances of these latter elements differ from most terrestrial crustal materials and so indicate an extraterrestrial origin (Genge et al. 2008).

Other indicators of an extraterrestrial origin are the presence of the radioactive isotopes ^{53}Mn, ^{10}Be and ^{26}Al, which are produced by irradiation in space by solar and galactic cosmic rays. Unmelted MMs also contain He and Ne implanted by the solar wind. These rare gases are different from their terrestrial counterparts both in their abundances and their isotopic compositions.

The irradiation findings point to MMs being small objects in space and not the product of meteorite ablation or fragmentation during atmospheric entry. This idea is supported by the similarity in the composition of MMs found in geographically diverse areas such as the deep sea, Greenland, and Antarctica. In contrast, MMs that derive from specific meteorites or impact events have compositions that mirror those of their parents, and they are restricted in time and space.

MICROMETEORITE COLLECTIONS

Researchers have worked for over a century to answer the seemingly simple question, "How much of each type of cosmic dust does the Earth accumulate?" The Earth only accretes about one MM per square meter per year, so a large collection requires a concentrating process, and a representative sample requires that this process be unbiased with respect to MM size and type. MMs must also be well preserved because weathering can preferentially destroy certain MM types and sizes. The flux calculations require a known area of contribution, precise age constraint, and a calibrated collection technique. Most collections cannot meet all these requirements. Because of different accumulation mechanisms, accumulation times, and weathering and destruction rates, each collection tends to sample different sized particles and time periods. On the plus side, this means they are complementary. Below, we describe an example from each of deep-sea, aeolian, ice, and snow MM collections (Table 1).

The deep sea, defined here as an area of low deposition below the carbonate compensation depth, continues to be an important source for MMs. During the 1970s, the "Cosmic Muck Rake" magnetically retrieved thousands of cosmic spherules from the top 10 cm of the pelagic red clays that lie on the Pacific Ocean floor. Similar techniques are being used today to retrieve MMs from the Indian Ocean. Grab samplers or cores can collect known areas of the seafloor (e.g. 50 × 50 cm) to estimate MM flux rates over ~50 ky time periods. Interestingly, deep-sea collections contain many I-type and G-type spherules, which are rare in polar samples.

The Transantarctic Mountain MMs are found in loose sediments accumulated in bedrock weathering pits and fractures at the tops of these Antarctic mountains (Fig. 2). These samples provide a window into the last ~1 My of MM deposition, as demonstrated by the presence of ~480 ka meteorite spherules (van Ginneken et al. 2010) and of ~800 ka Australasian microtektites (Folco et al. 2008). Microtektites are distally deposited glass spheres associated with large impacts on Earth. The Transantarctic Mountain collection is unique because it contains thousands of melted and unmelted MMs in the 200–800 µm range and hundreds in the 800–2,000 µm range, with several up to 3,000 µm in size. The large abundance of >500 µm MMs is likely due to the relatively long accumulation time, because the mass flux of MMs decreases with increasing size.

Tens of thousands of MMs that are 50–500 µm in size have been vacuumed from the bottom of the Amundsen-Scott South Pole Station water well. The age of the snow and ice at South Pole is known as a function of depth, making it possible to calculate the flux of MMs for the collection time periods of 800–1100 CE and 1100–1500 CE. This large collection and its well-quantified flux rate provides an excellent benchmark for the size, type, and compositional

