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Noble gases in enstatite chondrites II: The trapped component

ANDREA PATZER†* AND LUDOLF SCHULTZ

Max-Planck-Institut für Chemie, D-55020 Mainz, Germany
†Present address: Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA
*Correspondence author's e-mail address: apatzer@lpl.arizona.edu

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Abstract–The trapped noble gas record of 57 enstatite chondrites (E chondrites) has been investigated. Basically, two different gas patterns have been identified dependent on the petrologic type. All E chondrites of type 4 to 6 show a mixture of trapped common chondritic rare gases (Q) and a subsolar component (range of elemental ratios for E4–6 chondrites: $^{36}Ar/^{132}Xe = 582 \pm 270$ and $^{36}Ar/^{84}Kr = 242 \pm 88$). E3 chondrites usually contain Q gases, but also a composition with lower $^{36}Ar/^{132}Xe$ and $^{36}Ar/^{84}Kr$ ratios, which we call sub-Q ($^{36}Ar/^{132}Xe = 37.0 \pm 18.0$ and $^{36}Ar/^{84}Kr = 41.7 \pm 18.1$). The presence of either the subsolar or the sub-Q signature in particular petrologic types cannot be readily explained by parent body metamorphism as postulated for ordinary chondrites. We therefore present a different model that can explain the bimodal distribution and composition of trapped heavy noble gases in E chondrites.

Trapped solar noble gases have been observed only in some E3 chondrites. About 30% of each group, EH3 and EL3 chondrites, amounting to 9% of all analyzed E chondrites show the solar signature. Notably, only one of those meteorites has been explicitly described as a regolith breccia.

INTRODUCTION

The noble gases contained in meteoritic matter consist of different components. These components are distinguished in terms of their individual elemental and isotopic compositions and are either trapped or produced *in situ* (*e.g.*, Ozima and Podosek, 1983). In most meteorites, ^{36}Ar as well as Kr and Xe are essentially trapped primordial (presolar and common chondritic) noble gases. From trapped primordial noble gases we are able to obtain information, for instance, about the origin and early evolution of meteorites as they reflect compositional properties of meteoritic source regions (*e.g.*, Ozima and Nakazawa, 1980; Swindle, 1988; Pepin, 1992; Zahnle, 1993; Wieler, 1994; Huss *et al.*, 1996; Ozima *et al.*, 1998; Nakamura *et al.*, 1999a; Busemann *et al.*, 2000).

Enstatite chondrites are the most reduced meteorites known so far (see Patzer and Schultz, 2001 and references therein). First systematic investigations of the noble gases in these meteorites were published in the early 1980s (Crabb and Anders, 1981, 1982). E chondrites are generally known to be gas-rich with relatively high amounts of primordial Ar and radiogenic ^{129}Xe. In 1981, Crabb and Anders described a new component of primordial noble gases in E chondrites, which they inferred to be the source of relatively high Ar concentrations in many samples. Since the elemental composition of this component ranges between those of Q ($^{36}Ar/^{132}Xe \approx 74$ and $^{36}Ar/^{84}Kr \approx 89$; Wieler *et al.*, 1992) and the solar pattern ($^{36}Ar/^{132}Xe \approx 68\ 400$ and $^{36}Ar/^{84}Kr \approx 3320$; Anders and Grevesse, 1989), it was named "subsolar". Q is synonymous for the formerly called "planetary", common noble gas signature in ordinary and carbonaceous chondrites (Q = "quintessence"; Lewis *et al.*, 1975; see also Ott *et al.*, 1984; Zadnik *et al.*, 1985; Swindle, 1988; Huss *et al.*, 1996; Busemann *et al.*, 2000). For the subsolar $^{36}Ar/^{132}Xe$ ratio, Crabb and Anders (1981) give an extrapolated upper limit of 3800. Other authors who studied the noble gas characteristics of E chondrites observed similar high elemental ratios and refer to this pattern as "argon-rich component" (*e.g.*, Wacker and Marti, 1983).

The highest subsolar Ar/Kr and Kr/Xe ratios have been determined for South Oman, an EH4/5 chondrite ($^{36}Ar/^{132}Xe$ = 2660, $^{84}Kr/^{132}Xe = 5.86$; Crabb and Anders, 1981). According to Crabb and Anders (1981), no correlation exists between gas abundances and petrologic type as known for ordinary chondrites (Marti, 1967; Zähringer, 1968; Schultz *et al.*, 1990). However, Huss *et al.* (1996) detected a decrease of rare gas concentrations in phase Q, the carrier of the common chondritic noble gases, with increasing petrologic type in EH chondrites. Other meteorites that exhibit similarly high concentrations of trapped noble gases are ureilites (Mazor *et al.*, 1970). In addition, the relatively metal-rich CH chondritic samples Bencubbin, Kakangari, Acfer 182, and Allan Hills (ALH) 85085 as well as the acapulcoite Monument Draw (McCoy *et al.*, 1996), some unequilibrated ordinary and other carbonaceous chondrites also show subsolar gas characteristics (Schelhaas *et al.*, 1990; Scherer and Schultz, 2000; Schultz and Franke, 2000).

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TABLE 1. Investigated enstatite chondrites and trapped noble gas concentrations.*

