Physics, Chemistry, and Dynamics of Interplanetary Dust
ASP Conference Series, Vol. 104, 1996
Bo A. S. Gustafson and Martha S. Hanner (eds.)

Collection and Microanalysis of Antarctic Micrometeorites

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Abstract. Micrometeorites (MMs) represent the most common interplanetary dust particles (50-500 μm). They are similar to carbonaceous chondrites (CCs) but do not match, mineralogically and chemically, known CC types.

1. Introduction

The present day accretionary influx of extraterrestrial matter onto the Earth (about 40.000 t/a) is dominated by meteoroids in the size-range 50-400 μm with most of the mass being delivered by particles around 220 μm in diameter (Love & Brownlee 1993). Such large particles cannot survive atmospheric entry unaltered. They should be in general frictionally heated to such an extend that partial to total melting and even partial evaporation will occur (e.g., Kornblum 1969). However, for low entry velocities and almost tangential entry angles there exists a small window which allows large particles to enter without being melted (Brownlee 1981, Bonny et al. 1988). Unmelted particles were not found in deep sea sediments where they are indistinguishable from terrestrial matter. In contrast, cosmic spherules, the products of melting of sub-mm-sized interplanetary dust particles, can easily be identified and can also be found in sediments throughout geological times (e.g., Taylor & Brownlee 1991). Large unmelted interplanetary dust is also unlikely to be ever captured during U2 stratospheric collection flights for several reasons (e.g., Warren & Zolensky 1994). With the first successful recovery of large unmelted interplanetary dust particles - micrometeorites - from Greenland ice (Maurette et al. 1986) a new window into interplanetary matter was opened. Subsequent searches in Antarctica were highly successful and provided large amounts of unmelted and almost unaltered samples of the interplanetary dust particles which contribute most to the recent accretion rate on Earth (e.g., Maurette et al. 1991). For only a few years have such samples been available for study and, therefore, our knowledge of them is still fragmentary.

2. Collection

The first unmelted micrometeorite (MM) samples were collected in Greenland in July 1984 by sampling "cryoconite", a dark sediment consisting of dust and cocoons of blue algae and siderobacteria, from a melt water lake (Blue Lake I) situated about 20 km from the margin of the Sondestromfjord ice field. This lake contained sediments from melt water formed through about 2000 years (e.g., Maurette et al. 1986). Many more lakes were sampled during subsequent years and as of today a total mass of about 250 kg of wet cryoconite from more than 50 locations is available. Cryoconite typically contains fine-grained sand and dust (~10 g/kg), most of it of terrestrial origin. Extraterrestrial matter is present in minor amounts. On average ~800 cosmic spherules and ~200 partially melted to unmelted MMs are present in 1 kg of wet cryoconite. It is usually easy to recover cosmic spherules and MMs from cryoconite but some mechanical force has to be applied to remove the particles from the siderobacteria "cocoons". This and the metabolism of the siderobacteria leads to an unwanted bias in the collection because only tough particles survive to be analyzed. In spite of these shortcomings, the Greenland ice sheet remains the most promising location for collecting interplanetary particles >500 μm (minimeteorites).

The biases introduced by the cryoconite in Greenland can be avoided by searching for MMs in the Antarctic ice shield which is usually free of melt water and hence cannot support siderobacteria. The first attempt to recover micrometeorites from Antarctic ice by melting pockets of ice was highly successful (season December 1987 - January 1988; see also Maurette et al. 1994 for a summary). So far about >600 tons of ice have been melted and cosmic spherules and micrometeorites were collected in the size-range 50-$>$400 μm. The concentration of extraterrestrial matter in the blue ice fields of Antarctica is surprisingly high. About 100 cosmic spherules with diameters >50 μm were collected per ton of ice. The ratio of spherules to partially melted and unmelted MMs is <0.2 in the size-fraction richest (~10%) in extra-terrestrial matter (50-100 μm). Thus, the total amount of partially melted and unmelted MMs collected up to date is about 100.000. Future collecting is designed to extend the range in particle size in both directions in spite of the fact that the small (<50 μm) dust particles from Antarctic ice are heavily dominated by terrestrial eolian dust.

