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PHYSICAL PROPERTIES OF INTERPLANETARY GRAINS

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I. INTRODUCTION

This paper presents physical properties of interplanetary dust determined by in-situ techniques. It is probable that, like millimeter-sized meteoroids (Jacchia, et al. 1967), most interplanetary dust is cometary matter. Although a cometary origin for interplanetary dust is widely accepted (Whipple 1967) (Millman, 1972) there is currently no unambiguous proof of this hypothesis. The results presented here must be interpreted accordingly. It must also be remembered that even if interplanetary particles are cometary, they might possibly be altered in the interplanetary medium by collisions and by thermal effects during close perihelion passages, so the dust particles may not be representative of unaltered cometary material.

Over the past 5 years it has become possible to make relatively direct measurements of some physical properties of interplanetary dust. Morphological analysis of micrometeorite craters found on lunar rocks and returned spacecraft experiments has provided an opportunity to measure the properties on an unbiased sample of interplanetary particles, and the collection of genuine micrometeorites in the stratosphere has made it possible to do detailed laboratory investigation on them.

II. MICROMETEORITE CRATERS

The hypervelocity (>3 km s^{-1}) impact of an interplanetary dust grain onto a surface results in the almost total vaporization of the particle and in the production of a crater. Through laboratory simulation experiments and the analysis of craters on lunar rocks, criteria have been developed that enable reliable identification of such impact sites (Hartung et al., 1972). Laboratory calibration experiments (Vedder and Mandeville, 1974) make it possible to correlate crater morphological parameters with certain physical properties of the impacting projectiles.

a.) Shape and Density

Vedder and Mandeville's (1974) calibrations demonstrate that the circularities and depth/diameter ratios of micron-sized micrometeorite craters are determined in part by the shapes and densities of impacting meteoroids. By measurement of circularities and depth/diameter ratios for a large number of lunar microcraters, it was concluded that micron-sized meteoroids are roughly equidimensional and they have densities compatible with stony meteorites (Brownlee et al., 1973)(Horz et al., 1975). The high degree of circularity of lunar craters is strong evidence that grossly nonspherical shapes like platelets and rods are practically non-existent in the interplanetary medium. The measured depth/diameter ratios indicate meteoroid densities greater than 1 g cm^{-3} and less than 7 g cm^{-3}. Strict interpretation of the data implies a mean meteoroid density between 2 and 4 g cm^{-3}. Recent measurements of depths of craters on small lunar glass spherules by Smith et al. (1974) indicate three groupings of depth/diameter ratios corresponding to projectile densities of 8 g cm^{-3}, 3 g cm^{-3} and 1-2 g cm^{-3}. These measurements disagree with our measurements in that an abundance of particles as dense as metallic iron are reported. The existence of dense particles is currently a matter of dispute, but both groups agree that particles of extreme low density (<1 g cm^{-3}) do not exist. This result is in direct contradiction with the traditional concept of fluffy cometary meteoroids.

b.) Chemistry

In simulation experiments where micron-sized iron projectiles are impacted onto silicate targets, there normally is a detectable particle residue lining the crater floor. In hundreds of lunar craters examined, however, only one crater has been found which is reported to contain residue (Fechtig et al., 1975). In this case, Fe-Ni mounds were found inside a 0.5 mm crater. The lack of residue in the majority of lunar craters in silicates can be construed as evidence that metallic iron micrometeorites are rare and that whatever the composition of normal meteoroids is, it is totally vaporized upon impact onto silicate surfaces.

The impact processes in metal targets are somewhat different from those for silicates, as shown by the observation that for a given impact energy, craters in metals are nearly an order of magnitude more voluminous then craters in silicates. Conditions in metal targets are apparently more suitable for residue retention, as seems to be shown by the fact that the two craters found in the aluminum cover of S228 Skylab IV experiment both contained significant meteoroid residue (Brownlee et al., 1975). For the two Skylab craters it was estimated that ∿10% of each meteoroid survived as residue. Microprobe analysis showed that the larger crater (110μm diameter)(Figure 1) contained elemental abundances essentially identical with chondritic meteorites (Figure 2) and that the small crater

