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Interplanetary dust; A new source of extraterrestrial material for laboratory studies

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Abstract—Interplanetary dust particles are short-lived interplanetary bodies with probable cometary origins. Micron-sized particles can enter the earth's atmosphere without severe thermal alteration and they can be collected with stratospheric aircraft. Analysis of 300 interplanetary dust particles recovered from the atmosphere has shown that the particles are primitive solar system material similar to C1 meteorites. Although the particles show many similarities to C1 meteorites, they differ in ways which suggest that interplanetary dust is probably a unique material unrelated to known meteorite types. It is anticipated that in the near future it will be possible to recover large numbers of interplanetary particles from the stratosphere and that they will become available as a new type of extraterrestrial material for laboratory studies.

INTRODUCTION

INTERPLANETARY DUST PARTICLES are transient solar system bodies with typical lifetimes of less than 10^5 yr. In spite of short particle lifetimes, lunar microcrater studies (Hörz *et al.*, 1975) indicate that dust particles have existed in the interplanetary medium for a major fraction of the age of the solar system. The solar system dust cloud apparently is maintained in quasi-equilibrium by fairly continuous injection of new material. It is widely believed that the major source of new particles is the disintegration of short period comets (Millman, 1972). Fortunately, micron-sized interplanetary particles can enter the earth's atmosphere without destruction and they can be collected in large numbers for laboratory analysis. Techniques for routine recovery of these particles from the stratosphere have recently been developed, and interplanetary dust can now be considered a new source of extraterrestrial material for laboratory study.

ATMOSPHERIC ENTRY

All meteoroids which enter the atmosphere receive a frictionally generated thermal pulse whose duration and amplitude is determined by the particle's physical properties and entry parameters. Essentially all entering bodies larger than $\sim 200\,\mu$m undergo partial melting and ablation during entry. Micron-sized particles, however, can enter without being heated to their melting points, and such particles are officially designated "Micrometeorites" (Whipple, 1951). The instantaneous temperature of a small entering meteoroid, not undergoing ablation, is expressed by:

$$T = \left[\frac{\rho_a V^3}{8\sigma\epsilon}\right]^{1/4},$$

where ρ_a is the ambient air density, V the particle velocity, σ the Stefan–Boltzman constant, and ϵ the emissivity. Micron-sized bodies with moderate initial velocities ($<25\,\mathrm{km\,sec^{-1}}$) can become micrometeorites because they completely decelerate from cosmic velocity at altitudes above 100 km where the air density is small. Larger bodies penetrate to deeper atmospheric depths and cannot escape partial melting and ablation.

Figure 1 shows time-temperature curves for three micrometeoroid composition types entering with what are believed to be common initial entry parameters, $15\,\mathrm{km\,sec^{-1}}$ and 45°. It is seen that with constant initial entry parameters the maximum size limit for micrometeorites is strongly dependent on composition. The upper curve corresponds to a forsterite sphere which just

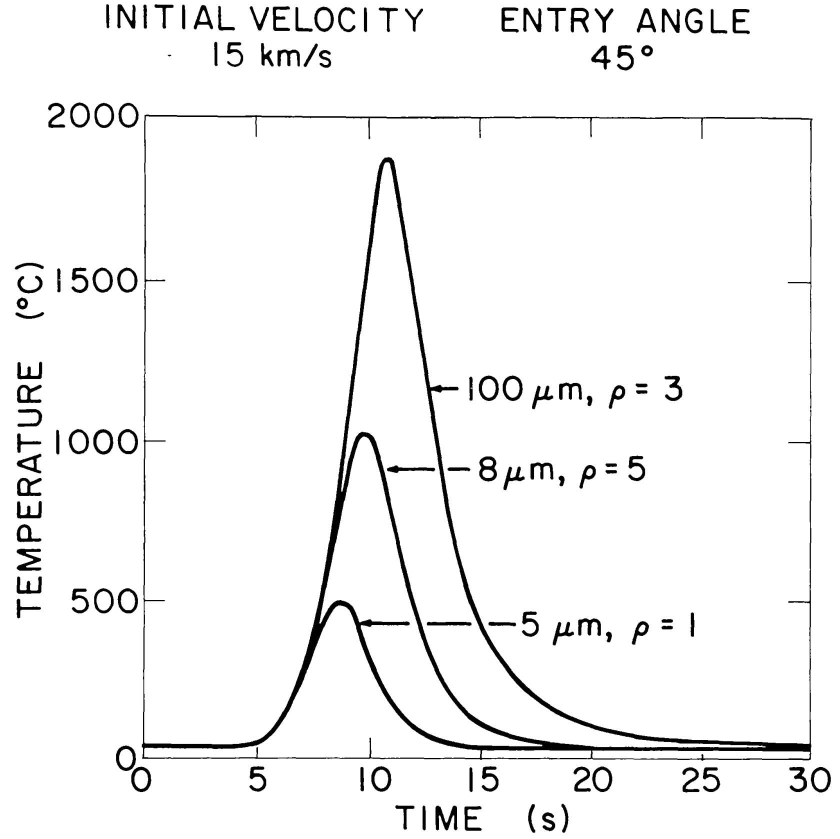

Fig. 1. Time-temperature curves for spherical micrometeoroids entering the atmosphere. The calculations assume that the only energy loss is by radiation. The curves illustrate the approximate maximum sizes for particles of forsterite ($\rho = 3$), troilite ($\rho = 5$), and porous hydrated silicates ($\rho = 1$) which can enter without melting or water loss.

reaches its melting point and the center curve corresponds to a FeS sphere nearly being heated to melting. The lower curve represents a spherical open aggregate of hydrated silicates heated to the point where it would experience rapid water loss. For each of the above cases, smaller, less dense, or irregular particles would be less strongly heated. Figure 1 demonstrates that while refractory particles as large as 100 μm or more can become micrometeorites, only particles smaller than ~15 μm can enter with only mild heating. Even very small particles can be strongly heated if their initial velocities are large.

