2.3.4 EXTRATERRESTRIAL PARTICLES IN THE STRATOSPHERE

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Over the past several years we have collected 2μm to 30μm particles from the stratosphere using high volume air sampling techniques. In 1970 and 1971 we flew balloon experiments to 34 km, sampling particles from 1.1 x 10^4 m^3 of ambient air. Beginning in March 1974 we have flown 100 hours of sampling time on a NASA U-2 aircraft yielding a sampling volume of 9.3 x 10^4 m^3. In both programs particles are collected by inertial deposition from a 200 ms^{-1} airstream on to clean surfaces coated with thick films of 500,000 centistokes silicone oil.

Collected particles are analyzed by individually removing them from collection surfaces, washing them in zylene and mounting on stubs for SEM analysis. The major data output from the analysis program is morphology and relative elemental abundances as determined in the SEM using a solid state X-ray detector. By raster scanning on the portion of the particle facing the X-ray detector and calibration with mineral standards (similar to the unknowns), element ratios are routinely determined to an accuracy better than a factor of two.

On all the U-2 and balloon flights the same types and spatial densities of particles have been collected. In all collections the most common particles have been pure Al_2O_3 spheres. Our data indicate that these particles have existed in the stratosphere at a density of 10^{-2} part. m^{-3} ($\geq$ 5μm) for the past five years. These particles are not extraterrestrial but are generated by solid fuel rocket engines. It may be that these particles can be used as a calibration source in future particle collection programs in the stratosphere. At 4 μm, ∿90% of the collected particles are Al_2O_3. In the submicron range the Al_2O_3 particles are insignificant compared to the sulfate aerosol and for sizes larger than 10μm, extraterrestrial particles are dominant.

Disregarding particles which are largely aluminum, half of the collected particles have elemental abundances which closely match bulk abundances of primitive meteorites or minerals which are common in C1 and C2 carbonaceous chondrite meteorites. These particles have compositions uniquely different from obvious stratospheric, laboratory and aircraft contaminant particles found in the collections (Al particles, skin flakes, TiO_2 paint, Cd plating, etc.). On the basis of elemental abundances we have identified 8 particles from the balloon flights and 115 from the U-2 flights which are almost certainly extraterrestrial. The majority of these particles have Mg, Fe, Si, S, Ca and Ni abundances within a factor of 2 of cosmic abundances. Importantly, we have not seen cosmic-abundance particles which contain detectable amounts of non-cosmically abundant elements (ie. Cu, Cl, Zn, Na, Cd etc.). Because no known terrestrial (or lunar) material can match cosmic abundances for the six most cosmically abundant elements, we feel the cosmic abundance criterion is a very strong diagnostic criterion for identifying undiffer entiated extraterrestrial materials. The particles which closely match cosmic abundances we refer to as "chondritic". No genetic association with chondrules or chondritic meteorites is intended.

In addition to the chondritic particles other composition groups have been identified as extraterrestrial by their physical association with chondritic particles. These composition groups have been found as single particles, as particles with chondritic material adhering to thei surfaces, as particles imbedded in single chondritic particles and as particles found inside chondritic particles which broke into fragments during collection or were intentionally crushed in the lab. From the observed associations it is clear that all identified extraterrestrial particle groups were at one time in intimate contact with each other.

We have defined three major compositional groups into which nearly all of the collected extraterrestrial particles can be placed. Sixty percent of the particles classify as chondritic, 30% as FSN and 10% as Mg, Fe silicates. The properties of these groups are as follows.

Chondritic - chondritic abundances

Chondritic particles generally have chondritic (cosmic) elementa abundances. Based on morphology and S abundance the chondritic particle fall into two subgroups.

Aggregates: Ninety percent of the chondritic particles are aggregates of 1000 A sized grains (Figure 1). In some particles the component grains are loosely bound and the particle structure is quite porous. Typically the aggregates are compact with little pore space.

