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# COSMIC DUST: COLLECTION AND RESEARCH

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## INTRODUCTION

The term "cosmic dust" as used here refers to particulate material that exists or has existed in the interplanetary medium as bodies smaller than 1 mm. The particles can be collected both in space and in the terrestrial environment, and they are a valuable resource of meteoritic material. The dust samples are complementary to the traditional meteorites that were much larger meteoroids in space. Because of their size, the analysis of collected dust particles is more difficult and limited than studies of meteorites. Nevertheless, collected dust samples are being vigorously investigated for two fundamentally important reasons. The first is that the most friable extraterrestrial materials can *only* be collected in the form of dust. Highly fragile materials cannot survive hypervelocity entry into the atmosphere in chunks as large as conventional meteorites. Most cometary meteoroids are known to be fragile, and dust collection is the only Earth-based technique for obtaining typical cometary solids.

The second reason why dust is important is that it is very abundant. Meteorites are exceedingly rare, but cosmic dust is so common that quite literally every footstep a person takes contacts a fragment of cosmic dust. Dust is so abundant that, with appropriate techniques, it can be recovered from historical deposits in deep-sea sediments and collected in real time in space and in the stratosphere. Stratigraphic layers in sediments record a continuous history of the terrestrial accretion of space debris that extends beyond $10^8$ yr ago. This record can be searched for temporal changes in the meteoroid complex, such as might occur during fluctuations in the number of comets in the inner solar system or during passage of the solar system through an interstellar cloud. Effects of isolated events, such as the terrestrial impact of a large body, are also contained in sediments. The flux



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of particles in space is high enough that it should be possible to design a collector that measures orbital parameters of the particles being collected. This would allow collection of material from identifiable sources, a project that was tried for conventional meteorites with very limited success because the collection rate was only one per decade (McCrosky et al 1971). Dust is abundant not only in terms of numbers but also in terms of mass. The bulk of the total mass of extraterrestrial material that is annually accreted by the Earth is in the 0.1–1 mm size range (Hughes 1978). Because of this and because of its rapid orbital evolution after release from parent bodies, the dust at 1 AU is likely to be a more representative sample of the entire meteoroid complex than are conventional meteorites.

This paper reviews the aspects of cosmic dust that are important to its collection and utilization as a resource of extraterrestrial material. Most of the collected dust particles appear to be primitive and sometimes unique solar system materials that contain important clues to early solar system processes and environments. Collected dust can also be studied to investigate selected properties of the interplanetary medium and the terrestrial environment. The treatment of the origin and evolution of dust in the solar system is focused here on aspects important to the interpretation of sample results. The bulk of the paper reviews the results of laboratory studies of dust samples collected in the stratosphere and deep-sea sediments.

## ORIGIN AND EVOLUTION

Dust particles in the interplanetary medium are transient bodies with individual lifetimes that are much shorter than the age of the solar system. Radiation pressure drag (the Poynting-Robertson effect) and self-collisions remove particles from the inner solar system on a time scale of less than $10^6$ yr (Dohnanyi 1978). It is not known how stable the dust inventory is, but hypervelocity microimpact craters found on meteoritic and lunar grains, which had ancient exposures to space, indicate that dust has existed in the interplanetary medium for billions of years (Brownlee & Rajan 1973). Presumably, the dust complex is maintained in some approximation to quasi-equilibrium, with new dust generated at a rate sufficient to replace the dust lost by the sink mechanisms.

All of the solid bodies in the solar system can inject particulates into the interplanetary medium, including planets like the Earth that release material during major impact events. For most of the lifetime of the solar system, however, the only two important dust sources within the solar system have been asteroids and comets. These are small bodies with low surface gravities and no permanent atmospheres. They are also by far the most abundant bodies in the planetary system. The solar system contains $>10^{11}$ comets and $\sim 10^6$ asteroids larger than a kilometer in diameter. Both of these parent materials appear to be relic planetesimals preserved since the time of planet formation. The asteroids are bodies ranging in size up to 1000 km. Presumably, they are fragments of planetesimals that formed in the Jupiter-Mars region of the solar nebula but that were never incorporated into a planet. Comets are enigmatic bodies that range in size up to at least 50 km. They are ice-rich bodies that sublime at temperatures above 150 K, and they are unstable in the terrestrial planet region of the solar system. The most popular theory for the origin of the comets is that they are ice/dust planetismals that formed in the Uranus-Pluto region of the nebula and that have been stored in much larger orbits for most of their lifetimes.

Comets produce visible dust tails and the annual meteor showers. They are the only proven source of dust, and they are widely believed to be the major source of both dust (Whipple 1967, Millman 1972) and the larger Earth-crossing meteoroids (Wetherill 1974). When the ice in a comet sublimes, it releases dust from the nucleus and propels it outward by gas drag. The dust then forms a tail, whose shape is determined by the interplay of gravity and light pressure (Sekanina 1980). Asteroids generate particles only as a by-product of collisions. A fraction of the dust at 1 AU certainly must be debris from main-belt asteroids, but no model of this source has ever suggested that it dominates comet production.

While comets are widely accepted as the most important dust source, the details of the supply mechanism are poorly understood. Long-period ($10^6$ yr) comets produce large quantities of dust, but the particles are not trapped in bound orbits and they are lost from the solar system. Comets with highly elliptical orbits have an almost perfect balance between kinetic and potential energy when they are close to the Sun and are generating particles. When sunlight shines on a newly liberated particle, its radial force due to momentum transfer counteracts part of the Sun's gravitational pull, the total energy of the particle becomes positive, and the particle escapes the solar system on a hyperbolic path (Harwit 1963). For parabolic comets passing close to the Sun, even particles of centimeter size whose ratio of light pressure force to gravity is only $10^{-5}$ can be "blown out" of the solar system by this mechanism.

Short-period comets have orbital periods of three to tens of years, and they can directly inject dust into bound solar orbits. Unfortunately, observed short-period comets fail by at least an order of magnitude in supplying the $10^7$ g s$^{-1}$ (Whipple 1967) of dust lost in the solar system by collisions and Poynting-Robertson drag (Kresak 1976, 1980, Roser 1976). It may be that most of the dust is released from rare and highly active comets. For example, both Whipple and Kresak suggest that the now nearly devolatilized Comet Encke must have been much more active in the past and may have itself produced the bulk of dust now in the inner solar system. Because the productive lifetimes of short-period comets are probably less than $10^4$ yr, while the survival lifetimes of generated particles are more like $10^5$ yr, this generation of dust in "pulses" could still result in a rather uniform concentration of particles in the solar system in time. Leinert et al (1983) suggest that most of the particles in the dust size range are debris from short-period comets, but that they were originally released as somewhat larger particles that later fragmented as a result of collisions.

In terms of interpreting laboratory studies of collected dust samples, there are many frustrating uncertainties about the origin of interplanetary dust. While comets are probably the major source, this has not been proven, and there is not a really good estimate of the ratio of asteroidal to cometary particles in the near-Earth environment. If comets are the major source, it is not known whether most particles originate from a single comet or thousands of comets. The nature and number of parents as well as the importance of collisions in dust evolution can fortunately be directly studied by laboratory analyses of collected samples. It is hoped that sample studies, combined with future data from spacecraft missions to comets, will shed new light on these problems.

## COLLECTION IN SPACE

Space would seemingly be the ideal environment for collection of cosmic dust. Space collection does offer some unique opportunities, but as a general technique it is limited because of low collection rates and high collection velocities. The impact rate of 10 $\mu$m and larger particles on an Earth satellite is only 1 $m^{-2}$ $day^{-1}$, and the typical impact velocity is probably $\sim$15 km $s^{-1}$. The lowest impact velocity possible is $\sim$3 km $s^{-1}$. This occurs when a particle approaches at the minimum velocity (escape velocity) and impacts the trailing end of the spacecraft on a trajectory that is parallel to the spacecraft orbit. At all of these velocities, however, the kinetic energy of the particle is higher than its binding energy, and the particle is largely destroyed upon "collection."