COLLECTION

After particles decelerate from cosmic velocity they settle slowly downward with typical settling velocities, in the stratosphere, of ~1 cm sec^{-1} for 10 μm particles. In the stratosphere terrestrial contamination is not a serious problem (for sizes >2 μm) and extraterrestrial particles can be collected by relatively simple techniques (Brownlee *et al.*, 1976a). The flux of micrometeorites in the stratosphere is similar to the meteoroid flux at 1 a.u. but because of the lower velocity, the spatial density is a million times higher. High volume air sampling techniques take advantage of the high particle concentration and are very effective in collecting particles larger than ~1 μm. The fundamental principle of an air sampling collector, utilizing inertial impaction, is illustrated in Fig. 2. A simple oil coated collection plate is rammed through the ambient air at a velocity high enough so that micron-sized particles impact the collector even though

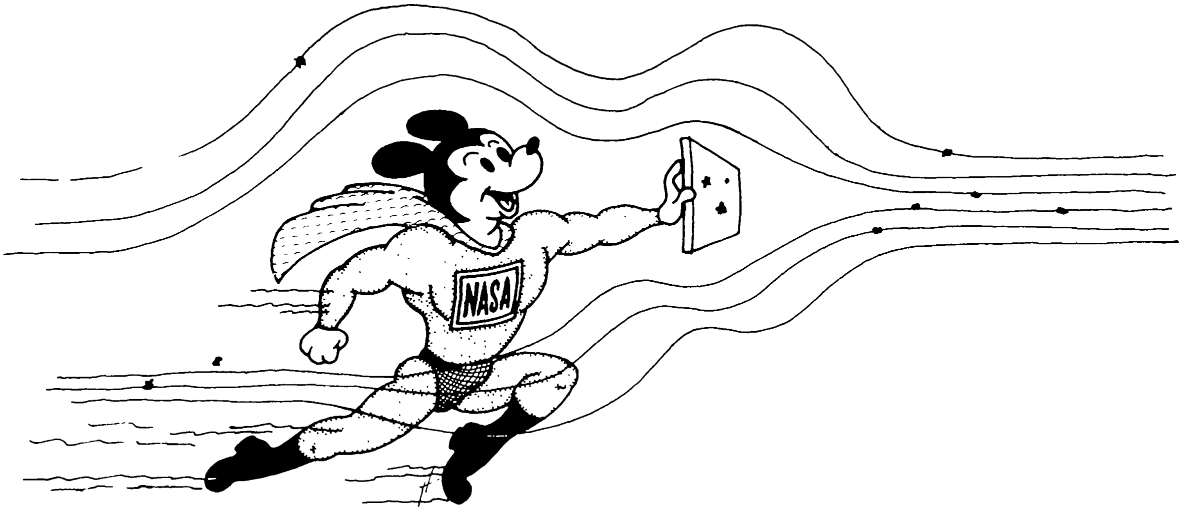

Fig. 2. An illustration of inertial impaction collection of interplanetary dust from the stratosphere. For actual collections a NASA U-2 aircraft is used to ram a 20 cm^2 oil coated collection plate through the ambient air at 20 km altitude. At the 200 m sec^{-1} cruise velocity particles >3 μm diameter cannot follow air stream lines around the collector and impact the collection plate. Smaller particles are more strongly coupled to the air flow and do not hit the collection plate.

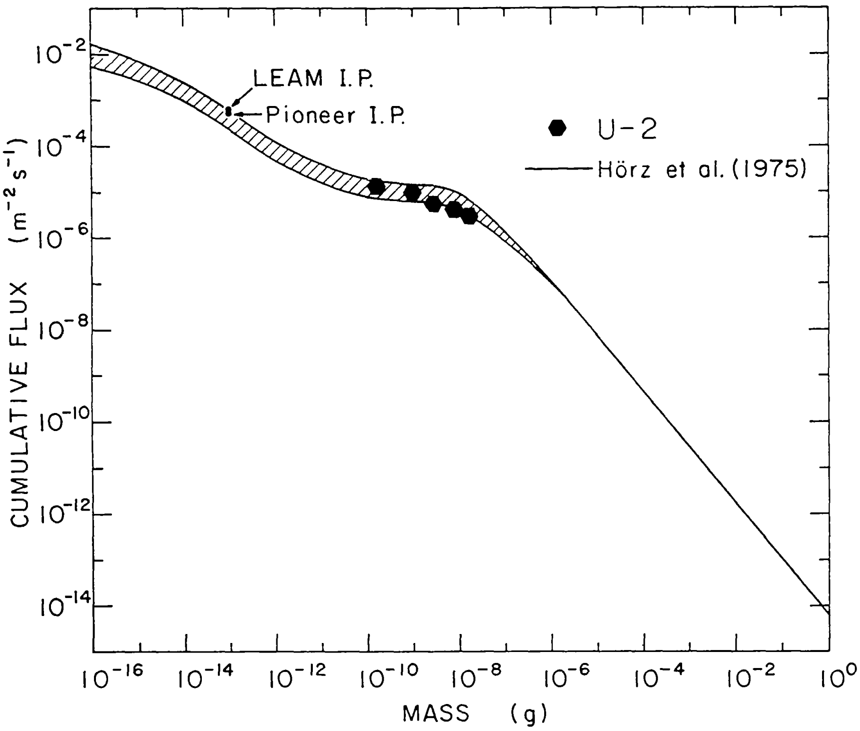

Fig. 3. The flux of stratospheric micrometeorites measured with U-2 aircraft, compared with the Hörz *et al.* compilation of space measurements of the micrometeoroid flux at 1 a.u.

smaller particles (larger area: mass ratios) and air molecules blow around it.