No.	Sample	Type	References†	$^{36}Ar_{tr}$	^{84}Kr	^{132}Xe	$^{129}Xe/^{132}Xe$
1	Abee	EH4 m.b.	1	3770	14.7	11.5	5.41
2	Acfer 287	E4	1	119	2.21	1.40	7.02
3 + 4	ALH 84170 + 206	EH3	1	4910	26.6	62.1	1.31
5	ALH 85119	EL3	1	8230	27.7	67.3	1.15
6 + 7	ALH 88046 + 070	EH3	1	2140	28.3	64.9	1.26
8	Atlanta	EL6	1	364	2.80	1.68	6.61
9	DaG 734	EL4	2	1010	27.2	2.70	1.86
10	Eagle	EL6	1	1420	9.07	5.90	3.52
11	EET 83322	EH3	1	1140	31.5	37.6	1.30
12	EET 87746	EH3	3	3260	257	346	1.02
13	EET 90102	EL6	1	38500	109	41.3	1.37
14	EET 90299	EL3	1	352	19.9	40.1	1.11
15	EET 92063	EL6	1	9020	29.2	10.9	3.56
16 + 17 + 18	EET 96103 + 135 + 299	EH4	1	5270	16.6	18.8	1.65
19	Forrest 033	EL6	1	8320	21.2	6.64	2.72
20	Galim b	EH3	3	478	6.15	4.97	3.23
21	Grein 002	EL4/5	1	12500	63.0	30.6	2.73
22	GRO 95517	EH3	1	651	26.7	38.1	1.34
23	GRO 95626	EL6	1	3760	14.5	5.25	4.36
24	Happy Canyon	EL6 m.b.	4	211	2.03	2.46	6.32
25	Hvittis	EL6	1	5950	15.8	10.1	2.62
26	Ilafegh 009	EL7 m.r.	1	231	1.78	1.47	3.69
27	Indarch	EH4	1	592	11.9	9.45	3.75
28	KaidunIV	EL3	1	839	11.6	14.4	1.36
29	Kota-Kota	EH3	1	644	9.99	11.1	1.93
30 + 31	LEW 87119 + 88714	EL6	1	7250	30.9	11.0	3.14
32	LEW 87223	E3 an	1	291	5.77	3.19	3.75
33	LEW 88180	EH5	1	12900	53.6	18.1	1.97
34	LON 94100	EL6	1	3110	11.3	5.82	4.64
35	MAC 88136	EL3	1	4780	17.7	22.4	1.46
36	PCA 82518	EH3	1	609	21.8	14.2	1.83
37	PCA 91020	EL3	1	592	15.0	15.3	1.87
38	Pillistfer	EL6	1	2570	13.7	7.97	2.19
39	Qingzhen	EH3	1	769	12.4	12.8	1.94
40 + 41	QUE 93351 + 94594	EL3	1	751	13.0	13.7	1.94
42	QUE 93372	EH5	1	2340	16.8	5.85	5.14
43	QUE 94204	EH7 m.r.	1	763	5.54	3.37	1.17
44	QUE 97462	EL6	1	21000	55.0	22.6	1.55
45	RKPA80259	EH5	1	10600	36.7	14.5	1.86
46 + 47	SAH 97096 + 166	EH3	1	954	29.1	18.3	1.95
48	St. Mark's	EH5	1	3800	16.5	6.97	3.68
49	Tanezrouft 031	EL5	1	5960	28.4	12.2	2.25
50	TIL 91714	EL5	1	8070	19.9	8.36	2.56
51	Y-691	EH3	1	2250	31.7	72.8	1.18
52	Y-74370	EH3	5	620	13.6	12.0	2.02
53 + 54	Y-791790 + 1810	EH4	6	10700	21.6	5.38	3.46
55	Y-792959	EH3	1	796	21.7	28.4	1.24
56	Y-793225	E6 an	7	6030	19.3	7.13	4.51
57	Y-8404	EH6	8	68.0	0.93	0.75	9.71

*All concentrations in 10^{-10} cm^3 STP/g. Measured Kr and Xe abundances are taken as entirely trapped. Estimated uncertainty of concentrations is 15%, of ratios 20%.

Abbreviations: m.b. = melt breccia, m.r. = melt rock, an = anomalous, tr = trapped, GRO = Grosvenor Mountains, LEW = Lewis Cliff, LON = Lonewolf Nunataks, PCA = Pecora Escarpment, QUE = Queen Alexandra Range, RPK = Reckling Peak, TIL = Thiel Mountains.

†References: 1 = MetBase (2000), 2 = Grossman (2000), 3 = Kong *et al.* (1997), 4 = Keil (1989), 5 = El Goresy (2000, pers. comm.), 6 = Kimura and Lin (1999), 7 = Lin and Kimura (1998), 8 = Lin and Kimura (1997). For previous noble gas investigations and provider see Patzer and Schultz (2001).

Since 1980, many new E chondrites have been found in cold and hot deserts and a more detailed investigation of the trapped noble gas record of E chondrites has become possible. On the basis of 43 new and 14 previously examined E chondrites (for samples and data see Table 1), we report the range of elemental ratios of the subsolar component. Furthermore, we found an additional noble gas composition with Ar/Kr/Xe ratios below Q values so far not described for E chondrites, which we name "sub-Q" (Patzer and Schultz, 1999; see also Patzer and Schultz, 2000a,b). Similarly low ^{36}Ar/^{84}Xe and ^{84}Kr/^{132}Xe ratios have been observed in an acapulcoite (Monument Draw; McCoy *et al.*, 1996). Mineralogical parallels between the acapulcoite-lodranite meteorites and E chondrites have led several authors to suggest that both classes might be genetically related to each other (*e.g.*, Yanai and Kojima, 1991; see also McCoy *et al.*, 2000). The noble gas data appear to strengthen this interpretation.

EXPERIMENTAL PROCEDURE AND RESULTS

Sample preparation, experimental procedure and corrections for mass discrimination as well as ion interference are given by Scherer *et al.* (1998) (see also Loeken *et al.*, 1992; Loeken, 1993; Patzer, 2000; Patzer and Schultz, 2001). The relevant trapped noble gas data for all analyzed samples are compiled in Table 1 with the complete data set given in Patzer and Schultz (2001). The precision of gas concentrations varies from 5 to 10% for Ar and from 10 to 15% for Kr and Xe. The Ar isotopic ratios are believed to be known to better than 1%, ^{129}Xe/^{132}Xe, trapped ^{36}Ar/^{132}Xe, and trapped ^{36}Ar/^{84}Kr to better than 20%. The given uncertainties include statistical errors, errors of mass discrimination, background, and ion interference corrections. The relatively high uncertainty of the Ar/Kr/Xe ratios is due to the fact that, for most samples, Kr and Xe abundances have been determined without Kr and Xe being separated from the Ar gas fraction. Eight E chondrites with subsolar gases have been determined for their isotopic composition of Xe (Table 2). In those cases, Kr and Xe were separated from Ar. Consequently, the Xe isotopic ratios could be determined to better than 5%.

No correction for terrestrial atmospheric contributions has been performed. We believe that this type of alteration has not considerably influenced the basic noble gas patterns present in E chondrites (see "Discussion"). The observed dualism in distribution and composition of rare gases is significant and gives important information about the noble gas record of enstatite chondrites even if certain degrees of atmospheric contamination are assumed.

DISCUSSION

The Neon Composition

In order to distinguish between individual noble gas components of a meteoritic sample three-isotope diagrams are used. In Fig. 1, the Ne isotopic composition of the investigated E chondrites is shown. For the majority of samples, cosmogenic Ne is the dominating component. Some meteorites contain mixtures of cosmogenic and trapped, most likely Q-Ne. Elephant Moraine (EET) 87746 (EH3) may have additionally incorporated some Ne-E or Ne-HL, a presolar noble gas component that is present in E chondritic diamonds and SiC (*e.g.*, Huss and Lewis, 1995). Five E chondrites plot on an imaginary line connecting the cosmogenic and solar signatures. Interestingly, these samples are all of type 3 with two EL3 chondrites showing the highest solar Ne contributions. In numbers, ~30% of EH3 chondrites (3 out of 11) and 30% of EL3 chondrites (2 out of 6) summing up to ~9% of all analyzed E chondrites exhibit solar noble gases (Table 3).

