IS THE DEPLETION OF MODERATELY VOLATILE ELEMENTS IN THE INNER SOLAR SYSTEM INHERITED FROM THE INTERSTELLAR MEDIUM? H. Palme, Institut für Mineralogie und Geochemie, Universität zu Köln, Zülpicher Strasse 49b, D-50674 Köln, Germany, palme@min.uni-koeln.de

Introduction: When normalized to refractory elements (Al, Ca, Ti) carbonaceous chondrites show increasing degrees of depletion of Mg, Si, Cr, Fe and all moderately volatile elements (Mn, Na, K, Zn, S etc.) in the sequence CI, CM, CO, CK and CV [1]. The abundances of moderately volatile lithophile elements in the primitive Earth mantle follow this trend (Fig. 1, a large fraction of the terrestrial Cr is in the core). Ordinary chondrites have very different patterns. They are depleted in refractory elements and undepleted in Mn and Na. As the Earth represents more than 50 % of the material of the inner solar system the carbonaceous chondrite depletion pattern must be typical of most of the inner solar system matter. Meteorites displaying different patterns are representative of smaller, more local environments [2]. Here we discuss the origin of the depletion of moderately volatile elements, in particular the possibility that this depletion is inherited from gas dust fractionation in the interstellar medium (ISM).

Possible mechanisms for depletion: (1) The depletion is inherited from the interstellar medium. It has been known for a long time that volatile and moderately volatile elements are depleted in the dust grains of the interstellar medium. The degree of depletion correlates with the condensation temperature of the elements ([3] and literature therein). This model is attractive since it does not require high nebular temperatures at the beginning of the solar system. (2) Depletion occurred during incomplete condensation at the beginning of the solar system. This requires almost complete vaporization and equilibration of the material of the inner solar system. (3) Loss of volatile elements during heating of interstellar material in the early solar nebula, either by global nebular heating affecting all materials in the inner solar system or by local heating events such as, for example, chondrule formation. (4) Loss of moderately volatile elements during accretion. (5) Loss of volatiles during magmatism on the surface of planets or planetesimals. (6) Depletion during aqueous alteration on the parent body. There is no evidence from the Moon or eucrite parent body for loss of volatiles during eruption of basaltic magmas (e.g [4]). Both elements Na and Mn are significantly depleted in the Earth's mantle, their ratio is, however, chondritic [5]. In heating experiments Na and K are lost at much lower temperatures than Mn which is in some experiments even less volatile than Cr ([6] and [7]). The chondritic Mn/Na ratio of he Earth and of chondritic meteorites argues against loss of Na by heating. Aqueous alteration is not considered a serious alternative to volatility controlled processes. The trend in Figure 1 is followed by lithophile, chalcophile and siderophile elements [8]. It is, for example, extremely unlikely that Na and Mn are affected by aqueous alteration in such a way as to produce the regular pattern in Fig. 1.

Volatile element depletion in ISM: The parent material of the Sun and the planets is the local interstellar medium, a mixture of dust and gas. Although only 1% of the ISM is in dust grains, they are the major reservoir for non-volatile elements. The abundances of elements in the gas phase of the ISM can be determined by spectroscopy. The composition of grains is calculated from the difference between gas-phase abundance and solar abundances. Volatile elements with low condensation temperatures are only slightly or not at all depleted from the gas phase. The most abundant heavy elements Si, Mg and Fe show variable depletions, with Mg and Si being less depleted than Fe and other siderophile elements, such as Ni, Co and also Cr. The refractory elements show the strongest depletions. This sequence is similar to what is expected to remain in a gas of solar composition after condensation of the first solids. This is not surprising since it is commonly assumed that the grains in the ISM formed by condensation in stellar outflows. In view of the similarity of presolar condensation processes and condensation processes during solar nebular formation one may ask if some of the volatility related fractionations seen in meteorites are of presolar origin [9]. A different behavior of gas and dust during the collapse phase of the nebula is not unexpected [10]. This would automatically lead to volatile/non-volatile element fractionations. If ISM grains would accrete preferentially during solar nebular formation, a pattern
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qualitatively similar to that seen in carbonaceous chondrites could be expected.

