Cosmic Dust: Building Blocks of Planets Falling from the Sky

Donald E. Brownlee[1]

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Throughout its history, Earth has accreted microscopic dust falling from space. Decelerating from cosmic speeds at the top of the atmosphere, the smallest particles can take weeks to reach the ground, failing a rate of 1 m^{-2} day^{-1}. Although usually hidden among terrestrial materials, extraterrestrial particles can be collected from select environments and positively identified by their unique properties. Unmelted cosmic dust is often composed of large numbers of smaller silicate, sulfide, and organic components—the preserved materials from the early Solar System. Cosmic dust particles are samples of comets and asteroids and they are important samples of the initial materials that were to build the solid planets.

KEYWORDS: interplanetary dust, cosmic dust, micrometeorite, comet, asteroid, meteorite, chondrite, presolar

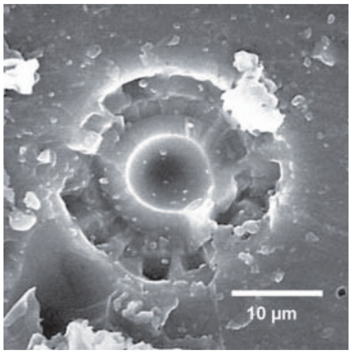

FIGURE 1 A hypervelocity impact crater (zap pit) on the surface of a lunar rock.

COSMIC DUST IN SPACE!

When the first lunar samples were examined after the Apollo lunar missions in the 1970s they were found to be covered with tiny glass-lined craters made by high-speed impact of cosmic dust: the astronauts called them "zap pits" (FIG. 1). In the early days of spaceflight, there had been concern that cosmic dust impacts might rapidly erode spacecraft, resulting in many early satellites carrying sensors to count the number of impacts. If you live far from city lights you can "see" cosmic dust as a glow in the dark night sky that extends along the zodiac after sunset or before sunrise. This "zodiacal light" is caused by sunlight reflecting off submillimeter cosmic dust that orbits the Sun in the plane of the planets (FIG. 2). Although rarely noticed by people looking into light-polluted skies, the zodiacal light is actually brighter than the combined light of all the stars in the night sky.

With telescopes, we can also "see" cosmic dust around other stars, indicating that circumstellar dust is a universal phenomenon. In some cases, dust can be imaged as starlight reflecting off disk-shaped populations of orbiting dust, but, in most cases, dust around other stars is detected and characterized by its infrared radiation. Cold dust that is heated by a hot star emits infrared light in excess of the infrared radiation that comes directly from the star itself. Spectral signatures in the 10–30 µm wavelength range are produced by the stretching and bending modes of Si–O bonds in silicates and provide a means to exploring the mineralogy of this extrasolar dust and to compare it with Solar System dust, e.g. the small particles shed by comets. An intriguing and puzzling aspect of the infrared spectral studies is that dust around other stars contains abundant crystalline silicates such as olivine and pyroxene. Silicate dust between stars, which is the feedstock used to form new stars and planetary systems, is largely amorphous.

FIGURE 2 Zodiacal light. This is sunlight that is reflected off dust orbiting the Sun. The Sun is below the horizon and the cone-shape appearance of the glow is due to both the concentration of particles along the plane of the planets (the zodiac as seen from Earth) and the strong dependence of the efficiency of light scattering as a function of the deflection angle. CREDIT: ESO/Y. BELETSKY

The presence of orbiting dust is common around both young and old stars. When stars and their planets form, dust is initially so abundant that it obscures the star. But over time all original dust is lost due to effects such as gas drag, planet formation, stellar winds, collisional grinding, vaporization, and light pressure effects. Except for very

1 University of Washington
Department of Astronomy
Box 351580
Seattle WA 98195, USA
E-mail: brownlee@astro.washington.edu

young stars, most dust spirals in towards the star unless the dust is so small that it gets blown into interstellar space by the light pressure force from the central star. The long-term presence of dust around most stars is due to the continual liberation of dust from larger bodies. Earth and all Solar System planets have always been bombarded by an endless migration of solid cosmic particles.

