Antarct. Meteorite Res., **13**, 153–169, 2000

Cosmic-ray exposure ages of enstatite chondrites

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Abstract: Eleven enstatite (E-) chondrites were analyzed for abundances and isotopic ratios of noble gases by total melting. Light noble gases, He, Ne and Ar are discussed. We obtained cosmic-ray exposure ages (T^{21}) based on cosmogenic ^{21}Ne that are divided into two groups, below 15 Myr and above 40 Myr. Both ranges of T^{21} contain various petrologic-types of E-chondrites. Isotopic ratios and concentration of Ne for Yamato (Y)-8414 and -86004 are almost the same, which suggests that they are from a common fragment. Identical exposure age T^{21} of 10 Myr for Y-8414 and -86004 supports their pairing. The pairing for Y-8414 and -86004 based on noble-gas signatures and T^{21} is consistent with their petrologic similarities. Pairing for Y-792959 and -793161 is also suggested by their similarities in mineral compositions, their close sampling location and the same petrologic-type. However, there are discrepancies in He and Ar contents between the two samples, which fails to support their pairing.

Including literature data, the exposure ages show no systematic correlation with petrologic type. Additionally, both EH- and EL-chondrites are found in both two peaks of T^{21}. The exposure age distribution has no implications about the structure of E-chondrite parent body. The parent body of E-chondrites has possibly lost the original structure after many collisions in the early solar system evolution.

1. Introduction

Enstatite (E) chondrites are assemblages of highly reduced minerals. They are divided into two subclasses based on their Fe contents in bulk stones: high-Fe (EH) and low-Fe (EL) groups (Sears *et al.*, 1982; Kallemeyn and Wasson, 1986). There is no continuity in their bulk compositions of nonvolatile major elements between the two groups (Keil, 1968; Baedecker and Wasson, 1975) and the hiatus in this chemical composition could not be accounted for by simple planetary metamorphism (Keil, 1968). In this context, separate parent bodies for EH- and EL-chondrites have been proposed by some authors (*e.g.*, Baedecker and Wasson, 1975; Sears *et al.*, 1982; Keil, 1989; Zhang *et al.*, 1995).

On the other hand, Wasson and Wai (1970) proposed a single parent body common to EH- and EL-chondrites based on the continuous variation of mineral composition. Biswas *et al.* (1980) and Kaczaral *et al.* (1988) also suggested a single parent body from volatile/mobile trace element trends. Oxygen isotopic compositions of the two subclasses that occupy the narrow region along the terrestrial fractionation line support these models on the single E-chondrite parent body (Clayton *et al.*, 1984). Recently, Kong *et al.* (1997) suggested a single parent body and two-stage metamorphism for EH- and EL-chondrites based on continuity in composition of moderately volatile elements, and on inverse variation of the abundances of these elements with petrologic type. In addition, Akridge and Sears (1999) suggested that the fractionation between metal and silicate can be produced on a single parent body. So the difference in bulk Fe-contents between EH- and EL-chondrites is not strong evidence for the different parent bodies for these chondrites.

Some noble-gas signatures characteristic of the E-chondrites have been reported: (1) high $^{36}Ar/^{132}Xe$ ratio compared to other chondrite classes (Zähringer, 1962, 1968; Crabb and Anders, 1981; Wacker and Marti, 1983), (2) absence of extensive correlation between trapped noble gas concentrations and petrologic type (Zähringer, 1966; Marti, 1967), and (3) high $^{129}Xe/^{132}Xe$ ratio relative to other chondrite classes (Reynolds, 1960; Zähringer, 1962; Crabb and Anders, 1981, 1982; Wacker and Marti, 1983). In addition, cosmic-ray exposure ages for eighteen E-chondrites showed a systematic difference with respect to petrologic type (Crabb and Anders, 1981): E4 chondrites have exposure ages below 16 Myr and most of E6's above 30 Myr. Based on this observation, Crabb and Anders (1981) suggested that the parent body has not been extensively mixed and accordingly a single petrologic-type dominates on the about 1 km scale of individual impacts.

Cosmogenic noble gases are produced by interactions between nuclides in meteoritic materials and galactic cosmic-rays. Thus, cosmic-ray exposure ages reflect recent irradiation records. An aim of this study is to examine the correlation between the exposure age distribution and petrologic types for E-chondrites. Our samples include EH6 chondrites which have not been measured by Crabb and Anders (1981). Pairing of the chondrites are also mentioned based on noble gas compositions. In this paper, light noble gases are discussed although all noble gases were measured. Full data sets of Kr and Xe, and discussion on their isotopic compositions will be presented elsewhere with data sets obtained by stepped crushing and heating experiments.

2. Samples and experimental methods

Samples are nine Antarctic enstatite chondrites (Allan Hills (ALH)-77295, Yamato (Y)-691, -74370, -791790, -792959, -793161, -793225, -8414, and -86004) and two non-Antarctic ones (Ilafegh 009 and Pillistfer), as listed in Table 1. They are eight EH- and two EL-chondrites, while Y-793225 is classified as petrologic-type 6, intermediate between EH- and EL-chondrites on the basis of the composition of (Mg, Mn, Fe)S solid solution (Lin and Kimura, 1998).

Noble gas analyses were performed by a conventional total melting method in order to reduce experimental uncertainties in concentrations and isotopic ratios.

