COLLECTION OF COSMIC DUST: PAST AND FUTURE

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The collection of cosmic dust began in the middle of the last century with the recovery of spheres from the ocean floor and from Greenland ice (Murray and Renard 1891). The occurence of native metal in some of the deep sea spheres was the first clue that they were extraterrestrial. The deep sea spheres were described as "chondres" and their origin was attributed to the atmospheric melting of meteors. Polar ice and the ocean floor sediments often contain only minor amounts of magnetic terrestrial particles > 100μm and in these sites it is possible to collect rather large magnetic extraterrestrial particles that fell in historic times. In the intervening century an extensive series of particle searches were carried out in nearly all likely types of terrestrial collection sites. These included glaciers, islands, beaches, deserts, lakes, rooftops, rainwater, and all levels of the atmosphere up to low Earth orbit. Most of these efforts were not successful in collecting particles that were later proven to be extraterrestrial. In addition to the earlier deep sea and polar work, successful recoveries were made from a beach sand, a desert, and the stratosphere. All of these efforts are described in an excellent review by Hodge (1981).

Dust particles whose extraterrestrial origin can be positively proven are routinely collected at the present time both from sediments and from the stratosphere. The analysis of these samples gradually has taken on new significance both as a source of information about the physical properties of cosmic dust and as a source of cosmochemical information about primitive solar system materials. The sequence of events that led to the current "modern era" of dust collection and analysis began with the pioneering efforts of Curtis L. Hemenway, to whom this talk is dedicated. Dr. Hemenway, starting in the late 1950s, began an extensive series of collection efforts that revolutionized cosmic dust collection and catalyzed a major expansion of the cosmic dust field. His first dramatic new experiment was the Venus Flytrap rocket collector he built along with Bob Soberman (Hemenway and Soberman 1962). Many rocket collectors followed that he flew into the mesophere and into noctilucent clouds. In space he pioneered collections by inspecting Mercury capsule parts and he built

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recoverable clamshell-like collectors exposed on Gemini missions (Hemenway et al. 1967). The first micrometeoroid impact craters recovered from space were obtained by these experiments which were, in addition, the first experiments directly retrieved from space by an astronaut during extravehicular activity (EVA). One collector was launched on an Agena and later picked up by Gemini. He also flew collectors on Skylab. An airlock he designed played a crucial role in saving the Skylab mission when it was used for erection on an emergency sunshade to cool the spacecraft. Ironically, the original problem was caused by a mechanical failure of a micrometeoroid shield during launch. On the space collectors and also on many of the rocket experiments Curt graciously invited investigators to build their own surfaces and fly them in his experiments. This established the tradition of joint investigators now used in LDEF and also provided a mechanism for many new and unestablished investigators (including the author) to get started in the then rapidly expanding und very exiting field.

Hemenway also conducted an extensive set of balloon collections. His balloon top settling plate collector, "Sesame" was the first experiment flown at the U.S. national scientific balloon flight facility at Palestine, Texas (Hemenway et al. 1967b). After many Sesame flights, he then developed the "Magellan"collector - a large funnel collector that was flown in the southern hemisphere below a superpressure balloon that circled the globe (Hallgren and Hemenway 1976). This was the pioneering effort for recovering a large payload flown on a long duration, superpressure balloon.

All of Hemenway's experiments were daring advances forward that utilized the rapidly advancing technology of space flight, ballooning and laboratory technique. These collections radically advanced the state of the art, even though only the craters on his orbital experiments can be confidently proven to be extraterrestrial. Most of the collections were controversial and did not collect particles that could be proven to be extraterrestrial on chemical or isotopic grounds. There were two major problems that plagued collections made in the 1960s. One was that it was widely, but not unanimously, believed that the flux was so high that particles could be collected with sounding rockets and settling plate collectors mounted on balloons. We now know that the flux of 10μm particles is only $1 m^{-2} day^{-1}$ and these techniques are not practical even if contamination problems could be totally eliminated. The only successful airborne particle collections have been made by balloon and aircraft collections that cleanly sample huge volumes of air. These devices collect one 10μm particle per 1000 ft^3 of air, a rate of one per hour. The second problem with earlier collections was the difficulty of analysis of collected samples. The scanning electron microscope (SEM) became commercially available in the 1960s, and Hemenway was quick to adapt this revolutionary new surface imaging technique to cosmic dust particles. Unfortunately, the commercial availability of solid state X-ray analyzers for the SEM did not come until several years later. This device provided, for the firs time, the capability for doing nondestructive chemical analysis of microparticles in seconds. Prior to the availability of this device, elemental analysis on particles could only be done with X-ray crystal spectrometers which are used on microprobes and were available on a few electron microscopes. The long integration times requird for these analyses caused great difficulty for analysis of small particles. An example is the analysis of high atomic number elements in "stardust" particles collected on Hemenway's rocket experiments. Spectrum scans for these very small particles took so long that the particles became obliterated by beam contamination (diffusion pump oil). This obliteration made it difficult to verify the analysis results by a second analysis, or even to confirm that the beam was always exactly on the sample.