COSMIC DUST IMPACTING THE EARTH

In the Solar System, essentially all of the >40,000 tons of cosmic dust annually accreted to Earth (Love and Brownlee 1993) is generated by the collisional grinding of asteroids and the degradation of comets. The submillimeter dust occupies the small end of a very broad size spectrum of interplanetary debris that has pounded all Solar System bodies since their formation. The annual mass of submillimeter cosmic dust reaching Earth greatly exceeds the contribution by normal meteorites and dominates the Earth's extraterrestrial mass accretion budget except for years when a body larger than about 50 meters strikes (thankfully a rare occurrence). Cosmic dust impacts the top of the atmosphere at a rate of about 1 m^{-2} day^{-1} for 10 µm diameter particles and about 1 m^{-2} y^{-1} for 100 µm particles. Particles enter the atmosphere at speeds from 11 km s^{-1} to as much as 72 km s^{-1}. Air friction causes these particles to rapidly decelerate and they experience strong heating that lasts just a second or so. The majority of 10 µm particles survive entry without melting: larger ones have increasing probabilities of melting or even evaporating depending on their speed, size, density and entry angle. Larger dust particles experience more severe heating because they penetrate deeper into the atmosphere at high velocity and are exposed to exponentially increasing air density, drag and frictional energy generated per second. For the smaller particles, the flux is high enough that they can be collected in the clean dry stratosphere with high-altitude aircraft before they enter the damp troposphere and land on the ground or in an ocean. They are called interplanetary dust particles or IDPs (Fig. 3). They thus differ technically from "micrometeorites," defined as particles that reach the Earth's surface and that can be collected in special places, such as in polar ice and in deep ocean sediments, where they can be both separated and distinguished from similar-sized terrestrial particles. Ironically, microscopic cosmic dust is all around us—in the air and on the ground—but in concentrations so low that the particles are almost impossible to find, except by using special collecting methods in special environments.

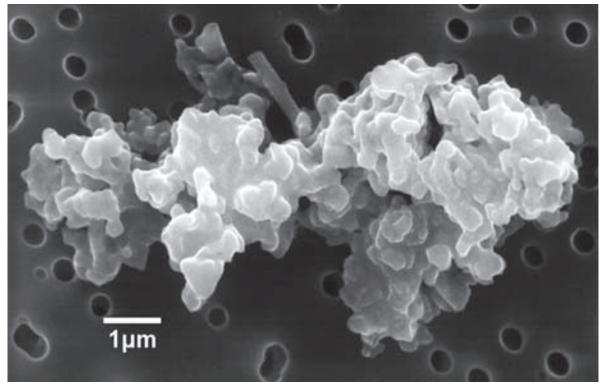

Figure 3 A 10 µm long interplanetary dust particle (IDP) collected in the stratosphere. This particle's composition roughly matches that of the Sun for rock-forming elements and is largely composed of submicron components. The blade-shaped grain at the top is a pyroxene (enstatite) whisker. Enstatite whiskers are commonly found in particles; they have also been found, albeit rarely, in meteorites (Hutchison et al. 1987). The shapes, internal structure and dislocations of the whiskers are consistent with vapor-phase growth.

VALUE OF COSMIC DUST

A Glimpse into the Early Solar System

Cosmic dust is scientifically exciting because it provides samples of comets and asteroids that are rare survivors from the initially vast population of planetesimals that were the first building blocks of the solid planets and that formed the cores of the gas-rich giant planets (Brownlee 1985). Probably the greatest value of cosmic dust, and the reason why it is so passionately investigated with ever-improving microanalytical methods, is that it provides samples of primitive materials from the early Solar System, some of which were either not incorporated or not commonly preserved in meteorites (the ancient rocks that are our major source of information on early Solar System materials). There is compelling evidence that a major fraction of the smaller cosmic dust particles are samples of ice-rich comets that formed in the outer Solar System (Nesvorný et al. 2010). Meteorites, on the other hand, are derived from asteroids that formed in the inner Solar System. As we will see, cosmic dust is a vitally important addition to our other sources of information on the early Solar System and its detailed laboratory study complements what we can learn from meteorites and spacecraft missions to comets and asteroids.