Samples were sliced in about 1 mm thickness using ethanol as a lubricant, and wrapped in Al-foil. They were mounted in a sample holder of an extraction furnace, and preheated at 150°C for one day so as to desorb atmospheric gases. Noble gases were extracted by heating the samples at 1800°C for 20 min. Evolved reactive gases (*e.g.* CO_2, H_2O and N_2) were eliminated using two hot Ti-Zr and two SORB-AC getters. Purified noble gases were separated into four fractions (He-Ne, Ar, Kr, and Xe) with two charcoal traps and a temperature-controlled cryogenic trap. Noble gases were measured with a modified VG5400 mass spectrometer (MS-II) at Laboratory for Earthquake Chemistry, University of Tokyo (*e.g.*, Nagao *et al.*, 1999). Sensitivities and mass discrimination of the mass spectrometer were calibrated by measuring known amounts of atmospheric noble gases and an isotopic ratio of helium standard gas ($^3He/^4He=1.71\times10^{-4}$) prepared by mixing of known amounts of ^3He and ^4He. The typical sensitivities (S) and correction factors (M) for the mass discrimination were as follows: $S(^4He)=3\times10^7$, $S(^{20}Ne)=5\times10^7$ and $S(^{36}Ar)=1\times10^8$ in volts/cm^3 STP; $M(^3He/^4He)=0.99\pm0.01$, $M(^{20}Ne/^{22}Ne)=0.955\pm0.001$, $M(^{21}Ne/^{22}Ne)=0.978\pm0.002$, $M(^{38}Ar/^{36}Ar)=1.018\pm0.001$ and $M(^{40}Ar/^{36}Ar)=1.036\pm0.002$. To check the calibration for sensitivities and mass discrimination, ALH-769 (L6), a laboratory standard sample, was measured in the series of total melting analyses. Blanks for noble gases at 1800°C are $^4He=6\times10^{-10}$, $^{20}Ne=2\times10^{-12}$, $^{36}Ar=5\times10^{-12}$ in cm^3 STP, and their isotopic ratios are atmospheric but slightly affected by memory from previous measurements of cosmogenic gases, except for a $^{40}Ar/^{36}Ar$ ratio. Errors sited in Table 1 are statistical ones (1σ). Uncertainties for the noble gas concentrations are estimated to be about 10%.

Bulk chemical compositions for Y-74370, -791790 and -793225 were also determined by electron probe microanalyzers (JEOL 733 superprobe and JEOL XA-8800R). The analyses were conducted at 12 nA and 15 kV with electron beam of 50 μm in diameter. The results are shown in Table 3. Since the analyses were made by assuming all cations to be oxides, oxygen contents in each sample are calculated to total up to 100 wt%.

3. Results and discussion

3.1. Noble gas concentrations and isotopic ratios

Table 1 shows noble gas isotopic ratios and concentrations of He, Ne and Ar. Analyzed samples weigh 5.0–19.1 mg (Table 1). Except for ALH-77295, ^3He in samples is cosmogenic, while ^4He is dominantly radiogenic. As shown in Ne isotope plot (Fig. 1a), ALH-77295 contains solar Ne, which has already been reported by others (Signer *et al.*, 1983; Wieler *et al.*, 1985). Solar He and Ar should be contained in this meteorite. Figure 1 also shows that Ne in equilibrated E-chondrites is dominated by a cosmogenic component, while Ne in unequilibrated ones is generally a mixture of cosmogenic and trapped ones. Isotopic ratios of Ar indicate that all samples contain cosmogenic and radiogenic components in addition to trapped one.

Table 1. Isotopic ratios[1] and concentrations[2] of He, Ne and Ar.

Sample	Class[3]	Analyzed weight (mg)	^{3}He	^{4}He	^{3}He/^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar
Y-691	EH3	16.9	29.7	4750	0.006256 ± 0.000046	28.7	9.01	12.9	2.2211 ± 0.0027	0.6983 ± 0.0016	111	21.5	12600	0.19361 ± 0.00028	113.34 ± 0.26
Y-791790	EH3	11.0	35.5	7920	0.004480 ± 0.000038	44.0	11.2	15.6	2.8206 ± 0.0070	0.7191 ± 0.0019	1480	278	67600	0.18812 ± 0.00016	45.678 ± 0.047
Y-792959	EH3	10.5	485	10200	0.04752 ± 0.00044	97.6	92.2	109	0.8956 ± 0.0016	0.8456 ± 0.0064	55.0	17.8	29300	0.32342 ± 0.00077	533.0 ± 1.1
Y-793161	E3	11.1	247	5500	0.04498 ± 0.00037	85.7	77.5	91.2	0.9399 ± 0.0020	0.8493 ± 0.0013	87.1	23.0	55400	0.26407 ± 0.00084	636.1 ± 1.3
ALH-77295	EH4	8.7	694	505000	0.001374 ± 0.000010	2140	143	315	6.786 ± 0.012	0.4542 ± 0.0018	269	60.2	52800	0.2239 ± 0.0011	196.13 ± 0.46
Y-74370(A)	EH4	10.5	10.6	2550	0.004138 ± 0.000026	13.9	4.23	5.93	2.344 ± 0.011	0.7131 ± 0.0036	26.2	5.08	25722	0.19402 ± 0.00055	981.8 ± 2.0
Y-74370(B)	EH4	19.1	24.0	6500	0.003685 ± 0.000030	18.4	5.60	7.80	2.3548 ± 0.0097	0.7184 ± 0.0025	67.1	12.9	55591	0.19298 ± 0.00019	828.5 ± 1.4
Y-8414	EH6	7.2	134	8960	0.01499 ± 0.00015	21.8	20.4	25.4	0.8595 ± 0.0046	0.8040 ± 0.0040	13.0	5.15	65500	0.3949 ± 0.0030	5022 ± 101
Y-86004	EH6	5.0	101	13200	0.00766 ± 0.00011	18.8	18.0	22.8	0.8242 ± 0.0078	0.7917 ± 0.0033	7.50	3.82	46300	0.5100 ± 0.0057	6178 ± 137
Y-793225	EH/EL6	7.4	562	8280	0.06790 ± 0.00022	99.8	101	121	0.8263 ± 0.0013	0.8399 ± 0.0032	469	96.1	38200	0.20506 ± 0.00041	81.564 ± 0.053
Pillistfer	EL6	12.7	76.8	10700	0.007180 ± 0.000053	29.3	28.2	30.8	0.9503 ± 0.0013	0.9168 ± 0.0013	289	56.9	67200	0.19686 ± 0.00024	232.47 ± 0.46
Ilafegh 009	EL-AN	13.3	128	8960	0.014236 ± 0.000040	38.6	38.4	42.4	0.9089 ± 0.0021	0.9055 ± 0.0037	41.3	11.7	38000	0.28300 ± 0.00091	921.60 ± 2.20

[1] Statistical 1σ errors are given for isotopic ratios.
[2] Concentrations of He, Ne and Ar are in 10^{-9} cm^3 STP/g, and their uncertainties are estimated to be about 10% for 1σ.
[3] References for classification are summarized in Appendix.