In the future it may be possible to nondestructively collect micrometeoroids in space by use of a gradual deceleration technique. At the present time the only practical method for collecting material is by approaches that essentially destroy most of the structural and chemical information in the particles but that retain valuable information on its elemental and isotopic composition. One technique is to have the particle impact onto an appropriate solid surface that favors retention of residue in the bottoms of hypervelocity impact craters formed in it. Simulation experiments and experience with microcraters on lunar samples indicate that silicates and probably most brittle materials are very poor substrates, but gold, aluminum, and probably other soft metals appear to be fairly effective because they couple the meteoroid's energy into the target without either vaporizing the sample or otherwise ejecting it from the crater. The first undisputed crater collection of this type was from a Hemenway et al (1967) experiment on *Gemini 10* where craters were collected in stainless steel. Residue found in several craters in more recent experiments has a composition that suggests an origin as high-velocity spacecraft or rocket debris (Clanton et al 1980). The only clear case of extraterrestrial material as residue in a crater was the residue with unfractionated chondritic elemental abundances in a 100 $\mu$m crater in aluminum exposed on *Skylab* (Brownlee et al 1974). The crater residue technique for collection in space works well with the correct collection substrate, and it will undoubtedly be used for future experiments.

The other space collection technique uses capture cells. This concept was invented by Herbert Zook at the NASA Johnson Space Center, and it is essentially an adaptation of the Whipple "meteor bumper" designed to shield spacecraft from destructive impacts. In a capture cell a meteoroid penetrates a thin diaphragm, which causes the meteoroid to vaporize. The vapor then condenses on the enclosed volume beneath the diaphragm. In theory, all condensable vapors are trapped in the cell and then can be later analyzed either by dissolving the sample out of the cell or by studying it in place with surface techniques like the ion microprobe. The first successful flight of a capture cell was made on a recent space shuttle flight (McDonnell et al 1984), and several capture cells, as well as crater collection experiments, are presently being exposed for a year on the *LDEF* satellite. Simulation studies by Zinner et al (1983b) indicate that high-quality isotopic measurements for selected elements can be made with the capture cell approach.

Space collections can at minimum determine the elemental compositions of individual particles in sizes up to $\sim 100$ $\mu$m and can provide some precise isotopic measurements. Space collections serve several unique purposes, one of which results from the fact that space collections are totally unbiased: all meteoroids are collected with equal efficiency. An additional advantage of space collections is that, in principle, they can be used to collect particles from known sources. A capture cell experiment to be flown on *Salyut* by Bibring et al (1983) will attempt to capture small particles from meteor showers by exposing the collector at the times of annual cometary meteor showers. The most convincing experiment along this line would precisely measure the velocity and impact direction of each particle, so that samples could be absolutely tied to a particular source. This active collection approach could also be used to identify the rare interstellar grains that constitute a small but finite fraction of the dust complex. The most direct approach for collecting cometary particles is to send an array of capture cells and cratering substrates directly through the dust coma that surrounds a cometary nucleus and return it to Earth. This type of mission, using a low-cost spacecraft launched on a free Earth return trajectory, was discussed by Tsou et al (1984).

## ATMOSPHERIC ENTRY

All particles entering the atmosphere have kinetic energies sufficient to cause total vaporization if deceleration occurs on a short enough time scale. The miraculous aspect of dust interaction with the atmosphere is that the deceleration from hypervelocity is gentle and allows particles not only to be slowed without severe heating, but also to be slowed without severe mechanical stress.

Particles with bound solar orbits enter the atmosphere with velocities ranging from the escape velocity of 11.2 km $s^{-1}$ to the 72.8 km $s^{-1}$ velocity of a head-on impact with a body on a parabolic orbit. Observations of radio meteors show that 0.1–1.0 mm dust particles enter with typical velocities only a few kilometers per second above the escape velocity (Southworth & Sekanina 1979). These low entry velocities are due, in part, to orbit circularization by Poynting-Robertson drag (Dohnanyi 1978). Micron-sized and smaller particles may have much higher entry velocities as a result of light pressure effects at the time of particle generation (Zook & Berg 1975).

The entry of dust into the atmosphere differs significantly from the entry of the larger meteoroids that produce conventional meteorites. The airflow around centimeter-sized and larger bodies is complicated by the development of gas caps on their leading edges, while for smaller objects the interaction is free molecular flow. Air molecules simply impact the particle, with no aerodynamic effects before impact (Öpik 1958). If we assume that each impacting air molecule transfers all of its relative momentum to the particle, then the velocity of the decelerating meteoroid is given by

$$V = V_0 \, e^{-m'/m},$$

where $V_0$ is the initial velocity, $m$ is the mass of the particle, and $m'$ is the mass of the air column that has been encountered by the cross-sectional area of the particle. A particle can usually be considered to have been decelerated from its cosmic velocity after it encounters an air column equal to twice the particle mass. As can be seen in Figure 1, the high-velocity interaction with the atmosphere for dust occurs exclusively at altitudes above 70 km, while larger objects retain high velocities down to atmospheric levels below 40 km. For free molecular flow, the dynamic ram pressure on a meteoroid with unity accommodation of air molecules is $\rho_a V^2$, where $\rho_a$ is the ambient air density. Dust loses its high velocity before it reaches dense air, and accordingly it is not subjected to high dynamic