Box 1 **Micrometeorites vs. Cosmic Dust Particles**
Fred Whipple (left) originally coined the term "micrometeorite" to describe dust-sized objects that enter the Earth's atmosphere without melting (Whipple 1950). Over time, the term micrometeorite has come to refer to the dust particles that reach the Earth's surface whether they have melted or not. Smaller (5–100 µm) particles that are collected in the stratosphere are also unmelted and by tradition are called interplanetary dust particles, or IDPs. Particles can escape being melted when the power generated by atmospheric drag can be thermally radiated below their melting temperature. In contrast, larger particles often melt and form cosmic spherules. Cosmic dust particles are one of the few extraterrestrial materials honored with a stamp (right).

Box 2 **Collecting Cosmic Dust**
Despite the many student science projects that involve setting out trays to collect micrometeorites from the atmosphere or cleaning out rain gutters, you will not find them easily using these methods to collect cosmic dust.. In all but very special places, the background of terrestrial particles is an insurmountable barrier to collection. Collecting fallen cosmic dust is, however, relatively straightforward in some polar regions, in deep-ocean sediments far from land, and in the stratosphere, but it is nearly impossible elsewhere. If collected, typical cosmic dust particles can usually be identified by their elemental composition, which is similar to the whole Earth but very different from common materials on the surface of our planet. The most common cosmic dust particles have Na, Mg, Al, Si, S, Ca, Ti, Cr, Mn, Fe, and Ni abundance ratios that match those of the Sun, and these abundances can be detected in just a few seconds time with typical X-ray detectors mounted on scanning electron microscopes, an instrument found at most universities.

Rare tracers in the atmosphere, sediments, and building blocks for life

Although this issue will focus on the cosmochemical information gleaned from cosmic dust, the dust is also of interest for a number of geophysical and astronomical reasons. Due to evaporation associated with atmospheric entry heating, cosmic dust delivers Na to the mesosphere, forming a layer at 90 km that can be excited with lasers. Stimulated fluorescence of the mesosphere is routinely used by adaptive optics methods to remove atmospheric distortion in modern telescopes. It has also been proposed to use spin precession of the Na atoms to map mesospheric magnetic field variations. Although cosmic dust is just a trace component on Earth, it adds appreciable amounts of rare components to terrestrial sediments, such as 3He and elements such as Ir. The concentrations of these rarer components may then be used as markers to estimate, for instance, sediment accumulation rates. For example, the global Ir-rich layer at the Cretaceous–Paleogene boundary (formerly known as the K–T boundary) that is associated with the extinction of the dinosaurs was only found because of the attempt to use Ir carried by cosmic dust to estimate sediment accumulation rates during this period of global mass extinction (Alvarez et al. 1980). Earth, Mars, and other planets are bombarded by a rain of cosmic particles (Fig. 4) but that flux was probably even higher in the early Solar System because asteroids and comets were more numerous and there may have been planetary migration events that perturbed interplanetary debris to Earth-crossing orbits (Gomes et al. 2005). Cosmic dust delivered complex organic matter, including amino acids, to Earth before life began. These organic-rich small particles from the outer Solar System plausibly played important roles in the origin of life (Anders 1989).

