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THE ABUNDANCE PATTERN OF ELEMENTS HAVING LOW NEBULAR CONDENSATION TEMPERATURES IN INTERPLANETARY DUST PARTICLES: EVIDENCE FOR A NEW CHEMICAL TYPE OF CHONDRITIC MATERIAL

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Abstract. The abundances of Ni. Fe, Cr, Mn, P, Cu, K, Na, Ga, Ge, Se, Zn, S, Br, and C were measured in interplanetary dust particles (IDPs) collected from the Earth's stratosphere. All elements with nebular condensation temperatures lower than Mn, except S, were enriched relative to the most volatile-rich type of meteorite while the refractory elements Cr and Ni were present at chondritic abundances. This element abundance pattern is consistent with nebular condensation, suggesting the IDPs condensed at either a different location or time in the evolving solar nebula than do the meteorites. The enrichments of the major elements C, Na, P, and K exclude the possibility that the volatile enrichment in IDPs results from a minor amount of contamination.

1. Introduction

Interplanetary dust particles (IDPs) from 5 to 50 microns in diameter are decelerated in the upper atmosphere and recovered from the Earth's stratosphere by NASA sampling aircraft (Warren & Zolensky, 1994). The majority of these IDPs are believed to be samples of asteroids and comets, though contributions from all solar system objects as well as interstellar dust are possible.

The abundances of refractory elements are generally similar among all types of chondritic meteorites, but abundances of elements with low nebular condensation temperatures decrease significantly increasing petrologic grade (see Figure 1). For example, carbon decreases systematically, by almost an order-of-magnitude, with increasing petrologic grade from CI(1) to CV(3) meteorites. Thus, the pattern of abundances of elements having low nebular condensation temperatures can distinguish between different types of chondritic material.

Those IDPs which are not dominated by single minerals (olivines, pyroxenes, or Fe-Ni-sulfides) have abundances of the major refractory elements which are similar, within $\pm$ 50%, to the chondritic meteorites. Schramm et al. (1989) demonstrated that the average content of major refractory elements (Mg, Al, Si, Fe, and Ni) in a set of 200 IDPs is approximately chondritic.

Volatile elements in these chondritic IDPs are generally enriched relative to the CI meteorites, which are believed to represent solar composition (Anders & Ebihara, 1982). Van der Stap et al. (1986) reported enrichments of 6 volatile trace elements in 3 IDPs examined by Proton Induced X-ray Emission, and suggested the IDPs sampled the volatile-rich residue of solar system formation. Flynn et al. (1993) found average enrichments by factors of 1.5 to 3 relative to CI for the volatile elements Cu, Zn, Ga, Ge, and Se and a larger enrichment for Br in a set of 51 IDPs. However, Arndt et al. (1995) noted these volatile enrichments are larger for the elements having the lowest abundances, and suggested that the apparent volatile enrichment could indicate a limit of detection problem, in which the abundances of elements near the detection limit are systematically overestimated, or could result from contamination, which requires only a small amount of non-indigenous material for the elements present in low abundances.

2. Measurement Techniques and Samples

The abundances of Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, Se, and Br were measured in 51 IDPs using the Synchrotron X-ray Fluorescence Microprobe on Beamline X-26 of the National Synchrotron Light Source at Brookhaven National Laboratory This X-ray Microprobe has a sensitivity of 1 to 3 ppm, in 10 micron chondritic particles, for elements from Fe to Sr. Abundances of Fe, Na, S, and C were measured on 71 IDPs using a scanning electron microscope equipped with a thin-window energy dispersive x-ray detector. The C detection limit is ~0.5%, while limits for Na, and S are ~0.1%. Abundances of Fe, K, Na, P and S were measured on 27 IDPs using an electron microprobe, with a detection limit of ~0.1%.

The IDPs analyzed range from 5 to 35 microns in size. These IDPs were collected from the stratosphere into silicone oil, which is impossible to remove completely, so the element abundances are normalized to Fe rather than Si. To minimize selection biases, all chondritic IDPs, i.e. all particles with contents of Mg, Al, Si, Fe, and Ni within a factor of two of CI, are included in the averages.