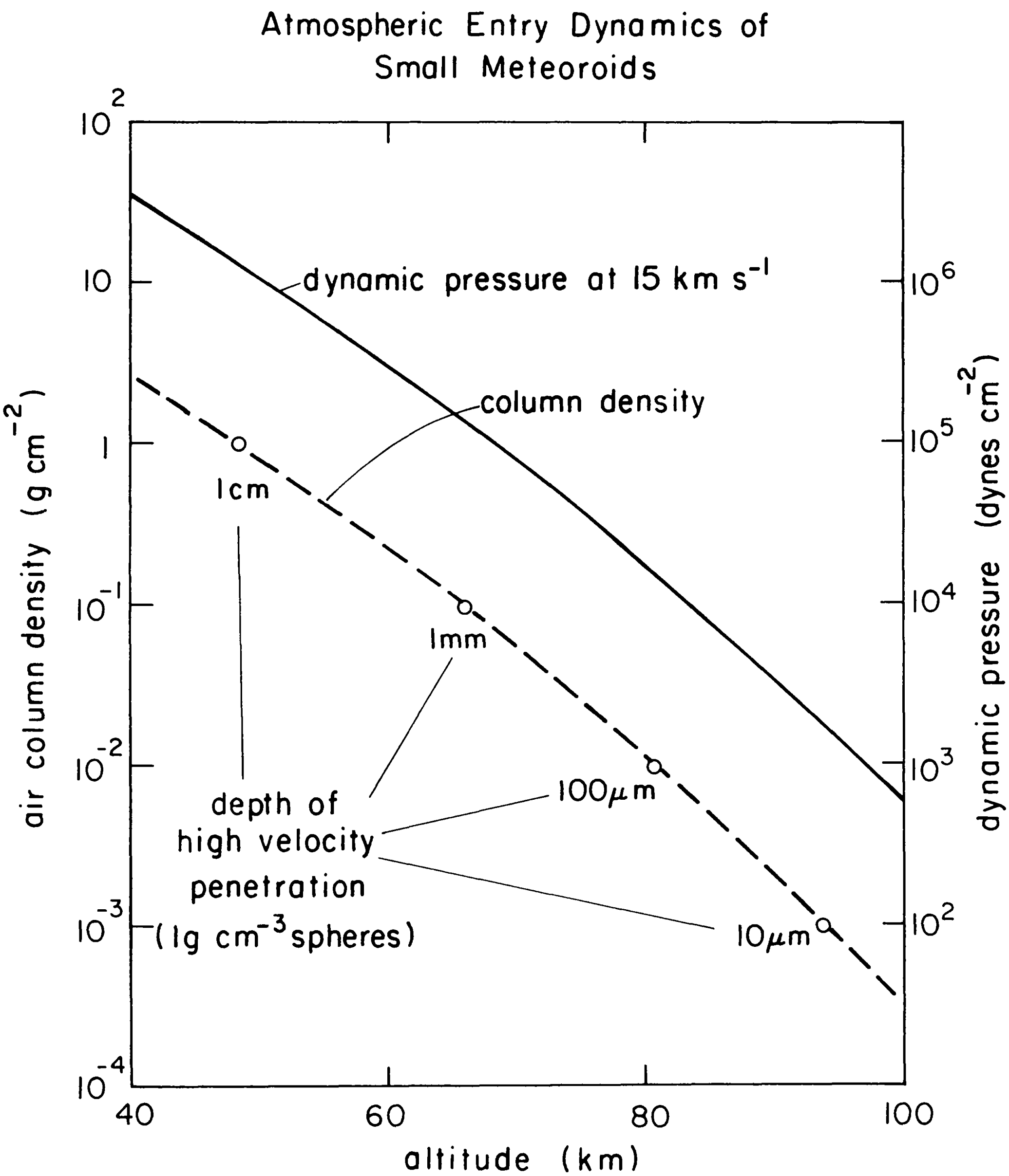


*Figure 1* The depth of penetration of normal incidence spherical meteoroids into the atmosphere, under the assumption of no mass loss. The dynamic ram pressure is shown for 15 km $s^{-1}$ travel at the various altitudes.

pressures. As can be seen in Figure 1, entering dust particles are not subjected to mechanical stress above $10^4$ dyn cm$^{-2}$ ($\sim$0.15 lb in$^{-2}$). This is the fundamental reason why dust is an important resource of primitive meteoritic material. Fragile materials with crushing strengths of only $10^2$ dyn cm$^{-2}$ can survive entry as dust, while only strong rocks can survive as pieces large enough to be found as conventional meteorites. This selection effect prevents typical cometary meteoroids from becoming meteorites. Meteor studies show that most bodies with cometary orbits fragment when the ram pressure exceeds $2 \times 10^4$ dyn cm$^{-2}$ (Verniani 1969). Wetherill & ReVelle (1982) have shown that uncommon cometary meteoroids survive atmospheric stresses of $\sim 10^7$ dyn cm$^{-2}$ and may be as strong as the weakest recovered meteorites.

Although rare and unusual cometary meteoroids may have survived to become meteorites, it is clear that the bulk of cometary materials can only survive in the form of millimeter-sized and smaller particles. As described by Verniani (1969), "Most meteors are of cometary origin and are porous crumbly objects composed of loosely conglomerate, spongelike material." Thus it appears that the only collectable samples of these objects are in the dust size regime.

Fragile materials can survive atmospheric entry in the form of dust, but they are all heated. Heating is actually more serious for dust than for conventional meteorites because dust particles are heated uniformly in their interiors and cannot have thermal gradients like in larger particles, where cool interiors coexist with molten exteriors. All dust particles are more strongly heated than the interiors of stony meteorites. Small particles decelerate at high enough altitudes that the power density generated by collision with air molecules can be matched by thermal radiation without the particle reaching its melting point ($\sim$1300°C for chondrites). Particles that do not melt are called "micrometeorites," a term coined by F. L. Whipple, who developed the theory of their survival (Whipple 1951). The temperature of an entering particle is given by

$$T = [\rho_a V^3/8\sigma\varepsilon]^{1/4},$$

where $\sigma$ is the Stefan-Boltzmann constant and $\varepsilon$ is the emissivity. The "maximum" diameter of a micrometeorite is usually considered to be $\sim$100 $\mu$m, but survival without melting is highly dependent on the particle density, the melting point, and the velocity and angle of entry into the atmosphere (Figure 2). Factors that favor survival are low density, high melting point, low entry velocity, and low entry angle. The "trick" for atmospheric entry without strong heating is to dissipate kinetic energy at high altitudes, where the power density input ($\frac{1}{2}\rho_a V^3$) is small. Particles as large as a millimeter can survive as micrometeorites if they enter at grazing incidence into the atmosphere; at the other extreme, metallic iron particles of 1 $\mu$m diameter will melt if they enter at a velocity of 70 km $s^{-1}$ and vertical incidence. Because of uncertainty in entry angle and velocity, it is not possible to predict what maximum temperature was experienced for any single collected particle. Fraundorf (1980) and Fraundorf et al (1982c) have calculated that the typical 10 $\mu$m diameter micrometeorites that are collected in the stratosphere are heated to temperatures of 500–800°C. Typical heating time scales are 5–15 s. For the stratospheric micrometeorites (< 50 $\mu$m) that have been collected, less than 5% of the particles with chondritic elemental composition melted to form spheres. In contrast, more than 90% of the extraterrestrial particles larger than 200 $\mu$m that have been collected in ocean sediments are spheres. The ocean collection technique is, however, biased toward melted materials. As a general rule of thumb, it appears that typical particles smaller than 50 $\mu$m do not melt, while those larger than 100 $\mu$m do.

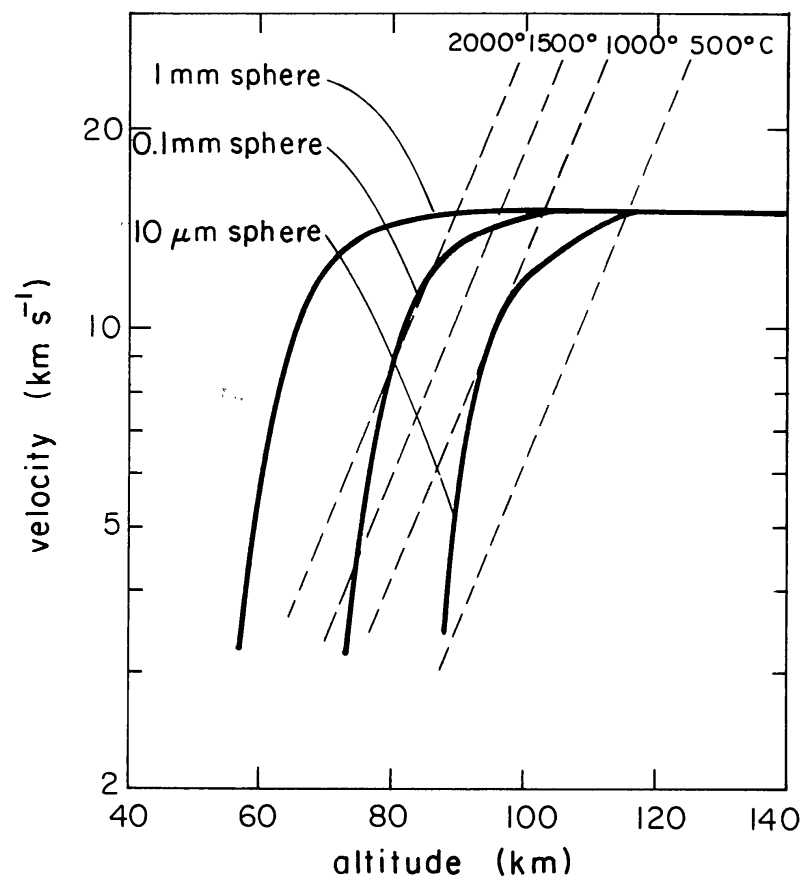


*Figure 2* The deceleration of 3 g $cm^{-3}$ nonablating spheres entering the atmosphere at normal incidence. The isotherms are calculated for perfect blackbody radiators.

An important consideration of atmospheric entry is whether survival is biased toward particles from particular sources. For a given size there is a strong bias against particles with high entry velocities. With only a few exceptions, visual meteors ($>1$ mm diameter) in the annual cometary showers have high entry velocities, and it would appear that atmospheric survival might favor asteroidal dust over comet dust. This, however, is probably not the case because dust particle orbits (not observable by meteor techniques) rapidly evolve as a result of light pressure effects and probably become relatively circular. This is consistent with the low entry velocities of the submillimeter particles observed as radio meteors. Orbital circularization reduces mean entry velocities for particles from parent bodies in the ecliptic plane, such as asteroids and short-period comets, but it cannot have a large effect on entry velocities for particles with high-inclination orbits. The entry process favors survival of particles from asteroids and comets with low-inclination orbits, and it is biased against particles from long-period comets and extrasolar grains.