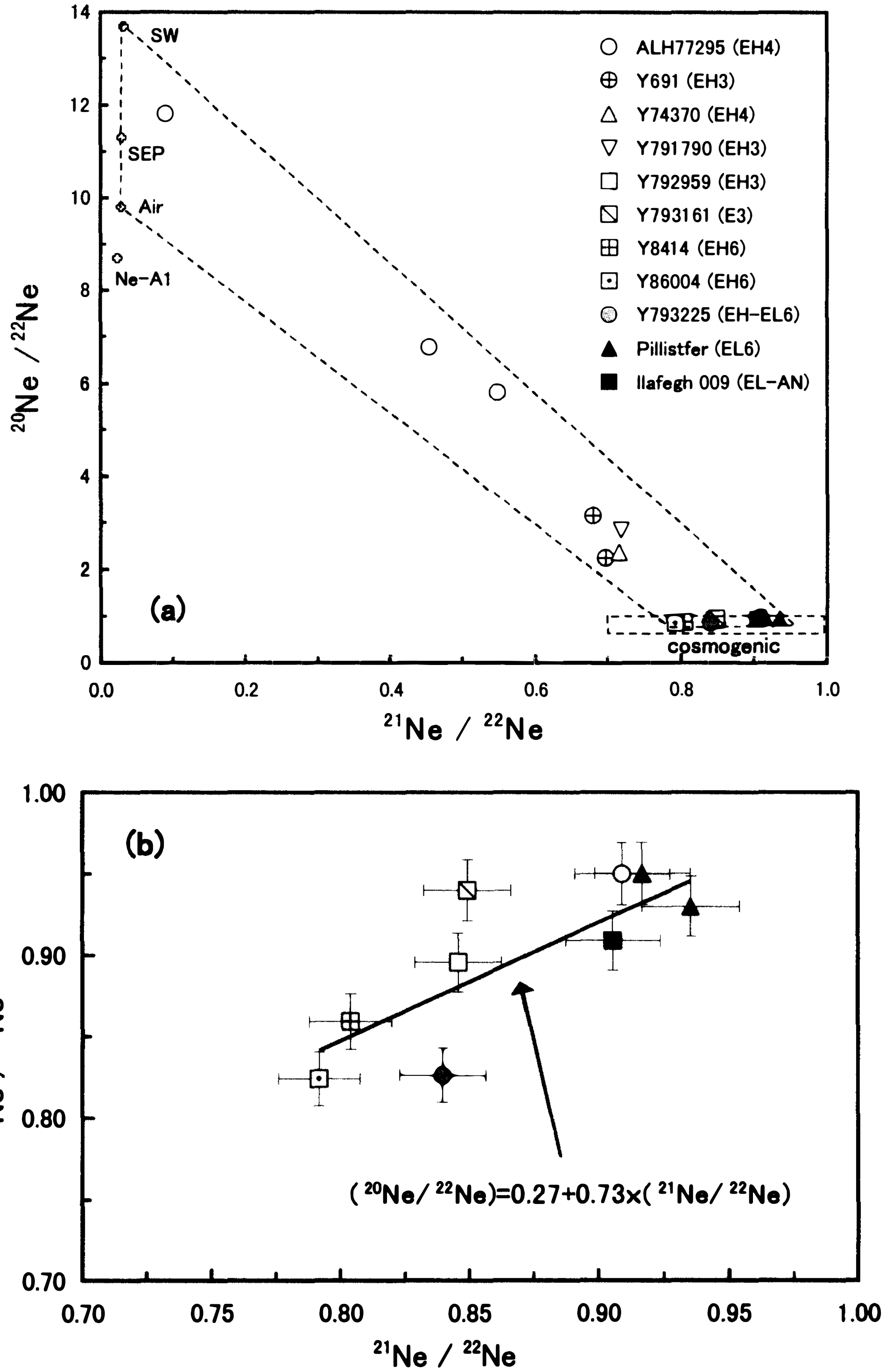

Fig. 1. Ne-three isotope diagram. Literature data for ALH-77295 (Wieler et al., 1985), Y-691 (Shima et al., 1973) and Pillistfer (Crabb and Anders, 1981) are also plotted for comparison. (a): Some EH-chondrites show existence of trapped Ne as well as cosmogenic one. (b): Enlarged cosmogenic area in the lower right of Fig. 1a. The least square fitting line was used to obtain cosmogenic $^{21}Ne/^{22}Ne$ ratios (see text).

Table 2. Abundances of cosmogenic noble gases and cosmic-ray exposure ages[1)].