Some of these IDPs have been examined in the Transmission Electron Microscope (TEM) to determine mineralogy and texture. Each set includes both anhydrous and hydrated IDPs. Some of these IDPs show well-developed magnetite rims, indicating they experienced severe atmospheric entry heating while others have textures and mineralogies indicating less severe atmospheric entry heating (Flynn et al., 1992, Keller et al., 1995). Since the loss of Zn (Flynn et al. 1992) and S (Fraundorf et al. 1983) has been linked to severe atmospheric entry heating, the abundances of the volatile elements measured in this work may underestimate the preatmospheric volatile contents of some IDPs.

3. Results

The abundances of most individual elements vary by an order-of-magnitude in each set of IDPs. This could be due either to the sampling of a multitude of chemically distinct parent objects (Schramm et al., 1989) or to heterogeneous distribution of these elements on the 10 micron scale in the parent body. Similar results are seen when individual fragments, up to 100 microns in size, of chondritic meteorites are measured by the same techniques, indicating significant heterogeneity of the meteorite parent bodies.

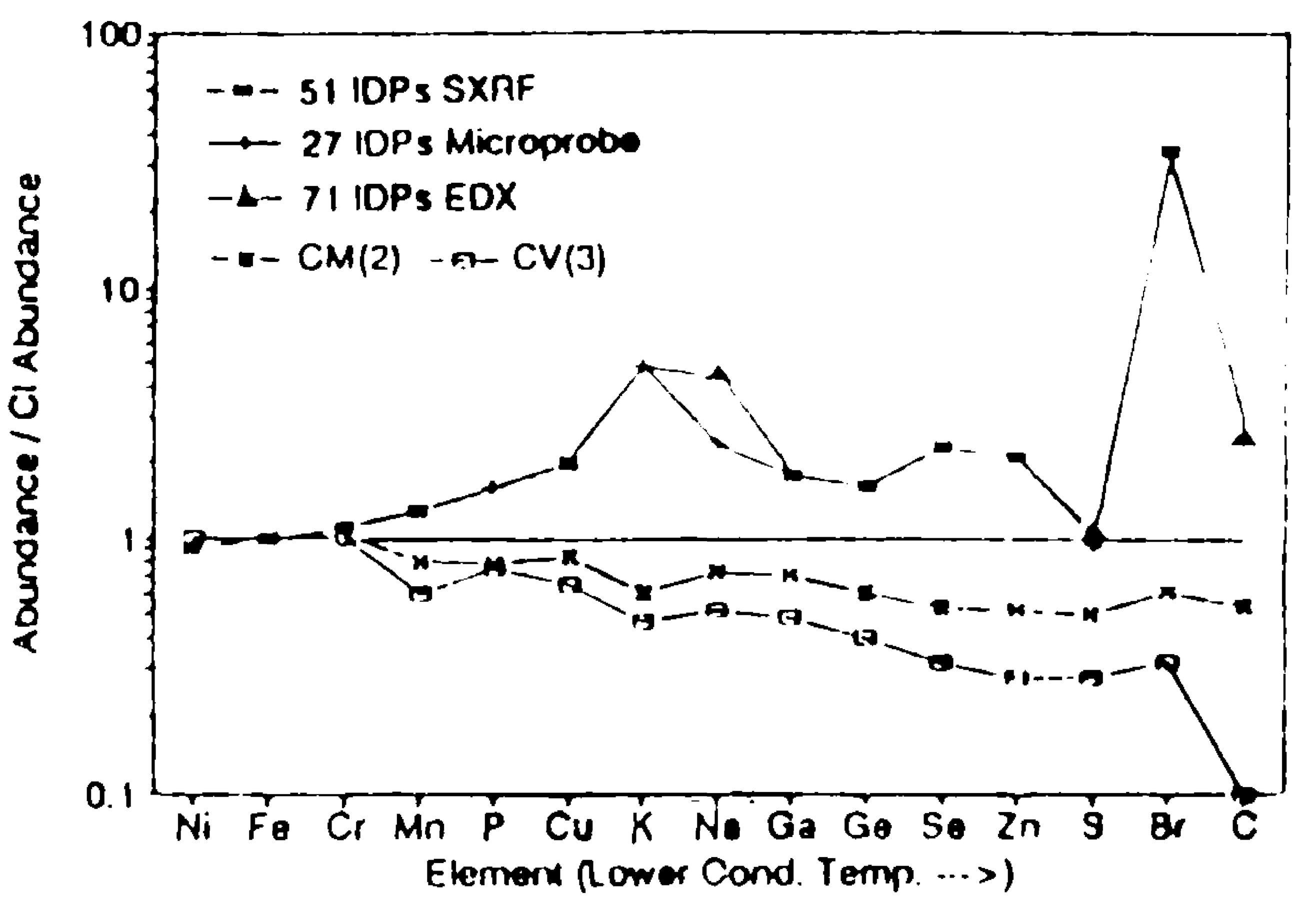
The CI and Fe normalized average element contents of the IDPs are shown in Figure 1. Sulfur and Na were measured on both the 27 and the 71 IDP sets. The S averages on the 27 and the 71 IDP sets are identical within errors, but the Na content is a factor of two higher in the 71 particle set. This could indicate the sample sets are too small to obtain a representative average over inhomogeneously distributed Na, or that Na is sufficiently volatile to be lost by to sample heating during the electron microbeam analysis.