SMALL SIZE IS KEY TO SURVIVING ATMOSPHERIC ENTRY

Cosmic dust collections in the stratosphere, in polar ice, and in deep-ocean sediments have yielded tens of thousands of extraterrestrial particles for laboratory study. The study of these particles and their components has often pushed the limits of analytical capability to smaller and smaller sizes (Westphal and Herzog 2016 this issue). Each particle is its own sample of a small Solar System body, and it is common to use a broad range of coordinated analytical methods to explore the diverse and often complex information that they contain. Many cosmic dust samples are themselves collections of unrelated submicron (and larger) solids that accreted somewhere during the formation of the early Solar System, and their study has revealed insights into the early Solar System processes and materials. Perhaps the most astounding aspect of cosmic dust work has been the finding that common cosmic dust particles are different from common meteorites. That is probably because of the way that interplanetary objects reach Earth and survive high-speed entry into the atmosphere. Hand-sized rocks and larger objects that become conventional meteorites only reach Earth because their orbits were changed to Earth-collision paths by gravitational tugs from other planets, principally Jupiter. These processes are very selective and favor materials from special regions of the Solar System. When rocks eventually hit the atmosphere they have to be strong enough that they are not fragmented by the crushing force that occurs during high-speed travel deep in the atmosphere. In contrast, the cross Solar System migration of cosmic dust is assisted by the pressure of sunlight, a drag effect that causes all small orbiting particles to spiral inwards on decaying orbits. Once cosmic dust particles reach Earth they do not have to be very strong to avoid fragmenting in the atmosphere because they decelerate from cosmic velocities when they reach near 100 km altitude where the density of air is orders of magnitude lower than that experienced by kilogram meteorites, which retain their high speed to below 40 km altitude. For a given velocity, the dynamic pressure of air drag is directly proportional to the ambient air density. Objects lose their initial high velocities after they have encountered a column of air whose mass is comparable to their own mass. Consider a centimeter-diameter marble falling from space at 12 km s^{-1}. It will lose its cosmic velocity after it collides with a column of air whose diameter is comparable to that of the marble but whose length is sufficient to enclose an air mass comparable to, or exceeding, that of the marble's. Larger particles, with their higher mass/area ratios, travel deeper into the atmosphere before they are stopped by air friction. Meteorites are a biased sample because only those with high mechanical strength survive atmospheric entry and they reach Earth solely by gravitational effects. While collected cosmic dust also has biases mostly related to the survival of atmospheric entry, extremely fragile dust from any place in the Solar System can reach Earth and, if it is small enough, it can survive and be collected. The most fragile and carbon-rich meteoritic materials are only found as cosmic dust.

Figure 4 Optical images of (top) a size sorted lag deposit on Mars and (bottom) magnetic particles >100 µm from mid-Pacific red clay in >4 km ocean floor sediment (Brownlee et al. 1997). All of the spheres in the bottom image are cosmic dust that fell within the last million years and were briefly melted during atmospheric entry due to their entry speed and large size. The shiny ones are magnetite–wüstite mantles enclosing Fe–Ni metal cores and the rough ones are composed of olivine, glass, and magnetite with chondritic bulk compositions. In the upper image, the spherical particles observed in the unusual Martian lag deposit are size-sorted and assumed by the author to be cosmic spheres that are expected to accumulate on the billion-year old Martian surface. The Martian and seafloor spheres in these images are less than a millimeter in diameter, the size that dominates the mass of solid extraterrestrial material accreted by planets with atmospheres. Image credit: NASA Mars Science Laboratory rover Curiosity image 1184MH0005480010402897C00 _ DXXX&s=1184

COSMIC DUST CONTENTS

Most cosmic dust particles have undifferentiated (solar-like) bulk elemental compositions for rock-forming elements, and they are rich in carbon. To a first approximation, most cosmic dust particles are similar to the carbon-rich matrices of some carbonaceous chondrites, a group of meteorites that represent only a few percent of the meteorites that are seen to fall out of the sky (and are the least biased sampling of extraterrestrial rocks that impact Earth). Many cosmic dust samples, however, appear to be materials that do not have meteoritic counterparts. For example, some cosmic dust particles are several times more carbon-rich than any known meteorite, and they are fragile porous aggregates of fine anhydrous materials. In contrast, most meteorites are comparatively strong compact rocks and all the carbon-rich ones contain hydrated silicates as well as secondary phases that are attributed to hydration reactions inside a warm wet parent body. Most meteorites were processed in their parent bodies to a degree that they became strong enough to survive high-speed entry into the atmosphere. The asteroidal parent bodies of meteorites were all heated for extended periods of time in the early Solar System to various degrees that ranged from the extreme of melting of all silicate phases, to less severe subsolidus thermal transformation of major phases, to alteration from contact with liquid water in the least heated materials. Some cosmic dust particles also came from bodies that experienced parent-body processing, such as aqueous alteration, but others did not.