Sample	Class	$[^3He]c$[2)]	$[^{21}Ne]c$	$[^{38}Ar]c$	$\left(\frac{^{21}Ne}{^{22}Ne}\right)_c$	F^3	F^{21}	F^{38}	P^3	P^{21}	P^{38}	T^3	T^{21}	T^{38}
		($\times 10^{-9}$ cm^3 STP/g)							($\times 10^{-9}$ cm^3 STP/g/Myr)			(Myr)		
Y-691	EH3	30	9.0	0.71	0.82	1.00	0.85	0.87	16	1.9	0.34	*1.9*	*4.8*	*2.1*
Y-791790	EH3	36	11	0.20	0.91	1.00	0.97	0.65	16	3.4	0.30	*2.2*	*3.3*	*0.7*
Y-792959	EH3	490	92	8.5	0.846	1.00	0.78	1.06	16	2.0	0.44	*31*	*47*	*20*
Y-793161	E3	250	78	7.6	0.849	1.00	0.77	0.88	16	2.0	0.36	*16*	*40*	*21*
ALH-77295	EH4	500	140	11	0.91	1.00	0.81	0.98	16	2.9	0.46	*31*	*48*	*24*
Y-74370	EH4	24	5.6	0.38	0.85	1.00	0.82	0.78	16	2.0	0.32	*1.5*	*2.7*	*1.2*
Y-8414	EH6	130	20	3.1	0.804	1.00	1.00	0.60	16	2.1	0.22	*8.4*	*10*	*14*
Y-86004	EH6	100	18	2.8	0.792	1.00	0.88	0.69	15	1.7	0.24	*6.5*	*10*	*11*
Y-793225	EH/EL[3)]6	560	100	9.7	0.840	1.00	0.93	0.91	16	2.3	0.37	*35*	*44*	*26*
Pillistfer	EL6	77	28	2.9	0.917	1.00	0.92	0.92	16	3.4	0.44	*4.7*	*8.4*	*6.7*
Ilafegh 009	EL-AN[4)]	130	38	4.5	0.906	1.00	0.87	0.80	16	3.0	0.37	*8.1*	*13*	*12*

$P^3 = F^3[2.09 - 0.43(^{22}Ne/^{21}Ne)_c]$

$P^{21} = 1.61F^{21}[21.77(^{22}Ne/^{21})_c - 19.32]^{-1}$

$P^{38} = F^{38}[0.125 - 0.071(^{22}Ne/^{21}Ne)_c]$ (P^n in units of 10^{-8} cm^3 STP/g per Myr; n: nuclide)

1) Uncertainties for cosmic-ray exposure ages are estimated to be 15% including 10% errors for cosmogenic gas contents and their production rates.

2) Assumed to be entirely cosmogenic except for ALH-77295 (see text).

3) An intermediate composition between EH- and EL-chondrites.

4) An impact-melt rock of EL-chondrite.

Cosmogenic ^3He, ^{21}Ne and ^{38}Ar concentrations listed in Table 2 were calculated by the following assumptions: Obtained ^3He is entirely cosmogenic except for ALH-77295, in which solar He is subtracted by assuming that isotopic ratios of trapped (t) and cosmogenic (c) components are $(^3He/^4He)_t = 3.8 \times 10^{-4}$ and $(^3He/^4He)_c = 0.25$, respectively. Radiogenic ^4He content would be negligible compared to more abundant solar ^4He in ALH-77295, because bulk ^4He contents in solar-Ne free E-chondrites are generally lower than 1.5×10^{-6} cm^3 STP/g (*e.g.*, Crabb and Anders, 1981; Wacker and Marti, 1983). Except for four samples (ALH-77295, Y-691, -74370 and -791790), measured $^{21}Ne/^{22}Ne$ ratios are regarded as cosmogenic ones because their $^{20}Ne/^{22}Ne$ ratios are within a range of cosmogenic Ne (Fig. 1a). Among ordinary chondrites, a cosmogenic $^{20}Ne/^{22}Ne$ ratio is in a narrow range irrespective of $^{21}Ne/^{22}Ne$, so the cosmogenic $^{21}Ne/^{22}Ne$ ratio is generally calculated from a point having the $^{20}Ne/^{22}Ne$ ratio of 0.85–0.90 on a mixing line of their trapped and cosmogenic Ne. However, the cosmogenic $^{20}Ne/^{22}Ne$ ratios for E-chondrites seem to be correlated with the $^{21}Ne/^{22}Ne$ ratios (Fig. 1b). Hence, we tentatively calculated the cosmogenic $^{21}Ne/^{22}Ne$ ratio from an intersection between a mixing line of trapped and measured Ne, and the least squares fitting line for the E-chondrites having cosmogenic $^{20}Ne/^{22}Ne$. Trapped Ne for Y-691, -74370 and -791790 is assumed to be atmospheric because stepped pyrolysis for some bulk E-chondrites revealed that their isotopic ratios of Ne plot along a mixing line between cosmogenic and air-like Ne (Okazaki R., unpublished data). Huss *et al.* (1996) also reported that Abee HF/HCl residues contain trapped Ne intermediate between Ne-P1 and Ne-A1, close to atmospheric Ne. For ALH-77295, which includes solar Ne, a least squares fitting to the data points including literature ones (Wieler *et al.*, 1985) is applied to get an intersection. Using these cosmogenic $^{21}Ne/^{22}Ne$ and $(^{21}Ne/^{22}Ne)_t=0.03$, trapped ^{21}Ne is subtracted from measured ^{21}Ne concentrations. For the calculation of cosmogenic ^{38}Ar, $(^{38}Ar/^{36}Ar)_t=0.188$, and $(^{38}Ar/^{36}Ar)_c=1.5$ are assumed for all samples.

3.2. Weathering

We performed duplicate measurements for Y-74370 in order to see the degree of sample heterogeneity due to small sample weights. These specimens are prepared from the same block (Y-74370, 67). Isotopic ratios of He, Ne and Ar, and Ne contents are in good agreement between Y-74370 (A) and (B), which suggests that the contribution of sample heterogeneity is not significant. Concentrations of He and Ar, however, varied between the specimens with 2- or 3-fold differences (Table 1).