3. Methods

The small size and mass of MMs allows only the application of microanalytical techniques. The investigation of a specific particle usually begins with a study of its shape and surface by optical microscopy. The mass is determined with an ultramicro-balance (typical masses are 1-20 μg). It is then analyzed for a variety of major and trace elements (up to 35 elements depending on sample mass and element content) by instrumental neutron activation analysis (INAA). Its surface is then investigated by analytical scanning electron microscopy (ASEM). Next either the whole particle or portions thereof are embedded in epoxy, polished, and studied by optical microscopy and ASEM and the bulk as well as the individual phases present are analyzed by utilizing an electron microprobe X-ray analyzer. Samples can be taken from the polished mounts as well as from splits of the particle and mounted in epoxy, ultramicrotomed and investigated with the transmission electron microscope. The same polished mount or aliquots can be analyzed by a variety of non-destructive (optical spectroscopy, cathodoluminescence, proton induced X-ray emission, synchrotron X-ray fluorescence, Raman spectroscopy, etc.), partly destructive (e.g., secondary ion mass spectrometry - SIMS, a diversity of laser ablation techniques, etc.), and finally totally destructive methods (e.g., rare gas analysis).

Fig. 1: Phyllosilicate-rich micrometeorite with abundant play and framboidal magnetites (white) typical of CI, CM, and CR chondrites. Note the large voids, probably the sites of water soluble minerals. Scanning electron microscope image of polished mount. Scale bar is 10 µm.

https://doi.org/10.1017/S0252921100501675 Published online by Cambridge University Press

4. Results

We present here a selection of the most important results published to date on micrometeorites. We will refer to other extraterrestrial matter like meteorites and to the small particle fraction of the interplanetary dust (the stratospheric interplanetary dust particles - SIDPs) only for comparison purposes. A large number of unmelted micrometeorites has suffered severe alteration by heating. Many of them are partially to almost totally melted, consisting of foamy glass with variable amounts of unmelted phases. Other MMs have been thermally altered (metamorphosed) but not melted. These and the few unaltered MMs provide the basis for the general characterization of MMs. We will also discuss the various alterations some MMs suffered in the terrestrial environment. The summary is mainly based on the reports by Maurette et al. (1991, 1993, 1994), Kurat et al. (1993, 1994a), Kloeck & Stadermann (1994), and a variety of special investigations which will be cited separately.

4.1 Mineralogy and Mineral Chemistry

The mineralogy of micrometeorites is surprisingly simple. Major minerals are olivine [$(Mg,Fe)_2SiO_4$], low-Ca pyroxene [$(Mg,Fe)SiO_3$], magnetite (Fe_3O_4), and hydrous Mg-Fe silicates (serpentine and clay minerals). Individual MMs are usually dense, low-porosity mixtures of varying proportions of anhydrous and hydrous phases (Fig. 1). Minor phases include Ca-rich pyroxenes -$(Ca,Mg,Fe)_2Si_2O_6$- , feldspars -$(Ca,Na,K)(Si,Al)_4O_8$, Fe-Ni sulfides and metal, Mg-Fe hydroxides, Mg-Al and Fe-Cr spinels -$(Mg,Fe)(Al,Cr)_2O_4$-, perovskite ($CaTiO_3$), ilmenite ($FeTiO_3$), hibonite [$Ca(Al,Ti)_{12}O_{18}$], and others. The major silicates are highly variable in their 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. The 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) compared to chondritic rocks.

The mineralogy, mineral chemistry, and the presence of refractory minerals in MMs are similar to those of carbonaceous chondrites, in particular CM-type (Mighei-type) and CR-type (Renazzo-type) carbonaceous chondrites. However, the match is not perfect. Major differences between MMs and CM/CR chondrites are 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.