An inertial impaction collector, conceptually identical to Fig. 2, has been flown at 20 km with NASA U-2 aircraft for more than 200 cumulative hours (Brownlee *et al.*, 1976b,c). A 20 cm^2 acrylic collection plate is rammed through the air at the aircraft's cruise velocity of 200 m sec^{-1} giving good collection efficiency for particles larger than 2 μm diameter. Out of a total volume of air of 2.5×10^5 m^3, 300 extraterrestrial particles (> 8 μm) have been collected and analyzed. These studies indicate a density of 10 μm extraterrestrial particles in the stratosphere of $\sim 10^{-3}$ m^{-3} and a flux which is similar to the space flux at 1 a.u. (Fig. 3). The collected particles range in size from 3 to 60 μm with the typical particle analyzed being about 10 μm.

PARTICLE PROPERTIES

Of the extraterrestrial particles collected from the stratosphere only a small fraction are spheres or otherwise exhibit evidence for melting. The detection of large concentrations of solar wind ^{4}He (Fig. 4) (Rajan *et al.*, 1977) in seven of ten particles analyzed for He is strong evidence against significant heating and is confirming evidence that typical micron-sized extraterrestrial particles in the stratosphere are true micrometeorites and not ablation debris or fragments of meteors.

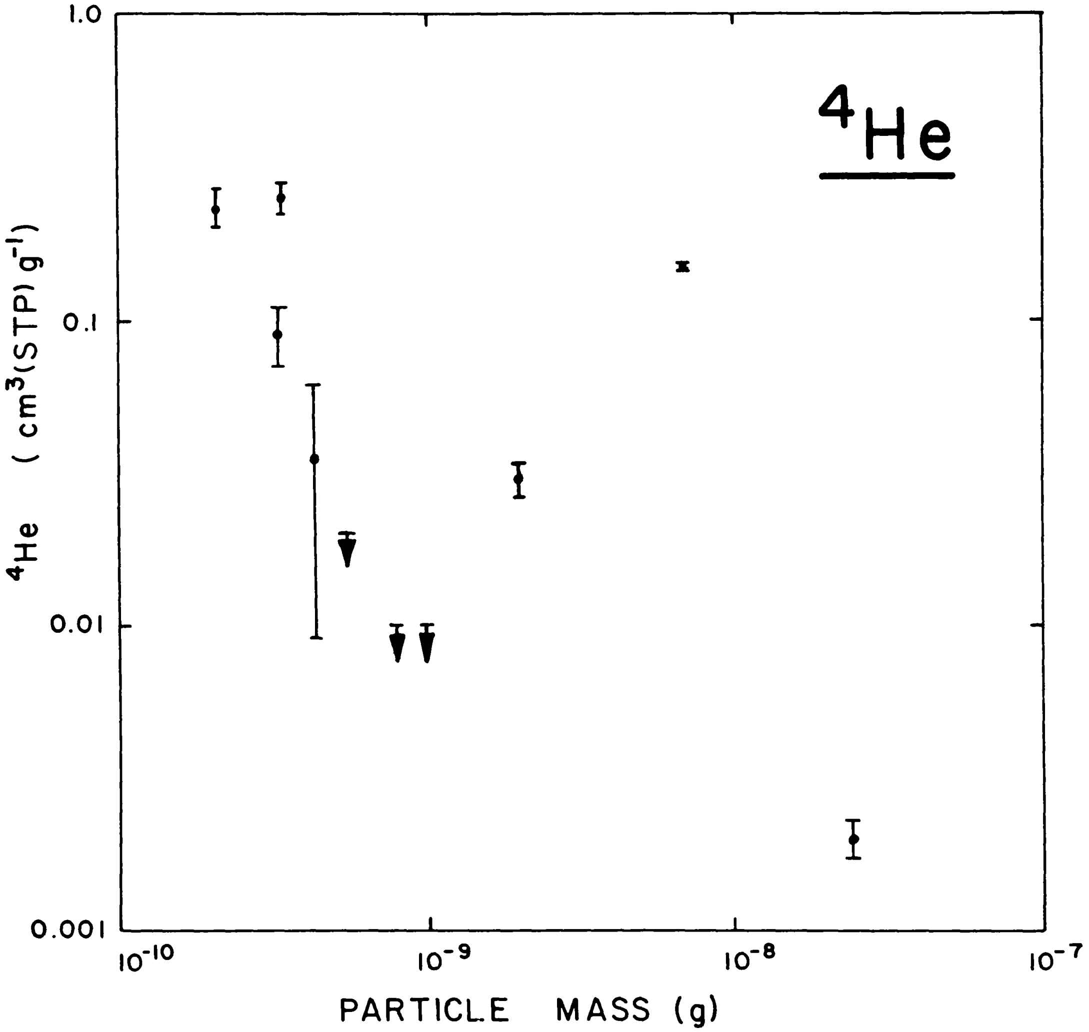

Fig. 4. Measured concentrations of ^{4}He in ten interplanetary dust particles recovered from the stratosphere (Rajan *et al.*, 1977).

Nearly all of the collected particles fall into three basic groups: chondritic, Ni-bearing iron sulfide, and iron-poor olivine and pyroxene (Brownlee *et al.*, 1976c). In the 5–10 μm size range, 60% of the particles are chondritic and 30% are sulfide. In the size range larger than 10 μm sulfides are almost non-existent, and for particles $>30\,\mu$m olivines and pyroxenes are very abundant. The compositional dependence on size for particles larger than $\sim 10\,\mu$m is probably a consequence of a filtering effect caused by the atmospheric entry process.