As mentioned, ^3He is almost cosmogenic, while ^{36}Ar and ^{38}Ar are mixtures of cosmogenic and trapped components. Cosmogenic ^{36}Ar and ^{38}Ar in meteorites are produced mainly from Ca and Fe via spallation reactions with galactic cosmic-rays. Kallemeyn and Wasson (1986) reported that weathered E-chondrites tend to be depleted in Ca, Mn, Na, K and Fe. The serious discrepancies in Ar concentrations are reasonably explained by that host phases for cosmogenic Ar are easy to be oxidized and susceptible to weathering. Such a weathering effect has been reported by previous studies (*e.g.*, Gibson and Bogard, 1978; Patzer and Schultz, 1999).

Cosmogenic ^3He is produced from O, Mg, Si, Fe and other heavy elements. The ratio of production rate of cosmogenic ^3He from metal to that from silicate is estimated $P^3_{(metal)}/P^3_{(silicate)}=0.66$ from geometric cross-sections (Bogard and Cressy, 1973). For cosmogenic ^{21}Ne, the production ratio of metal to silicate is calculated $P^{21}_{(metal)}/P^{21}_{(silicate)}=0.04$ from elemental production rates in Schultz and Freundel (1985) by assuming that a silicate composition is $MgSiO_3$. The production ratio $P^3_{(metal)}/P^3_{(silicate)}$ is $10\times$ larger than $P^{21}_{(metal)}/P^{21}_{(silicate)}$, indicating the fraction of $P^3_{(metal)}$ is significant. Therefore, the discrepancy in concentrations of cosmogenic ^3He as well as cosmogenic Ar is thought to come from weathering of metal and sulfides.

On the other hand, ^4He and ^{40}Ar are radiogenic. Parent nuclides for radiogenic ^4He and ^{40}Ar are U/Th and K, respectively. Potassium is susceptible to weathering (Gibson and Bogard, 1978; Kallemeyn and Wasson, 1986). The parent elements U and Th are heterogeneously distributed (Bogard *et al.*, 1983). Thus, the discrepancies in concentrations of ^4He and ^{40}Ar between Y-74370 (A) and (B) would be caused by sample heterogeneity and weathering, respectively, or both.

In this paper, we will use the results for the specimen Y-74370 (B), because more abundant He and Ar suggest that there is little weathering effect on the specimen (B). By stepped crushing and heating experiments (Okazaki R., unpublished data) for other samples using larger sample sizes (with 70–100 mg), it is confirmed that cosmogenic ^{21}Ne contents in the sample are essentially identical.

3.3. Cosmic-ray exposure age

A cosmic-ray exposure age (T^n) is calculated from the following equation:

$$T^n = A^n / P^n \ , \qquad (1)$$

where A^n and P^n are concentration and a production rate of cosmogenic stable nuclide n, respectively. The production rate depends on shielding conditions as well as energy and composition of incident cosmic-ray particles and a chemical composition of a target meteoroid. Eugster (1988) gave the production rates for chondrites considering these effects by the following equation:

$$P^n = F^n \cdot P^n{}_L \ , \qquad (2)$$

where $P^n{}_L$ is a production rate of nuclide n in L-chondrites and it is a function of a cosmogenic $(^{21}Ne/^{22}Ne)_c$ ratio which is used to correct the shielding condition. F^n is a correction factor for composition of target elements of a meteoroid. To determine precise exposure ages, it is necessary to get appropriate correction factors for the chemical composition and the shielding effect for each sample.

The cosmogenic $(^{21}Ne/^{22}Ne)_c$ ratio also depends on chemical compositions of samples. Reedy *et al.* (1979) has reported that the reaction $^{24}Mg(n,\alpha)^{21}Ne$ predominantly controls the correlation between $(^{21}Ne/^{22}Ne)_c$ and the shielding depth. It is suspected that $(^{21}Ne/^{22}Ne)_c$ of E-chondrites would be less sensitive to the shielding depth due to their low Mg contents compared to ordinary chondrites. We estimated the influence of the chemical composition on the correlation between $(^{21}Ne/^{22}Ne)_c$ and the shielding depth. We used elemental production rates for a 2π geometry (Hohenberg *et al.*, 1978) in the calculation, and assumed that the difference in the geometry is not significant to discuss the influence of the difference in bulk chemistries on the depth profiles of $(^{21}Ne/^{22}Ne)_c$. Bulk elemental compositions of each L- and E-chondrite are from Wasson and Kallemeyn (1988). The estimation shows no significant difference in the depth profile of $(^{21}Ne/^{22}Ne)_c$

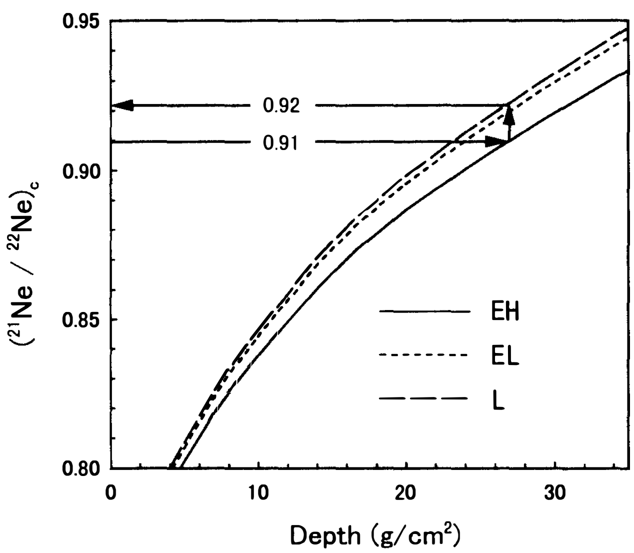

Fig. 2. Cosmogenic $^{21}Ne/^{22}Ne$ vs. shielding depth. Unit for the shielding depth is in g/cm^2.

between L- and EL-chondrites (Fig. 2), while there is a slight difference between L- and EH-chondrites. For example, $(^{21}Ne/^{22}Ne)_c$ estimated for ALH-77295 and Y-791790 is 0.91 (Table 2), which corresponds to $(^{21}Ne/^{22}Ne)_c=0.92$ at the same shielding depth within L-chondrite. However, the difference in $(^{21}Ne/^{22}Ne)_c$ between L- and EH-chondrites is only 1%, which may be within an uncertainty of $(^{21}Ne/^{22}Ne)_c$ estimated by the procedure mentioned earlier. Thus, the difference in $(^{21}Ne/^{22}Ne)_c$ due to chemical compositions can be ignored, and uncertainties for production rates of ^3He, ^{21}Ne and ^{38}Ar are assumed to be 10%.