Solar noble gases are characteristic for regolith breccias, which form on the surface of meteoritic parent bodies. The surface layers of these bodies are exposed to continuously incoming solar particles, which are subsequently implanted into the first few micrometers of the present minerals (*e.g.*, Wieler *et al.*, 2000). As only some E3 chondrites contain solar Ne and assuming an unbiased sample suite, the surface of their parent body(ies) must be exclusively made of type E3 chondritic rock matter. This conclusion is consistent with a parent body entirely made of E3 material or a spherically structured object as discussed for ordinary chondrites (onion-shell model).

Notably, only one EL3 sample has been petrologically described as a breccia so far (MacAlpine Hills (MAC) 88138; Lin *et al.*, 1991). All other solar gas-bearing E chondrites still have to be thoroughly investigated with respect to their texture. Weathering effects (limonitic staining) may play a crucial role in this context as they may mask the textural features of regolith breccias.

An interesting attribute regarding the Ne composition of E chondrites is related to the possible presence of some primordial Ne in E4 and E5 chondrites (Heymann and Mazor, 1968; Zähringer, 1968). We addressed this phenomenon and determined the amount of primordial Ne assuming a mixture of cosmogenic and trapped gases and using the formula given by Crabb and Anders (1981). As distinct from Crabb and Anders (1981), however, we applied a cosmogenic ^{21}Ne/^{20}Ne ratio of 1.07. Based on these data, samples of all petrologic types (even E6 chondrites) exhibit variable concentrations of primordial Ne. For most samples, these concentrations range well below 25% of the total ^{20}Ne abundance. However, no systematic trend is observed and, considering the predominance of cosmogenic Ne in most E chondrites, corrections are relatively high. It cannot be excluded that small quantities of atmospheric Ne are the cause for the slightly higher ^{20}Ne/^{22}Ne ratios.

Argon, Krypton, and Xenon of the Trapped Component

A graphical differentiation between the planetary and subsolar signature in E chondrites can be generated, for instance,

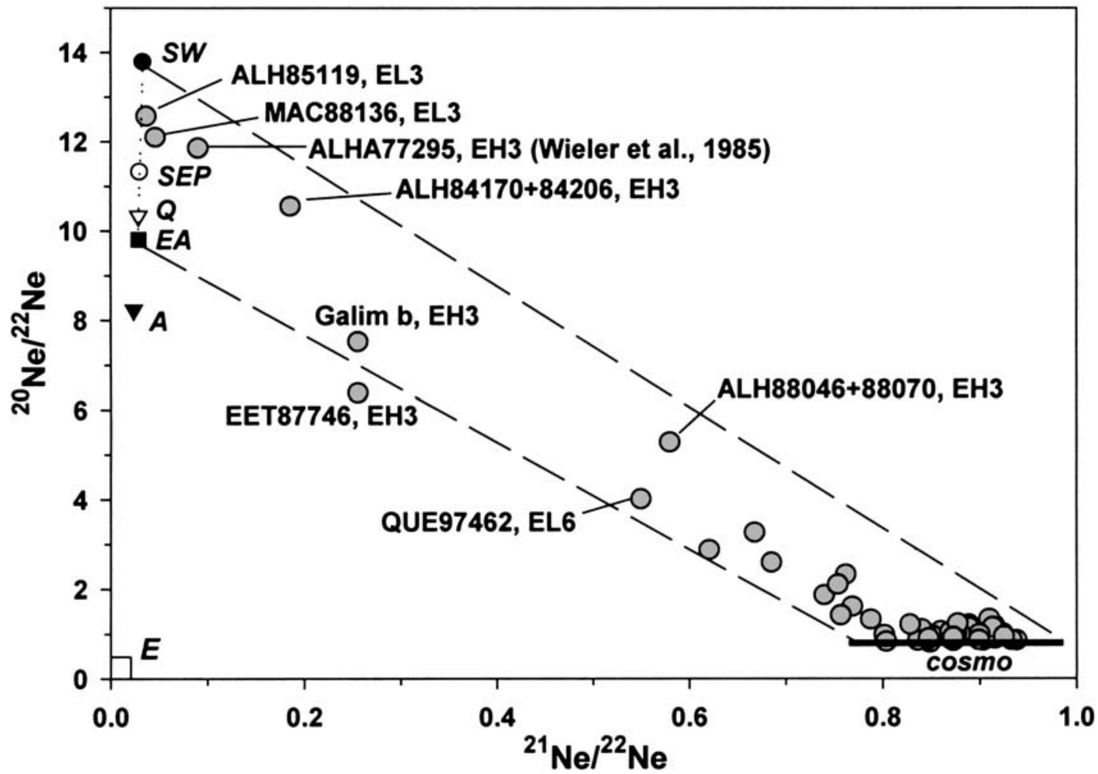

FIG. 1. Isotopic composition of Ne in E chondrites. The majority of samples is dominated by the cosmogenic component (cosmo). Some meteorites also show mixtures of at least two different noble gas pattern (EA = Earth's atmosphere, SW = solar wind, SEP = solar energetic particles, E = presolar neon, A = another primordial mixed signature). E chondrites exhibiting solar gases all belong to petrologic type 3.

TABLE 2. Isotopic composition of Xe in eight enstatite chondrites bearing subsolar gases, normalized to ^{132}Xe.

Sample	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
EET 90102	0.00471	0.00426	0.0832	1.360	0.164	0.823	0.379	0.315
EET 92063	0.00458	0.00426	0.0860	3.594	0.163	0.816	0.375	0.316
LEW 87119	0.00484	0.00438	0.0860	3.219	0.163	0.821	0.377	0.312
LEW 88714	0.00461	0.00428	0.0861	3.118	0.163	0.819	0.378	0.314
LEW 88180	0.00486	0.00426	0.0820	2.011	0.162	0.814	0.378	0.314
RKPA80259	0.00480	0.00428	0.0830	2.037	0.163	0.824	0.378	0.313
TIL 91714	0.00483	0.00415	0.0839	2.548	0.163	0.823	0.379	0.314
Y-791790	0.00498	0.00414	0.0850	4.040	0.161	0.821	0.380	0.310
Y-791810	0.00459	0.00440	0.0843	3.976	0.164	0.819	0.380	0.314
Y-793225	0.00458	0.00411	0.0845	4.527	0.163	0.811	0.381	0.314

Paired samples: LEW 87119 and LEW 88714, Y-791790 and Y-791810.

in a "three-element plot" with ^{36}Ar, ^{84}Kr and ^{132}Xe (Fig. 2). Aside from a few exceptions, all samples of type 4 to 6 show a subsolar composition of their heavy noble gases characterized by $^{36}Ar/^{132}Xe > 220$ and $^{84}Kr/^{132}Xe > 0.85$. The subsolar pattern has also been established in the isotopic composition of Xe (Table 2; Fig. 3). E3 chondrites, on the other hand, consistently yield a Q-like or sub-Q pattern.