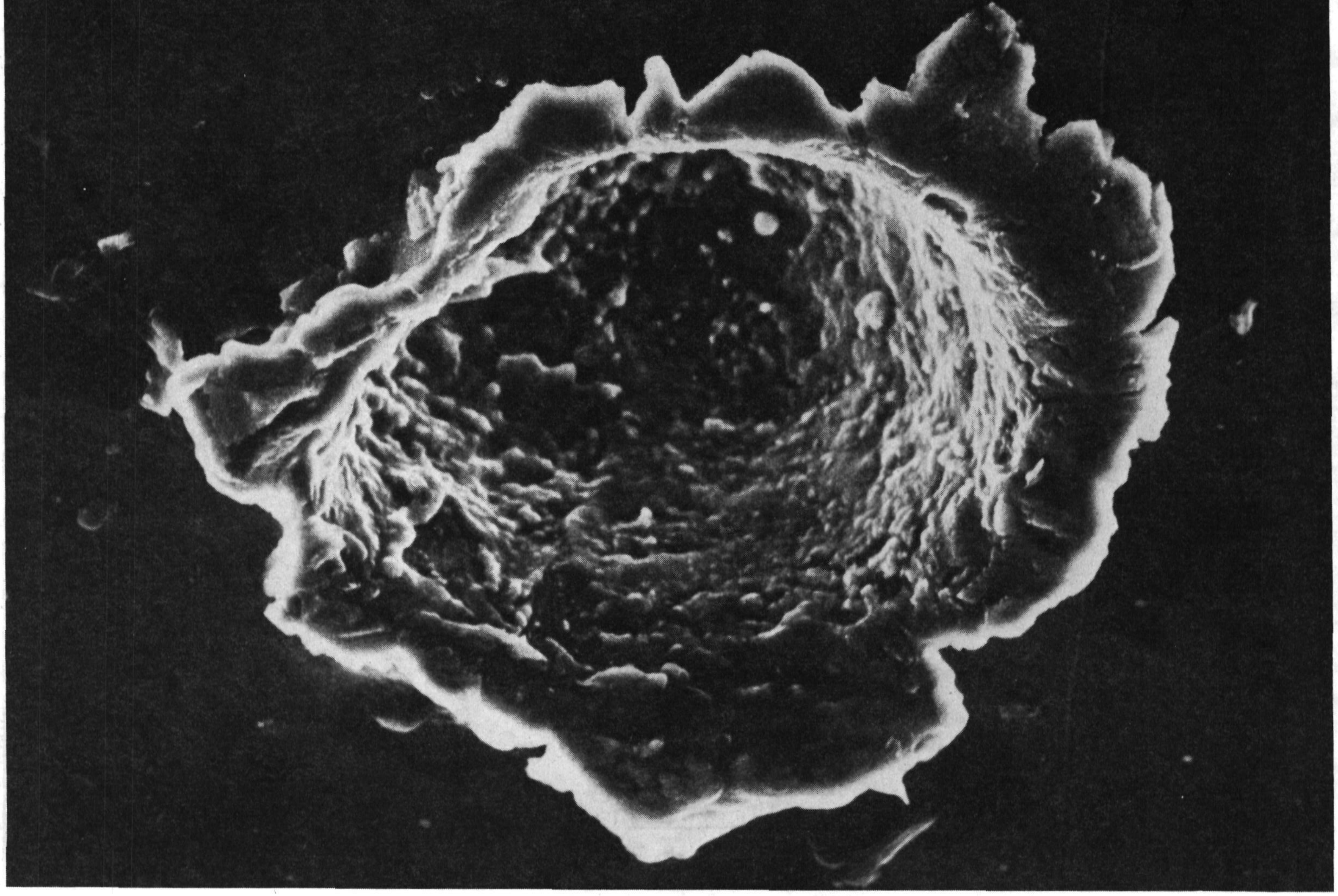

Figure 1 110μm diameter microcrater from Skylab IV.