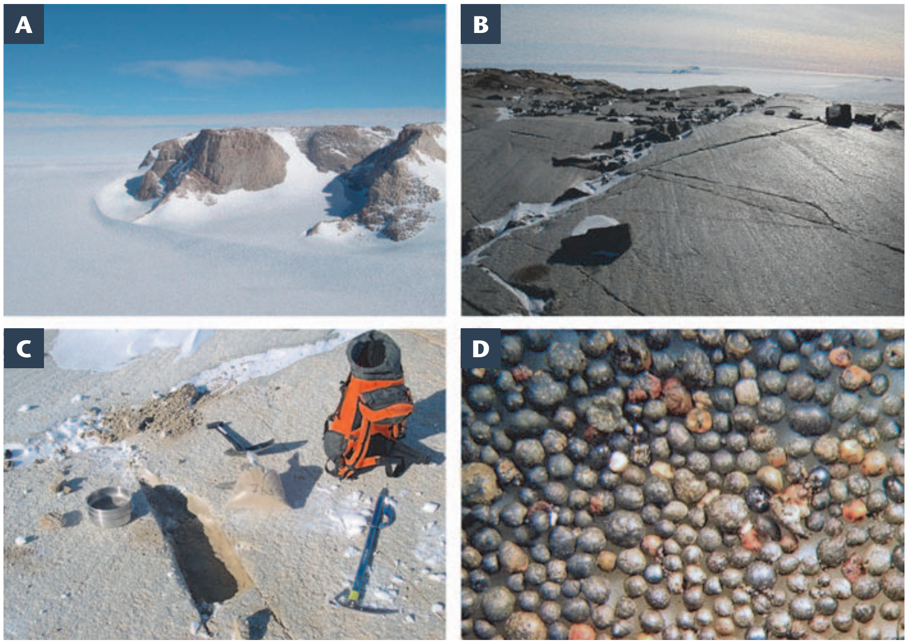

Figure 2 Micrometeorite (MM) collection surfaces on the summit plateaus of the Transantarctic Mountains. (**A**) Panoramic view of southwestern portion of Miller Butte where MMs are found. (**B**) The eroded top of Pian delle Tectiti, a nunatak in the Timber Peak area. (**C**) Detail of a crack where MMs are found on Pian delle Tectiti. The sediments in the joint act as a trap for in-falling MMs. (**D**) A stereomicroscope view of the magnetic MMs extracted from the 400–800 µm size fraction, whose typical concentrations are a few tens of MMs per 100 g of sediment. Image credit: L. Folco

properties of recent cosmic dust. The MMs collected from the South Pole water well are similar to those retrieved from Greenland cryoconite and Antarctic blue ice fields, but they differ from the much older deep-sea collections. Because of the large number collected, rare MMs with unusual compositions and textures were discovered. These include MMs thought to be from asteroid Vesta, a conclusion based on their Fe:Mg:Fe ratios and trace element abundances.

Micrometeorites deposited only in the last few decades have been collected in Antarctica from clean snow near the Concordia station at Dome C, and from clean snow and ice near Tottuki Point and Dome Fuji. Most of the MMs are <100 µm and provide a modern flux estimate for MMs of this size and smaller; they also form a link to interplanetary dust particle (IDP) collections. These recent MM collections contain previously described MM types as well as unusual fluffy fine-grained and unmelted MMs that are similar to the chondritic porous IDPs described below. Some so-called ultracarbonaceous MMs also occur in these collections, and these are made up of 50–85% carbon-rich material. Some of these carbonaceous MMs have deuterium and ^{15}N excesses in their carbon phases, which may trace the origin of these phases to pre-solar interstellar clouds.

INTERPLANETARY DUST PARTICLES

The most fragile and primitive cosmic dust particles are the so-called interplanetary dust particles (IDPs). These particles are collected at high altitudes in the stratosphere where background terrestrial dust is low. Yet, we are still faced with overcoming the low flux rate and the huge volumes of atmosphere that must be scoured for each dust particle. For decades, atmospheric IDP collection attempts by sounding rockets, aircraft, and balloons were plagued by terrestrial contaminants. The first successful stratospheric IDP collection overcame these problems by filtering air using the "vacuum monster" sampler that was flown on a high altitude (~35 km) balloon (Fig. 3a). Following this success, NASA established an IDP collection program that uses high-altitude (~18–20 km) airplanes (Fig. 3B), which were initially repurposed spy planes.

Interplanetary dust particle collectors are flat plastic plates about the size of a pie plate, or smaller, inserted into the subsonic airstream. Particles larger than a critical size (~2 µm) cannot follow the airstream lines around the plates and impact the plate. Coating the plates with a thin film of highly viscous silicone oil minimizes bounce-off of the IDPs. Oil-free polyurethane foam collectors have also successfully collected IDPs.

