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How to cite:

Busemann, H.; Baur, H. and Wieler, R. (2003). Solar noble bases in enstatite chondrites and implications for the formation of the terrestrial planets. In: 34th Lunar and Planetary Science Conference, 17-21 Mar 2003, Houston, Texas, USA.

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Introduction: In a companion abstract [1], we report evidence for tiny amounts of - most likely primordial - noble gases with solar-like elemental and isotopic composition admixed to Q-type primordial noble gases in an E chondrite. Here, we discuss possible implications of this finding for terrestrial planet formation.

The genetic relation of the noble gases in planetary bodies to those in the Sun, seemingly their most likely precursors, is largely unknown [2]. This knowledge, however, is essential to assess the processes that have led to the specific noble gas compositions observed now, e.g. the noble gas inventories of the terrestrial interior and atmosphere [3]. The trapping mechanism of the noble gases into Earth and, accordingly, their primordial composition are under debate [see e.g. 2-6]. Major mechanisms that have been proposed include:

Gravitational capture by proto-Earth (or sufficiently large precursor planetesimals) could have incorporated noble gases by dissolution into an early magma ocean. This would imply that Earth already had accreted a significant part (~30%) of its present mass [7] and the crust had melted before the solar nebula has completely dissipated (~10 Ma [8]).

Implantation of solar wind: The precursors of the Earth (e.g. ~10-100-km-sized planetesimals at present solar wind intensity [9]) could have trapped solar wind in their uppermost layers during an unshielded early solar irradiation. This would require a thin solar nebula at the location where the planetesimals formed.

He and Ne in the terrestrial mantle are solar, whereas Ar-Xe are not yet sufficiently constrained [2]. In view of many compositional similarities of Earth to carbonaceous [10] and enstatite [11] chondrites, it seems surprising that primordial solar-like noble gases have hardly ever been reported in meteorites. An exception is olivine in the pallasite Brenham [12].

A quite prominent component with a composition somewhat closer to solar than the typical primordial component in meteorites is the subsolar component, reported in many cases, in particular E chondrites. This component might provide a link between the inferred terrestrial primordial noble gas composition and primitive meteorites, in being enriched in Ar relative to Xe and showing He-Ar isotopic ratios closer to solar [13].

E chondrites: Based on their subsolar noble gases and other observations [14], E chondrites have been suggested to have formed closer to the Sun than other chondrites and thus might be particularly suitable to

record processes that occurred to material that accreted to Earth. The oxygen isotopic composition of E chondrites plotting close to the terrestrial fractionation line [15] supports this view.

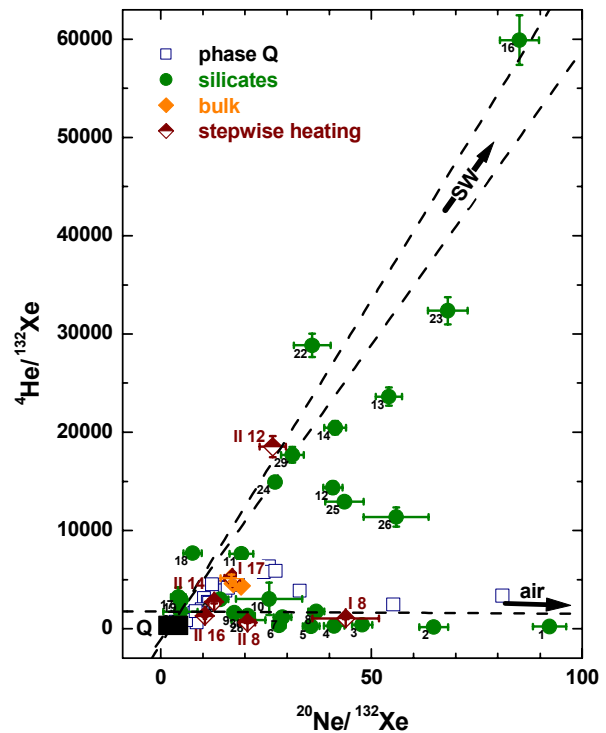


Fig. 1: Noble gases in St. Mark's. High-resolution etch data suggest a mixture of primordial solar-like gas, Q and air. The stepwise heating data follow, less pronounced, a similar trend. See [1] for details. Q data: [24]; SW-range: [26].