## COLLECTION IN THE TERRESTRIAL ENVIRONMENT

Roughly $10^4$ tons of interplanetary dust impact the atmosphere each year. The flux of 10 $\mu$m particles is $\sim 1\ m^{-2}\ day^{-1}$, and that of 100 $\mu$m particles is $\sim 1\ m^{-2}\ yr^{-1}$ (McDonnell et al 1984, McDonnell 1978). Particles can be collected on land, from the ocean floor, and from the stratosphere. It may not be practical to collect large masses of dust, but it is feasible to collect millions of particles in the 10 $\mu$m to 1 mm size range.

### *Stratosphere*

The most pristine dust particles are collected in the stratosphere. Collectable stratospheric particles are generally limited to the 2–50 $\mu$m diameter range because larger particles are too rare and smaller ones are swamped by the enormous background of submicron sulfate aerosol. Stratospheric particles of proven extraterrestrial origin were first collected in 1970 using a balloon-borne collector called the Vacuum Monster (Brownlee et al 1973, Brownlee & Hodge 1973). Successful collections using NASA U2 aircraft began in 1974 (Brownlee et al 1977), and at the present time routine collection and curation of particles for distribution to interested researchers is performed by the NASA Johnson Space Center in Houston, Texas (Clanton et al 1982).

In the stratosphere, 10-$\mu$m particles fall at a velocity of $\sim 1$ cm $s^{-1}$ (Kasten 1968), a reduction of $10^6$ from their velocity in space. Because flux is conserved, the concentration of 10-$\mu$m particles in the stratosphere is enhanced by a factor of $10^6$ over the space value. The atmospheric density of 10 $\mu$m particles (Brownlee et al 1976) is $3 \times 10^{-4}$ $m^{-3}$, and it is just barely possible to collect significant numbers of particles by high-volume air sampling onto very clean collection substrates. All collections have been made by inertial impaction of particles from a $>200$ m $s^{-1}$ airstream onto clean plastic surfaces coated with several microns of a tarlike silicone oil. After collection, particles are individually picked off of collection surfaces and washed for analysis.

Stratospheric collections have been very successful, but future improvements are certainly possible. Collection with larger impactors would gather more of the rare large particles and would provide a greatly improved capability for sampling debris from events such as large meteors or showers. The mass increase in most showers is only minor (Erickson 1969), but it should be possible to collect material from the extraordinary showers that occur every few decades. To preserve the temporal signature of such events, it is necessary to collect large particles because their fall times to collection altitudes are short. Very high altitude collections ($>40$ km) may rise above the sulfate aerosol and allow collection of submicron extraterrestrial material. A particularly interesting possibility is the collection of small condensates from the fraction of the meteoroid complex that vaporizes in the atmosphere (Hunten et al 1980).

### *Deep-Sea Sediments*

It is not really practical to collect particles larger than 100 $\mu$m in the atmosphere because of their low flux and high fall speed. It is quite simple, however, to collect such particles from deep-sea sediments, where low accumulation rates and long exposure times allow particles to collect in significantly greater concentrations than in any other terrestrial environment. For common Pacific red clay with accumulation rates of $2 \times 10^{-6}$ m $yr^{-1}$, the total concentration of extraterrestrial material should be on the order of several parts per million by weight. At least 20 ppb of this material is recoverable in the form of spheres larger than 200 $\mu$m (Murrell et al 1980). Because of the size range sampled, of weathering problems, and of collection biases, most particles recovered from sediments are spheres in the 50 $\mu$m to 2 mm size range that formed by melting of particles too large to survive as micrometeorites. Totally unmelted particles up to a millimeter in diameter are rare in comparison with spheres, but they can be collected in large numbers (Brownlee et al 1980).

The majority of particles larger than 100 $\mu$m are ferromagnetic because of magnetite formation during atmospheric entry. Particles that melt usually crystallize to form spheres composed of olivine, magnetite, and glass, a material very similar to the fusion crusts of chondritic meteorites

(Blanchard et al 1980, Brownlee et al 1975). Large terrestrial magnetic spheres are rare in deep abyssal sediments far from continents and islands, and meteoric spheres can easily be collected with simple magnets. Spheres were first collected over a century ago by running a hand magnet through recovered abyssal clays (Murray & Renard 1891). Large-scale recovery of spheres from tons of recovered sediment was made by Millard & Finkelman (1970); spheres were also collected directly from the seafloor by use of towed sleds or rakes (Bruun et al 1955, Brownlee et al 1979). A remarkable collection effort by Finkelman (1972) showed that the denser iron-type spheres are concentrated in manganese nodules by factors of more than a hundred above that in the surrounding sediment.

Deep-sea collections have been reviewed by Petterson & Fredriksson (1957), Hodge (1981), Parkin & Tilles (1968), and Brownlee (1981). Approximately a million cosmic spheres have been collected from the ocean floor, and they are perhaps the least biased collection of interplanetary material, because once materials melt and form spheres, structural properties for atmospheric survival become equalized. All deep-sea particles were strongly heated during atmospheric entry, and they are exposed to chemical alteration in the sediments for typical time scales that are much longer than the few-thousand-year time scale for weathering of stony meteorites on land. Spheres are affected by heating, but they are changed in predictable ways; fortunately, weathering on the frigid ocean floor is simple and quite slow. The oldest recovered stony spheres are 50 Myr old, and all that remains is magnetite and the iron-rich rims of olivine grains. Typical younger stony spheres have an unaltered core surrounded by a rim where glass has been dissolved out, and sometimes the Mg-rich cores of olivine grains are also attacked. It is likely that the spheres survive in recognizable forms even in the oldest seafloor sediments.

### *Surface Collections*

It is possible to collect extraterrestrial dust on the surface of the Earth, although it is much more difficult than in deep-sea sediments because the concentration is much lower and the abundance of terrestrial magnetic particles is high. Particles are collectable in polar ices (Wagstaff & King 1981) and also in much more complicated "contamination" environments, such as beach sands (Marvin & Einaudi 1967) and even desert soil (Fredriksson & Gowdy 1963). Surface collections are valuable in that they may provide material from specific sources, such as the Tunguska event as reported by Zbik (1984) and Ganapathy (1983). Correlation of particles with events might be done by taking particles from specific areas, from dated cores, or from material eroding out of specific units (such as was the source of the beach sand deposit studied by Marvin & Einaudi).

# PARTICLE TYPES

Particles collected in the stratosphere are well preserved but small, whereas those collected from deep-sea sediments are large but significantly altered. It is by no means straightforward to compare particle types from both collections. If particle types from both collections can be correlated, then the deep-sea materials can provide milligram particles of materials that can be collected in the stratosphere only as nanogram samples. These large sample masses are critical for several important isotopic and trace-element analyses.

## *Deep-Sea Particles*

The obvious extraterrestrial particles in sediments are magnetic spheres. These are usually considered to be melt products of atmospheric entry, but some may have originated in space by collisions (Parkin et al 1977). Most of the collected spheres are either the iron (I) type composed of FeNi metal, magnetite, and wustite (Figure 3) or the stony type (S) composed of olivine, magnetite, and glass with approximately chondritic elemental abundances (Figure 4). The two sphere types occur with approximately equal abundance at the 300 $\mu$m size. In fairly common Pacific red clay, nearly all magnetic spheres larger than 300 $\mu$m are extraterrestrial, although some sediments do contain large numbers of spheres of terrestrial origin. It certainly cannot be assumed that typical spheres in deep-sea sediments are extraterrestrial. Fortunately, the cosmic spheres have distinctive properties, and they can usually be absolutely identified when examined in polished section in a scanning electron microscope (SEM). The extraterrestrial origin for the spheres was first proposed in 1876 by Sir J. Murray because the I spheres had metallic iron cores with no obvious terrestrial origin. A large amount of supportive evidence implies that both the type I and S spheres are extraterrestrial. This evidence includes the occurrence of wustite in the I spheres (Marvin & Einaudi 1967), major- and trace-element composition for the S spheres (Ganapathy et al 1978), high $^{87}Sr/^{86}Sr$ ratios (Papanastassiou et al 1983), and oxygen isotopic composition (Mayeda et al 1983). Perhaps the most conclusive evidence has been the detection of the cosmogenic isotopes $^{53}Mn$ (Nishiizumi 1983) and $^{26}Al$ and $^{10}Be$ (Raisbeck et al 1983) that imply space exposure of on the order of $10^6$ yr. Shimamura et al (1977) also reported anomalous potassium isotopic ratios that they attributed to cosmic-ray spallation.