As mentioned above, cosmogenic He and Ar are easily lost by weathering of their host phases. In addition to the weathering affects, diffusive loss of He would cause a short ^3He-age. Compared to the cosmogenic ^3He, cosmogenic ^{21}Ne is less sensitive to diffusive loss, although ^{21}Ne-loss from plagioclase has been reported (Bogard and Cressy, 1973). Considering these reasons, exposure ages based on cosmogenic ^{21}Ne is more reliable than those on cosmogenic ^3He and ^{38}Ar. We use exposure ages based on cosmogenic ^{21}Ne in the following discussion.

Cosmogenic gas contents and cosmic-ray exposure ages are listed in Table 2 along with their production rates. We assume single-stage 4π exposures to galactic cosmic rays. Uncertainties for concentrations and production rates for cosmogenic noble gases are estimated to be 10%, so those for cosmic-ray exposure ages are 15%. Sample heterogeneity and gas loss due to weathering are not considered for the uncertainties. In this study, the correction factors F^n were calculated following the procedures by Eugster (1988). In the calculation, measured chemical compositions listed in Table 3 were used, because EH6 has not been included in chemical compositions (Wasson and Kallemeyn, 1988) used in Eugster (1988). The chemical composition of Y-793225 by Lin and Kimura (1998) is different from that determined in this study (Table 3), and shows a extremely low Fe/Mg atomic ratio (0.17) compared to those of other E-chondrites (*e.g.*, EH: 1.19; EL: 0.68; Wasson and Kallemeyn, 1988). So we will adopt our result for Y-793225.

The noble gas data for two EH6 and one EH/EL6 chondrites are the first report on high petrologic types of EH-chondrites and a newly recognized E-chondrite having an intermediate composition of (Mg, Mn, Fe)S solid solution between EH- and EL-chondrites (Lin and Kimura, 1998). Petrologic and mineralogical studies by Lin and Kimura (1998) indicate that Y-8414 and -86004 are paired. Our noble gas data shows that isotopic ratios and concentrations of Ne are in good agreement between these two meteorites. The identical exposure ages (10 Myr) supports their potential pairing. Thus, Y-8414 and -86004 should be regarded to be paired. Another possible pair is two E3 meteorites, Y-792959 and -793161. They have identical mineral compositions, and were recovered at a close location in Antarctica (Yanai and Kojima, 1995), which suggests that they might have fallen as a meteorite shower with many fragments. Their isotopic ratios of He, Ne and Ar are identical. Although there are some differences in concentrations, especially in ^3He, ^4He and ^{40}Ar contents, such differences in noble gas abundances are also observed in Y-74370 (Table 1). Thus, we will treat Y-792959 and -793161 as a pair in the following discussion, according to their mineralogical and petrologic

Table 3. Bulk chemical composition and chemical correction factors F^n.*

	Y-691[1), 2)] (average)	Y-791790[3)]	Y-792959[2)]	Y-793161[2)]	ALH-77295[4)]	Y-74370[3)]	Y-74370[2)]	Y-74370 (average)
Si	16.97	19.85	15.09	15.50	16.69	17.03	15.96	16.49
Al	1.55	1.02	1.20	0.99	0.95	1.08	1.33	1.20
Fe	28.91	20.16	28.10	27.85	30.60	25.02	27.74	26.38
Mn	0.19	0.19	0.21	0.19	0.21	0.16	0.18	0.17
Mg	11.82	13.71	10.69	10.65	11.06	12.01	10.98	11.49
Ca	0.92	0.24	0.90	0.82	0.90	0.63	0.79	0.71
Na	0.62	0.91	0.42	0.57	0.58	0.96	0.55	0.75
K	0.06	0.09	0.04	0.02	0.06	0.01	0.07	0.04
O**	30.9	37.3	36.8	36.8	31.8	38.6	35.8	37.2
Ni	1.71	1.21	1.41	1.40	1.83	0.32	1.51	0.91
Co	0.08	–	0.059	0.047	0.09	0.003	0.051	0.027
Ti	0.05	0.04	0.04	0.05	0.07	0.04	0.07	0.05
Cr	0.31	0.30	0.23	0.29	0.27	0.16	0.29	0.23
S	5.95	5.03	4.84	4.82	4.92	3.98	4.66	4.32
Total cation	69.1	62.7	63.2	63.2	68.2	61.4	64.2	62.8
F^{3}	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
F^{21}	0.85	0.97	0.78	0.77	0.81	0.85	0.80	0.82
F^{38}	0.87	0.65	1.06	0.88	0.98	0.66	0.91	0.78