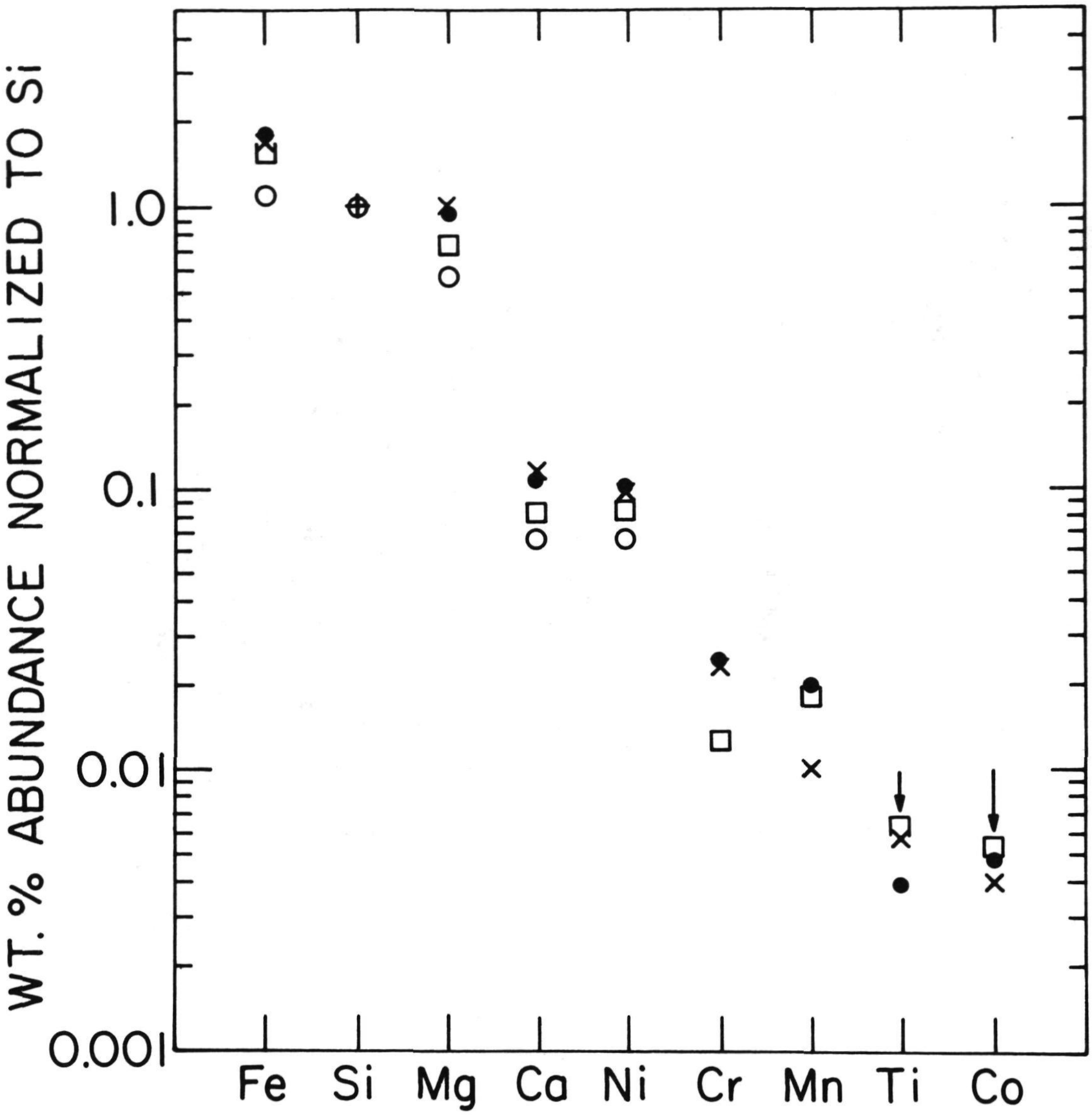

Figure 2 Microprobe analysis of meteoroid residue in the 110μm Skylab IV crater. The open squares and open circles represent independent microprobe analyses of 30μ spots on the crater floor. Filled circles and crosses, respectively, are C1 and C3 meteorite averages (Mason, 1971). Sulfur was analyzed in a separate probe run and was found to be qualitatively similar to the Fe, Mg, Si group.

(30μm) contained residue of an iron sulfide meteoroid with minor amounts of Ni and Mg. Because no known mineral contains chondritic abundances, the close agreement of the 110μm crater residue indicates that the impacting meteoroid was an aggregate of grains. For the bulk particle composition to be so close to chondritic the average grain sizes in the aggregate must have been considerably smaller than the 30μm diameter particle that produced the crater.

III. MICROMETEORITES

Small interplanetary particles, because of their large surface area/mass ratios, can survive high velocity entry into the atmosphere (Whipple, 1951). The micrometeorite flux is extremely low, but our measurements indicate that, for particle sizes larger than 10μm, extraterrestrial particles are the dominant particulate in the stratosphere. We have collected particles by inertial deposition from a high velocity air stream onto clean, oil-coated collection surfaces. The collection technique is successful because it is clean and because it samples enormous volumes of air. We have had two successful sampling flights at 34 km with a balloon sampler (Brownlee *et al.*, 1973) and 3 long-duration sampling runs at 20 km with an impactor mounted on a NASA U-2 aircraft. The five flights have cumulatively sampled 6×10^4 m^3 of ambient air. Collected particles range in size from 2μm to 20μm. All five collections produced similar densities and types of particles.

Disregarding particles which are primarily aluminum oxide (a common stratospheric contaminant), 50% of the collected particles with diameters >5μm are with iron sulfides with some Ni or are particles with abundances of Fe, Si, Mg, Ca, Ni and S consistent with chondritic meteorites. We have collected and analyzed 50 chrondritic particles and 26 iron-sulfur-nickel (FSN) particles. The measured stratospheric flux of both types is 4 x 10^{-6} part. m^{-2} s^{-1} for diameters $\geq$ 6μm.

The particles are analyzed qualitatively using energy dispersive X-ray techniques in the SEM. The FSN particle compositions are consistent with troilite (or pyrrhotite) containing 1-5% Ni. These particles (see Figure 4) contain no other detectable elements and the Ni has never been found to be higher than 5%. The chondritic particles agree remarkably well with chondritic meteorites (Figure 3), with Mg, Si, and Fe relative abundances usually within a factor of 2 of chondritic values. Most of these particles contain sulfur at approximately the 5 wt % level, and Ca and Ni at the 1% level, but no higher. With long integration times minor amounts of Cr and Mn usually also can be detected. In the optical microscope the particles are very black, suggesting the existence of an appreciable carbon content. We do not see particles with near-chondritic compositions that have anomalously high abundances of non-cosmically abundant elements, (i.e. Al, Ca, Na, K, Cu, Ti, etc.).

One particle has been ground in half, polished and analyzed quantitatively with standard microprobe techniques. This particle, because of its spherical shape, its depletion of sulfur and the existence of small magnetite grains, similar to those seen in meteorite fusion crusts (Blanchard and Cunningham, 1974), is believed to be a meteor ablation droplet. Considering the fact that the particle is only 12μm in diameter, the agreement with chondritic abundances is remarkable (see Table I).

That a large fraction of the collected particles have chondritic abundance patterns is very strong evidence that the particles are bona-fide micrometeorites and not contamination artifacts. A close match