4.2. Bulk Chemistry

Bulk major and minor element abundances (Fig. 2) in phyllosilicate-rich MMs are chondritic, except for Ca, Na, Ni, and S, which are depleted with respect to CI (and CM/CR) carbonaceous chondrites. 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. 3) straddle the abundance pattern of CM chondrites (which is also similar to that of CR chondrites) and deviate from

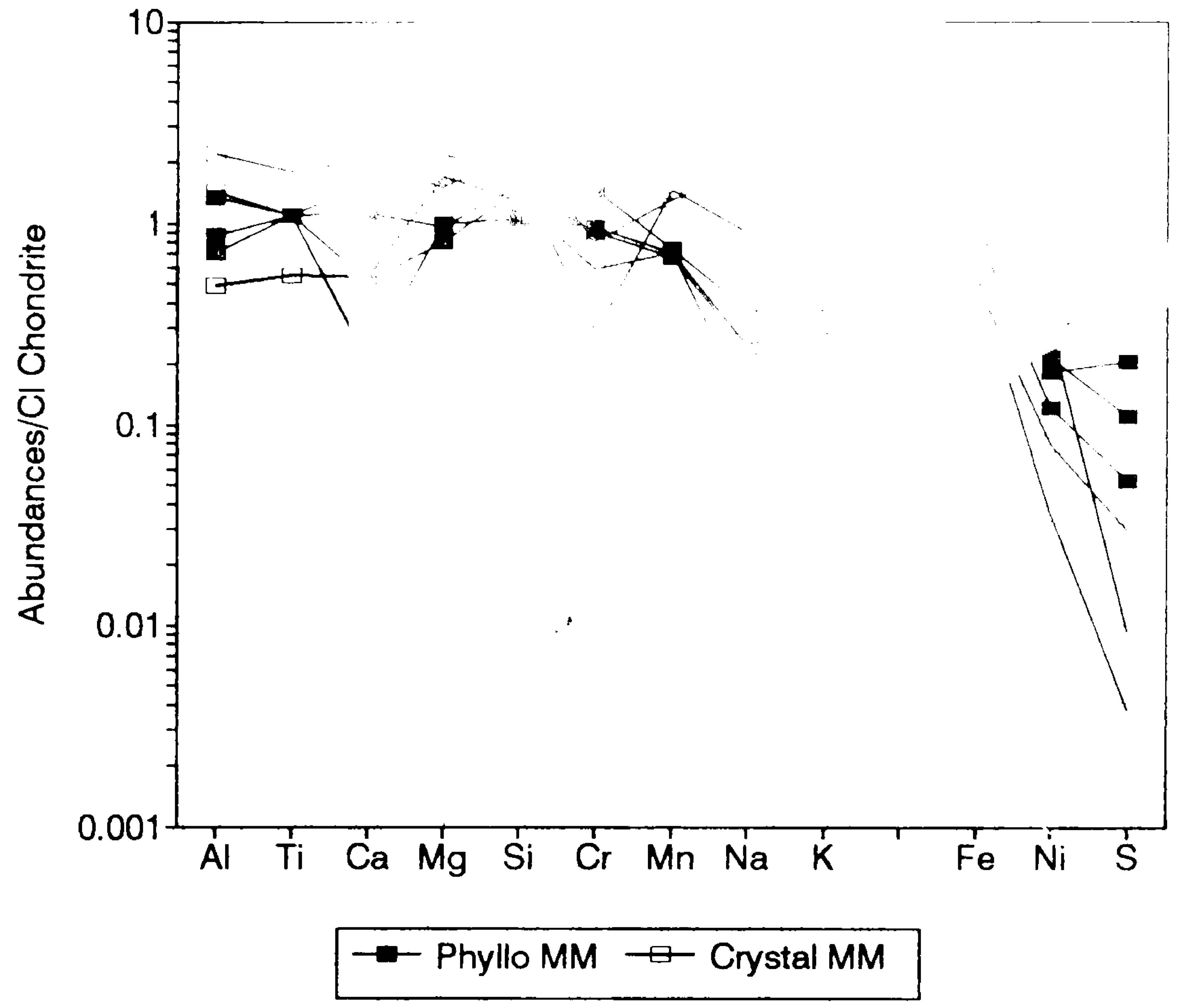

Fig. 2: Chondrite-normalized major and minor element abundances in phyllosilicate-rich and coarse-grained crystalline micro-meteorites (electron microprobe data from Kurat et al. 1994). Lithophile (left) and siderophile (right) elements are arranged in order of increasing volatility.