	Y-8414[5]	Y-86004[5]	Y-793225[3]	Y-793225[5]	Pillistfer[6),7),8)] (average)	Ilafegh 009[9]	Average of EH-chondrite[10]	Average of EL-chondrite[10]
Si	24.07	24.07	20.81	25.09	18.62	17.81	16.70	18.60
Al	1.19	1.19	2.16	0.46	1.15	0.87	0.81	1.05
Fe	17.48	17.48	13.50	7.76	27.78	30.01	29.00	22.00
Mn	0.18	0.18	0.11	0.03	0.02	0.21	0.22	0.16
Mg	13.73	13.73	12.99	19.92	12.63	12.43	10.60	14.10
Ca	0.18	0.18	0.96	0.36	0.44	0.56	0.85	1.01
Na	1.07	1.07	1.42	0.29	0.59	0.49	0.68	0.58
K	0.10	0.10	0.17	0.02	0.07	0.03	0.08	0.07
O**	36.9	36.9	41.7	42.4	33.5	32.4	28.0	31.0
Ni	1.06	1.06	0.83	0.31	1.68	1.79	1.75	1.30
Co	0.049	0.049	-	0.015	0.080	0.082	0.084	0.067
Ti	0.02	0.02	0.02	0.07	-	0.07	0.05	0.06
Cr	0.18	0.18	0.16	0.45	0.14	0.13	0.32	0.31
S	3.77	3.77	1.54	2.76	3.29	3.15	5.80	3.30
Total Cation	63.1	63.1	96.4	99.9	66.5	67.6	94.9	93.6
F^3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
F^{21}	1.00	0.88	0.93	1.30	0.92	0.87	0.78	0.96
F^{38}	0.60	0.69	0.91	0.33	0.92	0.80	0.98	0.89

$F^n = Q^n_{\mathrm{sample}}/Q^n_{\mathrm{L\text{-}chondrite}}$ (n: nuclide)

$Q^3 = 0.0174[\mathrm{Ti}+\mathrm{Cr}+\mathrm{Mn}+\mathrm{Fe}+\mathrm{Ni}]+0.0266(100-[\mathrm{Ti}+\mathrm{Cr}+\mathrm{Mn}+\mathrm{Fe}+\mathrm{Ni}])$

$Q^{21} = 1.63[\mathrm{Mg}]+0.6[\mathrm{Al}]+0.32[\mathrm{Si}]+0.22[\mathrm{S}]+0.07[\mathrm{Ca}]+0.021[\mathrm{Fe}+\mathrm{Ni}]$

$Q^{38} = 1.58[\mathrm{Ca}]+0.086[\mathrm{Fe}+\mathrm{Ni}]+0.33[\mathrm{Ti}+\mathrm{Cr}+\mathrm{Mn}]+11[\mathrm{K}]$

([X]: concentration of element X as weight fraction; Q^n in units of 10^{-8} cm^3 STP/g per Myr)

* The elemental abundances are in weight percent.

** Oxygen content is calculated by subtracting total cation from 100%.

References: 1) Shima (1974); 2) Yanai and Kojima (1995); 3) this study; 4) Jarosewich (1990); 5) Lin and Kimura (1998); 6) Dyakonova (1968); 7) Jarosewich and Mason (1969); 8) Von Michaelis *et al.* (1969); 9) McCoy *et al.* (1995); 10) Wasson and Kallemeyn (1988).

similarities, and their near sampling locations. Cosmic-ray exposure ages of 10 and 44 Myr are adopted for Y-8414 and -86004, and Y-792959 and -793161, respectively.

3.4. Distribution of cosmic-ray exposure ages of E-chondrites

Figure 3 shows distribution of the cosmic-ray exposure ages of twenty nine E-chondrites studied in this work and previously reported ones. Present study adds new data for seven E-chondrites on the distribution proposed by Crabb and Anders (1981). In addition, recently reported four E-chondrites, LEW-87223 (Schultz *et al.*, 1998), Qingzhen (Shima *et al.*, 1973), Parsa (Murty, 1992) and Kishima (Nagao *et al.*, 1993) are also plotted. Kishima meteorite has been reported as EL-chondrite (Nagao *et al.*, 1993), but recently it was classified as EL6 (reported as Kijima meteorite; Okada and Shima, 1998).

Crabb and Anders (1981) reported that exposure ages for E-chondrites have a bimodal pattern and there are systematic differences correlated with petrologic types. Most E4 chondrites show T^{21} below 16 Myr, while T^{21} for E6 chondrites are above 30 Myr. They proposed that there was a single E-chondrite parent body,