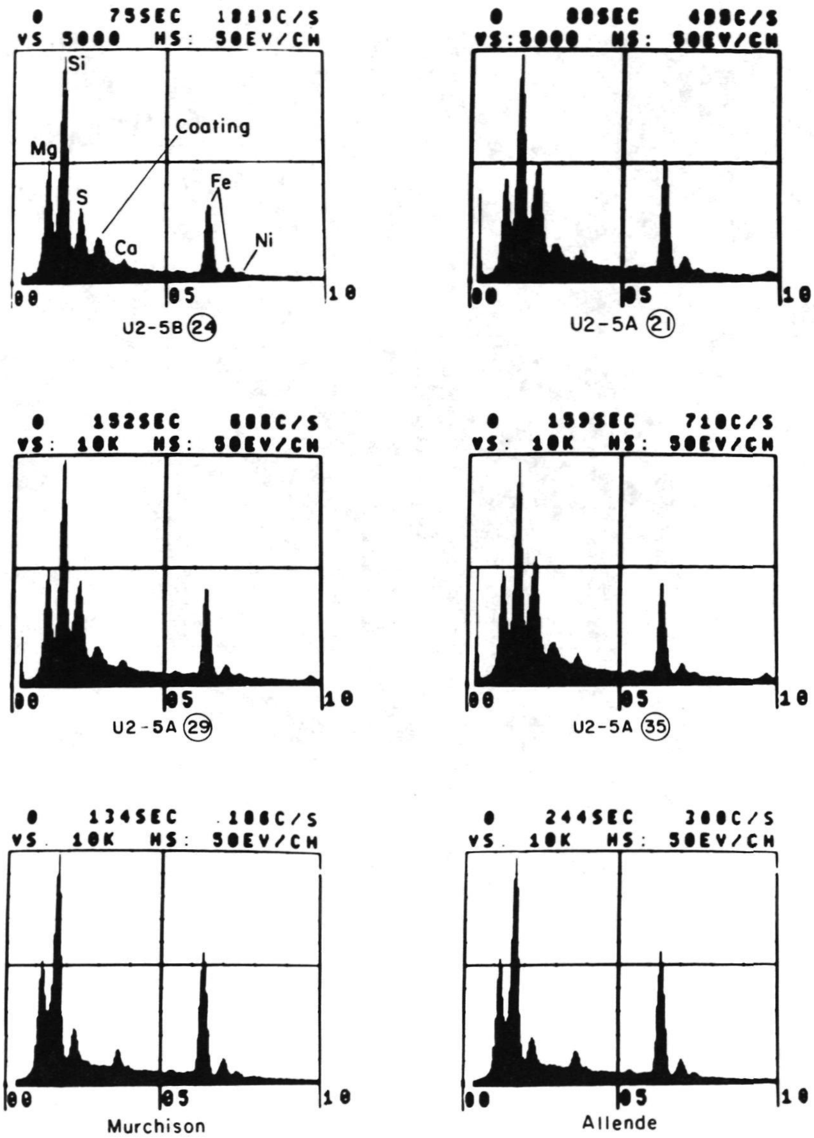

Figure 3 Energy dispersive X-ray spectra of 4 chondritic micrometeorites collected at 20 km altitude, compared with representative spectra of the Murchison and Allende carbonaceous chondrites. Each spectrum is a plot of the number of detected X-ray photons vs. photon energy (Kev). The line marked "coating" is Pd. The gold line is coincident with Sulfur and makes the U2-5A sulfur peaks appear ∿25% higher than they should be. The small peak near 10 Kev in the U2-A particles is a gold L line.

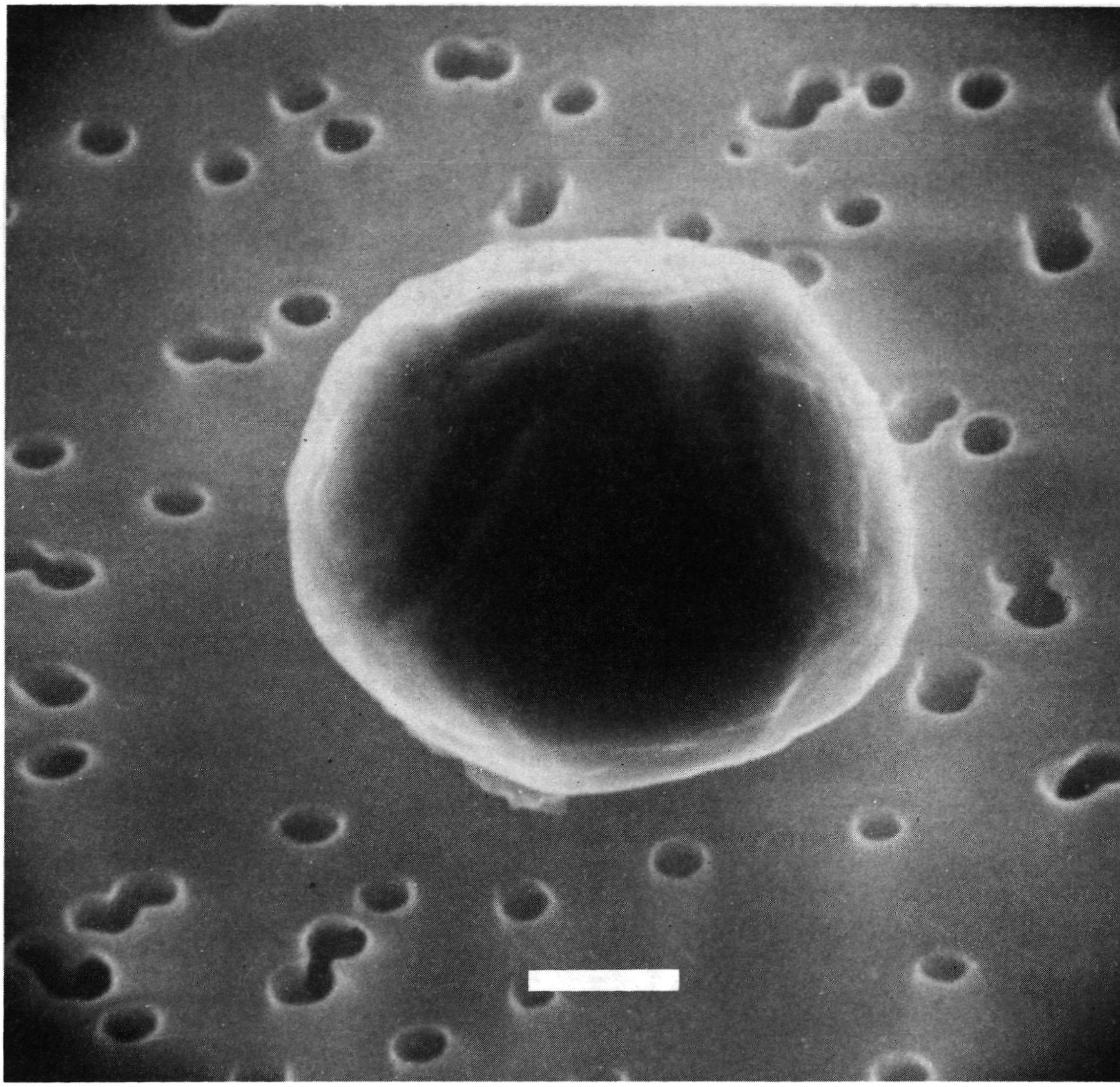

Figure 4 SEM picture of U2-5B (3), a iron-sulfur-nickel micrometeorite collected with a U2 aircraft at 20 Km. This particle is a single crystal which makes it unique among the collected FSN particles. Most of the FSN particles are spheres. The iron:nickel ratio is 11:1 weight percent. Scale bar = 1μm.