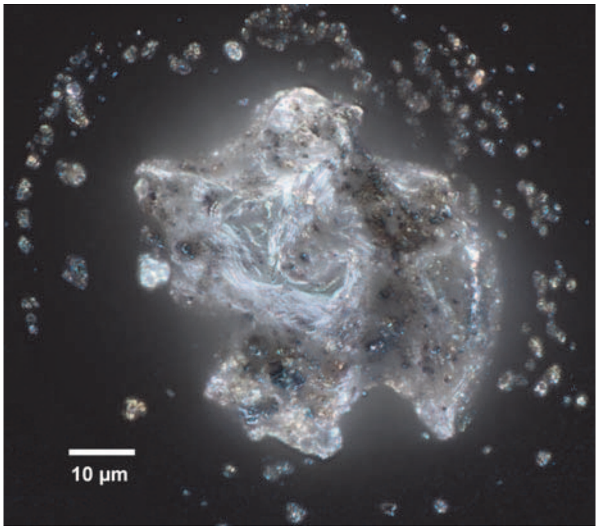

FIGURE 6 Some IDPs are not aggregates of fine components and do not have elemental compositions that are similar to primitive meteorites. This optical image shows a rare 60 µm transparent interplanetary dust particle composed of olivine and glass. Before entering the atmosphere, the particle was embedded in a matrix of loose fines identical to those in Figure 5. In this image, fines are seen as opaque and transparent materials adhering to the particle's surface, as well as debris that fell to the supporting substrate. The orange fines are Fe–Ni sulfides and the black ones have chondritic elemental compositions and are opaque due to their content of nanophase metal and sulfide and/or carbon.

Certain subgroups of dust particles deserve special notice. Of particular significance are the IDP aggregates that are made up of uncompacted and well-preserved assemblies of dissimilar submicron (FIG. 5). and larger components (FIG. 6). These objects do not appear to have been significantly transformed inside their parent body hosts for over four billion years: they have been protected for essentially the age of the Solar System. The most porous aggregates are probably samples of comets from which ice between the grains has been lost by sublimation. The most primitive cosmic dust particles contain minor amounts of isotopically anomalous presolar grains. Such grains are usually less than a micron in size and have dramatically distinctive isotopic compositions, suggesting that they formed around other stars and so predate the formation of the Sun and planets. Although <1,000 ppm, the abundances of these presolar grains are still higher than found in most primitive meteorites and are similar to those found in comet samples collected by NASA's *Stardust* mission. Many IDPs also contain higher contents of organic components than do meteorites, and IDPs commonly have micron-sized "hot spots" with elevated D/H and $^{15}N/^{14}N$ ratios, which indicates that they formed at very low temperatures. Finally, primitive cosmic dust also commonly contains abundant submicron components called GEMS (glass with embedded metal and sulfide) (FIG. 7) that rarely, if ever, are preserved or seen in meteorites. All the evidence, therefore, leads us to