Timing of depletion: The absence of a significant anomaly in $^{182}\text{W}/^{186}\text{W}$ of lunar samples and the presence of large anomalies in eucrites indicate that the Moon formed late, some 50 million years after the formation of the solar system. At least a major accretionary event and/or core formation on the Moon is required at this time [11]. The low initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition of the Moon clearly indicates that the major Rb/Sr fractionation must have occurred very early, at the beginning of the solar system. More detailed modeling may require some additional loss of Rb at the time of the formation of the Moon [12].

The timing of the Mn depletion is obtained from $^{53}\text{Cr}-^{55}\text{Mn}$ systematics. Four carbonaceous chondrites form an isochron in an $^{53}\text{Cr}/^{52}\text{Cr} - ^{55}\text{Mn}/^{52}\text{Cr}$ diagram defining an age of 4.568 Gyr with an estimated uncertainty of one million years [13]. The Earth falls on the same isochron [14], assuming the core to be free of Mn but containing a major fraction of Cr. This supports the similarity of carbonaceous chondrites with Earth material. The Sr-isotopic data of chondritic meteorites are consistent with the hypothesis that the major Rb/Sr fractionation occurred at the same time as the Mn/Cr fractionation.

Basic isotopic and elemental uniformity of solar system material: If the variability in moderately volatile and volatile elements in inner solar system materials is inherited from the ISM, one should expect variations in the isotopic composition of Sr and Cr at the time of formation of the solar system. Grains of the ISM are expected to have very low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as they have not seen Rb (which is in the gas phase) for a long time. If the variability in solar system Rb/Sr ratios is older than the solar system, variations in $^{87}\text{Sr}/^{86}\text{Sr}$ at 4.566 Gyr would be expected. But they are not observed. As Mn is largely in the gas of ISM the uniform $^{53}\text{Cr}/^{52}\text{Cr}$ ratios in carbonaceous chondrites and in the Earth at the time of formation of the solar system requires homogenization of Cr isotopes at the beginning of the solar system. Here the time constraints are much more severe.

The small variations in $^{53}\text{Cr}/^{52}\text{Cr}$ ratios in H-chondrites, Eucrite parent body and Mars are not related to variations in Mn/Cr ratios [15]. These variations may record incomplete homogenization of $^{53}\text{Mn}$. The comparatively high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of eucrites may similarly reflect incomplete mixing of Sr-isotopes. Eucrites may have formed from a region slightly enhanced in $^{87}\text{Sr}/^{86}\text{Sr}$ relative to the region where carbonaceous chondrites formed. Other evidence for incomplete mixing at the beginning of the solar system includes $^{54}\text{Cr}$ in carbonaceous chondrites ([16] and [17]).

In the ISM Pb is in the gas and U in grains. If there were cold unprocessed interstellar grains in chondritic meteorites, they should have large excesses of radiogenic Pb. So far, no such enrichments in $^{207}\text{Pb}$ have been detected.

Conclusions: The major global, volatile element depletion event occurred around 4.566 to 4.571 Gyr [18] and affected material of the inner solar system. Almost complete elemental and isotopic equilibrium was established. Small residual variations in initial $^{87}\text{Sr}$ may reflect pre-solar volatile-refractory fractionations in the ISM. Local anomalies of $^{54}\text{Cr}$ and in Ti [19] reflect incomplete evaporation. Presolar grains were added later during nebular cooling. At a later stage the initially reduced protoplanetary material was partly oxidized by addition of $^{17}\text{O}$-rich gas. The depletion of volatile elements either reflects incomplete condensation or partial evaporation. Various arguments make the evaporation hypothesis very unlikely. The delicate pattern of Fig. 1 can hardly be produced by evaporation [8]. Also, there is no evidence for isotopic fractionation of K or other elements expected from massive evaporation [20].