The majority of the interplanetary dust particles recovered from the stratosphere appear to have been produced by gentle disintegration (probably in space) of a common type of parent material. The parent material is a black aggregate of grains which range in size from ~ 10 A to microns but have typical sizes of ~ 1000 A. The aggregates have densities estimated to range from 1–2.5 g cm^{-3}, are very fragile and often fragment during collection or handling. Occasional grains of Ni-bearing pyrrhotite and Fe-poor olivine and pyroxene are found in the aggregates as particles ranging in size from <1000 A to several microns. The major mineral phase in the aggregate material is very fine grained and is tentatively identified as a poorly crystallized hydrated silicate. The elemental compositions of most of the recovered interplanetary dust particles are close to chondritic abundances.

In many ways the analyzed dust particles show strong similarities to C1 and C2 meteorites. Like the meteorites, interplanetary dust particles are unequilibrated fine grained aggregates of minerals with widely differing equilibrium condensation temperatures. The following properties of interplanetary dust imply a close similarity to C1 and C2 meteorites and distinction from most other meteorite classes: (1) very fine grained (~1000 A), (2) carbon and sulfur contents >4%, (3) contain $Fe_{1-x}S$ with >1% Ni, (4) contain iron-poor olivine and pyroxene, (5) contain magnetite, and (6) contain hydrated silicates (tentative identification). The carbon and sulfur contents of many of the collected particles indicate closest similarity to C1 meteorites (Fig. 5).

Although interplanetary dust shows strong similarities to carbonaceous chondrites, it differs in ways which suggest that it is a unique material unlike known meteorites. In Fig. 5 the composition of 13 interplanetary particles from the stratosphere are compared with the bulk abundances of the Murchison C2 meteorite. The particle data were taken with an ARL electron microprobe and reduced with the ZAF correction procedure for particles developed by Armstrong and Buseck (1975). In general the U-2 particle compositions agree quite well with chondritic values but there appear to be some systematic deviations. Fe and Ni and the refractory elements Ca, Al, and Ti all seem to be depleted. Although the iron content shows relatively large variation, it is well correlated with Ni (Fig. 6). The high S and C abundances indicate that micrometeorites are most like C1 chondrites. A major difference however is that the ~10 μm sized U-2 particles agree with chondritic abundances better than do similar volumes of C1 material or even the bulk of the fine grained "matrix" of C1's. A conspicuous difference shown in Fig. 5 is that while S, Ca, and Na are relatively normal in interplanetary dust, they are highly depleted in C1 fine grained material (McSween and Richardson, 1977). The process (leaching?) which redistributed S, Ca, and Na in C1 meteorites apparently did not occur in the interplanetary dust parent bodies.

A major difference between C1 and C2 meteorites and interplanetary dust is the detailed nature of their microstructure as revealed in high resolution SEM and TEM observations. The fine grained materials in the meteorites are typically rather compact masses of platelets, crumpled foils, and fibers. In comparison the dust particles examined are more porous, finer grained, more complex, and generally they do not contain the fibrous platey textures commonly seen in C1 and C2 meteorites. Figure 7 illustrates the complex microstructure seen in many of the dust particles examined. In the TEM many of the ~1000 A grains seen in Fig. 7 are revealed to be aggregates of grains in the 10–500 A size range (Figs. 8, 9). The complex, porous, fragile structure of many interplanetary dust particles may be incompatible with a prior history of residence in a regolith environment.

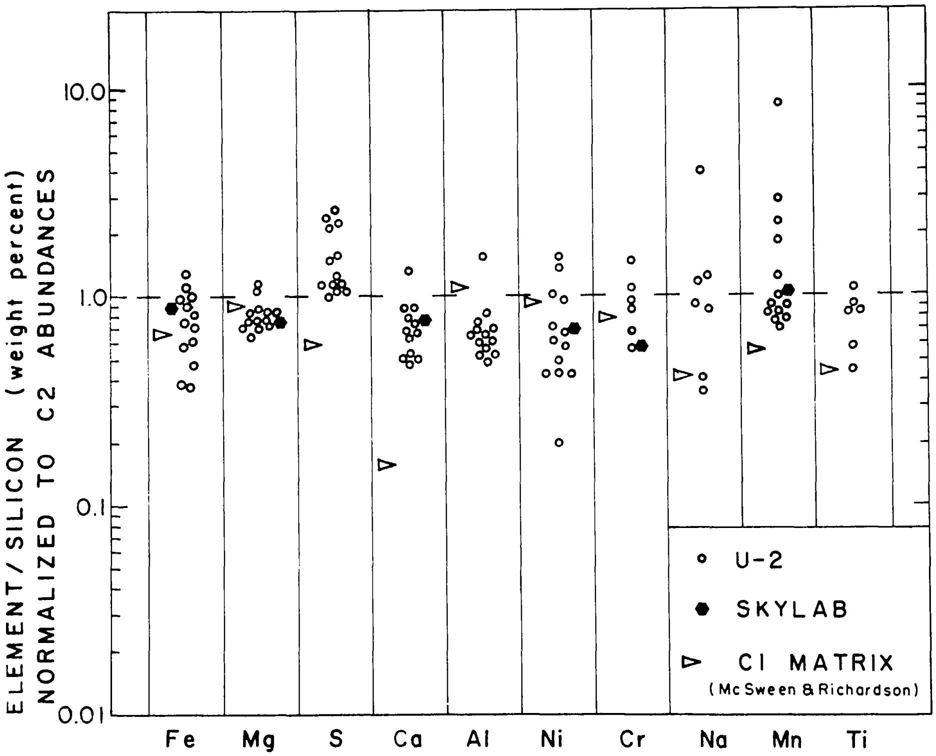

Fig. 5. Elemental composition of 13 U-2 micrometeorites (diameters 3–30 μm), meteoroid residue found lining a 110 μm crater found on Skylab IV (Brownlee *et al.*, 1974) and the averaged fine grained fraction of C1 meteorites (McSween and Richardson, 1977). All data was taken with electron microprobes and is normalized to the Murchison C2 chondritic (Fuchs *et al.*, 1973).