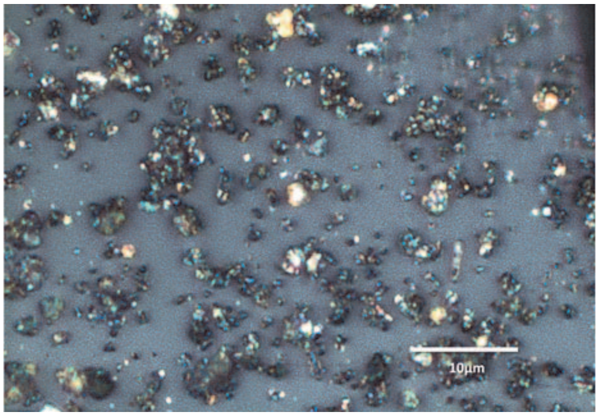

FIGURE 5 This reflected light image shows a small fraction of a large aggregate interplanetary dust particle whose diverse components were gently separated from each other and spread across a polished glass surface. The components include sulfides (orange), organics, silicate minerals (including two enstatite whiskers) and amorphous silicates. The amorphous silicates include so-called GEMS (glass with embedded metal and sulfide), enigmatic submicron components of interplanetary dust particles (IDPs), which are composed of glass and nanophase metal and sulfide blebs. Many of the components in the image are themselves composites of different unequilibrated materials. It is possible that most micron grains seen around other stars are very similar to these grains.

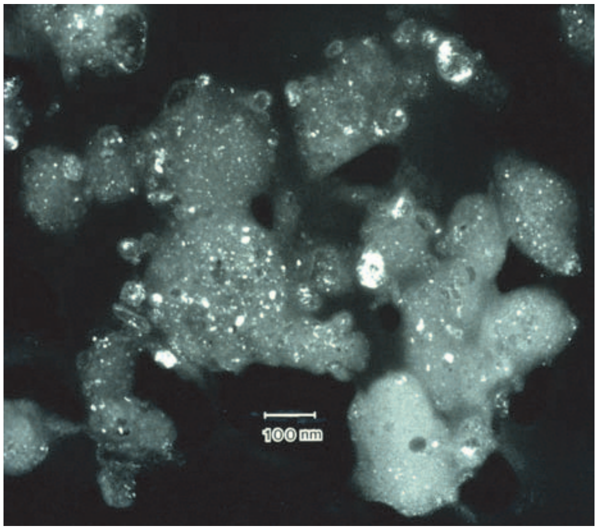

FIGURE 7 Dark field transmission electron microscope image of GEMS (glass with embedded metal and sulfide), the mysterious submicron components of interplanetary dust particles that are composed of Mg-silicate glass filled with nanophase Fe–Ni metal and sulfide beads. The grey areas are amorphous silicate and the bright areas are metal and sulfide. IMAGE CREDIT: J. BRADLEY, USED WITH PERMISSION

conclude that some cosmic dust particles represent primitive Solar System materials that are less processed than those commonly preserved in meteorites (FIG. 8).

A long-standing goal in cosmic dust work has been to compare these microscopic particles with the different types of meteorites. While comparing nanogram to microgram dust particles with kilogram meteorites might seem to be an insuperable challenge, it is possible because many dust particles contain large numbers of distinctive unequilibrated components that can be studied by microbeam analytical methods. Initially, it was commonly thought that cosmic dust falling on Earth would just be fragments of common meteorites: however, this did not turn out to be the case.

Primitive meteorites are called chondrites. They have bulk compositions similar to the Sun for rock-forming elements, but they do not have the extensive fractionation of lithophile and siderophile elements that characterize Earthly rocks. Chondrites are classified into a number of groups that are based on distinctive properties: these include Fe/Si ratios, oxidation state, the abundance of volatile and refractory elements, carbon content, mineralogical differences and oxygen isotopes. Most primitive meteorites can be grouped into the classes with names like E, L, LL, H, CM, CR and CI. Many of the distinctive properties of these groups appear to relate to regional variations of materials in the locales where specific meteorite parent bodies formed. As mentioned, all meteorites have been heated and processed to some degree inside their parent asteroids; thus meteorites in a given class are also subdivided into metamorphic classes that reflect the severity of their alteration. Typical primitive meteorites experienced sufficient metamorphic heading to cause equilibration and grain growth of their silicate components. Most small cosmic dust particles are very fine grained, they are not chemically equilibrated, and they have high carbon contents, in some cases >10 wt%. They are most similar to the rare carbonaceous chondrite meteorites (e.g. the CM, CI, or CRs), and some IDPs are surely just samples of the parent bodies of these meteorites. However, typical carbon-rich anhydrous IDPs, with their high carbon contents, lack of aqueous alteration and high presolar grain contents, are clearly a material that is not represented in the established meteorite classes. One of the greatest values of studies of collected dust is that it gives us insight into a broader range of early Solar System materials than are usually preserved in meteorites.