Collector surfaces are then scanned using an optical microscope in a clean room. Even after 40 hours of flight time, the collectors are extremely clean and typically contain just a few dozen extraterrestrial particles. Each particle is picked off the collector with a fine-tipped glass needle attached to a micromanipulator and then carefully washed with hexane to remove the collection oil. The particles are examined using a scanning electron microscope to determine their elemental abundances and other basic physical properties. NASA publishes this information in cosmic dust catalogues used for sample allocation.

CHARACTERISTICS OF INTERPLANETARY DUST PARTICLES

Despite sampling at high altitude, the stratosphere contains not only cosmic dust but also volcanic ash, rocket exhaust, and other contaminants. Most cosmic dust particles can be distinguished from terrestrial materials by their major element abundance patterns (Na, Mg, Al, Si, Ca, Cr, Mn, Fe, S, and Ni), which are found to be within a factor of ~2

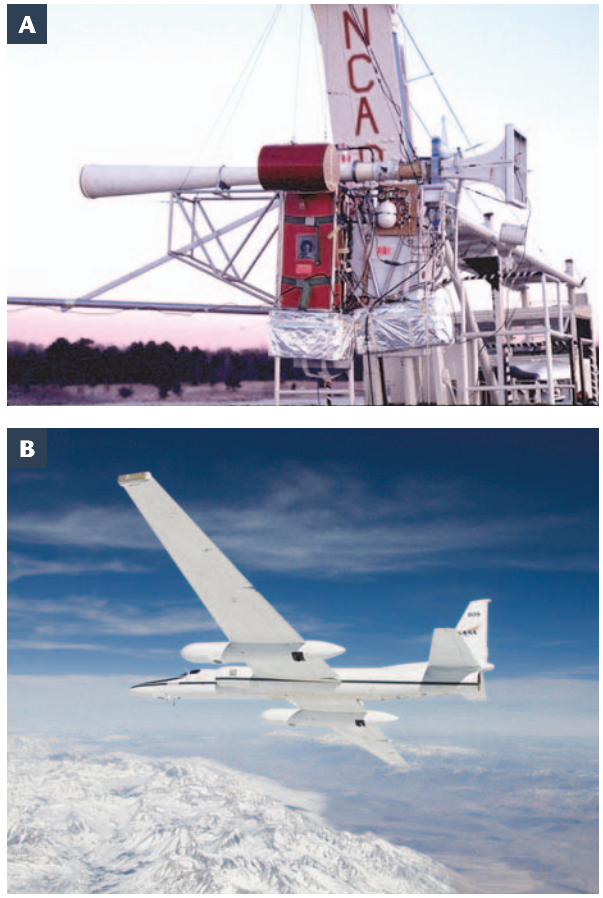

Figure 3 (**A**) The "Vacuum Monster," a balloon-borne collector for stratospheric interplanetary dust particles (IDPs). (**B**) High altitude airplane routinely used to collect IDPs from the stratosphere. Image credit: NASA

of bulk Solar System abundances. Noble gases implanted by the solar wind and radiation damage tracks from solar cosmic rays in these particles demonstrate their extraterrestrial origin. These observations reflect the prolonged exposure of the surfaces of these particles to the space environment over 1,000–100,000 year timescales. Rare IDPs have so much radiation damage that they may have been in space for as long as 10^6 years. Unlike terrestrial materials, many IDPs have H, C, O, and N isotopic compositions that indicate they contain circumstellar dust and interstellar organic matter that predates the origin of the Solar System. Isotopically anomalous pre-solar grains are found at 1,000 ppm concentrations in some IDPs, a value that exceeds that of the most primitive meteorites, which have pre-solar grain abundances of ~100 ppm.

Under an optical microscope, IDPs are often recognizable by their dark appearance and aggregate structures. Many IDPs are so fragile that they break apart into hundreds of fragments when they strike the collector surface. Fragile, fine-grained IDPs are typically made up of anhydrous minerals and carbonaceous material, and these are known as chondritic-porous IDPs (Fig. 4A). Other IDPs are stronger, compact particles composed of hydrous silicates (chondritic smooth IDPs) (Fig. 4B) that bear mineralogical similarities to carbonaceous chondrites.