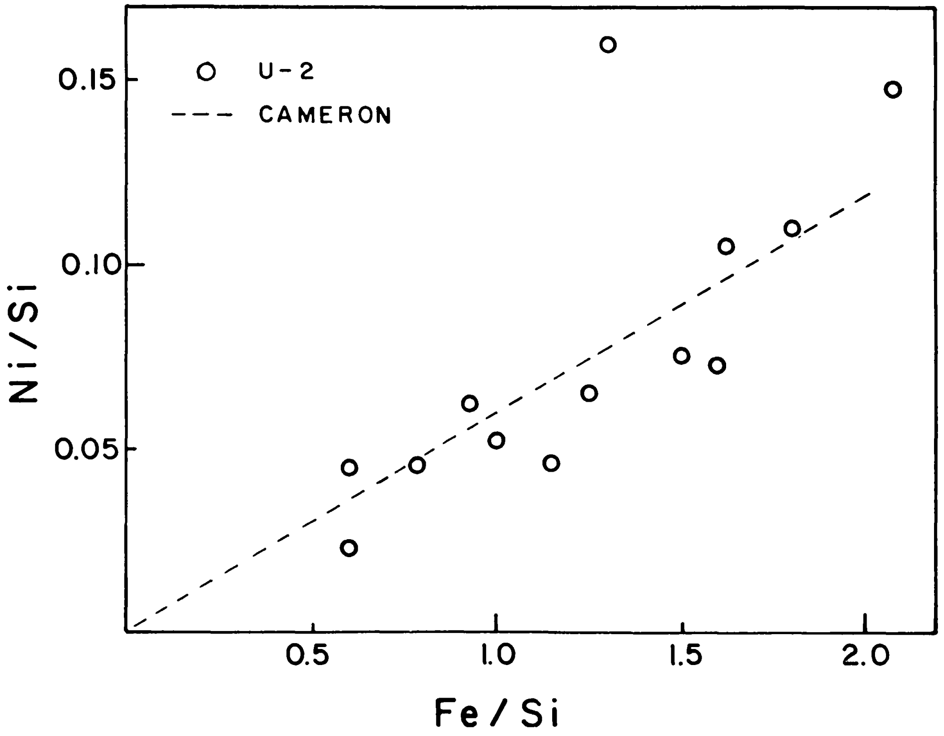

Fig. 6. Correlation of iron and nickel for the U-2 particles plotted in Fig. 5. The dashed line is the solar system average estimated by (Cameron, 1970).