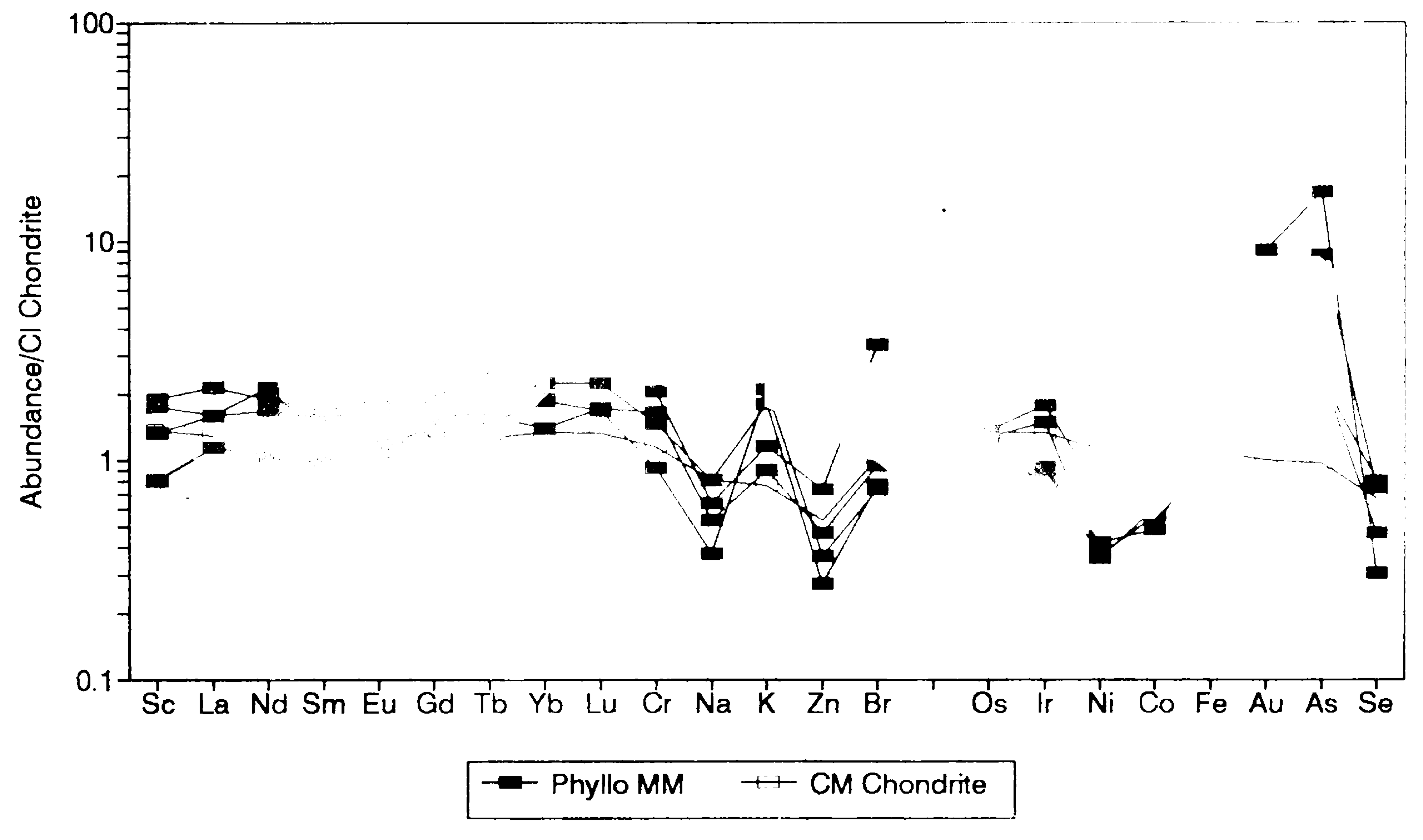

Fig. 3: Chondrite-normalized abundances of selected trace elements in phyllosilicate-rich micrometeorites (INAA data from Kurat et al. 1994) and CM (~CR) chondrites. Lithophile (left) and siderophile (right) elements are arranged in order of increasing volatility.