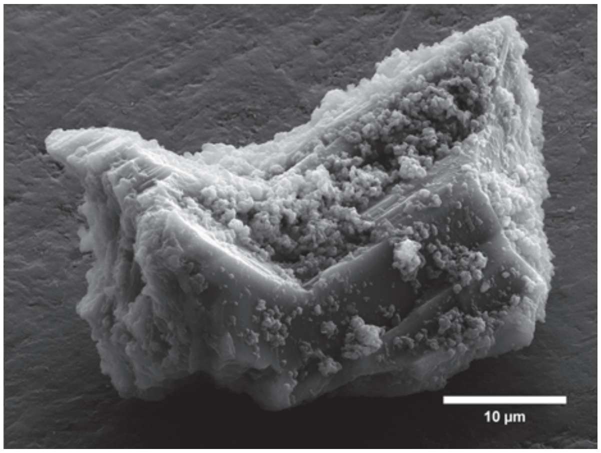

FIGURE 8 A scanning electron microscope image of a 40 µm enstatite grain that was extracted from a much larger loosely aggregated stratospheric interplanetary dust particle. The particle's pristine surface appears to be unaltered by residence inside its parent body, atmospheric entry heating, or terrestrial weathering processes. The adhering surface debris is identical to the solar-composition fine matrix debris shown in Figures 3, 5 and 6 and is optically seen as black grains on the larger transparent particle. Growth steps or fractures and several enstatite whiskers are visible on the surface of this particle. The magnificently preserved surface of this grain probably formed during that brief period (a few million years only) when the Solar System was filled with gas and dust—the initial planetary building blocks.

PREVIEW OF THIS ISSUE

This issue provides an overview into research on cosmic dust. Taylor et al. (2016 this issue) illustrate what solar cosmic dust looks like and how it is collected from deep-ocean sediments, polar ice, and the stratosphere. The mineralogical, elemental, and isotopic compositions and the sources of cosmic dust are covered by Flynn et al. (2016 this issue), and the nature and implication of the organic components nitrogen and water are described by Sandford et al. (2016 this issue). Peucker-Ehrenbrink et al. (2016 this issue) describe how cosmic dust in terrestrial sediments can be used as tracers on Earth: one can imagine how analogous studies can be done in the future on Mars to study accumulation rates and redistribution processes. Westphal and Herzog (2016 this issue) describe the history and dramatic evolution of some of the instruments and analytical techniques that are used to analyze these tiny dust particles to extract the myriad types of information that is recorded in their minute components.

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COMMON COSMIC DUST TERMS & ABBREVIATIONS

CHON — components composed of carbon, hydrogen, oxygen and nitrogen, first seen in dust from comet Halley.

Chondrite or Chondritic refers to those meteorites that have elemental proportions that are similar those found in the Sun for rock forming elements. Although chondrites do show bulk compositional variations, they have not experienced large scale differentiation of siderophile and lithophile elements as seen in planetary materials.

CI — carbonaceous rich similar to the Ivuna meteorite

CM — carbon rich including complex mix of organic compounds similar to the Mighei and Murchison meteorites

OC — ordinary chondrites-most common type of stony meteorite found.

CC — carbonaceous chondrites, general term

COSIMA — cometary secondary ion mass analyzer

CRE — cosmic-ray exposure

ET — extraterrestrial

GEMS — glass with embedded metal and sulfides

GIADA — grain impact analyzer and dust accumulator

IDP — interplanetary dust particles

CS — chondritic smooth

CP — chondritic porous

Cluster

IOM — insoluble organic matter

I-type spherule — melted cosmic spherule usually composed of a Fe–Ni metal surrounded by a wüstite, magnetite shell.