EL3 and EH3 chondrites that have been identified to contain a solar gas pattern are not plotted in Figs. 2, 4, and 5 as solar gases essentially mask all other noble gas components. In addition, all melt rocks and anomalous samples as well as Galim b have been excluded from further interpretation. Galim b, an EH3 chondrite, represents a special case. This sample was found close to six non-weathered LL6-chondrite pieces (Galim a) in Cameroon in 1952 (Christophe-Michel-Lévy and Bourot-Denise, 1988). It has been suggested that both types correspond to one fall and that the Galim meteoroid was a LL chondritic polymict breccia with EH-chondritic clasts (Rubin, 1997).

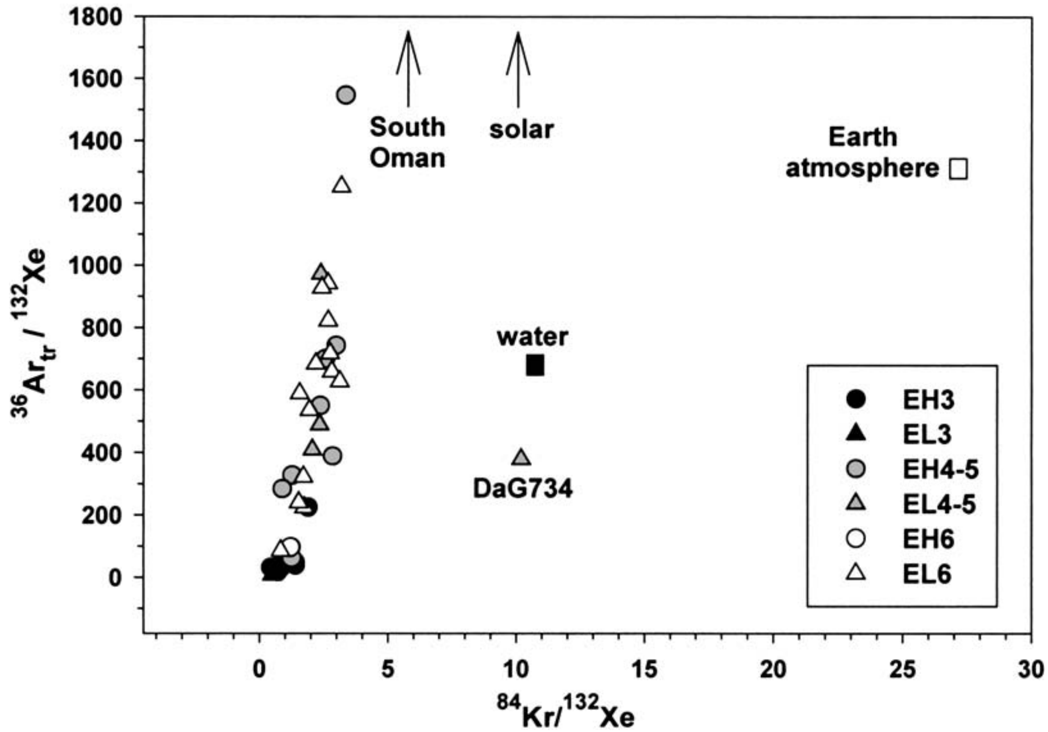

FIG. 2. Trapped $^{36}Ar/^{132}Xe$ ratios as a function of $^{84}Kr/^{132}Xe$. The elemental compositions of "Earth, atmosphere" and "water" (*i.e.*, noble gases dissolved in water) have been taken from Scherer and Schultz (2000). The only sample that shows a considerable effect on its elemental ratios due to weathering is DaG 734, an EL4 from the Sahara. Many other E chondrites may be contaminated as well. However, the alteration does not lead to a significant modification of the original bimodal character of $^{36}Ar/^{84}Kr/^{132}Xe$ ratios (see also Fig. 3).

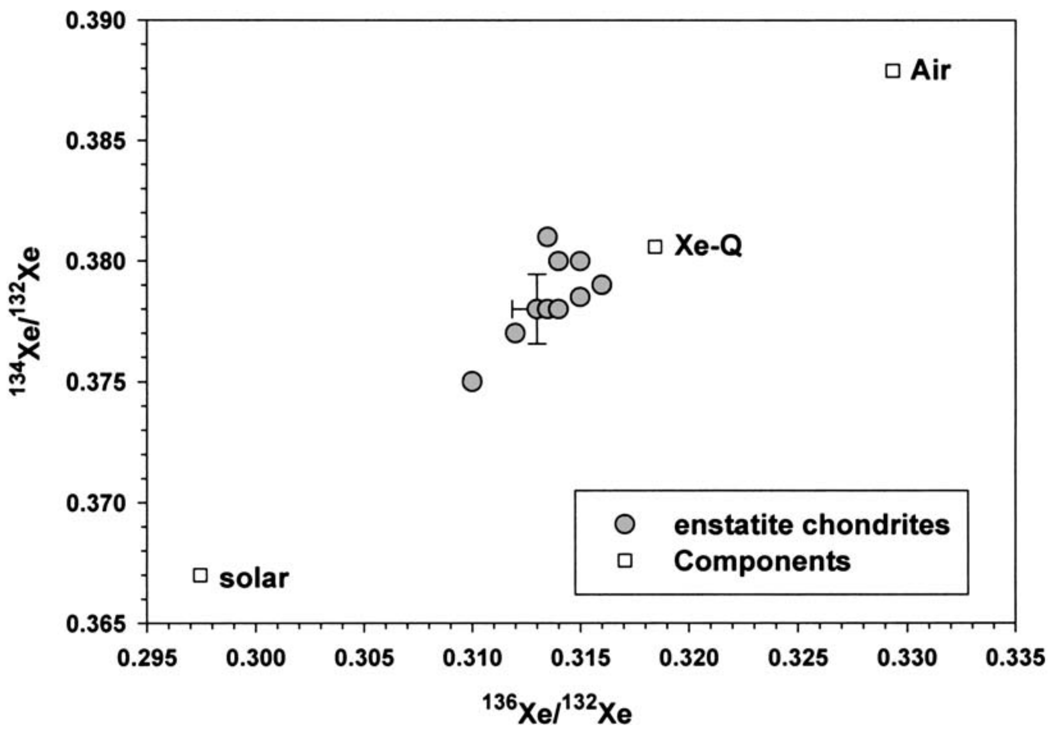

FIG. 3. Isotopic composition of Xe in samples with subsolar gases (see Table 2). The error bars indicate the typical uncertainty of measured ratios. The diagram displays $^{134}Xe/^{132}Xe$ and $^{136}Xe/^{132}Xe$ values ranging between Q- and solar Xe and reveals the same bimodal character as observed for the $^{36}Ar/^{84}Kr/^{132}Xe$ elemental ratios in E4–6 chondrites, namely a mixture between subsolar and common chondritic gases.