that only in the abundance of K. However, the abundances of siderophile element in MMs are significantly fractionated as compared to CI and CM/CR chondrites Only the highly refractory elements Os and Ir and the highly volatile Se are preser at CI and CM/CR chondrite abundances. The common siderophile elements Ni an Co are depleted compared to chondritic abundances and also fractionated from eac other (the Ni/Co ratio is non-chondritic). Enriched over chondritic abundances ar Fe (moderately) and Au and As (stongly). The depletion in Ni, Co, and S has bee shown (Presper et al. 1993) to be due to terrestrial leaching of Ni-bearing Mg-F sulfates from MMs. Indeed, MMs do not contain sulfates which are abundant i CM and CI chondrites. Large voids present in some MMs may have been occupie by a soluble mineral (Fig. 1). Similarily, the depletion of MMs in Ca as compare to CM chondrites is possibly due to leaching of carbonates, minerals which ar common in CM chondrites but absent from MMs. The enrichments of MMs in Au As, and K over chondritic levels must be due to terrestrial contamination. All thre elements are strongly enriched in the terrestrial crust as compared to chondrites. A very special compositional feature of MMs (and also SIDPs) is their richness i carbon. Perreau et al. (1993) and Engrand et al. (1994) showed that MMs hav 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 chondrites - anothe distinct difference between these two solar system matters.

4.3. Isotopic Compositions

A few attemps have been made to measure stable isotope abundances in MMs. A search for D anomalies was negative (Alexander et al. 1992) and subsequer searches (unpublished) were also not successful. This is in clear contrast to th results obtained from SIDPs which commonly bear D anomalies (e.g., Messenge & Walker, this volume). Also, searches for anomalies in isotopic abundances of (and N failed (Stadermann & Olinger 1992). Anomalies in O isotope abundance have been found in several refractory spinel-rich objects in MMs (Hoppe et al 1995). The anomalies in MM ^{16}O abundances are comparable to those i chondrites and SIDPs (e.g., McKeegan 1987). Calcium and Ti isotope anomalie have not yet been seen in MMs.

4.4 Rare Gas Analysis

So far only the concentration and isotopic composition of Ne have been measure in MMs and cosmic spherules (Olinger 1990, Maurette et al. 1991). Many of th MMs have - not unexpectedly (Eberhardt & Eberhardt 1988) - very high N contents - in excess of $10^{-5}cm^{-3}g^{-1}$ at STP, comparable only to a few very gas-ric chondrites and the lunar soil. Neon isotope abundances confirm the extraterrestria origin of MMs (and some cosmic spherules) as they are comparable to those o solar energetic particles (SEP) neon. In addition, a small contribution from cosmi ray spallation neon was also identified. Thus, MMs were exposed to cosmic ray and to the solar wind. For the solar wind exposure the particles must have been o the size as recovered. Thus, MMs (and by anology also the SIDPs - see Nier & Schlutter 1990) are true interplanetary dust meteoroids and cannot be products o the break-up of a larger meteoroid in the atmosphere.

5. Discussion

The collection of data on MMs is still very incomplete. However, what is available today is sufficient to place some constraints on the nature of the matter constituting the main mass of the interplanetary dust of the solar system. There can be (and probably is) a bias in our sample against highly porous and friable particles. Such particles constitute about half of the SIDPs (Brownlee 1985) and are not known from any other extraterrestrial material available to us. It is likely that this porous matter is not very abundant among the larger interplanetary dust particles but some can be expected. The physical weakness of these particles, however, prevented their recovery. New recovery procedures should help to answer that question.