The aggregate particles typically have chondritic abundances (factor of 2) for Fe, Mg, Si, S, Ca and Ni (Brownlee et al. 1975A). Mn and Cr are at the limits of detection but can often be detected at concentrations compatible with cosmic abundances. Optically the aggregates are very black suggesting a carbon content of 2% or more. X-ray diffraction of two of these particles has shown definite existence of Fe_3O_4 and FeS. X-ray powder patterns from these two particles are very similar to powder patterns obtained from matrix material from the Murchison (C2) meteorite which had been heated to 450°C (Fuchs et al. 1973). Electron diffraction of two crushed particles implies that most of the constituent grains in the chondritic particles are crystalline.

Ablation spheres: Ten percent of the chondritic particles are spherules which are not porous and do not contain sulfur. The S depletion is probably the result of thermal alteration and the particle shapes imply the particles were molten at one time. In composition and texture these spherules are very similar to fusion crusts of chondritic meteorites. We believe that these particles are secondary micrometeorites produced by ablation of meteoric bodies (Brownlee et al. 1975B).

FSN - An iron-sulfur mineral with a few percent nickel

The FSN particles are roughly similar to meteoritic troilite or pyrrhotite containing a few percent Ni. In many of the particles, sulfur is deficient relative to FeS by factors of 50% or more. The FSN particles may be related to the poorly characterized Fe, S, O, and Fe, S, C phases reported in carbonaceous chondrites or they may be combinations of FeS and FeO.

Unlike the chondritic particles, which have fairly uniform structures, the FSN particles come in a wide variety of forms. The majority of the FSN particles are spheres, but they also have been found as solid irregular masses, aggregates, well defined single crystals (octahedron with cubic truncation), and stacks of platelets (Figure 2). Some of the nonspherical FSN particles show remarkable similarities to magnetite forms found in C1 meteorites as reported by Jebwab (1971). The FSN spheres may be ablation debris, while the irregular shapes are probably not.

Mg, Fe SILICATES - olivine or pyroxene

These particles are iron poor olivine and pyroxenes with clumps of chondritic aggregates adhering to their surfaces (Figure 3). One euhedral crystal has been found but typically they are subhedral to irregular.

The FSN and most of the Mg, Fe silicate particles are believed to be extraterrestrial because they have been found in physical association with (e.g., actually inside) chondritic aggregate particles. Other particle types, although rare, have been found in crushed chondritic aggregates. For example, on one flight a chondritic aggregate particle was collected that broke into ∿100 fragments upon impacting the collection surface. Most of the fragments were small pieces of chondritic aggregate material but also found in the debris were FSN particles, enstatite, olivine, an opaque high Si mineral (SiC?) and two fragments of a Si, Al, Ca Ti mineral (high temperature condensate?).

Other extraterrestrial particle types probably exist in our collections but have not been identified as extraterrestrial either because they have not been found in physical association with the three major micrometeorite groups or because they do not have distinctive compositions Because almost all of the collected particles are either high Al particles identified micrometeorites, or obvious contaminants, we believe other micrometeorite types probably constitute only a minor component (<10%) of the extraterrestrial particles normally in the stratosphere.

Our collections indicate that the flux of extraterrestrial dust in the stratosphere is 3×10^{-6} particles m^{-2} s^{-1} (diameter $\geq 10\mu m$). In the 2-30 μm size range most of the particles are true micrometeorites and have not melted during atmospheric entry. Although a variety of particle types has been observed it presently appears that they all originate from a common parent body type, possibly typical for interplanetary meteoroids, which consists of an opaque fine-grained matrix material containing minor amounts of inclusions. The matrix is an aggregate of 1000 A sized grains whose cumulative composition is close to cosmic abundances; it is very black and probably contains >2% finely dispersed carbon. Imbedded in the fine-grained matrix are occasional micron-sized inclusions, primarily Ni bearing iron sulfides, (similar to troilite) and olivines and pyroxenes with compositions clustering towards forsterite and enstatite. The only known materials which are similar to the recovered micrometeorites in elemental abundances, texture, mineralogy and inclusion content are type 1 and the matrix of type 2 carbonaceous chondrite meteorites. If micrometeorites are cometary particles which formed by aggregation of pre-solar interstellar grains, (Cameron 1973) then the similarity of micrometeorites and C1 chondrites may indicate that a significant fraction of interstellar grains formed in environments similar to those which produced C. chondrite meteorites.