TABLE 1

Microprobe analysis of the 12μ diameter spherical micrometeorite VM II A-4 -- a probable meteor ablation debris.

	VMII A-4	C3 Chondrite Average (Mason Handbook)
SiO_2	33.05	33.20
TiO_2	.35	.14
Al_2O_3	4.47	2.59
Cr_2O_3	.35	.51
FeO	10.75	32.36
Fe_2O_3*	13.80	---
NiO	2.30	1.78
MgO	28.58	24.00
CaO	3.60	2.38
Na_2O	< .027	.47
S	< .15	2.19
total	97.25**	

*The partition of Fe between FeO and Fe_2O is based on the optical microscope estimate that ~20% of the polished section is magnetite.

**The low total may be due to the presence of carbon. Carbon is present in the fusion crusts of some carbonaceous chondrites.

with chondritic abundances for Fe, Mg, Si, S, Ca and Ni is a highly diagnostic identification criterion. We know of no single natural or man-made material from the earth or from the moon with similar abundances. Over 50% of the FSN particles are spheres and it is possible that they are meteor ablation debris. Only 10% of the chondritic particles are spheres. The non-spherical chondritic particles have structural textures and sulfur abundances that suggest that they are particles which have not been thermally altered by passage through the atmosphere. Except for the spheres, all of the chondritic particles are aggregates of very small grains. Typical grain sizes are in the range 1000 A - 10,000 A (Figures 5-8). There appears to be a filling material between many of the grains and the major visible difference from particle to particle appears to be in the abundance of the filling material. The particles with very little filling between grains have porosities which would give the particles bulk densities on the order of 1 g cm^{-3}. Typical particles have sufficient filling material to give bulk densities on the order of 2 g cm^{-3} or higher.

IV. DISCUSSION

As a stereotype interplanetary dust particle, for optical scattering calculations, we suggest a model meteoroid which is roughly spherical and has a density of 2 g cm^{-3}. The model particle has chondritic elemental abundances. Like C 1 chondrites the model also contains a high content ($\gtrsim$ 4%) of finely dispersed carbon which has a dominating effect on optical properties.

Both particle collections and microcrater analyses indicate that micron-sized interplanetary particles have densities greater than 1 g cm^{-3}.

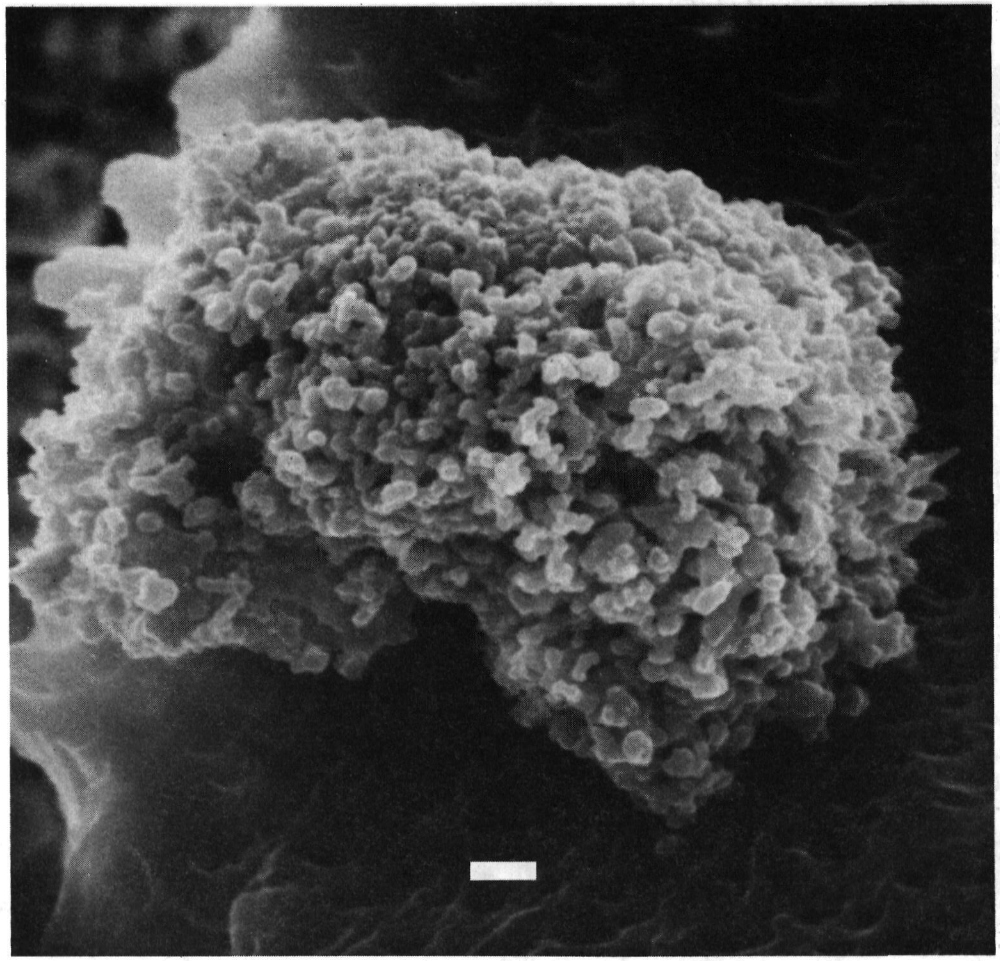

Figure 5 Chondritic micrometeorite U2-5A (21). This is the highest porosity micrometeorite collected by the balloon or U2 collection program. Scale bar = 1μm.

