These properties contribute to a state of high free energy that wild determine particle alteration when energy to activate mineral reactions is scarce. The principal components of chondritic IDPs collected in the lower stratosphere contain a tremendous amount of information on the nature of dusts and processes in the solar nebula. They are a window to the earliest time of our solar system, and to ongoing processes in our galaxy.

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1.5 Cosmogenic Matter in Terrestrial Environments

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The accretionary influx of extraterrestrial matter onto the Earth amounts to about 40000 t/a and is delivered mainly by meteoroids in the size range 50–400 μm (median 220 μm – Love and Brownlee 1993). Not all particles of this size can survive atmospheric entry unaltered. Most are frictionally heated to such an extent that partial to total melting and also partial evaporation takes place (e.g., Kornblum 1969). However, small particles and some of the larger ones penetrating the atmosphere at low velocities and almost tangential entry angles can enter without being melted (Brownlee 1981; Bonny and Balageas 1988; Love and Brownlee 1991).

Melted interplanetary dust particles, cosmic spherules, are omnipresent in sediments throughout geological times (e.g., Taylor and Brownlee 1921). Unmelted interplanetary dust is certainly also present but not easily distinguished from terrestrial dust. It can, therefore, be collected only in places were there are low amounts of terrestrial dust.

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One such place is the stratosphere, where interplanetary dust can be collected utilizing high-flying aircraft or balloons (e.g., Brownlee 1985). However, only small dust particles (average diameter about 10 µm) can be collected in this way, but not the large ones, for several reasons (e.g., Warren and Zolensky 1994). Such particles (stratospheric interplanetary dust particles – SIDPs, unfortunately commonly called IDPs) have been available for study for more than 15 years. Since 1984 also large unmelted interplanetary dust particles – micrometeorites (MMs) – have been available from Greenland ice (Maurette et al. 1986) and subsequently also from Antarctica (Maurette et al. 1991).

In Greenland, micrometeorites can be retrieved from "cryoconite", a dark sediment in melt-water lakes, which consists of dust and cocoons of blue algae and siderobacteria. On average, cryoconite contains about 10 g/kg fine-grained sand and dust, mostly of terrestrial origin, and about 800 cosmic spherules and 200 unmelted to partially melted micrometeorites.

In Antarctica, micrometeorites can be harvested by artificially melting the proper ice. One ton of Antarctic blue ice contains about 100 cosmic spherules with diameters >50 µm and about 500 unmelted to partially melted MMs 50–400 µm in size. Now, fortunately, large amounts of unmelted and almost unaltered samples of the interplanetary dust particles which contribute most to the recent accretion rate on Earth are available for study.

The Nature of Interplanetary Dust

Many micrometeorites have suffered severe alteration by frictional heating in the atmosphere. They are partially to almost totally melted, consisting of foamy glass with variable amounts of unmelted phases. Others have been thermally altered (metamorphosed) but not melted and a few have grossly retained their pristine mineralogy. Some micrometeorites suffered additional alterations in the hostile terrestrial environment.

The pristine mineralogy of micrometeorites is surprisingly simple (e.g., Maurette et al. 1991, 1994; Kurat et al. 1993, 1994a; Klöck and Stadermann 1994). Major minerals are olivine, low-Ca pyroxene, magnetite, and hydrous Mg-Fe silicates (phyllosilicates) like serpentine and saponite. Individual MMs are usually dense, low-porosity mixtures of anhydrous and hydrous phases in proportions ranging from fully anhydrous (coarse-grained "crystalline" micrometeorites) to fully hydrous mineral assemblages (phyllosilicate micrometeorites).

Minor phases comprise Ca-rich pyroxenes, feldspars, Fe-Ni sulfides and metal, Mg-Fe hydroxides, Mg-Al and Fe-Cr spinels, perovskite, ilmenite, hibonite, and others.

The major silicates have highly variable Fe/Mg ratios, even within a given particle (unequilibrated mineral assemblage) and are usually very rich in minor elements as compared to their terrestrial counterparts (Fig. 10).

The hydrous minerals contain some elements in chondritic abundances (e.g., Ti, Al, Cr, Na, K).

