A WORKING TAXONOMY FOR MICROMETEORITES
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A simple classification system for micrometeorites has been derived from examination of nearly 500 extraterrestrial particles collected in the stratosphere. The system is intended to be useful in categorizing particles with routine SEM-EDX and optical examinations.

Ablation Spherules
A minor fraction of 5μm to 50μm particles are ablation spherules and by definition are not true micrometeorites. The most common of these are the type S and the FSN spheres. The type S (stony) particles are similar to the most common 0.1 to 1mm "cosmic spheres" in ocean sediments (1) and are opaque particles composed of olivine, magnetite and residual glass. Like the deep sea type S spheres the stratospheric ones have chondritic elemental compositions except for large depletions in Na and S, due to volatilization, and moderate to large depletion in Ni which occurs due to loss of a siderophile-rich melt during atmospheric heating. The FSN spheres are composed of nickel bearing iron sulfide and magnetite, and are believed to be the product of atmospheric melting and oxidation of sulfide. They have not been found as >100μm deep sea spherules. This may be due to total volatilization of S during atmospheric entry, or to low surface tension of the sulfide melt which causes large droplets to break up before reaching the earth's surface. Rare ablation spherules are the type I and the CAT particles. The type I (iron) are composed of magnetite, wüstite and kamacite or taenite. The type I's are common as >100μm spheres in ocean sediment but are rare in the stratosphere as particles <100μm. The CAT spheres are transparent silicate spheres which have compositions depleted in S and Fe and enriched in Ca, Al and Ti relative to chondritic proportions. Although it is not certain that CAT spheres are really extraterrestrial they could be the products of extreme heating of chondritic materials in which S, Fe and Si are depleted by vaporization.

Chondritic Micrometeorites
The majority of stratospheric extraterrestrial particles in the 5μm to 50μm size range are fine grained black particles with chondritic elemental compositions. At the sensitivity of SEM-EDX analyses, the elements Na, Mg, Al, Si, S, Ca, Cr, Mn, Fe and Ni are detectable and match CI abundances typically within a factor of 2 for all elements. The most variant element is Ca which ranges from CI abundance to depletions of more than a factor of ten. Significant deviations of other elements from chondritic ratios are often due to modulation by inclusion of a large single mineral grain embedded in the particle. For example, abnormally high S is often accompanied by high Fe due to the existence of a single large sulfide grain buried in the particle.

The basic chondritic particle types are samples of the fundamental parent materials from which nearly all interplanetary particles are derived. Most of the particles with non-chondritic compositions are particles which have fine grained chondritic composition materials adhering to their surfaces implying that the particles originally were embedded in a chondritic composition matrix. In general the non-chondritic particles are named for their dominant mineral. In nearly all cases non-chondritic materials collected as individual particles <5μm are also found as submicron grains in "normal" chondritic particles.

The chondritic particles are highly complex and the present classification system is only a first attempt to place them into distinct groups. TEM studies have shown diversity among particles within a given group (2) but at present it is not obvious that these subclasses can be detected without detailed and time consuming TEM observation. Hopefully second generation criteria will be developed for SEM-EDX classification of chondritic particles because classification on a routine and nondestructive basis is really only practical with the SEM.

CP (chondritic, porous) The CP's are very fragile, porous particles which have no meteoritic counterparts. These are porous aggregates of relatively equidimensional sub-micron grains with the aggregate porosity ranging to well over 50% in some cases. The
CP's commonly fragment during collection and handling and are difficult to work with. They usually contain a few micron sized grains of pyrrhotite, enstatite or olivine but the mineralogy of the bulk of the submicron grains is poorly understood. There is no evidence suggesting that these particles contain hydrated phases.

CF (chondritic, filled) The CP's are black aggregates of submicron grains and appear to be identical to the CP's except that there are no pore spaces between grains. There is not a clear dichotomy between CF and CP but rather they are end members of a continuous range of porosity. Controlled pulsed heating experiments done on CP and CF particles do not indicate that the porosity difference is a result of atmospheric heating. X-ray diffraction patterns for these particles are very weak indicating that the dominant materials are poorly ordered or extremely fine grained. Observed lines in descending frequency of occurrence are pyrrhotite, magnetite, olivine and kamacite. The sulfide lines are primary but it is suspected that all of the others may be due to decomposition and reduction of the matrix during atmospheric heating. Distinction of a true CF from a large single mineral grain encrusted with CP or CF material often requires very careful optical and SEM-EDX examination.

CS (chondritic, smooth) As seen in the SEM the surfaces of CS particles are smooth on a scale of microns or they contain regions which are smooth and have chondritic compositions. In the SEM the CS particles resemble CI/CM matrix. Some but not all of the particles have large Ca depletions and some contain phyllosilicates as identified by XRD and TEM techniques. Like CI material, these particles sometimes weather in ambient laboratory conditions with sulfate and other materials forming hair-like growths protruding from the particle surface.

MMS (metal mound silicate alias mickey mouse spheres). The MMS particles are composed of silicate materials covered with kamacite mounds. Some of the MMS are surrounded by carbonaceous material which is assumed to be graphite. Extensive laboratory simulation studies indicate that these are CP, CF or CS particles which were heated to temperatures near to or above their 1300°C melting point in an environment of low oxygen partial pressure. The metal is produced by reduction from the silicate by carbon.

Non-chondritic Micrometeorites

FSN (iron, sulfur, nickel) The most common non-chondritic particles are composed of pyrrhotite, magnetite and sometimes pentlandite. Presumably the magnetite is the result of atmospheric heating. The FSN particles occur as broken fragments, rounded particles, euherdal crystals and stacks of platelets. They have not been observed to occur with metal although they have been seen associated with olivine and pyroxene. Most of the particles contain detectable Ni and a minor fraction contain Zn up to a few percent. FSN particles above 10 μm that survive atmospheric entry without melting are exceedingly rare, probably due to their low melting point and high density.

Mafic The mafic particles are usually composed of enstatite or olivine and they occur both as monomineralic and polymetallic materials. The particles range from angular to rounded but only rarely show crystal facets. Many of the particles have chondritic surface material which sometimes makes the particles nearly opaque. Some of the particles have sulfide mounds and mafic particles have been observed that have attached phosphates and diopside.

FN (nickel, iron sometimes with magnetite) These particles usually have roughly the cosmic Fe/Ni ratio and no detectable Cr by EDX. The particles have been observed as crystals and, irregular shapes and flakes.

Carbonate The only carbonate which has been identified is a translucent white calcite particle with chondritic surface material. EDX and XRD indicates that the particle is fairly pure calcite.

Phosphate Phosphate micrometeorites are rare but they appear to be more abundant than phosphates in carbonaceous chondrites. Both Ca and Mg phosphates occur.

Ca Al Silicates A few silicates were found whose compositions are consistent with high temperature condensates. The particles are polymetallic but the major phase appears to be melilitte.