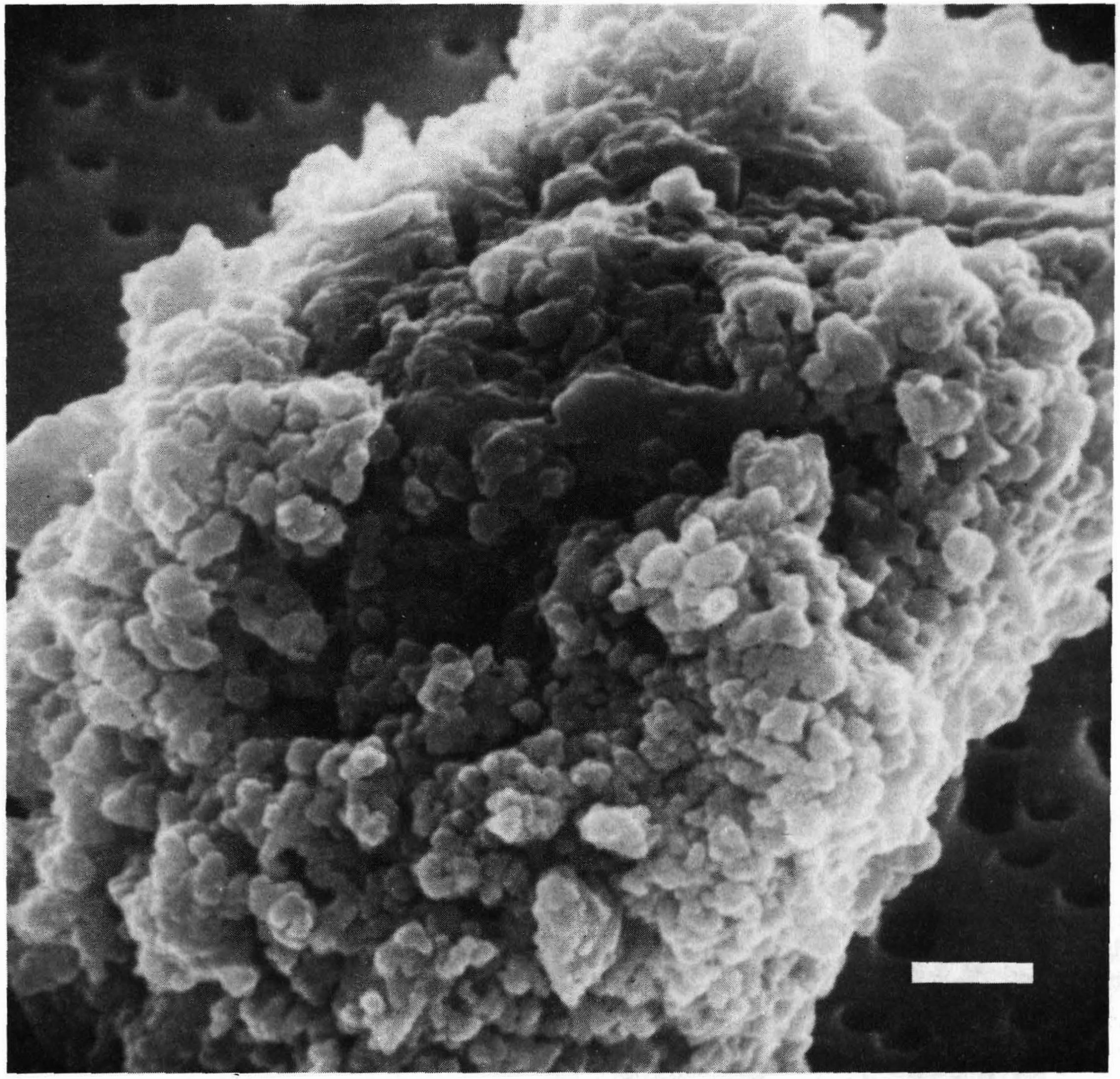

Figure 6 Chondritic micrometeorite U2-5A (35). Scale bar = 1μm.