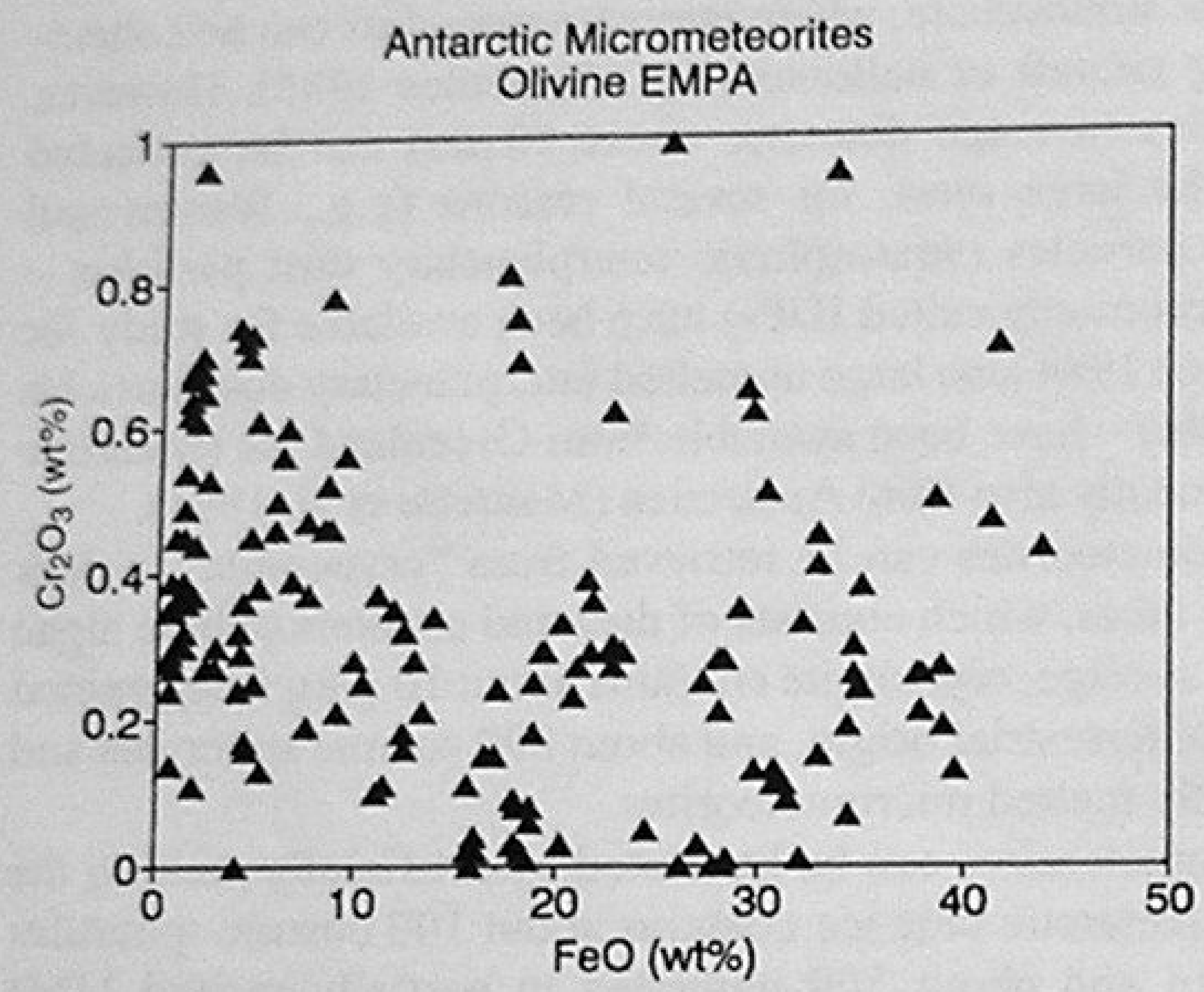

Fig. 10. Plot of Cr_2O_3 vs. FeO contents (wt.%) of olivines from micrometeorites which have varying FeO contents and commonly high Cr_2O_3 contents (terrestrial olivines usually do not contain Cr). Olivines with <0.5 wt% FeO, which are common in CM and CR chondrites, are very rare in MMs

Refractory minerals like Mg-Al spinel are strongly enriched in refractory trace elements (e.g., rare earth elements, Sc, Zr, Hf, etc. – Kurat et al. 1994b) as compared to chondritic rocks.

The mineralogy, mineral chemistry, and the presence of refractory minerals in MMs are similar to those of CM-type (Mighei-type) an CR-type (Renazzo-type) carbonaceous chondrites. However, there are some differences between MMs and CM/CR chondrites, like the presence of abundant Ca-poor pyroxene in MMs (most CM chondrites do not contain such pyroxenes), the lack of very Fe-poor olivines with high Al and Ca contents in MMs (they are common in CM and CR chondrites), and the high abundance of Fe-rich olivines and pyroxenes in MMs.