All the elements with nebular condensation temperatures lower than Mn (~1170 K) show enrichments by factors from 1.5 to 5xCI, except for Br which is enriched over CI by a factor of 40 and S which is present at the CI concentration. Carbon, the major element having the lowest nebular condensation temperature of the set analyzed, is enriched by a factor of 3 over CI. Overall, the enrichment pattern seen in these IDPs is suggestive of a mirror image of the depletion pattern relative to CI for the CM(2) and CV(3) meteorites (see Figure 1).

4. Conclusions

The enrichments of both major (C, Na, K, P) and trace elements (Cu, Zn, Ga, Ge, Se, and Br) in IDPs demonstrate that the volatile enrichment previously reported for only the trace elements (Flynn et al. 1993) does not result from either a limit of detection problem or contamination of those elements present in the lowest abundances. The trace elements Cu and Zn are typically present at ~100 times the detection limit of the X-ray Microprobe, and only one particle in the 51 IDP set has a Zn abundance near the detection limit. Jessberger et al. (1992) suggest all of the enrichment above CI levels could result from contamination acquired during atmospheric residence of weeks to months. For contamination to explain these enrichments, those IDPs which contain the highest abundances of C, Na, and K would have to consist of more than 50% contaminant material, and the average IDP would have to consist of about 10% contaminant material. Such extreme levels of contamination should be discernible in the mineralogical and textural examination of IDPs in the TEM. Although Rietmeijer (1995) has found

Figure 1: Average Fe and CI normalized abundances of elements in chondritic IDPs, CM(2), and CV(3) meteorites. Elements are ordered with decreasing nebular condensation temperature to the right.



evidence of KCl surface contamination in one IDP, no obvious contamination of the magnitude required to explain these enrichments has been observed.

Nonetheless, contamination of trace elements cannot be excluded. Mackinnon and Mogk (1985) have detected a thin (~150 angstrom) S-rich layer on the surface of some particles from the stratosphere, but the total mass of S in this layer is inadequate to significantly perturb the bulk S in IDPs. Flynn et al. (1995) have demonstrated that ~50% of the Br in 2 IDPs is very weakly bound and Stephan et al. (1994) found a halogen-rich rim on one IDP. These results suggest that a significant portion of the Br enrichment may result from contamination, most likely acquired during stratospheric residence.

Each of the chondritic IDPs included in this study has a carbon content greater than any carbonaceous chondrite. In comparison, stony meteorites are dominated by the carbon-poor ordinary chondrites. This indicates the chondritic IDPs sample a different, more carbon-rich, reservoir than that sampled by the stony meteorites.

The IDPs included in this study are, on average, more volatile-rich than the most volatile-rich meteorites, the CI chondrites, in a pattern indicative of nebular condensation. This suggests the IDPs, or some subset of the IDPs, are a new chemical type of extraterrestrial material, not sampled by the meteorites. This conclusion is consistent with TEM observations, which have demonstrated that most IDPs are mineralogically distinct from meteorites, and a large subset of the IDPs are mineralogically more primitive (i.e., exhibit less thermal and aqueous alteration) than any type of chondritic meteorite (Mackinnon and Rietmeijer, 1987). This is consistent with the suggestion of van der Stap. et al. (1986) that the IDPs formed during a late stage of nebular condensation, when some elements with high condensation temperatures had already been depleted in the gas phase.

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