With the technology available prior to about 1970 it was difficult to identify collected particles as either terrestrial or extraterrestrial. In the majority of cases it was simply assumed that the recovered samples were extraterrestrial by virtue of their morphology or location of collection. Unfortunately, these two criteria are really only useful in deep ocean sediments and even then they are by no means infallible. In the past 15 years new information on extraterrestrial particles and new and fairly common analytical tools have made the identification of at least the majority of cosmic dust particles a fairly straightforward task. Fortunately, the majority of cosmic dust particles larger than 5μm have chondritic elemental compositions. Within a factor of 2-3 typical abundances match type 1 carbonaceous chondrites for all elements. No known terrestrial particle matches chondritic composition for more than a few elements. As an operational criterion, when a particle is analyzed in an electron microprobe or SEM, if it has chondritic abundances for C, Na, Mg, Al, Si, S, Ca, Cr, Mn, Fe and Ni, it is almost certainly extraterrestrial. Particles that melt during atmospheric entry to form spheres differ from the chondritic pattern in that they are usually depleted in volatile elements such as Na, S and C and siderophile elements such as Ni, Co and Cr (a siderophile under reducing conditions). Many cosmic dust particles, of course, do not have chondritic compositions and establishing an extraterrestrial origin for these is more difficult. Typical large deviations from a chondritic pattern occur when a particle's composition is dominated by a single mineral. Regardless of its composition, if a collected particle was a small particle in space, then its extraterrestrial nature can be absolutely verified by the detection of implanted solar wind (Hudson et al. 1981), solar flare tracks (Bradley et al. 1984) or the existence of ^{26}Al, ^{10}Be, or ^{53}Mn produced by cosmic ray bombardement (Nishiizumi 1983; Raisbeck et al. 1983). The composition of a particle can be determined in seconds but the other techniques for determining its origin are complex and cannot be routinely used on a large number of samples. The track and rare gas tests can be done on 10μm particles but only if they were not strongly heated during atmosphere entry. The cosmogenic isotope effects require particles of 300μm in diameter or larger.

Particle collections experiments are currently being conducted in the stratosphere, polar ice, ocean sediments and earth orbit. The most pristine material will always come from the stratosphere, but particles will generally be smaller than 50µm because of the flux problem. Important goals of future atmopsheric collections will be to collect particles from meteor showers or fireballs and to collect rare large particles (~50µm) that have suffered minimal alteration by atmosphereic heating. Air sampling collectors become increasingly inefficient for larger particles and perhaps the best approach for > 50µm particles is the Hemenway Magellan collector, which flies a large funnel (settling plate) for a period of months. A few percent of 50µm particles enter the atmosphere at very low incidence angle and suffer only minor heating. This process actually allows a much smaller fraction of millimeter-size particles to survive without melting and thus become legal "micrometeorites". A major goal of future sediment collections will be to collect these giant micrometeorites. These particles are unmelted, but are not nearly as well preserved as the atmospheric dust because of weathering processes at the Earth's surface. Their size, however, makes them very important for a variety of analytical techniques that are best done in large samples. Future efforts on the sediment particles should also include detailed studies to detect temporal changes in the flux, size or composition of particles that have entered the atmosphere over the 2×10^8 -year record of Earth history preserved in deep sea sediment cores.

The collection area that will undoubtedly see the greatest change in coming years is space. Although it is probably impossible to collect particles in space in a truly nondestructive manner, it should be possible to collect analyzable material in a nonselective fashion in regards to physical properties and, most importantly, it should be possible to collect particles with known orbital parameters. Some of the stratospheric particles are highly porous fragile objects. It is possible that there are even more fragile particle types that do not survive atmospheric entry and could only be collected in space. While it does not appear practical to capture such fragile particles intact, it should be possible to capture solid debris resulting from the impact into a capture cell or the collection surface. Chemical analysis of the fragments can provide an excellent means of characterization of the original particle.

One of the most important aspects of space collections is to collect samples from a known source. The straightforward approach, of course, is take the collector directly to the source, such as a cometary coma, and then return it to the Earth. Such missions are currently under study for low cost sample returns with flyby velocities of 10 kms^{-1}. For Earth orbiting experiments "matching" a single particle with a known source requires precise measurement of its orbital parameters by electronic techniques. Because of orbital evolution it cannot be expected that many collected particles could be reliably matched with a known source but some can. This is particularly true for large particles whose collisional lifetimes are much smaller than their Poynting-Robertson evolution times. With a suitably large collector it appears possible to collect a significant number of 10µm particles from known comets and even contemporary interstellar grains in transit through the solar system.

The current work on collected particles has provided a detailed chemical and structural information on what are probably typical interplanetary dust particles in the 5μm-50μm size range. Most of these particles are black aggregates of small grains but there is actually wide diversity among the collected samples. Particles range from solid mineral chunks such als FeS to fragile porous aggregates composed of millions of tiny but distinct mineral grains. Future work will provide increasingly detailed information about the source materials of interplanetary dust. Work on dated sediments has provided initial data on the time history of the Earth's accretion of dust and has indicated that future efforts may provide powerful constraints on the temporal variations in the meteoroid complex. Recent work on tracks in stratospheric micrometeorites and cosmogenic isotopes in deep sea spheres has provided the first real measurement of particle lifetimes that can be used to constrain models of the dynamical evolution of interplanetary dust.

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