Bulk major and minor element abundances in phyllosilicate-rich MMs are chondritic, except for Ca, Na, Ni, and S, which are depleted with respect to CI (and CM/CR) chondrites (Fig. 11). Coarse-grained crystalline, anhydrous MMs deviate from the chondritic composition, a feature typical also for anhydrous aggregates and chondrules in carbonaceous chondrites.

Lithophile trace element abundances in phyllosilicate-rich MMs (Fig. 12) follow the abundance pattern of CM chondrites (which is also similar to that of CR chondrites) and deviate from that only in the abundance of K. However, the abundances of siderophile elements in MMs, deviate significantly from those of CI and CM/CR chondrites.

Only the highly refractory elements Os and Ir and the highly volatile Se have abundances similar to those in CI and CM/CR chondrites. The common

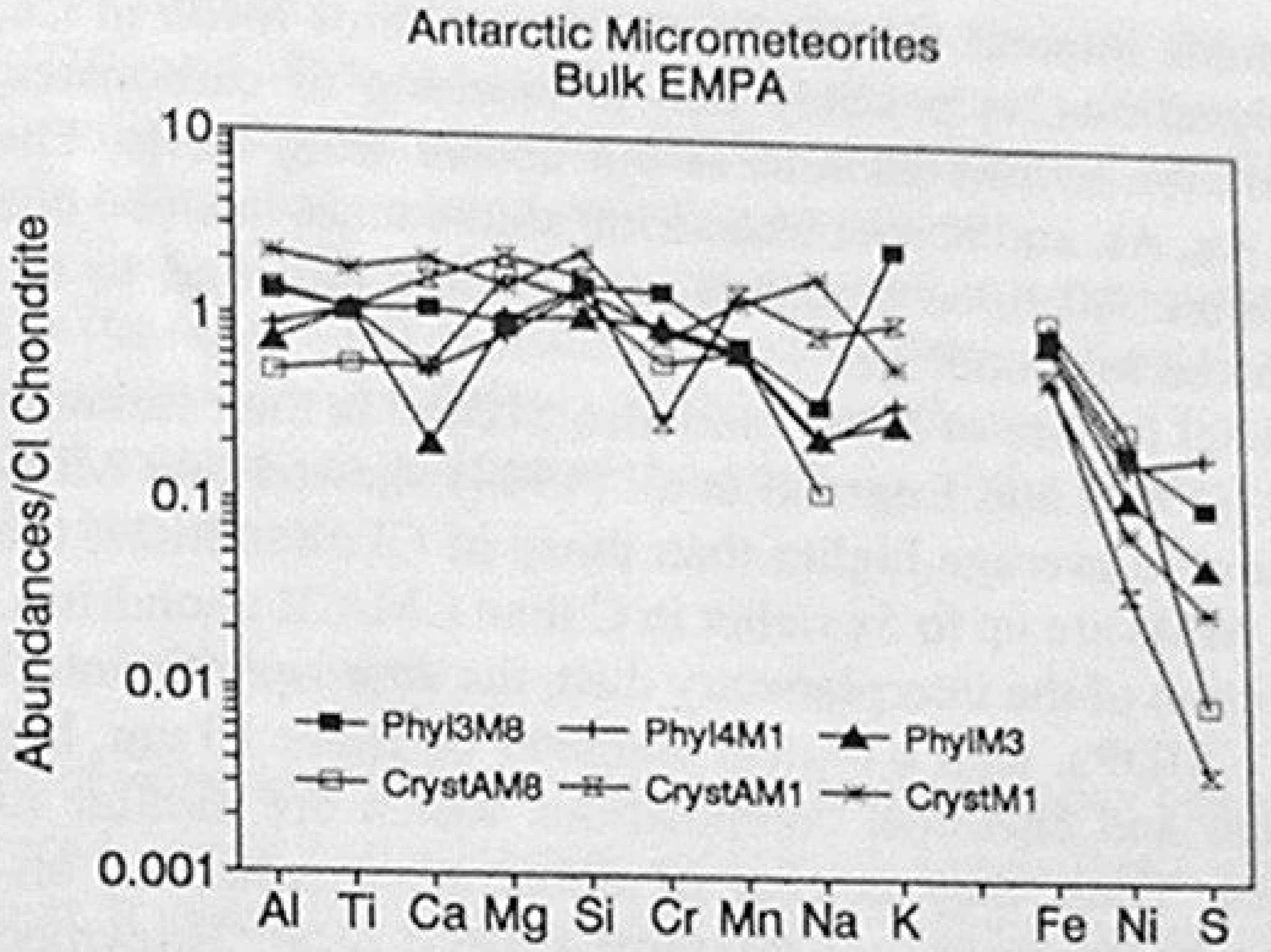

Fig. 11. Chondrite-normalized major and minor element abundances in phyllosilicate-rich and anhydrous crystalline micrometeorites (electron microprobe data from Kurat et al. 1994). Lithophile (*left*) and siderophile (*right*) elements are arranged in order of increasing volatility