As to the composition of MMs, the mineralogical and bulk chemical characteristics unequivocally point towards carbonaceous chondrite matter, in particular CM and/or CR carbonaceous chondrites. Such chondrites are rare, representing less than 3% of all recent meteorite falls (e.g., Dodd 1981). The most common meteorites, ordinary chondrites (80% of falls) appear to be represented by <1% of MMs (Walter et al. 1995) and other types seem to be even less abundant. Thus, the main mass of matter accreting on the Earth today is similar to rare meteorite types. This could either mean that CM/CR chondrite-type planetesimals dominate today's source region of the dust or CM/CR chondrites are rare aggregates of the most common dust in the solar system. Of course, the dust could not have survived as such for 4.6×10^9 a and, therefore, must have been stored somewhere for most of its life time and released in recent geologic time. The CM/CR chondrite parent bodies must be excluded from the possible storage candidates for several reasons. The composition and abundance of minerals in MMs do not fit those of CM/CR chondrites. The constituents of MMs could be primitive solar system matter which was processed in the solar nebula more extensively than the matter which constitutes the CM/CR chondrites. This is indicated by the high abundance of Ca-poor pyroxene (a reaction product of olivine with the solar nebula gas) and Fe-rich olivines and pyroxenes (Fe was introduced into the phases at a late stage by Mg-Fe exchange between the solids and the solar nebula gas - see Kurat 1988). In addition, the high C content of MMs precludes their derivation from CM/CR chondrite parent bodies and also points towards prolonged processing in and accumulation (organic compounds) from the solar nebula. Finally, of the >500 particles investigated by us so far, none shows any evidence of physical damage - a feature to be expected for dust produced by shattering large, dense rocks.

We are left with a few possibilities which could provide shelter for small particles for a very long time and gently release them in recent times. The only possible way to accomplish this seems to be a storage in an icy body. This way, the particles will be protected and can be gently released by sublimation of the ice. Only a few solar system bodies meet these requirements with clearly the best match provided by comets (e.g., Whipple 1950). The high C content of MMs also points into that direction. The common belief that hydrous silicates cannot be present in comets is based on another belief, namely that hydrous phases cannot be formed in the solar nebula, which certainly is erroneous.

6. Conclusions

We have good reason to believe that our sample of MMs is biased in favour of the physically tough particles of the interplanetary dust. However, this bias cannot be larger than about 50% of the total infall as the MM recovery from the ice indicates a flux of about 20.000 t/a, which compares favourably with the 40.000 t/a measured in near-Earth space. In any case, the sample we have reveals a clear picture which by all likelihood will not be fundamentally altered by addition of the possibly missing matter. Thus, it can be firmly stated that the matter accreting onto the Earth today bears some similarities to the rare CM/CR carbonaceous chondrites but differs from 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, and the bulk C content. Some deviations of the MM composition from that of chondrites are due to extraction of water soluble sulfates and carbonates. We cannot be sure about where this extraction took place. If MMs come mainly from comets, the loss of water soluble phases could already have happened on the comet parent. However, the terrestrial environment clearly offers more efficient possibilities. We do not have any hint as for the source(s) of MMs. However, we have good reasons to favour comets as the source of most of the interplanetary dust in the solar system - in accordance with conclusions reached by others on the basis of different data sets (e.g., Whipple 1967, Bradley & Brownlee 1986).

Acknowledgements

This work was done with the help of Franz Brandstätter, Christian Koeberl, Jürgen Walter, Thomas Presper, and Michel Perreau. Support was recieved from IN2P3, CNES, IFRTO, and the European Community SCIENCE Program in France and from FWF in Austria. Two anonymous reviewers contributed to the improvement of the report.