The iron spheres are composed of magnetite and wustite that commonly enclose either a small metallic FeNi core or a smaller nugget of platinum group elements (Brownlee et al 1984). The spheres with FeNi cores are in an intermediate state of oxidation, while those with the Pt nuggets are nearly completely oxidized, with all platinum group elements concentrated into a bead only a few percent the size of the entire sphere. When the initially pure molten metal particle begins to oxidize, Ni and other siderophiles concentrate in the remaining metal phase. Spheres with FeNi metal cores often have Ni/Fe ratios in the metal that are much higher than the chondritic ratio. With nearly complete oxidation, Ni goes into the oxide, leaving only a nugget of platinum group elements whose diameter is only a few percent of the size of the entire sphere. The elemental composition of most of the nuggets matches chondritic abundances for the platinum group elements, with some depletion of the more volatile ones.

The iron spheres may have been derived from original metal in meteoroids, or they may have formed by reduction from fine-grained, carbon-rich meteoroids pulse heated at the top of the atmosphere. Certainly some, if not most, of the iron spheres form by reduction followed by inertial separation of stony and metallic phases (Brownlee et al 1983). This process explains why most stony spheres are depleted in Ni (and Cr),

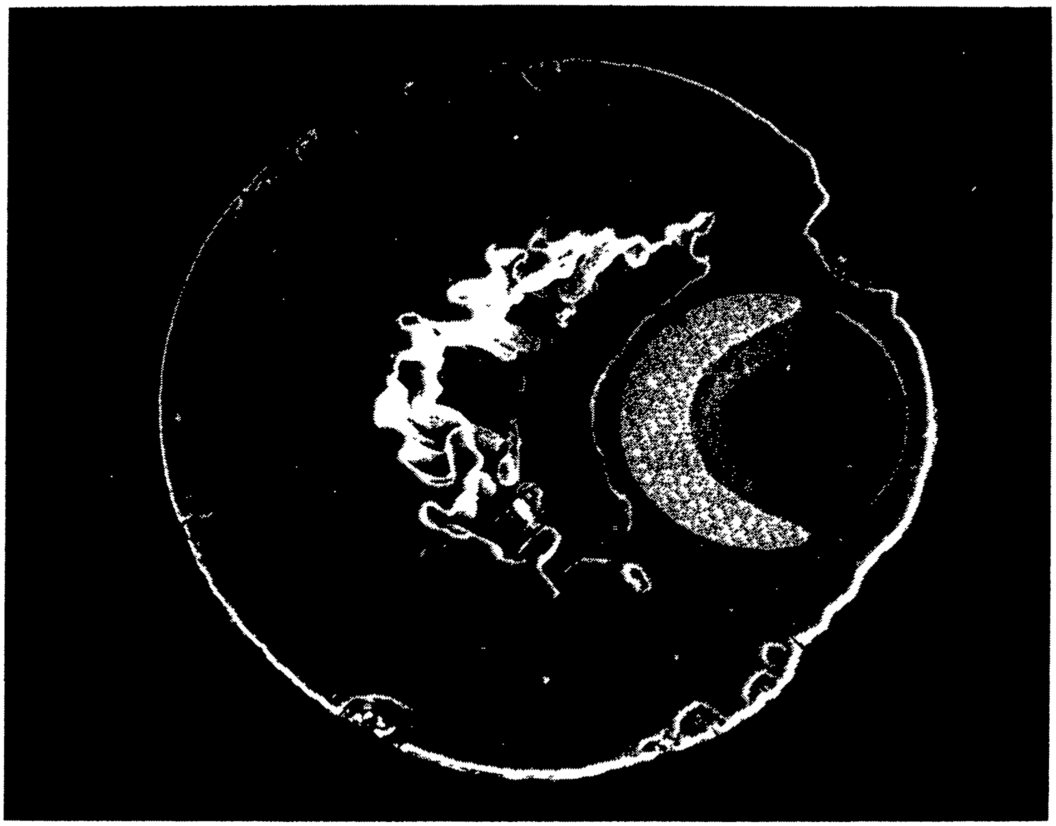

*Figure 3* An "iron" cosmic deep-sea sphere 250 μm in diameter. The bulk of the particle is magnetite and wustite. The crystal-lined central vug is fairly common in the smaller spheres. The off-center core is metal and contains most of the nickel in the sphere. The interior of the core has been altered by weathering.

why I and S spheres are found in similar abundance, and why the $^{53}Mn$ (a lithopile) is depleted in the iron cosmic spheres relative to the stony ones (Nishiizumi 1983).

The stony spheres are composed almost exclusively of olivine, magnetite, and glass. They most commonly have barred textures and less frequently have porphyritic textures. Rare spheres contain a NiFe metal bead at one end or two beads at opposite ends of a prolate spheroid. Some spheres contain troilite spheroids or relict mineral grains [usually either forsterite, enstatite, or chromite (Blanchard et al 1980)]. Roughly 5% of the stony spheres larger than 200 $\mu$m contain relict grains, and a smaller number are essentially true unmelted micrometeorites (Brownlee et al 1980). The unmelted particles are usually composed of either forsterite, sulfide, and enstatite (with no fine-grained matrix) or forsterite, sulfide, and enstatite grains embedded in a submicron matrix with chondritic composition. The unmelted particles are best found in polished sections and can be identified by their composition.

The bulk composition of the stony spheres is chondritic, except for Na

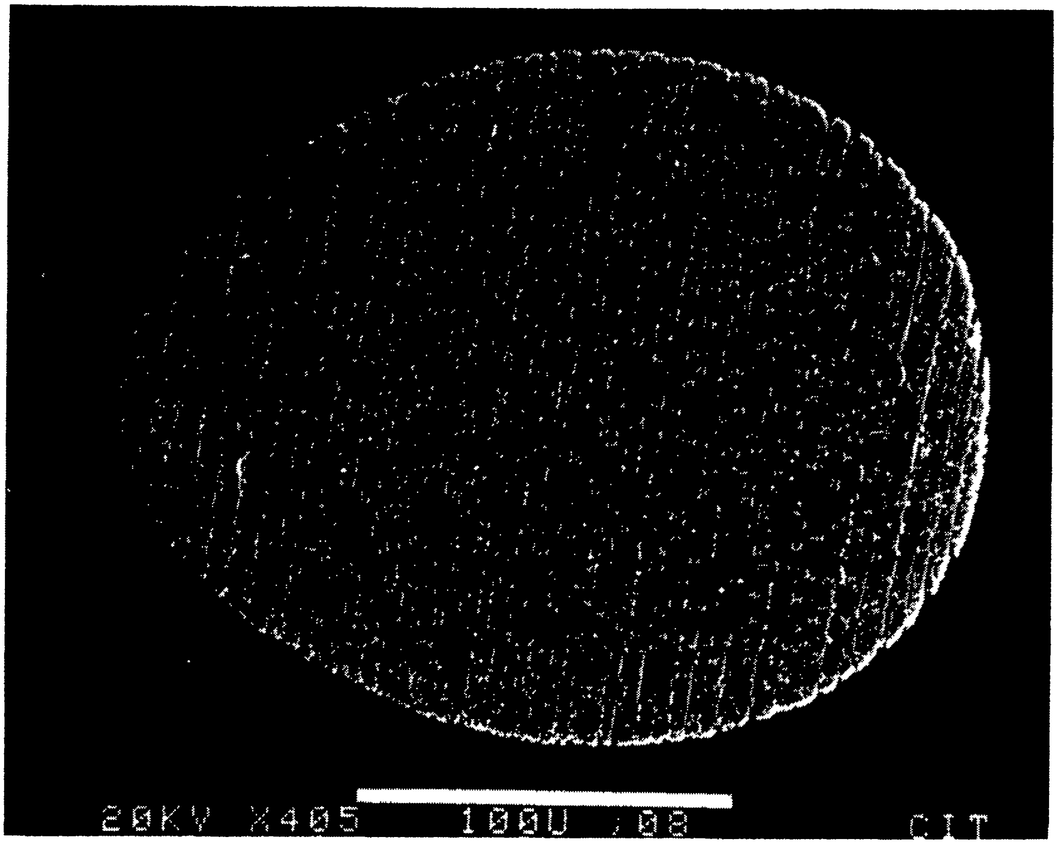


*Figure 4* A barred stony deep-sea sphere composed of olivine, magnetite, and glass. The small bright grains are magnetite. Glass has weathered out of the outer 10 $\mu$m of the particle, leaving only olivine bars and magnetite (scale bar = 100 $\mu$m).