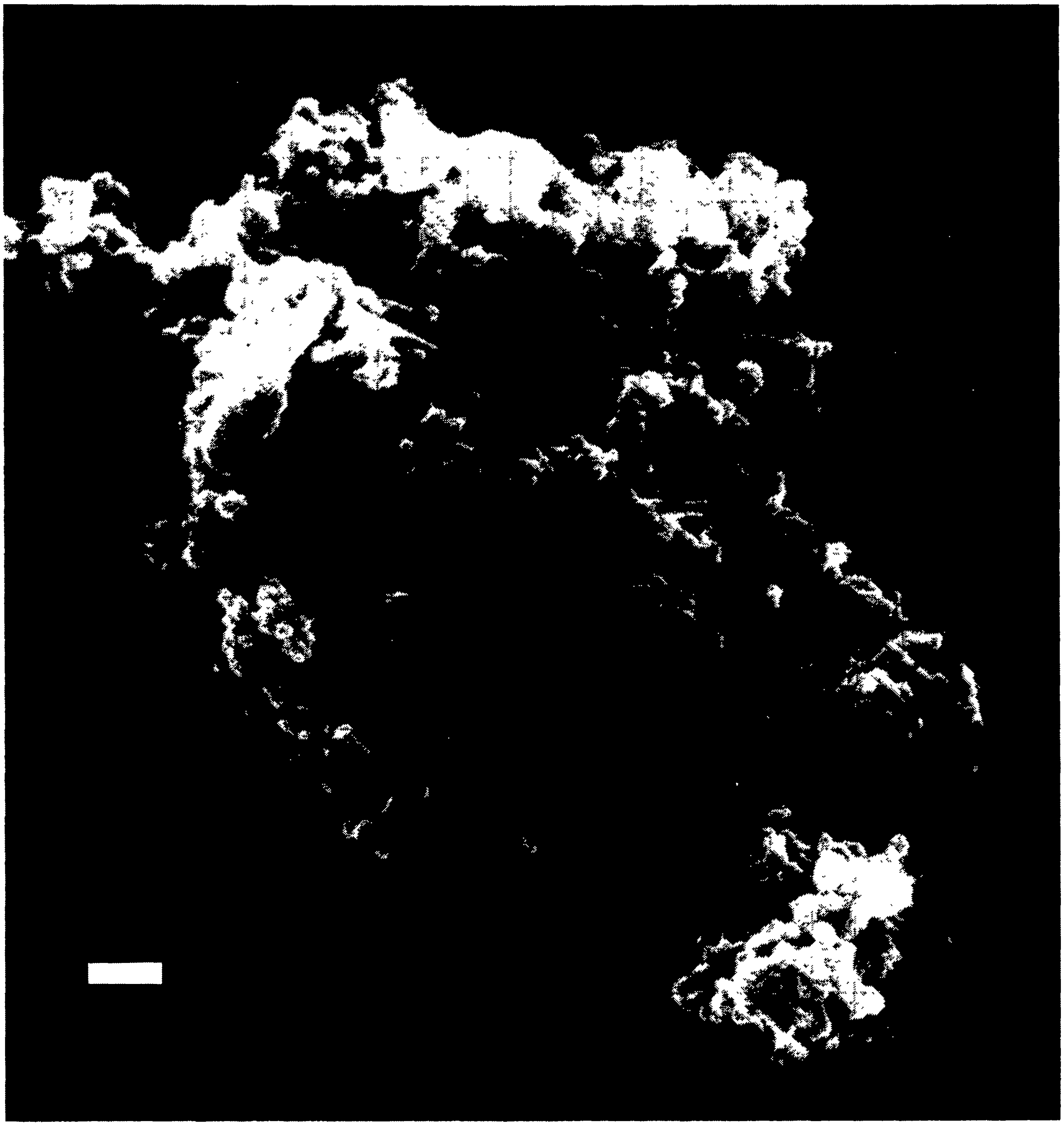

Fig. 7. A SEM micrograph of a porous chondritic aggregate interplanetary dust particle showing the basic ~1000 A size grain structure. Scale bar = 1 μ.

Short period comets which are major dust producers cannot have regoliths because of the high loss rate of surface material due to the ablation of ices.

INTERPLANETARY DUST AS A RESOURCE

Available data suggest that most interplanetary dust particles are primitive solar system materials in the sense that they are volatile-rich and show no obvious evidence of extensive alteration. The dust particles, like carbonaceous chondrites, are volatile-rich, fine grained aggregates which contain minerals of

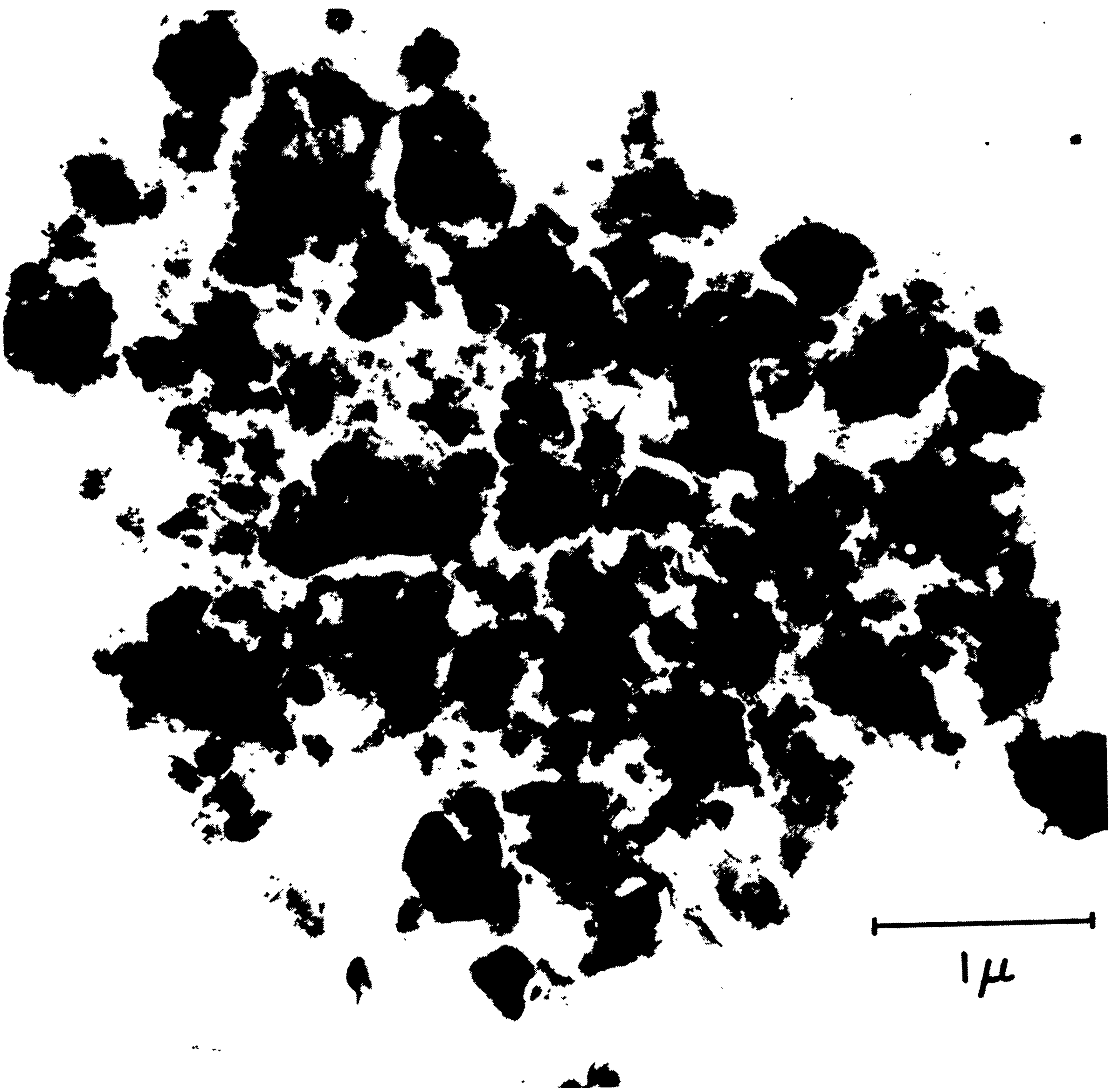

Fig. 8. A TEM micrograph of a crushed chondritic aggregate micrometeorite showing the basic 1000 A size grain structure. Some of the individual 1000 A size grains are single crystalline particles while others are themselves aggregates of much smaller particles.

widely varying equilibrium condensation temperatures. The origins of interplanetary dust are not known with certainty, but a variety of information indicates that SP comets are the major source.