Experiment: We therefore performed several experiments [1] to determine the noble gas systematics of the EH5 chondrite St. Mark's, which is especially suitable to detect even small primordial He and Ne concentrations, because its cosmic-ray exposure age is extremely short.

Results: These experiments allowed us to detect traces of unfractionated solar noble gases, including He and Ne in the *bulk* of St. Mark's (Fig. 1). Solar noble gases were also found in phase Q, "diluted" with Q-gas. Thus, the "subsolar" component in St. Mark's [16] actually is a mixture of tiny amounts of solar, typical Q-type and terrestrial noble gases (see [1] for details).

Discussion: Neither St Mark's nor most of the other E chondrites containing "subsolar" noble gases

are known to be brecciated [17]. Unless this does not turn out to be wrong in all cases, the solar gases have not been incorporated into these E chondrites during a putative residence in the parent body's regolith. The presence of both Q- and solar gases in phase Q [1,18], further supports a pre-accretion irradiation.

It is well known that the HF/HCl-dissolvable fraction of many meteorites contains trapped gases that have usually been referred to as subsolar or Ar-rich [13]. This has been observed e.g. for several LL, CO and CV chondrites by comparing the Ar-Xe concentrations of bulk samples and HF/HCl-resistant residues [19-21]. Due to large contributions of cosmogenic He and Ne, this subtraction technique does not allow reliable estimates of the trapped He and Ne. However, these observations imply that the early irradiation inferred for E chondrites might also be - to a lesser extent - a viable scenario for chondrites of other classes showing signs of "subsolar" gases. This suggestion is in line with observations on grains of CV chondrites reported to contain traces of a pre-accretion irradiation [22].

Chondrules in the E chondrite Y-791790 carry large concentrations of subsolar Ar-Xe. This has been explained by an irradiation prior to the accretion of the chondrule precursors [23]. However, the lack of He and Ne remains mysterious because other constituents of the E chondrites apparently kept some He and Ne.

The possibility of solar gas in phase Q might help to explain the differences found in the isotopic compositions of Ar-Q and especially Ne-Q observed in phase Q in several meteorites of different classes [24]. While Ne-Q and Ar-Q might significantly be affected by the irradiation with solar wind, due to the large depletion of Ne and Ar in phase Q relative to solar wind and Xe, the Kr-Q and Xe-Q composition remains unaffected and thus remarkably constant. The admixtures of solar gas in phase Q of St. Mark's are considerably larger than in carbonaceous chondrites, possibly indicating a more severe irradiation in the solar nebula, closer to the inner edge of the solar nebula as suggested in [25].

Conclusions: The observation of unfractionated solar noble gases including He and Ne in meteorites that were not trapped upon regolith irradiation allows us to explain the so-called "Ar-rich" or "subsolar" noble gas component that is found especially in E chondrites as a mixture of small amounts of solar gases, admixed to Q gases plus terrestrial contamination. The incorporation of traces of solar gas took place prior to the accretion of the meteorite's parent bodies. This process probably was most effective in the region where the E chondrites formed.

The presence of solar gases in chondrites can not be the result of gravitational capture into molten precursors because of the undifferentiated character of the

chondrites. These observations combined with the similarities of chondrites and the terrestrial planets suggest that the precursor planetesimals of Earth and Venus could have accumulated their primordial noble gas inventories by irradiation with solar wind when the solar nebula had already cleared.

It is useful to compare the solar concentrations found in St. Mark's with those in the terrestrial mantle, although the Earth must have lost 90% of its primordial noble gases [3] and substantial non-solar gas amounts in St. Mark's reside in phase Q. We calculate a solar ^{36}Ar concentration in St. Mark's of some $10^{-11} \text{ cm}^3/\text{g}$. This is comparable with or an order of magnitude lower than the ^{36}Ar concentrations estimated for the mantle [3]. Being far from suggesting that E chondritic planetesimals actually delivered noble gases to Earth, we nonetheless conclude that a pre-irradiation similar to that of St. Mark's, a relatively gas-poor E chondrite, is able to incorporate significant amounts of solar gas into material in the early solar system.

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