LDEF — long duration exposure facility

LIME — low iron magnesium enriched

MM — micrometeorites

NASA — National Aeronautics and Space Administration

PAH — polycyclic aromatic hydrocarbons

S-type spherule — melted stony cosmic spherule

UCAMM — ultracarbonaceous antarctic micrometeorites

COMMON ANALYTICAL AND SPECTROSCOPIC TECHNIQUES FOR COSMIC DUST RESEARCH

Technique	Acronym	Incident particles	Signal	Science Goal
Imaging				
Scanning Electron Microscope	**SEM**	Electrons	Electrons + X-Ray photons	Submicron morphology
(Scanning) Transmission Electron Microscopy	**(S)TEM**	Electrons	Electrons + X-Ray photons	Nanoscale morphology
High-resolution Transmission Electron Microscopy	**HRTEM**	Electrons	Electrons	Crystal structure and atomic scale defects
Helium Ion Microscopy	**HIM**	Ions	Electrons and ions	Particle structure
Elemental Composition (major, minor and organics)				
Electron Probe Microanalysis	**EPMA**	Electrons	Electrons + X-Ray photons	Submicron morphology and composition
Energy-dispersive X-ray Spectroscopy	**EDX or EDS**	Electrons, ions, or X-Ray photons	X-Ray photons	Sample composition (similar to XRF)
Synchrotron-based X-ray Fluorescence Spectroscopy	**SXRF**	X-Ray photons	X-Ray photons	Sample composition (similar to EDS)
Atom Probe Tomography	**APT**	photons	Ions	Nano morphology, element abundances and isotopic ratios
Two-Step Laser Desorption Mass Spectrometry	**L2MS**	photons	Ions	Trace element abundances and isotopic ratios
Laser Ablation Inductively Coupled Plasma Mass Spectroscopy	**LA-ICPMS**	photons	Ions	Trace element abundances and isotopic ratios
Liquid Chromatography with Fluorescence Detection/ Time-of-Flight Mass Spectrometry	**LC-FD/TOF-MS**	photons	ions	Composition of organics
Liquid Gas Chromatograph Mass Spectroscopy	**LGCMS**	Electrons	Ions	Composition of organics
Quark Gluon Plasma Femtoprobe	**QGP-FP* (*hypothetical)**	yoctons	zeptons	You know, Life, The Universe, and Everything
Isotopic Composition				
Accelerator Mass Spectrometry	**AMS**	Ions	Ions	Isotopic composition
Secondary Ionization Mass Spectroscopy	**SIMS**	Ions	Ions	Isotopic ratios of elements
nanometer resolution Secondary Ionization Mass Spectroscopy	**nanoSIMS**	Ions	Ions	Isotopic ratios of elements
Noble Gas Mass Spectrometry		Electrons	Ions	Noble gas concentration and isotopic ratios
Resonance Ionization Mass Spectroscopy	**RIMS**	Ions + photons	Ions	N/A
Mineralogy				
Electron Energy-Loss Spectroscopy	**EELS**	Electrons	Electrons	Chemical environment of a specific element
X-ray Absorption Near-Edge Spectroscopy	**XANES**	X-Ray photons	X-Ray photons	Chemical environment of a specific element (similar to EELS)
Atom Location by CHanneling Enhanced MIcroanalysis	**ALCHEMI**	Electrons	Electrons	Site occupancies
Fourier Transform Infrared Spectroscopy	**FTIR**	Infrared photons	Infrared photons	Bonds
nanometer resolution FTIR	**nanoFTIR**	Infrared photons	Infrared photons	Bonds
Ptychography/STXM	**pSTXM**	X-Ray photons	X-Ray photons	Nanoscale morphology and chemistry (similar to XANES)
Synchrotron-based X-ray Diffraction	**SXRD**	X-Ray photons	X-Ray photons	Crystal structure
Sample Preparation				
Focused Ion Beam Milling	**FIB**	Ions	Electrons and ions	Sample Preparation