As a resource, interplanetary dust can be mined from the stratosphere to provide material for laboratory investigations. With a 1000 cm^2 collector on the U-2 and the use of batch processing, it should be possible to collect >10,000 10 μm particles per year. This would be $\sim 100\ \mu g$ of sample and would be enough particles to solidly cover an area more than 1 mm^2. Although enormous numbers of individual particles can be collected it seems unlikely that massive

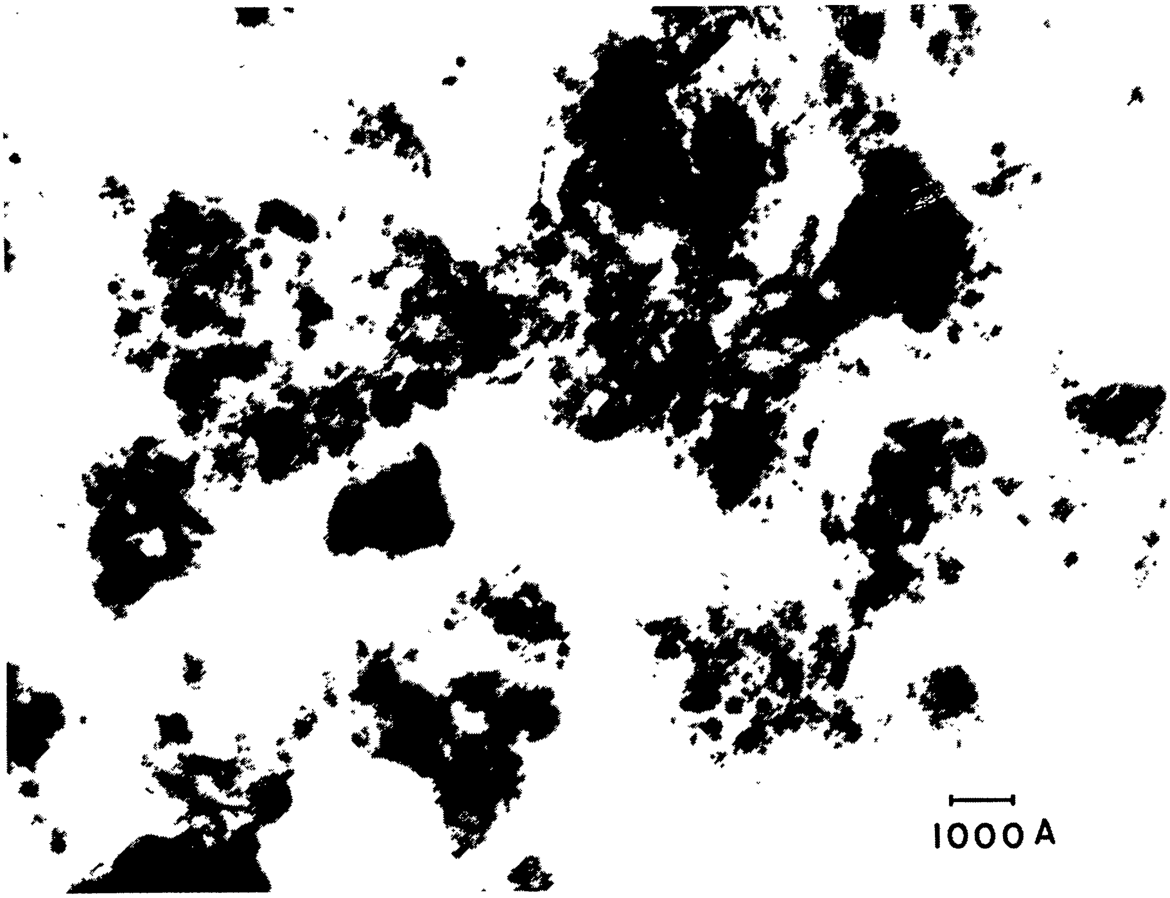

Fig. 9. A TEM micrograph illustrating the 10–1000 A components found inside many of the submicron grains, from crushed chondritic aggregate interplanetary dust particles.

collections (>10 mg) will ever be realized in the stratosphere. Future interplanetary dust investigations will have to rely on techniques which deal either with single nanogram particles or microgram collections of many small particles. Particles larger than 4 μm are easy to individually manipulate and they can be prepared for a variety of analysis procedures. Particles can be transferred from one surface to another; they can be mounted on small needles for diffraction work; they can be cut in half for etching or microprobe analysis; and they can be crushed and mounted on thin films for TEM work.

Although particles larger than 100 μm can be collected, only particles ~10 μm and smaller escape significant heating during entry. Unfortunately then the best samples of recoverable interplanetary dust are those in the 3–10 μm size range. Even small individual micrometeorites, however, contain a wealth of information. A single 10 μm chondritic interplanetary dust particle is an aggregate collection of over a million individual grains. Using presently available TEM and SEM techniques most of the individual grains could in principle be analyzed for mineralogy and elemental composition. An example of the complex components in a single 10 μm particle can be seen in Fig. 10.