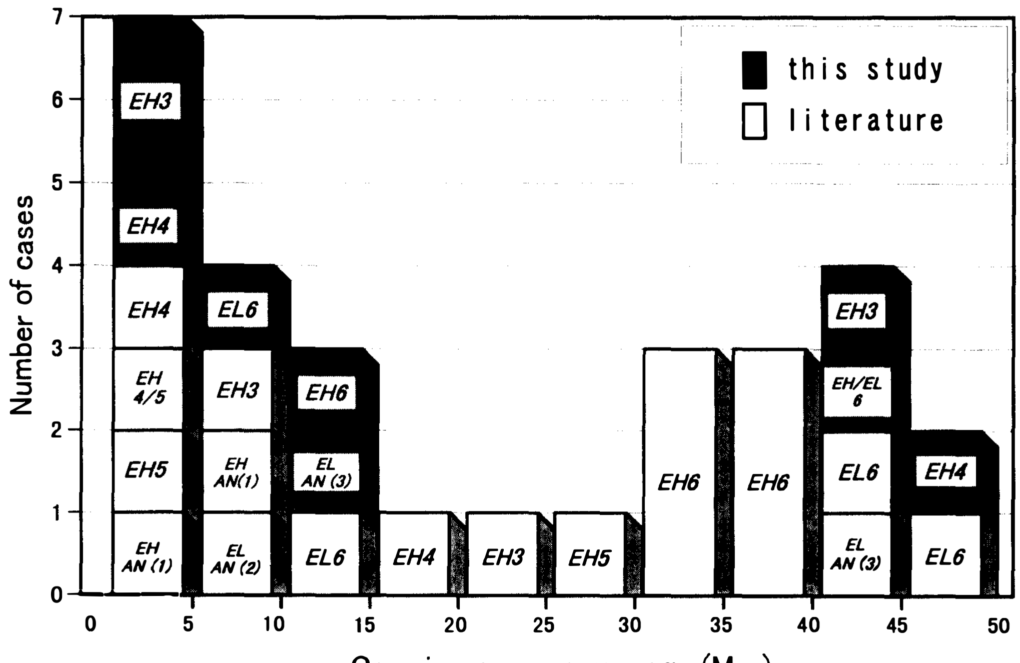

Fig. 3. Distribution of cosmic-ray exposure ages based on cosmogenic ^{21}Ne. Average exposure ages of our results and literature ones (Crabb and Anders, 1981) are 7.6 and 3.8 Myr for Pillistfer and Y-691, respectively. AN means exceptional stones in their petrologic types: (1) Abee and Adhi Kot have been reported as EH4 chondrites (Sears et al., 1982), and later as EH impact-melt breccias (Rubin, 1995; Rubin and Scott, 1997). (2) LEW-87223 is interpreted as an anomalous E3 chondrite (Zhang et al., 1995) or an anomalous EL-chondrite (Zhang and Sears, 1996). (3) McCoy et al. (1995) has reported that Ilafegh 009 and Happy Canyon are an impact-melt rock and an impact-melt breccia of EL-chondrites, respectively.

which contained predominantly a single petrologic type on the scale of individual impacts, based on the systematic distribution of cosmic-ray exposure ages. Contrary to the report of Crabb and Anders (1981), no systematic difference in the exposure ages with respect to petrologic types is observed (Fig. 3). Exposure ages obtained for type 3 and 4 E-chondrites cluster around 3.5 Myr and 45 Myr, while those for higher petrologic types of E-chondrites do around 10 Myr except for Y-793225 (EH/EL6) with 45 Myr (Table 2). The peaks around 5 and 40 Myr contain both E3 and E6 chondrites. Patzer and Schultz (1998) also reported no relation between exposure ages and petrologic types. In addition, the present study discovered that both EH- and EL-chondrites are found in both peaks, that is, there is little difference in the exposure age distribution between EH- and EL-subclasses. Thus, the exposure age distribution hardly give information on the structure of the parent body (or bodies) of E-chondrites. The most simple explanation for the exposure age distribution is that the parent body (or bodies) had been collapsed prior to collisions which threw out meter-sized E-chondritic materials.

Exposure ages reflect the last irradiation episode in space after fragmentation into meter-sized objects. Therefore, the exposure age of E-chondrites does not imply their origin and the structure of their parent body, unlike some arguments previously presented (*e.g.*, Crabb and Anders, 1981; Kong *et al.*, 1997).

4. Summary

Light noble gas data for eleven E-chondrites are presented. Based on the noble gas signatures and their exposure ages (T^{21}), potential pairing between Y-8414 (EH6) and -86004 (EH6) is suggested. Cosmic-ray exposure ages for EH- and EL-chondrites have correlation with respect to neither their petrologic types nor chemical classification. The exposure age distribution would not reflect the original structure of E-chondrite parent body.

Acknowledgments

We will express our appreciation to the NIPR for providing ALH-77295, Y-691, -74370, -791790, -792959, -793161, -793225, -8414 and -86004, and to Drs. K. Keil and A. Yamaguchi for providing Ilafegh 009. We would like to thank Drs. D. W. G. Sears and K. Nishiizumi for their constructive and invaluable reviews. We also thank Mr. K. Shimada, Dr. A. Yasuda and Ms. M. Otsuki for their technical assistance in electron microprobe analyses.

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(Received September 6, 1999; Revised manuscript received January 24, 2000)

Appendix

Appendix. Samples discussed in this study, and their references for classification and noble gas data.

Sample	Classification	References of chemical class	References of petrologic type	References of noble gases
Abee	EH imapct-melt breccia	1	2	3
Adhi Kot	EH imapct-melt breccia	1	2	3
ALH-77295	EH4	4	4	5
Atlanta	EL6	1	6	3
Bethune	EH4	1	7	3
Blithfield	EL6	1	6	3
Daniel's Kuil	EL6	1	6	3
Happy Canyon	EL impact-melt breccia	8	8	3
Hvittis	EL6	1	6	3
Ilafegh 009	EL impact-melt rock	9, 10	11	5
Indarch	EH4	1	6	3
Jajh Deh Kot Lalu	EL6	1	6	3
Khairpur	EL6	1	6	3
Kishima	EL	12	13	12
LEW-87223	anomalous EL3	14	15	16
North West Forrest	EL6	1	6	3
Parsa	EH3	1	11, 17	18
Pillistfer	EL6	1	6	3, 5
Qingzhen	EH3	19	20	21
Saint-Sauveur	EH5	1	6	3
South Oman	EH4/5	1	6	3
St. Mark's	EH5	1	6	3
Y-691	EH3	1	22	3, 5, 23
Y-74370	EH4	4	4	5
Y-791790	EH3	7	4	5
Y-792959	EH3	7	4	5
Y-793161	E3	—	4	5
Y-793225	type 6 chondrite with an intermediate between EH and EL	24	24	5
Y-8414	EH6	24	24	5
Y-86004	EH6	24	24	5
Yilmia	EL6	1	6	3

References: 1) Sears *et al.* (1982); 2) Rubin and Scott (1997); 3) Crabb and Anders (1981); 4) Yanai and Kojima (1995); 5) this study; 6) Van Schumus and Wood (1967); 7) Rubin *et al.* (1997); 8) McCoy *et al.* (1995); 9) McCoy *et al.* (1992); 10) Bishoff *et al.* (1992); 11) Prinz *et al.* (1984); 12) Nagao *et al.* (1993); 13) Okada and Shima (1998) ; 14) Zhang *et al.* (1995); 15) Zhang and Sears (1996); 16) Schultz *et al.* (1998); 17) Nehru *et al.* (1984); 18) Murty (1992); 19) Sheng *et al.* (1982); 20) Wang and Xie (1981); 21) Eugster *et al.* (1993); 22) El Goresy *et al.* (1988); 23) Shima *et al.* (1973); 24) Lin and Kimura (1998).