and S (which are presumably depleted by volatilization) and Ni and Cr (which are probably partially lost by formation and ejection of a metal or sulfide droplet). In the stony spheres with a metal bead at one end, Ni is completely concentrated in the metal phase.

## *Stratospheric Particles*

Collectable stratospheric particles are usually smaller than 50 $\mu$m. On good collections when the stratosphere is not dominated by volcanic particles, extraterrestrial particles constitute roughly 30% of all irregular particles larger than 5 $\mu$m. Most extraterrestrial particles are easily identified because they have chondritic elemental abundances or contain fragments of such material. Only a relatively minor number of particles cannot be identified as having either an extraterrestrial or an obviously terrestrial origin on the basis of their elemental composition. It is very unlikely that any abundant type of micrometeorite would be overlooked in the stratosphere.

Because the stratospheric particles are small, it is difficult to classify them in ways that are both meaningful and operationally useful. Unfortunately, the most meaningful taxonomy schemes are likely to be so complex that they cannot be used on routine samples. Classification schemes have been presented by Brownlee (1978), Fraundorf et al (1982d), Brownlee et al (1982), MacKinnon et al (1982), and Kordesh et al (1983). Basically, the particles can be split into two categories: those that obviously melted (ablation spheres), and those that did not melt (micrometeorites). Simple subdivisions can be made on the basis of bulk composition, mineralogy, and structure. Relative abundances of particle types determined by bulk processing of a collection surface were reported by Zolensky et al (1984).

The ablation spheres in the stratosphere are rare and comprise less than 10% of 10-$\mu$m particles. In addition to the familiar iron and chondritic stony spheres found in deep-sea sediments, sulfide and nonchondritic silicate spheres are found in the stratosphere. The sulfide spheres are the most common type; oddly, they have never been found in deep-sea sediments, even though sulfides clearly survive weathering as relict grains in unmelted particles. It is likely that they do not occur in sizes as large as collectable deep-sea particles. The sulfide spheres are composed of magnetite and pyrrhotite and have been called FSN because they are composed of iron, sulfur, and nickel. Silicate spheres, depleted in Fe and enriched in Ca, Al, and Ti relative to chondritic abundances, have been found and are called CAT or CAS particles. Unlike the chondritic composition spheres, these are transparent. The only real evidence that the CAT or CAS spheres are extraterrestrial is the 11‰ isotopic fractionation in Mg in one such particle measured by Esat et al (1979). These spheres may be the residues of meteoroids that were so strongly heated that Fe, Si, and possibly Mg were depleted by volatilization. The final type of ablation particle is really intermediate between a micrometeorite and a true stony ablation sphere. These are the MMS (metal mound silicate) particles, composed of rounded or spheroidal silicates covered with small mounds of FeNi metal. Sometimes these occur in groups embedded in a lacy carbonaceous material. The MMS particles have been perfectly simulated by taking the most common type of chondritic micrometeorite (metal free) and flash melting them in vacuum with an electron beam. The MMS particles apparently form during atmospheric entry and dramatically illustrate the formation of metal by reduction from carbon-rich particles.

True micrometeorites can be put into two groups: those that have chondritic abundances (within a factor of 3) for the 12 most abundant elements, and those that do not. The nonchondritic particles that have been identified are most often dominated by a single mineral grain, but they also usually have some chondritic material attached to their surfaces. These grains were apparently previously embedded in fine-grained chondritic material. Many lines of evidence indicate that chondritic micrometeorites are extraterrestrial and that there is little likelihood that any particle with a truly chondritic elemental composition could be terrestrial. The strongest evidence that these dust particles are truly interplanetary is the detection of very high abundances of rare gases that almost certainly are implanted by the solar wind (Rajan et al 1977, Hudson et al 1981) and the detection of solar flare tracks (Bradley et al 1984b).

The chondritic particles are very fine grained, and there is considerable variation between samples at the submicron scale (Fraundorf 1981), which indicates the existence of several subgroups. All have very similar bulk elemental compositions. A complicating factor in interpreting these particles is that the effects of atmospheric heating are poorly understood. Infrared transmission spectroscopy (Fraundorf et al 1980, Sandford 1983) has shown that the chondritic particles fall into three groups, with infrared spectra similar to olivine, pyroxene, and hydrated silicates. Brownlee et al (1982) separated the chondritic particles into two main morphological groups discernible by SEM observation. This is a convenient (but crude) scheme that cannot be unambiguously used for all particles. One group is porous (CP, or chondritic porous) on the micron scale, and the other major group (CS) is smooth on the micron scale and yet has a chondritic composition on that same size scale. Both types are optically black. The CP particles have a classic cluster-of-grapes morphology that is distinct from all known meteoritic materials (Figure 5). The morphology is not unique, however, and is similar to many powders composed of submicron, fairly equidimensional grains. The majority of the CP particles are generally anhydrous and are composed of large numbers of mineral grains, ranging in size from ~50 Å to several microns. In the SEM, the particles appear as clusters of grains averaging ~0.3 μm in diameter. Examination in the transmission electron microscope (TEM) shows, however, that in some particles many of these submicron grains are single minerals, while in others most of the grains are composed of enormous numbers of much smaller crystals embedded in amorphous material. Most of the particles contain significant amounts of amorphous carbonaceous material and possibly amorphous silicates as well.

The major minerals larger than a micron are enstatite, olivine, and pyrrhotite. Less-abundant phases are pentlandite, NiFe carbide, diopside, albite, kamacite, magnetite, chromite, Ca carbonate, and Mg and Ca phosphate. The elemental composition of the CP particles is similar to CI meteorites, including carbon, but the mineralogy and texture of the particles are distinctly different from those of any classified meteorite. The