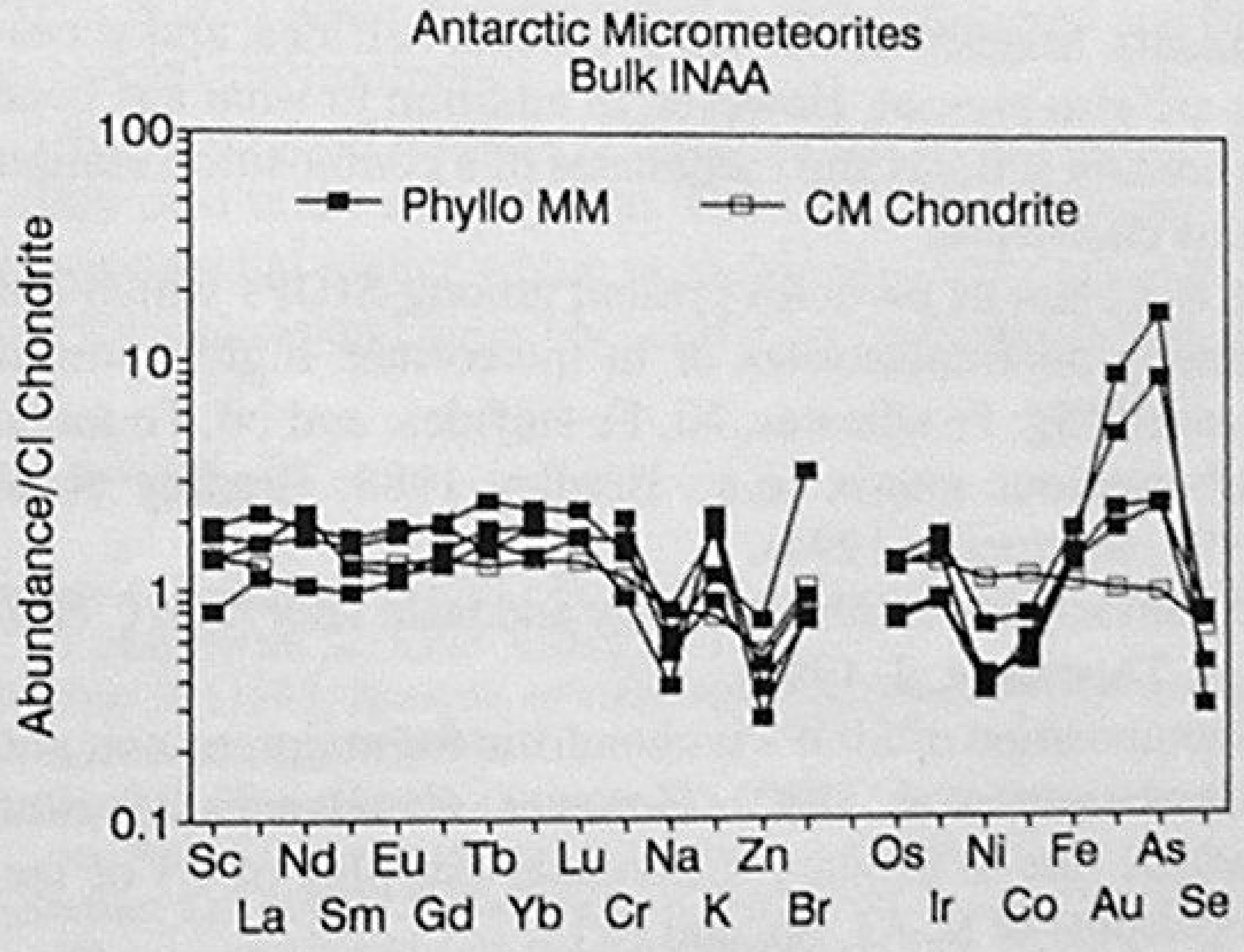

Fig. 12. Chondrite-mormalized abundances of selected trace elements in phyllocilicate-rich micrometeorites (INAA data from Kurat et al. 1994). Lithophile (*left*) and siderophile (*right*) elements are arranged in order of increasing volatility

siderophile elements Ni and Co are depleted compared to chondritic abundances and also fractionated from each other (the Ni/Co ratio is nonchondritic). Iron is enriched over chondritic abundances (moderately), as are Au and As (strongly). The depletion in Ni, Co, and S has been shown (Presper et al. 1993) to be due to terrestrial leaching of Ni-bearing Mg-Fe sulfates from MMs.