The weak, porous structures of chondritic-porous IDPs are consistent with the very low strength of cometary meteors. Indeed, chondritic-porous IDPs are remarkably similar in appearance to particle aggregates from the comet 67P/Churyumov–Gerasimenko, which was recently analyzed by the COSIMA instrument on the *Rosetta*

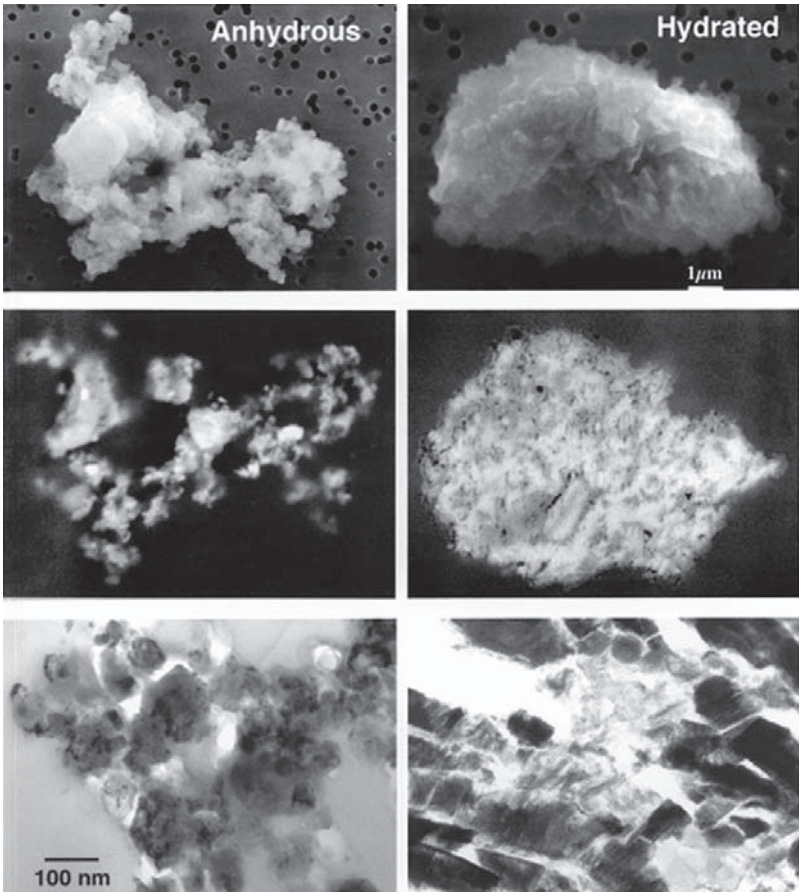

FIGURE 4 (**TOP ROW**) Scanning electron microscope images of an anhydrous, chondritic porous interplanetary dust particle (IDP) and a hydrated, chondritic smooth IDP. (**MIDDLE ROW**) Backscatter electron images of microtome sections of the same two particles where brightness is determined by mean atomic number. (**BOTTOM ROW**) Transmission electron microscope images of 60 nm microtome sections of the same particles showing that the chondritic porous IDP (left) is a mix of anhydrous minerals, glass, sulfides and organic material, while the chondritic smooth IDP (right) is dominated by layered silicates, such as smectite and other hydrated phases. IMAGE CREDIT: D. E. AND D. J. JOSWIAK

spacecraft. No similarly fragile materials occur among meteorites. Chondritic-porous IDPs have also been linked with cometary parent bodies by their anhydrous mineralogy and high abundances of interstellar materials and organic matter. Although these links are not definitive, chondritic-porous IDPs clearly originated from highly primitive parent bodies that lacked conditions to support liquid water.

The hydrated chondritic smooth IDPs are usually thought to come from asteroids because of their mineralogical similarities with meteorites and because some asteroids are known to have undergone aqueous alteration. Yet, there are mineralogical differences, and the chondritic-smooth IDPs tend to have significantly higher C contents, suggesting that they come from different asteroids than do meteorites. Possibly, the different process by which IDPs reach Earth could explain the compositional differences; alternatively, some hydrated IDPs could come from comets that have experienced internal heating and aqueous alteration.