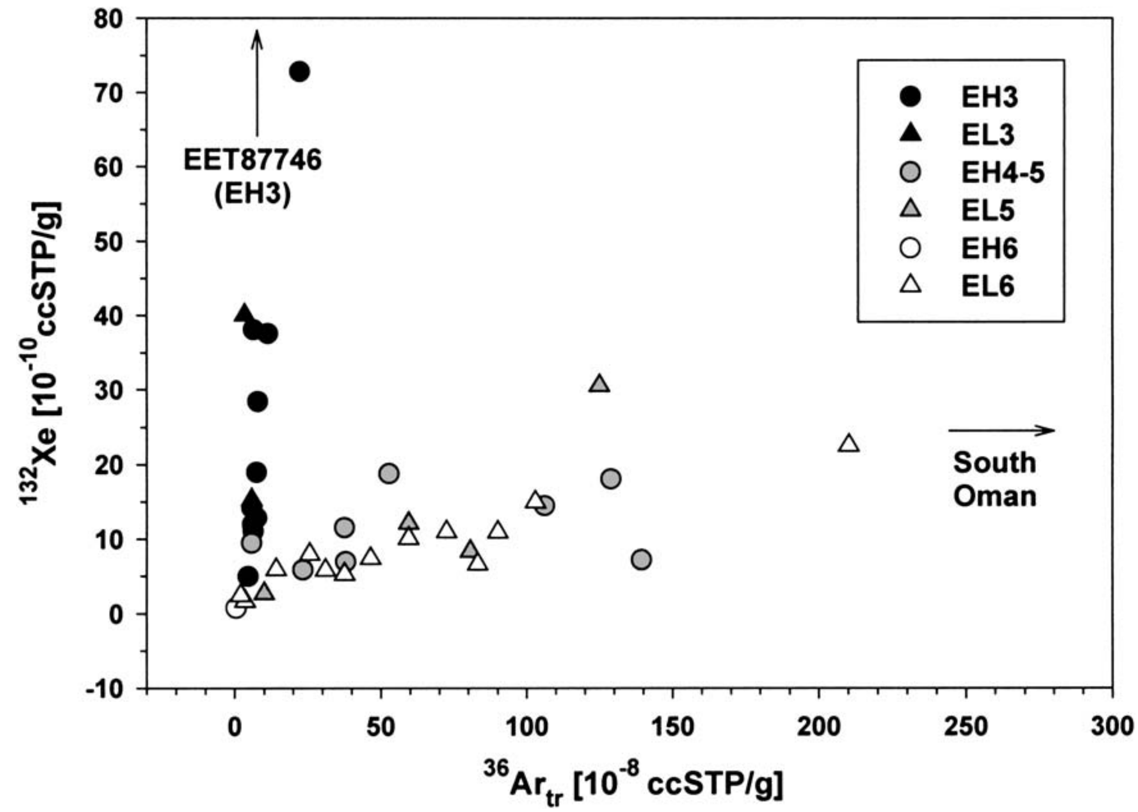

FIG. 4. Concentrations of trapped ^{132}Xe *vs.* ^{36}Ar. This plot reveals a bimodal composition of the trapped heavy noble gases. E3 chondrites show low to high Xe abundances along with low trapped Ar concentrations. E4–6 chondrites, on the other hand, contain low to high amounts of trapped Ar coupled with variable Xe contents.

TABLE 3. Enstatite chondrites with solar noble gases.

Sample	Type	^{4}He	^{4}He/^{3}He	^{20}Ne	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne
ALH 84170 + 206	EH3	193380	1785	899	10.56	0.186
ALH 85119	EL3	77945	2978	1560	12.58	0.037
ALH 88046 + 070	EH3	35420	579	128	5.29	0.580
MAC 88136	EL3	123720	3130	982	12.10	0.046
ALHA77295*	EH3	249200	2443	1656	11.86	0.091

*Wieler *et al.* (1985). Concentrations in 10^{-8} cm^3 STP/g.

According to Rubin (1997) the incorporation of an EH3 impactor into a LL chondritic asteroid resulted in a complex chemical modification of the EH chondritic material. Based, among others, on the comparatively high trapped ^{36}Ar/^{132}Xe ratio of ~96 in Galim b, we suspect that its noble gas record was also influenced.

Figure 2 demonstrates that terrestrial alteration of trapped Ar, Kr and Xe does not play a major role with respect to their elemental ratios. Weathering processes affecting especially meteorites from hot deserts by leading to the incorporation of water-dissolved Kr and Xe may have contributed to the absolute abundance of these rare gases (*e.g.*, Scherer *et al.*, 1994). In E chondrites, however, neither the elemental ratios of Ar/Kr/Xe (Fig. 2) nor the isotopic ratios of Xe (Fig. 3) indicate the occurrence of considerable amounts of atmospheric noble gases. The only meteorite, which clearly incorporated terrestrial gases, is Dar al Gani (DaG) 734. This EL4 chondrite also shows macroscopically the heaviest weathering features of the entire sample suite. A correction for air contamination critically depends on the isotopic ratio for trapped Ar (^{36}Ar/^{38}Ar)$_{tr}$, which is not well known. For this reason, we do not expect the data to be refined by any attempt to correct for atmospheric Ar, Kr or Xe.