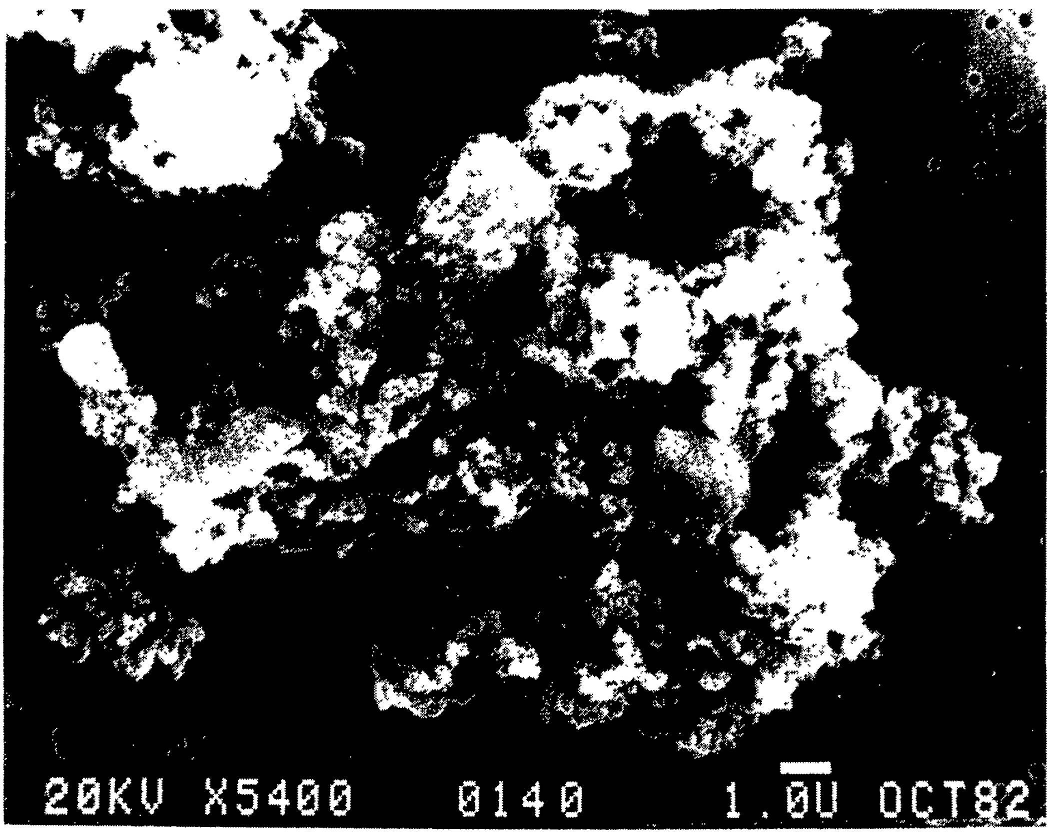


*Figure 5* A porous chondritic composition (CP) particle that is an aggregate of a large number of submicron grains. This particle is unlike established meteorite groups and is a new type of chondritic material. Of all extraterrestrial materials, this particle type most commonly matches the physical properties of cometary meteoroids.

measured densities range from 0.7 to 2.2 g $cm^{-3}$ and the CP particles are also far more porous than any conventional meteorite (Fraundorf et al 1982b). Rare particles crush on collection and cover areas as large as 300 $\mu$m with fine-grained debris. It is possible that these unusual chondritic particles had densities $\ll 1$ g $cm^{-3}$ before collection. The CP particles are apparently a new type of carbonaceous chondrite that has no analog in conventional meteorites. They are the first known case of anhydrous, carbon-rich chondrites. MacKinnon & Rietmeijer (1983), however, indicate that at least one particle in this class does contain hydrated phases.

The CS particles (Figure 6) have smooth regions that have chondritic compositions, and when viewed in the SEM they do not look like porous aggregates of rather equidimensional grains. Smooth areas must be "matrix" and not simply large mineral grains. Some of the CS particles are depleted in Ca, and some have been shown to be composed of hydrated silicates (Tomeoka & Buseck 1984, Sandford 1984). Morphologically, the

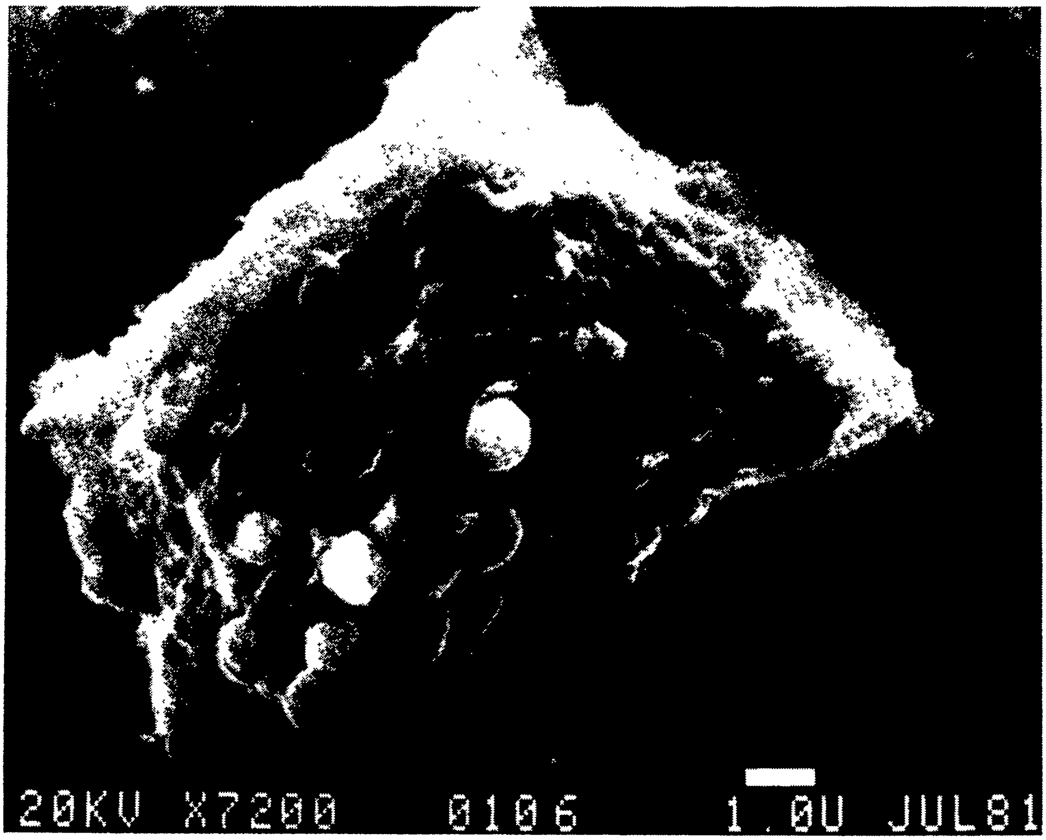


*Figure 6* A smooth chondritic (CS) stratospheric meteorite that is composed of hydrated silicates. The 1-$\mu$m grains in the front of the particle are magnetite occurring in a cluster characteristic of CI chondrites. This particle is probably CI material.

CS particles are similar to fragments of the phyllosilicate matrix of CI and CM meteorites.

The most common nonchondritic micrometeorites are pyrrhotite, enstatite, forsterite, kamacite, phosphate, and carbonate, in approximate order of abundance. To be positively identified as extraterrestrial, these particles usually must be associated with chondritic material. This is probably not a serious selection effect, because a large proportion of particles suspected of being extraterrestrial on mineralogical grounds do have coatings of fine-grained chondritic material. The black chondritic surface material varies from isolated patches to heavy encrustations. Encrusted particles sometimes appear to be chondritic aggregate particles that significantly deviate from chondritic composition. Nearly all of the nonchondritic particles appear to be simply large mineral grains or clumps of large grains that were previously embedded in CP or CS material. If collisional evolution is important in the meteoritic complex, then these comparatively strong particles may be overabundant in the interplanetary medium in relation to their abundance inside the original parent bodies.

## ANALYSIS IMPLICATIONS

### *Parent Materials*

Almost all of the dust particles that have been analyzed appear to be samples of primitive solar system material. The bulk of the stratospheric micrometeorites are extremely fine-grained chondritic materials whose only possible meteoritic analogs are CIs and CMs. The fine-grained material in deep-sea particles is not preserved, but the bulk compositions and minerals of large relict grains provide powerful constraints on the parent meteoroids. Analysis of the major refractory elements (Mg, Ca, Al, and Ti) in hundreds of stony spheres show that $\sim 85\%$ of the spheres have abundances that match CI/CM values and are distinct from other types of meteorites. The abundances of these elements are not changed during entry or in the seafloor for unweathered material, and they are very diagnostic of the parent material. Analysis of minor-element abundances in forsterite relict grains match CM forsterite and are distinct from measurements of other terrestrial and extraterrestrial materials (Smith et al 1984). Abundant evidence indicates that the great majority of interplanetary dust is compositionally similar to CM and CI meteorites. This frequency is dramatically different from normal meteorites, where less than 3% of falls are CI or CM meteorites (Wasson 1974), the only true carbon-rich chondrites. Either the composition of the meteoroids is size dependent, or else conventional meteorites are a very poor sampling of the meteoroid complex.