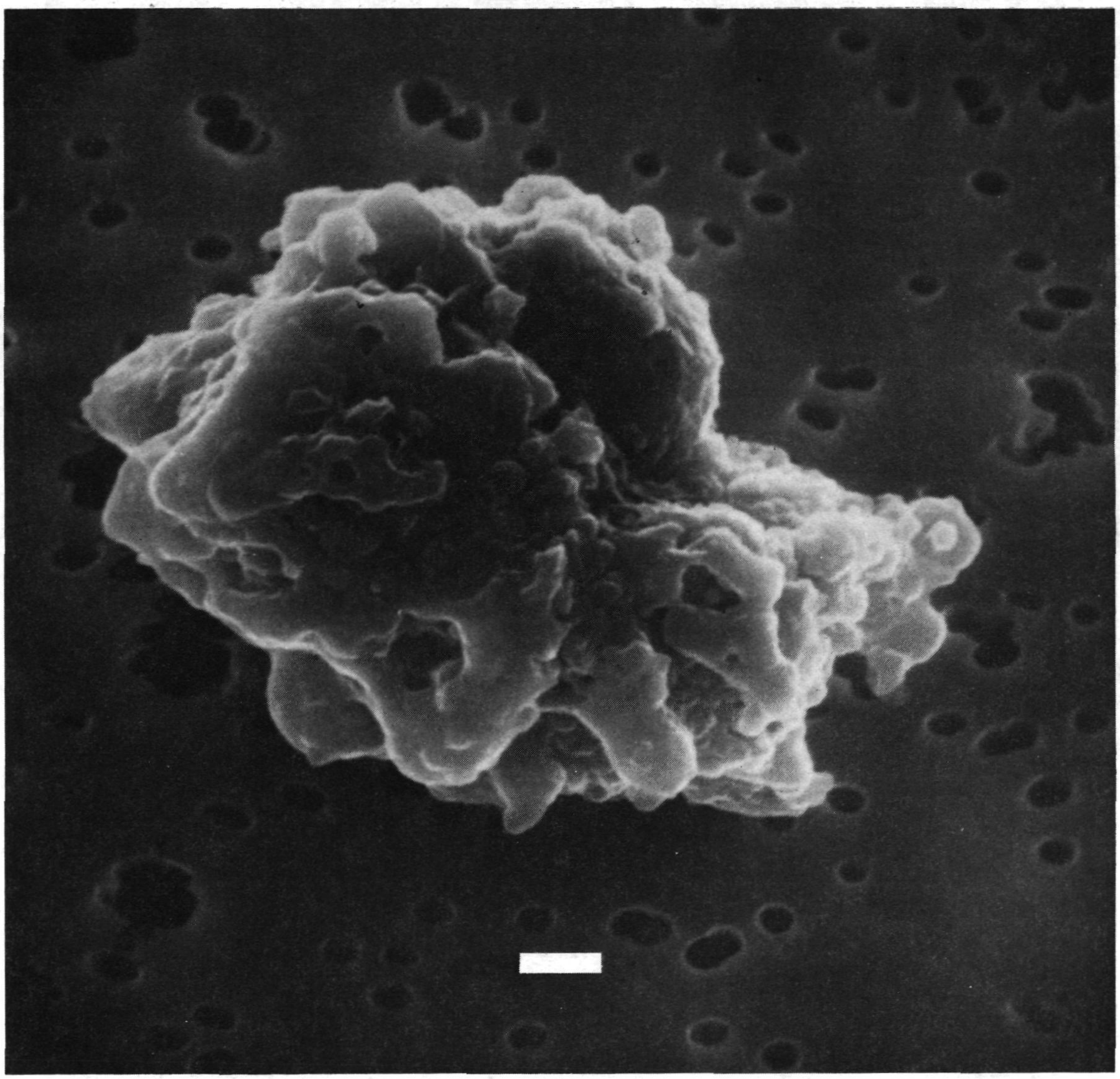

Figure 7 Chondritic micrometeorite U2-5A (29). This particle has an aggregate structure but contains a large amount of inter-grain filling material resulting in a rather low porosity. Scal bar = 1μm.