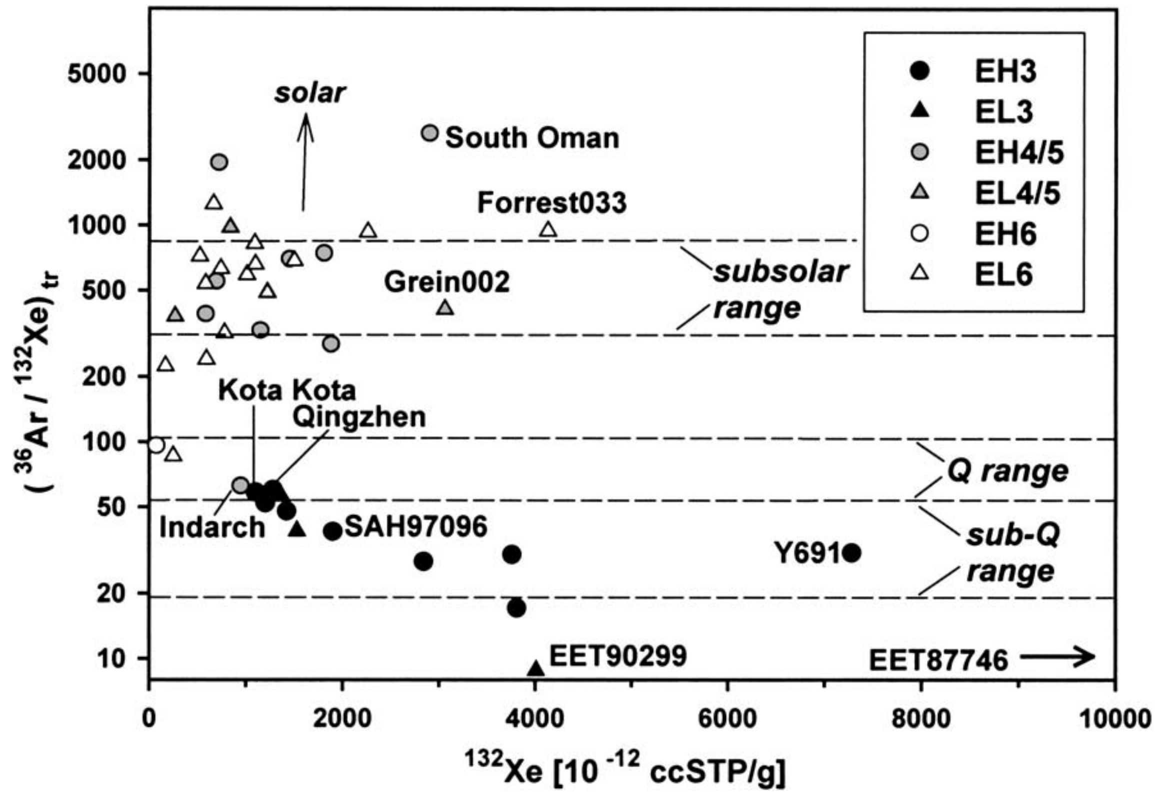

FIG. 5. Trapped $^{36}Ar/^{132}Xe$ dependent on the ^{132}Xe concentrations. This diagram clearly resolves the bimodal composition of rare gases in E chondrites. All E chondrites of type 3 exhibit a Q-like signature as a combination of different concentrations of Q and sub-Q while nearly all types 4 to 6 contain a less fractionated component called subsolar (Crabb and Anders, 1981). The noble gas data of South Oman has been taken from Crabb and Anders (1981), the range of Q values has been published in Busemann *et al.* (2000). The ranges of subsolar and sub-Q ratios as determined in this work are defined as the standard deviation of the average.

Figure 4 reveals that E3 chondrites are generally characterized by variable Xe concentrations combined with low Ar contents. As opposed to them, most E chondrites of petrologic type 4 to 6 contain high Ar abundances along with variable but basically less high Xe concentrations (*i.e.*, the diagnostic subsolar pattern).

Comparing the trapped $^{36}Ar/^{132}Xe$ ratios with ^{132}Xe abundances (Fig. 5), the systematic distribution of two components is even more obvious. Apparently, E3 chondrites plot not only around the specific ratios of Q but in some cases also exhibit lower ratios than Q. In detail, the $^{36}Ar/^{132}Xe$ ratios tend to decrease with increasing ^{132}Xe concentrations. The range of $^{36}Ar/^{132}Xe$ and $^{36}Ar/^{84}Kr$ ratios of E3 chondrites is 37.0 ± 18.0 and 41.7 ± 18.1, respectively. In analogy to subsolar, we call this signature "sub-Q". For the subsolar gases in E4–6 chondrites, we have calculated an array of $^{36}Ar/^{132}Xe$ and $^{36}Ar/^{84}Kr$ ratios of 582 ± 270 and 242 ± 88, respectively. This is consistent with the extrapolated upper limit of 3800 for $^{36}Ar/^{132}Xe$ given by Crabb and Anders (1981). Figure 5 accordingly reflects the two different principal gas patterns, which occur in E chondrites: variable concentrations of Q and subsolar noble gases are contained in samples of type 4 to 6, and variable concentrations of Q and sub-Q are observed in solar gas-free E3 chondrites.

The Origin of Subsolar Gases

Chondrites with solar gases are generally regolith breccias. It is conceivable that subsolar gases originated from the alteration of regolith material by parent body metamorphism. Some E3 chondritic samples contain solar gases. It appears unlikely, however, that these gases were fractionated into subsolar gases and subsequently introduced into type 4 to 6 E chondrites during a major metamorphic event. In such a scenario, the irradiated surface layer, which can only represent a small part of the object in question, must have been buried deep into the parent body and metamorphosed. In addition, no similar process has been observed for ordinary chondrites. It therefore seems more likely that subsolar gases were incorporated into E chondritic matter before the parent bodies accreted.

Several chemical and mineralogical phenomena of E3 chondrites in general and EH3 chondrites in particular have been reported and give evidence to a specific origin or evolution of E3 chondrites as opposed to E chondrites of petrologic type 4 to 6 (*e.g.*, El Goresy *et al.*, 1988; Hutson and Ruzicka, 2000). Kamacite of EH3 chondites, for instance, shows diagnostically low Ni abundances in comparison to EH4/5 and EL6 chondrites whereas EL3 chondrites are distinguished by relatively low contents of Si in the metal phase. In addition, variations exist in the oxygen isotopic composition. Oxygen isotopes in E3 chondrites plot along the terrestrial mass fractionation line at lower $\delta^{17}O$ and $\delta^{18}O$ values than EH5 and EL6 chondrites (Weisberg *et al.*, 1995; Newton *et al.*, 2000). All these phenomena cannot be produced by parent body metamorphism but they were possibly caused during condensation of E chondritic minerals prior to accretion. Applying this hypothesis to the noble gas inventory of E chondrites, the origin of subsolar gases might be related to the pre-accretional irradiation of silicates by an early solar wind.

Recent work by Okazaki *et al.* (2000) on chondrules of Yamato (Y)-791790, an EH4 chondrite, reports significant concentrations of subsolar gases located in porphyritic pyroxene chondrules. These gases could be derived from solar wind incorporated into chondrule precursors. The required fractionation of the solar gases may have been caused by diffusional loss of the light elements He and Ne from the still hot mineral grains. This model, however, is hypothetical and certainly needs further investigation. In this respect, the host phase of subsolar gases in enstatite chondrites may reveal important constraints to its origin.

In earlier studies, Y-791790 has been assigned an EH3 chondrite (Yanai and Kojima, 1995; Rubin *et al.*, 1997). Yet, the classification of E chondrites has been proven to be more complicated than that of ordinary chondrites leading to repeated reclassifications (*e.g.*, Zhang *et al.*, 1995; see also Patzer and Schultz, 2001). Regarding Y-791790, Okazaki *et al.* (2000) see evidence that justifies a grouping with type 4 E chondrites. We support the latter assignment judging from its noble gas inventory as, according to our study, only enstatite chondrites of petrologic type 4 or higher exhibit the presence of the subsolar component.

The Host Phases of the Subsolar and Planetary Components of E Chondrites

Crabb and Anders (1981, 1982) separated different E chondritic mineral phases in order to explore the carrier of Q and subsolar gases. The main part of the common chondritic noble gases was detected in a fine-grained host being resistant to HCl and HF but soluble in HNO_3. These attributes correspond to those of the usual Q-gas carrier of ordinary and carbonaceous chondrites (phase Q; Lewis *et al.*, 1975; see also Busemann *et al.*, 2000).