The elemental abundances of most analyzed dust samples are similar to CI and CM chondrites, but this does not imply an origin from CI and CM parent bodies. Certainly, some of the dust particles must come from the same sources as CI and CM meteorites, but other parent bodies appear to be represented as well. Some of the hydrated stratospheric particles could be CI or CM material, as could some of the unmelted deep-sea particles composed of mafic grains and sulfides embedded in a fine-grained chondrite matrix. The oxygen isotopic composition of the stony spheres is compatible with the CM anhydrous component (Mayeda et al 1983). The previously mentioned minor-element abundances in forsterite are consistent with a CM origin, as are the high Cr contents in metal spheres found in some forsterite grains. It is difficult to reliably identify particles as genuine CI or CM material unless they contain unique features, such as the distinctive forsterite grains or magnetite framboids. Future work, both on the meteorites and the dust, should provide a good estimate of the fraction of the dust complex that is actually conventional carbonaceous chondrite material. Evidence that not all of the hydrated particles are actually related to known meteorites comes from the TEM work of Tomeoka & Buseck (1984). They identified the dominant hydrated phase in one particle as Mg smectite. The major hydrated phase in carbonaceous chondrites is serpentine, and smectite has not been previously identified in meteorites.

The anhydrous CP particles are aggregates of submicron grains, and they are clearly a type of material that has not been seen in meteorites. A simple and fundamental distinction is that the elemental abundances of the particles match the bulk CI value, and yet no fine-grained material in meteorites has chondritic composition on the size scale of the stratospheric particles. Chondrites, by definition, have bulk chondritic composition for major and minor elements, but the submicron matrix regions of all major groups of carbonaceous and unequilibrated chondrites have significant deviations from the bulk composition. In the case of the CI and CM meteorites, these deviations have been attributed to element redistribution by aqueous alteration (McSween 1979). Redistribution in all of the meteorites is likely the result of processes that occurred inside the parent bodies. This implies that the stratospheric particles may be the least altered solar system material.

Other unique properties of the CP particles also suggest that they are truly well-preserved materials. The occurrence of epsilon iron carbide and enstatite crystals with unusual growth habits suggests that some original solids that formed from the vapor phase have survived. Epsilon nickel-iron carbide has been identified by Christoffersen & Buseck (1983) and Bradley et al (1984a) using TEM techniques. It occurs in association with metal, magnetite, amorphous carbon, and (rarely) graphite. This phase had not been previously reported in natural systems, but it has been produced in laboratories by catalytic reactions involving carbon monoxide and grain surfaces. It is also considered a low-temperature phase.

Most of the particles also contain minor amounts of enstatite, which occurs either in the form of rods (whiskers), ribbons, or platelets. Some of the rods have axial screw dislocations, and the ribbons and platelets are flattened, or extended, along axes not consistent with cleavage, parting, or crystallization from a melt. The observed forms and growth habits are consistent with whisker and platelet growth from vapor (Bradley et al 1983). The survival of these fragile crystals suggests that many other vapor phase products may have also survived in the CP particles. One intriguing mystery is why the particles contain no metal. For common pressures discussed for the solar nebula, iron condenses at the same temperature as enstatite. The survival of thin enstatite platelets implies that the metal should have also survived without incorporation into oxidized phases, and yet the particles contain only traces of metal. If the enstatite condensed in equilibrium with solar nebula gas, then the metal condensation phase was apparently skipped. Some of the metal that did form was converted to carbide.

Some of the hydrated particles are similar to CI and CM chondrites, and like these meteorites, they may have been extensively altered by liquid water inside a parent body (Bunch & Chang 1980, McSween 1979). The porous aggregate particles are anhydrous and show no evidence of such processing. Although there is no proof, the porous anhydrous particles are probably cometary material. It is interesting to speculate that parent body alteration of this material might produce CI and CM meteorites as well as the hydrated micrometeorites.

### *Comets and Interstellar Grains*

Fifteen years ago, Fred Whipple pointed out that there was no single collected particle that could be positively identified as interplanetary dust. There are now large numbers of collected interplanetary dust particles that have been positively identified, but the original question can now be applied to comets. Comet dust is abundant in space, and there is no obvious process that could prevent this dust from surviving as micrometeorites and ablation spheres. Comet dust should be a significant and possibly a major component of the dust collections. It is not presently known how to identify cometary materials, but analysis of individual particles on future comet missions may provide important clues. Sandford (1983) has shown that the shape of the infrared silicate feature measured for Comet Kohoutek can be matched by adding spectra of the three infrared dust groups.

The CP particles most closely match the common description of cometary dust as fragile, porous particles. Actually, it is possible that the most porous CP particles could not survive in an asteroidal body because of their collisional histories. If the CP particles are representative of cometary solids, then this would indicate that comet formation included a phase of gentle aggregation of submicron grains, along with ices and carbonaceous matter. The grains in CP particles have diverse properties and are anhydrous, which implies that they never equilibrated at low temperature with solar-nebula-type gas. The porous particles are black and would presumably be very dark, even when filled with ice. A comet nucleus made of CP material would have a low albedo and would have ice and dust mixed on a very fine scale.

Some presolar interstellar materials may have been well preserved in comets, and identification of such grains is a major rationale for the analysis of cometary solids. The most direct information that might indicate a presolar origin is isotopic composition. If the aggregate particles are mixtures of preserved interstellar grains, then this is a difficult measurement because most of their constituent grains are less than a micron in size. Isotopic analysis of CP particles for Mg by Esat et al (1979) showed a hint of a nonlinear effect at the 4‰ level, but the main result was that the Mg isotopic ratios were normal in the particles at the 1% level. Recent ion microprobe measurements of hydrogen in several micrometeorites have shown that whole particles are significantly enriched in deuterium and that some portions of particles are enriched by 2500‰ (Zinner et al 1983a, Zinner & McKeegan 1984). Only a unique carbonaceous chondrite (Renazzo) contains such fractionated hydrogen. The high D/H ratios may be indicators of interstellar carbonaceous material and may be related to even higher ratios thought to be produced by ion-molecule reactions in molecular clouds. Another possible method of linking collected particles with interstellar grains is through their infrared signatures (Sandford 1984, Sandford & Walker 1984).

## *Information About the Earth*

Cosmic dust in sediments records major events in the Earth's history when large amounts of extraterrestrial material were accreted into the atmosphere. Dust particles also contain records of other terrestrial processes. Isotopic measurements by Mayeda et al (1983) have shown that the atmospheric oxygen that forms cosmic iron spheres is enriched in $^{18}O$ by 50‰. This oxygen is picked up at ~80 km, where the particles melt, and it is evidence for possible large fractionation of atmospheric oxygen at this altitude. It has recently been discovered that platinum nugget formation in these iron spheres is critically dependent on the partial pressure of oxygen in the atmosphere (Brownlee et al 1984), and the first appearance of these extraterrestrial nuggets in the geological record may provide a marker for when oxygen in the atmosphere first rose to half its present value.

## CONCLUSION

Small interplanetary particles are an important resource of primitive solar system material, because meteoroid types that are too fragile to survive atmospheric entry to become conventional meteorites can be collected in the form of dust. The most common cometary particles are almost certainly represented in the dust collections, and they may be abundant. The particles in the collections that are most likely to be cometary are black particles composed of porous aggregates of submicron grains whose bulk composition matches relative solar abundances. These particles are similar to carbon-rich chondrites in bulk elemental composition, but they differ in many significant ways, including mineralogy, morphology, and D/H ratio.

Dust studies are complicated by the small masses of available material, but it is likely that much of the important information in primitive materials is in micron and smaller grains anyway. Even if kilogram samples of some of the particle types were available, analyses would still be done at the smallest possible size scale. This is particularly true with reference to searches for presolar interstellar grains. Techniques being developed for analysis of collected dust samples are also being used for studying other extraterrestrial materials; these techniques will be very valuable for the analysis of the first comet samples that are directly collected from the nucleus of an active comet.

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