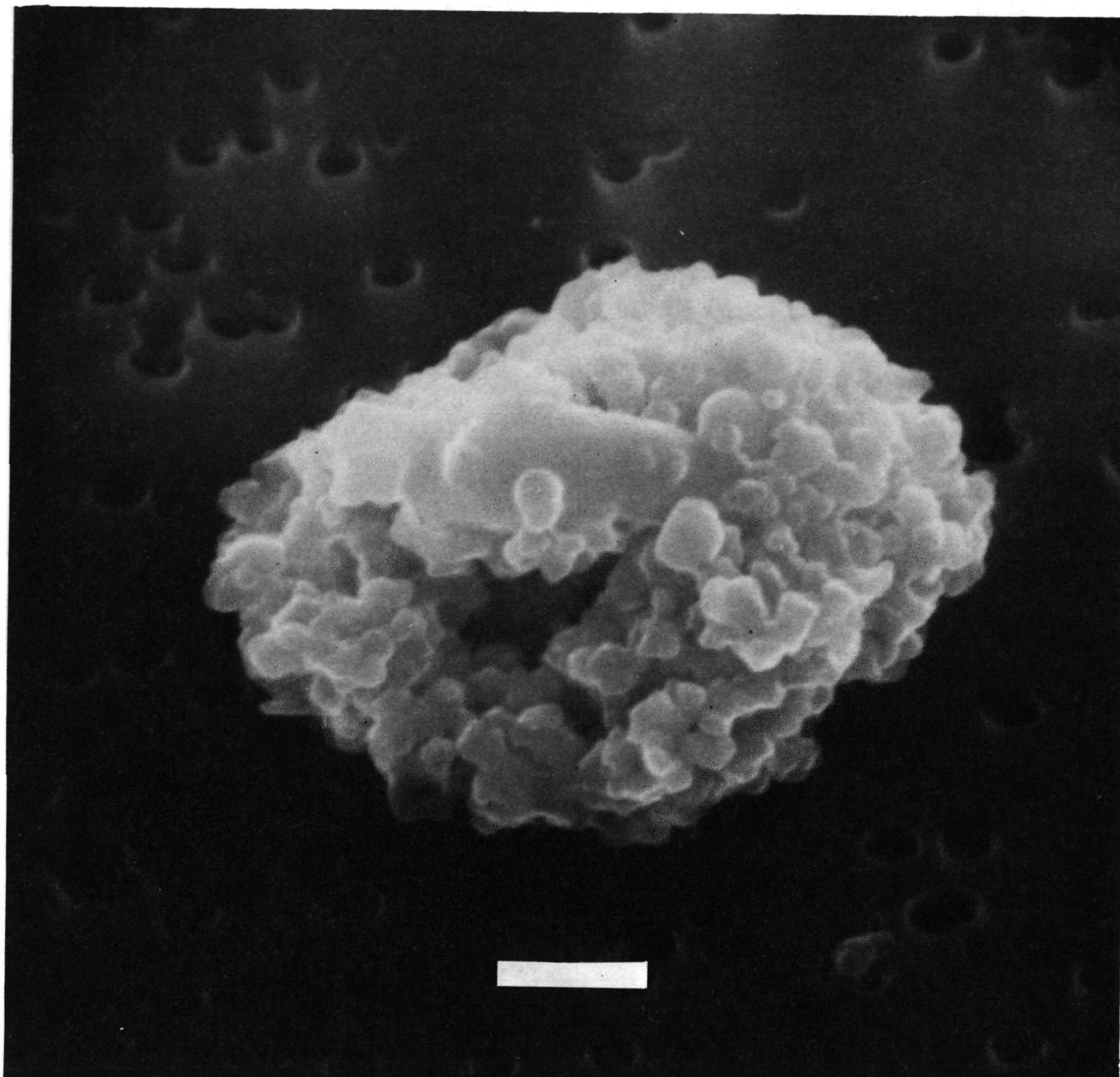

Figure 8 Chondritic micrometeorite U2-5B (24). This particle contains a moderate amount of filling material and the structure is rather typical of the chondritic micrometeorites. Scale bar = 1μm.

Consideration of both data sources suggests that typical particles have densities between 1 g cm^{-3} and 4 g cm^{-3}. Although the collection data might be affected by selection effects, the crater data is not. The laboratory calibrations very closely simulate the actual impact conditions on lunar rocks and it is believed that the density lower limit derived from crater data is quite reliable. These results indicate that the widely-accepted hypothesis that interplanetary grains have extremely low densities is incorrect. If a cometary origin of micrometeoroids as well as the reported mean densities of 0.3 g cm^{-3} for the somewhat larger cometary meteors are correct, then our results indicate a structure of cometary matter such that high porosity does not exist in particles smaller than about 50μm.

Our observations indicate that the majority of interplanetary dust grains are rather equidimensional aggregates of sub-micron grains with bulk elemental abundances very similar to primitive meteorites. Analysis of meteor spectra (Millman, 1972) (Harvey, 1973), measurement of ion enrichment in the mesosphere during some meteor showers (Goldberg and Aikin, 1973) and the characterization of the micrometeoritic component in lunar soils (Anders et al., 1973) also indicate that the majority of small interplanetary particles have abundances similar to primitive chondritic meteorites. In addition, our results indicate that a smaller but significant fraction of interplanetary particles are iron sulfides which contain a few percent nickel. It is significant that both FSN-like particles and fine grained aggregate particles with chondritic compositions could be produced by crushing primitive meteorites to a 10μm particle size. Iron sulfides with a few percent Ni are common in C2 and C3 meteorites and the matrix of all carbonaceous chondrites is similar to the chondritic particles. Analyses of 5μm square areas on polished surfaces of Orgueil

(C1), Murchison (CM2) and Allende (CV3) show abundance dispersions very similar to those observed in the 50 chondritic particles collected from the stratosphere.

The similarity between interplanetary dust and meteorites is probably not a consequence of a common origin but rather a result of their both being accretional aggregates of small particles which condensed from a gas of cosmic composition. It is generally accepted that primitive meteorites are aggregates of particles which formed in the solar nebula within 5 AU of the sun. If the particles analyzed in this study are cometary then it is possible that they formed at much greater distances from the sun, either by accretion of condensates from the solar nebula or by accretion of pre-existing interstellar grains. It may be feasable to investigate these possibilities by detailed investigations of chondritic micrometeorites. Primitive meteorites contain a variety of inclusions (chondrules, calcium aluminum inclusions, olivine, glass, etc.) some of which may have been produced only in the inner parts of the solar nebulae and would not be expected to be incorporated in bodies formed further out. Searches for meteoritic-like inclusions plus comparitive mineralogical (via electron and X-ray diffraction techniques) and morphological studies of micrometeorites may be capable of determining whether or not micrometeorite and meteorite parent bodies formed in the same region of the solar system.

Preliminary investigation of grain shapes in interplanetary dust indicates that they are not similar to common grain shapes in carbonaceous chondrites. The constituent grains in micrometeorites are fairly equidimensional while grains in most carbonaceous chondrites are typically platelet shaped. The only mineralogical information obtained to date, for an unablated particle, is an X-ray diffraction pattern obtained for the largest particle collected. The pattern shows the definite existence of magnetite. Magnetite is a low temperature mineral, in meteorites, and is only found in abundance in type 1 carbonaceous chondrites.

Existing microanalysis techniques are very powerful. It is anticipated that further SEM and transmission electron microscope studies on micrometeorites will result in a rather detailed knowledge of their mineralogy and structure. This information is potentially capable of providing rather fundamental insights into the processes that formed cometary bodies.

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DISCUSSION

F. L. Whipple: My only comment is that the classical diameter of interstellar grains is 2000Å!

S. Auer: How could you collect a highly porous and fragile looking particle without destroying it?

D. Brownlee: It was collected from an aircraft at a small relative velocity of 600 ft/s.

S. Auer: What is your argument that this particle has an extraterrestrial origin?

D. Brownlee: The only argument is the similarity between its composition and the composition of carbonaceous chondrites. Terrestrial particles should have a different composition.