References

Alexander, C.M. O'D., Maurette, M., Swan, P., & Walker, R.M. 1992 Lunar Planet. Sci., XXIII, 7

Bonny, P., Balageas, D., & Maurette, M. 1988 Lunar Planet. Sci., XXI, 111

Bradley, J.P. & Brownlee, D.E. 1986, Science, 231, 1542

Brownlee, D.E. 1981 in The Sea, C. Emiliani (ed.), J. Wiley, vol. 7, 773

Brownlee, D.E. 1985 Ann. Rev. Earth Planet. Sci., 13, 147

Dodd, R.T. 1981, Meteorites, Cambridge: Cambr. Univ. Press, 368pp

Eberhardt, A. & Eberhardt P. 1988 Lunar Planet. Sci., XIX, 289

Engrand, C., Christophe Michel-Levy, M., Jouret, J., Kurat, G., Maurette, M., & Perreau, M. 1994 Meteoritics, 29, 464

Hoppe, P., Kurat, G., Walter, J., & Maurette, M. 1995 Lunar Planet. Sci., XXVI, 623

Klöck, W. & Stadermann, F.J 1994 in Analysis of Interplanetary Dust, M.E. Zolensky, T.L. Wilson, F.J.M. Rietmeijer, & G.J. Flynn (eds.) New York: Amer. Inst. Physics, 51

Kornblum, J.J. 1969 J Geophys. Res., 74, 1893

Kurat, G. 1988 Phil. Trans. R. Soc. London, A 325, 459

Kurat, G., Brandstätter, F., Presper, T., Koeberl, C., & Maurette, M. 1993 Russ. Geol. Geophys., 34, 132
Kurat, G., Koeberl, C., Presper, T., Brandstätter, F., & Maurette, M. 1994a Geochim. Cosmochim. Acta 58, 3879
Kurat, G., Hoppe, P., & Maurette, M. 1994b Lunar Planet. Sci., XXV, 763
Love, S.G. & Brownlee, D.E. 1993 Science, 262, 550 Lunar Planet Sci., XXII, 7
Maurette, M., Hammer, C., Brownlee, D.E., Reeh, N., & Thomsen, H.H. 1986 Science, 233, 869
Maurette, M., Immel, G., Hammer, C., Harvey, R., Kurat, G., & Taylor, S. 1994, in Analysis of Interplanetary Dust, M.E. Zolensky, T.L. Wilson, F.J.M. Rietmeijer, & G.J Flynn (eds.) New York: Amer.Inst. Physics, 277
Maurette, M., Kurat, G., Perreau, M., & Engrand, C. 1993 Microbeam Anal., 2, 239
Maurette, M., Olinger, C., Christophe Michel-Levy, M., Kurat, G., Pourchet, M., Brandstätter, F. & Bourot-Denise, M. 1991 Nature, 351, 44
McKeegan, K.D. 1987 Ph.D. Thesis, Washington University, St. Louis
Messenger, S. & Walker, R.M. this volume
Nier, A.O. & Schlutter, D.J 1990 Meteoritics, 25, 263
Olinger, C.T 1990 Ph.D. Thesis, Washington University, St. Louis
Perreau,M., Engrand, C., Maurette, M., Kurat, G. & Presper, T. 1993 Lunar Planet.Sci. Conf.XXIV, 1125
Presper, T., Kurat, G., Koeberl, C., Palme, H., & Maurette, M. 1993 Lunar Planet. Sci., XXIV, 1177
Stadermann, F.J. & Olinger, C.T 1992 Meteoritics, 27, 291
Taylor, S. & Brownlee, D.E. 1991 Meteoritics, 26, 203
Walter, J., Kurat, G., Brandstätter, F., Koeberl, C., & Maurette, M. 1995 Meteoritics, 30, 592
Warren J.L. & Zolensky, M.E. 1994 in Analysis of Interplanetary Dust, M.E. Zolensky, T.L. Wilson, F.J.M. Rietmeijer, & G.J. Flynn (eds.), New York: Amer. Inst. Physics, 245
Whipple, F.L. 1950 AJ, 111, 375
Whipple, F.L. 1967, in the Zodiacal Light and the Interplanetary Medium, J.L.Weinberg (ed.), Houston: NASA SP-150, 409
Yates, P.D., Arden, J.W., Wright, I.P., Pillinger, C.T., & Huchison, R. 1992, Meteoritics, 27, 309
Zolensky, M.E. & Barrett, R. 1994, in Analysis of Interplanetary Dust, M.E. Zolensky, T.L. Wilson, F.J.M. Rietmeijer, & G.J. Flynn (eds.), New York: Amer. Inst. Physics, 105