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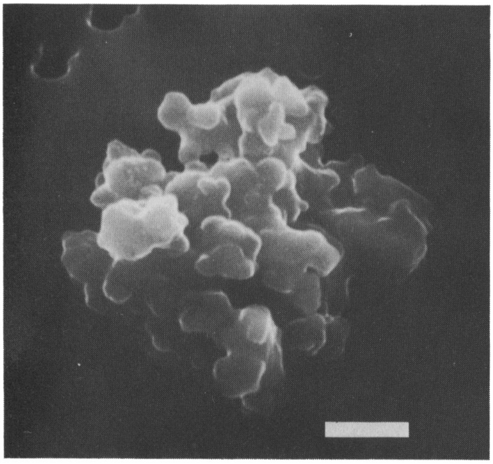

Fig. 1 Typical chondritic aggregate particle. All scale bars = 1 µm.

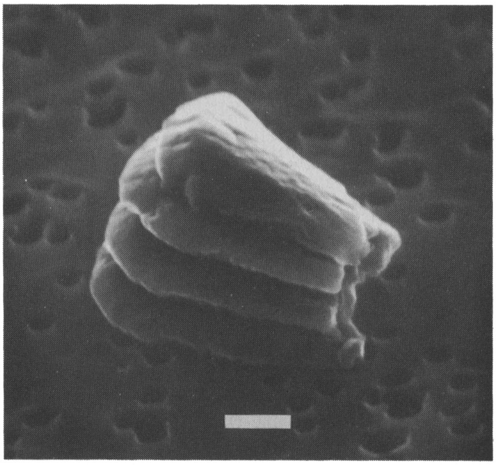

Fig. 2 FSN particle with morphology similar to Cl magnetite (Jedwab, 1971).

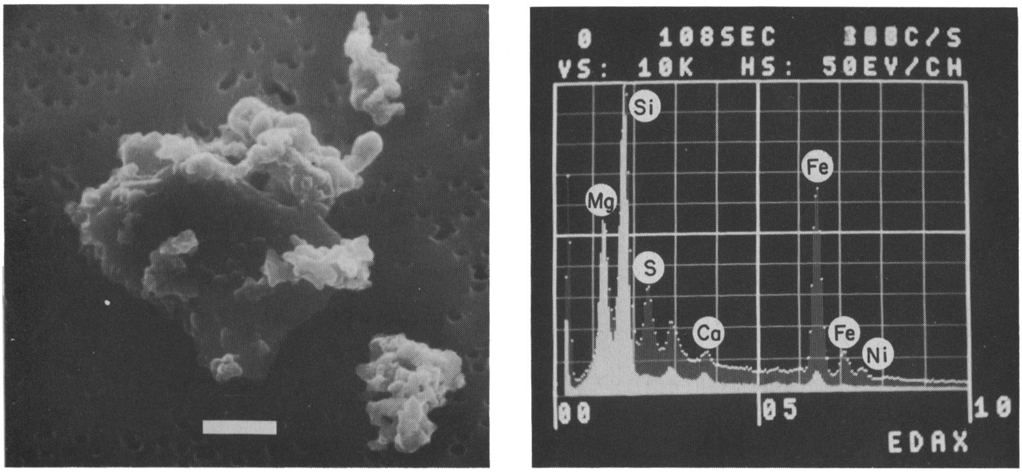

Fig. 3 A 3µm enstatite grain with chondritic material adhering to its surface and lying next to it. The double X-ray spectra (20 KV excitation) are for the enstatite grain (solid bright bars) and for adhering chondritic clump (faint bars topped with dots). The Mg and Si peaks are identical for both spectra. The condritic spectra is an exact match with cosmic abundances. Peak between S and Ca is Pd coating.