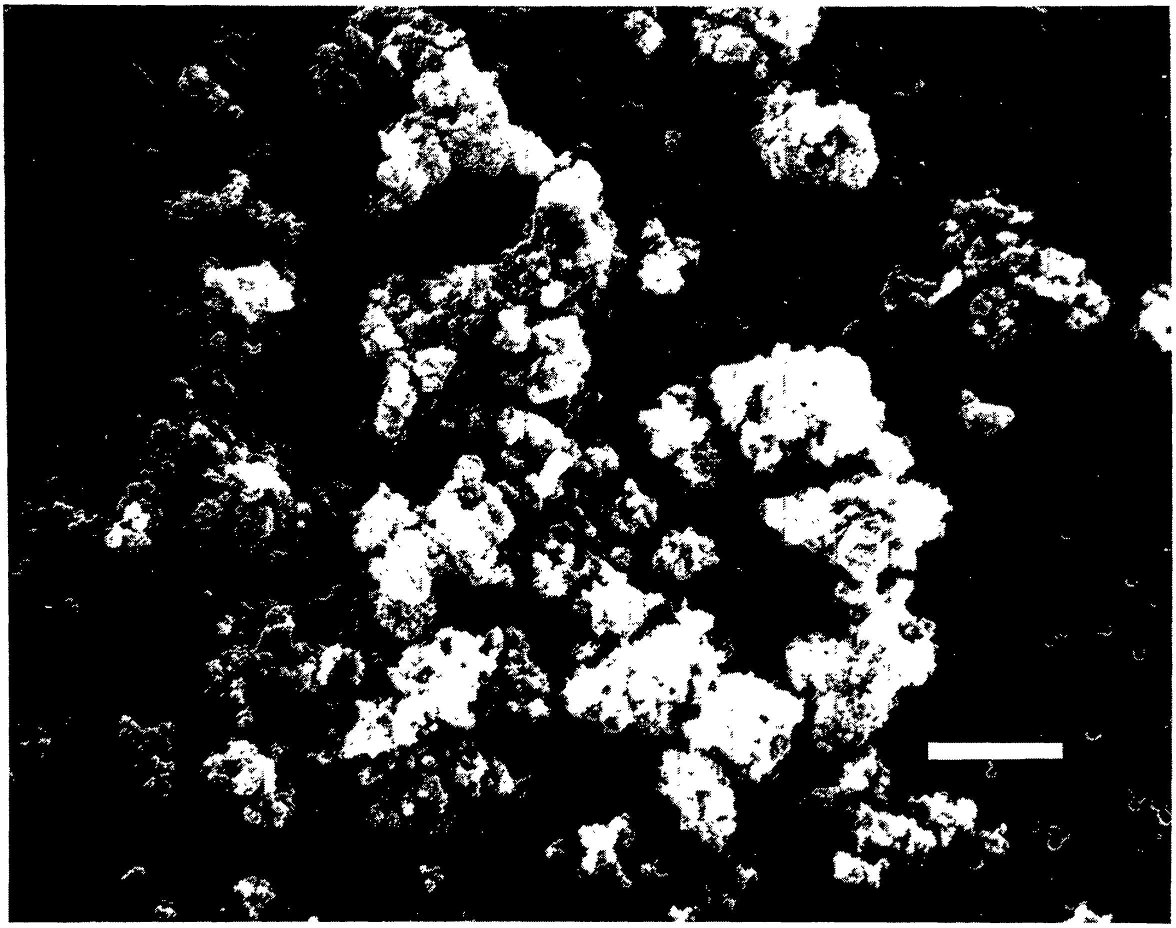

Fig. 10. SEM photograph of a single 10 μm interplanetary dust particle which fragmented during collection. The fine grained particles have chondritic compositions; the smooth surfaced particles larger than 5000 A are usually either pyrrhotite or enstatite or iron-poor olivine. High Ca, Al, Ti grains and unidentified minerals also exist in the particle. Scale bar = 5 μ.

REFERENCES

Armstrong J. T. and Buseck P. R. (1975) Quantitative chemical analysis of individual microparticles using the electron microprobe. *Anal. Chem.* **47**, 2178–2192.

Brownlee D. E., Ferry G. V., and Tomandl D. A. (1976a) Stratospheric aluminum oxide. *Science* **191**, 1270–1271.

Brownlee D. E., Hörz F., Tomandl D. A., and Hodge P. W. (1976b) Physical properties of interplanetary grains in the study of comets. NASA SP-393, p. 962–982.

Brownlee D. E., Tomandl D. A., Hodge P. W., and Hörz F. (1974) Elemental abundances in interplanetary dust. *Nature* **252**, 667–669.

Brownlee D. E., Tomandl D. A., and Hodge P. W. (1976c) Extraterrestrial particles in the stratosphere. In *Interplanetary Dust and Zodiacal Light* (H. Elsaesser and H. Fechtig, eds.), p. 279–283. Springer-Verlag, New York.

Cameron A. G. W. (1970) Abundances of the elements in the solar system. *Space Sci. Rev.* **15**, 121–146.

Fuchs L., Olsen E., and Jensen K. (1973) Mineralogy, mineral-chemistry and composition of the Murchison (C2) meteorite. *Smithson. Contrib. Earth Sci.* **10**. 39 pp.

Hörz F., Brownlee D. E., Fechtig H., Hartung J. B., Morrison D. A., Neukum G., Schneider E., Vedder J. F., and Gault D. E. (1975) Lunar microcraters: Implications for the micrometeoroid complex. *Planet. Space. Sci.* **23**, 151–172.

McSween H. Y. and Richardson S. M. (1977) The composition of carbonaceous chondrite matrix. *Geochim. Cosmochim. Acta.* In press.

Millman P. M. (1972) Cometary meteoroids. In *Nobel Symposium #21: From Plasma to Planet* (A. Elvius, ed.), p. 157. Wiley, New York.

Rajan R. S., Brownlee D. E., Tomandl D. A., Hodge P. W., Farrar H., and Britten R. A. (1977) Detection of ^{4}He in stratospheric particles gives evidence of extraterrestrial origin. *Nature* **267**, 133–134.

Whipple F. L. (1951) The theory of micrometeorites. *Proc. Nat. Acad. Sci.* (*USA*) **37**, 19–30.