Micrometeorites do not contain sulfates which, on the other hand, are abundant in CM and CI chondrites. Large voids present in some MMs may have been occupied by a soluble mineral. Similarly, the depletion of MMs in Ca, as compared to CM chondrites, is possibly due to leaching of carbonates, minerals which are common in CM chondrites but absent from MMs. The enrichments of MMs in Au, As, and K over chondritic abundances must be due to terrestrial contamination. All three elements are strongly enriched in the terrestrial crust as compared to chondrites.

A special compositional feature of MMs (and also SIDPs) is their richness in carbon. Perreau et al. (1993) and Engrand et al. (1994) showed that MMs have C/O ratios which are on average higher than those of CI chondrites, the most C-rich chondrites.. MMs are up to 5x richer in C than CM/CR chondrites.

The small particle portion of the interplanetary dust, the stratospheric interplanetary dust particles – SIDPs, with a typical diameter of about 10 µm, has in principle mineralogical and chemical compositions which are similar to those of micrometeorites. Thus, they consist of either phyllosilicates, anhydrous silicates (olivine or pyroxene), or mixtures thereof (e.g., Brownlee 1985; Bradley 1988; Klöck and Stadermann 1994; Zolensky and Barrett 1994). Also, the chemistry of the major phases is very similar to that of MM phases, i.e., olivine and pyroxene have varying Fe/Mg ratios, and high contents of minor elements and phyllosilicates are mostly saponite with minor serpentine, both rich in minor elements. Magnetite, Ca-rich pyroxene, sulfides, and accessory refractory phases are also present. However, in addition to what has been found in MMs, SIDPs contain sulfates and carbonates of a composition similar to those of carbonaceous chondrites.

Furthermore, there is a class of particles present among SIDPs which has not yet been found among micrometeorites or in meteorites: highly porous aggregates of sub-µm-sized Mg, Fe silicates, Ni, Fe sulfides, and Ni, Fe metal in a glassy and/or carbonaceous matrix (e.g., Bradley 1988; Bradley et al. 1992; Thomas et al. 1994; Rietmeijer 1994).

These aggregates commonly are extremely fluffy and have very high C contents (up to 13×CI, e.g., Thomas et al. 1994).

The chemical bulk composition of SIDPs is chondritic for major, minor, and trace elements (e.g., Jessberger et al. 1992). However, abundances of some elements are nonchondritic due to primary differences (surplus of C) or terrestrial contamination (surplus of K, As, Sb, and Br).

The isotopic composition of several elements has been found to be nonterrestrial and, in some cases, also nonsolar, in both MMs and SIDPs (e.g., McKeegan 1987; Stadermann 1991; Hoppe et al. 1995; Engrand et al. 1996). Specifically, anomalies in isotopic abundances of H/D, C, N, and O have been found.

Interplanetary dust has been exposed to the solar wind and cosmic rays for a sufficiently long time to accumulate large amounts of noble gases and spallogenic isotopes. They have, for example, very high He (up to 10^{-1} $cm^3 g^{-1}$ at STP) and Ne contents – in excess of 10^{-5} $cm^3 g^{-1}$ at STP – comparable to only a few very gas-rich chondrites and the lunar soil (e.g., Maurette et al. 1991; Nier 1994).

Helium and neon isotope abundances confirm the extraterrestrial origin of SIDPs and MMs (and some cosmic spherules) as they are comparable to those of solar energetic particles (SEP). In addition, a small contribution from cosmic ray spallation neon was also identified.

Thus, SIDPs and MMs were exposed to cosmic rays and to the solar wind. For the solar wind exposure, the particles must have been of the size recovered. Thus, MMs and SIDPs (e.g., Nier and Schlutter 1990) are true interplanetary dust meteoroids and cannot be products of the breakup of a larger meteoroid in the atmosphere.

Conclusions

Interplanetary dust accreting onto the Earth today bears some similarities to the rare CM/CR carbonaceous chondrites, but differs form them in so many ways that it must be considered a Solar System matter of its own. The features making it different from chondrites are likely to be of primordial origin. These include the mineral abundances, mineral chemistry, the bulk C content, and the presence of unique, fluffy, fine-grained aggregates.

Some deviations in the dust composition from that of chondrites are due to extraction of water-soluble sulfates and carbonates and contamination from the terrestrial environment.

We have good reasons to favor comets as the source of most of the interplanetary dust in the solar system. Therefore, interplanetary dust allows us to study the primordial matter which probably supplied the Earth with volatile elements and the oceans and, possibly, with the ingredients for the development of life.

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