In contrast to that, the host mineral of the subsolar signature is insoluble in HCl and HNO_3 but reacts with HF/HCl (Crabb and Anders, 1981). The chemical behavior suggests a silicate as carrier. According to further investigations of E6 chondrites by Crabb and Anders (1982), high $^{36}Ar/^{132}Xe$ ratios that are typical for the subsolar component strongly cohere with enstatite or a minor phase tightly associated with the pyroxene fraction. However, enstatite has been found not to be the only subsolar gas carrier. High $^{36}Ar/^{132}Xe$ ratios have also been observed in an acid-resistant residue of St. Mark's (EH5; Busemann *et al.*, 2001).

The key question at this point is why the enstatite of E3 chondrites, as distinct from pyroxene in the other petrologic types, does not show any subsolar signature? Further detailed measurements of mineral separates are definitely necessary to shed more light on the relevant carrier minerals and, as a consequence, to diminish the hypothetical character of any model reconstructing the evolution of noble gases in E chondrites. In this context, *in situ* analysis of graphite and enstatite by a combination of precise laser ablation and mass spectrometry may prove to be a very successful method (see also Nakamura *et al.*, 1999b).

Trapped Noble Gases in Enstatite and Ordinary Chondrites: A Comparison

As illustrated above and with the exception of the occurrence of solar gases in some E3 chondritic meteorites, the noble gas record of E chondrites cannot be readily explained in accord with the onion-shell model as derived from ordinary chondrite data. The parent bodies of ordinary chondrites are interpreted to represent so-called rubble piles (*i.e.*, stony objects reassembled from numerous rock pieces of various petrologic types) (*e.g.*, Crabb and Schultz, 1981; Keil *et al.*, 1994). The rock fragments resulted from a formerly intact asteroid that was broken up by impacts. The original asteroid displayed a layered structure with the most metamorphosed rocks of petrologic type 6 in its center followed by continuously less equilibrated ordinary chondrite material of types 5 to 3 (onion-shell model). In terms of temperature, type 6 in the core corresponds to a maximum of 950 °C and type 3 at the surface to a maximum of 600 °C, respectively (*e.g.*, Crabb and Schultz, 1981; Herbert, 1989; McKay *et al.*, 1989; Bennett and McSween, 1996; McSween, 1999). The rubble-pile model is based, among others, on the fact that solar noble gases are known to occur in all petrologic types of ordinary chondrites (Schultz and Franke, 2000). Since solar noble gases in E chondrites are restricted to type 3 and assuming an unbiased sample suite, the according parent body would exhibit a cover layer of only type 3 rock material.

For ordinary chondrites, the trapped noble gas content of Q correlates with petrologic type and gradually decreases from type 3 to 6 (Schultz *et al.*, 1990; Fig. 6). These findings support the onion-shell model and can be explained by gas loss as a result of increasing temperatures. A correlation of $(^{36}Ar/^{132}Xe)_Q$ and $(^{84}Kr/^{132}Xe)_Q$ with petrologic type has been proven for both, ordinary and carbonaceous chondrites (Busemann *et al.*, 2000). For E chondrites, however, observations lead to a different

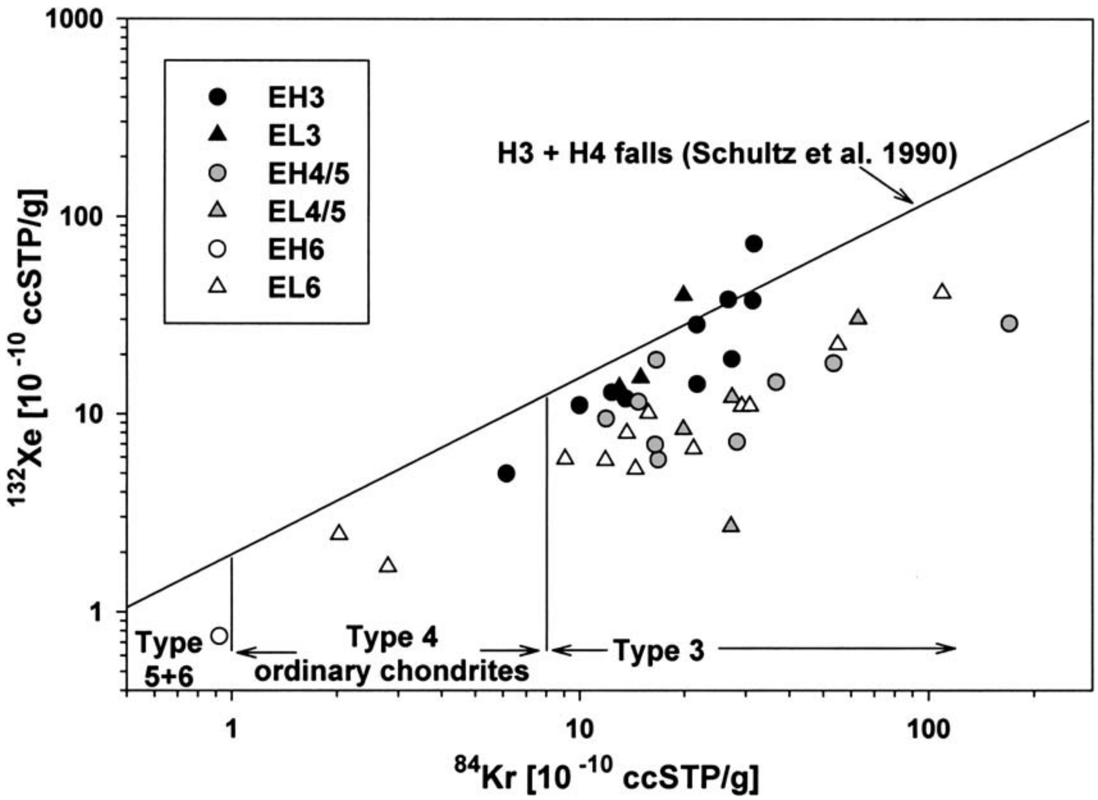

FIG. 6. Correlation between petrologic type and noble gas concentration as observed for ordinary chondrites (Schultz *et al.*, 1990). The same systematics, however, do not hold for E chondrites. Hence, another mechanism than parent body metamorphism must be responsible for both the distribution and composition of noble gas components in these meteorites.

picture and reflect the establishment of noble gas signatures independent from parent body metamorphism. The acquisition of noble gases does not seem to be related to the metamorphic process, which generated types 4 to 6, as bulk gas abundances are in the same range for many samples despite different petrologic type (Fig. 5). In addition, the composition of the dominant noble gas pattern in E4, E5, and E6 chondrites is less fractionated and relatively ^{36}Ar-rich or ^{132}Xe-poor in comparison to E3 chondrites and therefore definitely inconsistent with a simple sequential metamorphic overprinting.