STRATOSPHERIC COLLECTIONS OF METEOR SHOWERS

Stratospheric collections have also been made to coincide with specific meteor showers: these collections have attempted to catch dust from short-period comets. Visible meteors are composed of relatively large particles (mm–cm range) released by comets and, rarely, asteroids in Earth-crossing orbits. The most luminous and, therefore, spectacular meteor showers encounter the Earth at very high velocity. For example, the well-known Leonid meteor shower from comet 55p/Tempel–Tuttle has an Earth-encounter velocity of 72 km s^{-1}. Such velocities are much too high for particles to survive without melting or vaporizing during atmospheric entry. The Leonid meteor shower was targeted for stratospheric dust collection in 2002. Unfortunately, the search for Leonid melt particles was inconclusive.

Promising targets for IDP collections are Earth-crossing comets that produce low-velocity (<20 km s^{-1}) meteor streams. Particles from these meteor streams should survive atmospheric entry without significant thermal damage. Four such streams are so young (<100 years) that it may be possible to identify particles from their parent comets by low space-exposure ages. Space exposure ages can be constrained by low abundances of solar noble gas and a lack of solar flare tracks. Remarkably, some particles from a collection targeted to comet 26P/Grigg–Skjellerup have low noble gas abundances and extraordinarily high abundances of silicate stardust grains. These properties are consistent with an origin from that comet.

Opportunities for targeted IDP collections can also arise unexpectedly. There may be changes in cometary orbits that place comet debris in Earth's path or there may be sudden bursts of cometary activity. An example of the latter was when comet 73P/Schwassmann–Wachmann 3 suddenly broke apart as it approached the Sun in 2006 and generated a stream of cosmic dust. Recently, NASA has tried to collect dust from comet 21P/Giacobini–Zinner following a meteor storm detected by radar. Samples from this collection are currently being studied.

FUTURE COLLECTIONS

New collections of present-day MMs are underway that involve suctioning particles >10 μm out of the clean air that is over the Pacific Ocean and the Antarctic. Such collections could quantify the flux and size distribution of small MMs, thereby providing a link to IDPs collected in the stratosphere. These collections may also make it possible to track variations in the flux or compositions of particles on monthly timescales. Short temporal collections might also obtain unusual particles from specific comets.

Interplanetary dust particle collecting precedures are transitioning to new substrates that collect particles without the use of silicone oil. Oil-free collectors avoid using a nuisance contaminant containing the key elements Si, O, C, and H, all of which may be a component of the cosmic dust itself. Furthermore, oil-free particles never have to be exposed to the strong organic solvents that are needed to remove the collection oil. The first successful oil-free collection used polyurethane foam. This material effectively traps impacting particles within individual cells of the foam, but the fragile particles tend to disintegrate upon impact.

CONCLUDING REMARKS

By collecting primitive materials from Earth's atmosphere and surface we expand the inventory of Solar System materials, and these can then be analyzed using state-of-the-art laboratory instruments. Our challenge is to link individual particles to specific parent bodies: then we have known samples of those Solar System objects without the need for very expensive space missions.

Various pieces of evidence indicate that most cosmic dust comes from different parent objects than do most meteorites. About 80% of the stony melted MMs have bulk compositions similar to rare CI and CM meteorites and not the more common ordinary chondrites thought to come from asteroids. This percentage appears to change with size, with >500 µm MMs being more similar to ordinary chondrites and some <50 µm unmelted MMs having similarities to IDPs. In some unmelted MMs and IDPs, the presence of vapor-deposited minerals, abundant organic matter, subgrains of interstellar materials, and both high- and low-temperature nebular solids indicate that these unmelted MMs and IDPs are pristine, primitive, extraterrestrial materials. Their porous fragile structures and their nonhomogeneous compositions suggest that they have not been processed in large objects.

Collectively, these tiny samples of cosmic dust, be they MMs or IDPs, are windows showing us the types of minerals and carbon compounds from which our Solar System formed.

ACKNOWLEDGMENTS

The authors thank Drs M. Genge and N.G. Rudraswami for reviewing this article and providing many helpful suggestions. We also acknowledge the help received from the *Elements* editors Jodi Rosso and Friedhelm von Blanckenburg. ST thanks her student, Lauren Sachs, for taking some of the photographs in Figure 1.

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