We suggest that two different evolution paths were established when E chondritic material started forming (Fig. 7). Spatial heterogeneity in the formation area of enstatite chondrites resulted in the condensation of E3 chondritic material on one hand and E3-like precursor material of E4–6 chondrites on the other. Prior or during accretion, E3 chondritic rock matter incorporated Q- and sub-Q gases. Subsequently, metamorphism took place. The hypothesis of an individual evolutionary path for E3 chondrites may be supported by other observations as mentioned above. The alteration of E3 chondritic matter by metamorphism has been subject of previous studies. For instance, the E3 chondrite Qingzhen and others were overprinted by a thermal event as inferred from mineralogical evidence (El Goresy *et al.*, 1988; Torigoye and Shima, 1993). In addition, Hicks *et al.* (2000) report a metamorphic sequence among non-equilibrated EH chondrites based on olivine and silica abundance. Interestingly, the same sequence is reflected by the sub-Q gas concentrations of these meteorites (Fig. 5). Two of the most metamorphosed EH3 chondrites according to Hicks *et al.* (2000) are Kota-Kota and Qingzhen. They show the lowest Xe abundances and a rather Q-dominated noble gas signature. On the other hand, the more primitive sample Sahara (SAH) 97092 (paired with SAH 97096 of our sample suite) reveals a higher Xe amount and sub-Q elemental ratios while Y-691, according to El Goresy *et al.* (1988) the most primitive sample, exhibits a considerably lower ^{36}Ar/^{132}Xe ratio (pure sub-Q?). These findings suggest that the sub-Q composition was not produced *in situ* (on the E3 chondritic parent body) but may have been fractionated from Q gases at an earlier point (*i.e.* prior to accretion). During metamorphism on the E3 chondritic parent body the host phase of the sub-Q gases proportionally degassed with increasing temperatures leaving behind the abundance pattern as described above.

Separate from the E3 chondritic parent body, slightly differently composed (see above), though probably unequilibrated enstatite chondritic matter formed another object (Fig. 7). Prior (or during?) the accretion of this body, solar gases implanted or trapped in particular carrier phases or

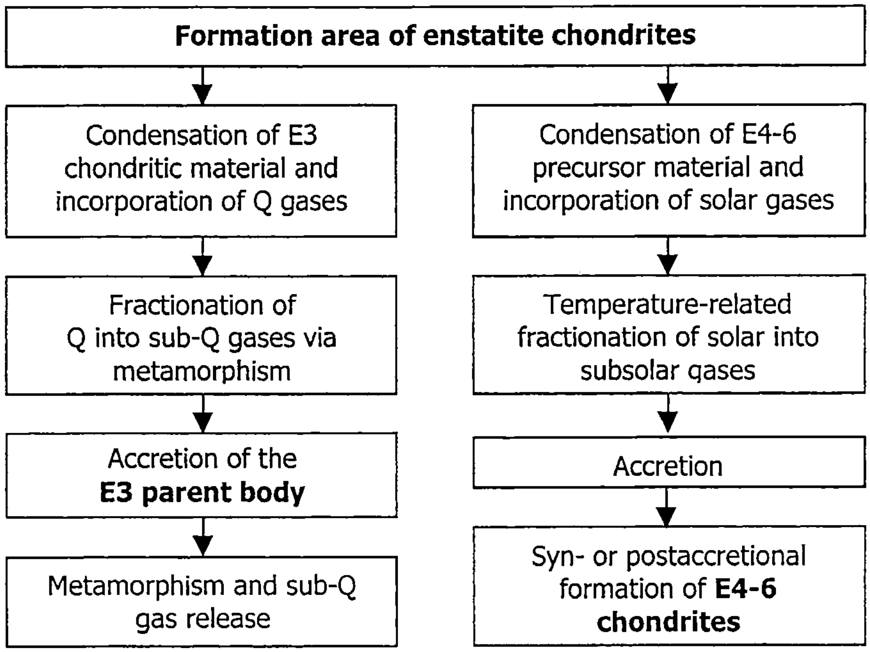

FIG. 7. Hypothetical evolutionary paths of enstatite chondrites. We assume a spatially distinguished evolution of petrologic types 3 on one and types 4 to 6 on the other hand. Compositional differences between E3 and E4–6 chondrites are due to spatial heterogeneities. Processes modifying the noble gas content of rock material on both parent bodies were related to metamorphism.

specific constituents (*e.g.*, chondrules) were fractionated to the subsolar signature. Crushing experiments on E chondrites showed that appreciable amounts of trapped gases can be lost by mechanical sample preparation (Takaoka *et al.*, 2000). These findings favor, for instance, micro-vesicles along grain boundaries as gas trapping sites and may imply that the gas component was released from the host mineral during fractionation and retrapped during accretion (also see Takaoka *et al.*, 1994). The generation of type 4, 5 and 6 E chondrites might have occurred in the course of the accretion process as well. However, different degrees of equilibration as indicated by the different petrologic types are not reflected by the subsolar pattern. This observation therefore rather hints at a distinct metamorphic event.

CONCLUSIONS

According to the bulk analyses of 57 E chondrites, the composition and distribution of noble gases in this meteorite class basically differ from those in ordinary chondrites. Only some type 3 samples of E chondrites contain solar noble gases and, consequently, are regolith breccias. So far, the noble gas inventory of ~30% of E3 chondrites is dominated by the solar component. Solar gas-free E3 samples show a Q-like pattern with variable concentrations of Q and of a composition exhibiting lower trapped $^{36}Ar/^{132}Xe$ and $^{84}Kr/^{132}Xe$ ratios than Q, which we call sub-Q.

The trapped heavy noble gases of more equilibrated E chondrites, classified as petrologic types 4 to 6, predominantly reveal subsolar gases, which are less fractionated than Q. Hence, in more metamorphosed E chondrites a noble gas component exists that cannot be derived from simple thermal overprinting of type 3 E chondrites. Regarding the concentrations of subsolar rare gases, no obvious correlation between gas abundances and metamorphic type in E chondrites is found.

From the noble gas point of view, the bimodal composition and distribution of noble gases in E chondrites is inconsistent with the onion-shell model that has been established for ordinary chondrites. Instead, the incorporation of noble gases from two major reservoirs, solar and Q, into E chondritic minerals and their possible fractionation to subsolar and sub-Q compositions appear to have taken place prior or during accretion. In this scenario, both E3 and E4–6 chondrites evolved separately (*i.e.*, on different parent bodies). The discrepancies between the observed noble gas signatures are due to spatial heterogeneity in the formation area of enstatite chondrites. The sub-Q pattern may have been fractionated from Q gases prior to the accretion of the E3 chondritic parent body whereas the subsolar component was possibly derived from solar gases shortly after chondrule formation. As distinct from the subsolar gas concentrations, the sub-Q abundances appear to vary systematically with the degree of metamorphism of E3 chondrites possibly hinting at a difference in the physicochemical behavior of their respective carriers.

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