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Cosmic-ray exposure histories of two Antarctic meteorites from Chinese collections and the Guangmingshan and Zhuanghe chondrites

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Abstract Concentrations of noble gases of two Antarctic meteorites (GRV 98002, 98004) from Chinese collections, and the Guangmingshan and Zhuanghe chondrites were measured. Based on the petrography and mineralogy of these meteorites, and production rates of the cosmogenic nuclides, we calculated cosmic-ray exposure and gas retention ages of the four chondrites. Exposure ages of the four chondrites are 0.052 Ma ± 0.008 Ma (GRV 98004, H5), 17.0 Ma ± 2.5 Ma (GRV98002, L5), 3.8 Ma ± 0.6 Ma (Zhuanghe, H5), and 68.9 Ma ± 10 Ma (Guangmingshan, H5), respectively. The exposure age of GRV 98004 is the lowest value of Antarctic meteorites reported up to date; while that of Guangmingshan is higher than other Chinese meteorites of H-group. Both GRV 98002 and Zhuanghe have low ^{4}He concentrations, probably due to shock effects or solar heating at orbits with small perihelion distances during cosmic-ray exposure. On the other hand, losses of cosmogenic ^{3}He and ^{4}He are correlated with both GRV 98002 and Guangmingshan.

Keywords: chondrite, noble gas, cosmic-ray exposure age.

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In this paper, we report cosmic-ray exposure ages (^{3}He, ^{21}Ne, ^{38}Ar) and gas retention ages (^{4}He, ^{40}Ar) of two Antarctic meteorites, and the Guangmingshan and Zhuanghe ordinary chondrites. The Antarctic meteorites (GRV98002 and GRV98004) were collected on blue ice in the Grove Mountains region, Antarctica by the 15th Chinese Antarctic Expedition Team[1]. Both Guangmingshan and Zhuanghe meteorites fell in Zhuanghe County, Liaoning Province, China in 1976 and 1996, respectively[2]. The fall sites are in about 20 km. Chemical-petrographic classification of the four meteorites is listed in table 1. Isotopic analyses of bulk He, Ne and Ar of the meteorites were carried out in the Institute of Physics, University of Bern, Switzerland. For the preparation of samples and analyzing procedure, refer to refs. [3—7].

1 Calculation of cosmic-ray exposure ages

With concentrations of cosmogenic nuclides of meteorites, the cosmic-ray exposure ages can be calculated based on eq. (1).

Table 1 Classification of GRV98002, GRV98004, Guangmingshan and Zhuanghe ordinary chondrites

Meteorites	Fa/mol%	Fs/mol%	Wo/mol%	An/mol%	Co-content of kamacite/wt%	Refs.
GRV98002 (L5)	25.1	21.1	1.8			[8]
GRV98004 (H5)	18.6	16.6	1.3			[8]
Guangmingshan (H5)	19.5 (n = 89) 18.5—21.6	17.3 (n = 30) 16.4—18.7	1.2	12.1 (n = 27) 10.2—13.5	0.39—0.55	[2]
Zhuanghe (H5)	19.7 (n = 38) 18.3—20.7	17.3 (n = 28) 15.7—18.6	1.2	11.7 (n = 21) 10.8—12.5	0.40—0.65	[2]

n, the number of analyzed grains; ranges are in italic.

$$T_s = C^s/P^s, \tag{1}$$

where T_s stands for the age (Ma), C^s, the concentrations (10^{-8} cm^3 STP/g) of stable cosmogenic nuclides (^{3}He, ^{21}Ne, ^{38}Ar), and P^s, the production rates of the nuclides (10^{-8} cm^3 STP/g·Ma). The concentrations of cosmogenic (c), trapped (tr), and radiogenic (r) nuclides can be determined from the analyses of the noble gases, using some experiential isotopic ratios given in table 2.

Table 2 Isotopic ratios for calculating concentrations of cosmogenic (c), trapped (tr), and radiogenic (r) nuclides

	$(^{20}Ne/^{22}Ne)_{tr}$	$(^{21}Ne/^{22}Ne)_{tr}$	$(^{20}Ne/^{22}Ne)_c$
$(^{20}Ne/^{36}Ar)_{tr} < 1$	8.46	0.035	0.8
$(^{20}Ne/^{36}Ar)_{tr} > 1$	12.4	0.0310	0.8
Terrestrial Ne	9.80	0.0290	0.8

$^3He_{tr} = 0$; $^4He_{tr} = 0$; $(^4He/^3He)_c = 5$; $(^{36}Ar/^{38}Ar)_c = 0.65$ or 0.63; $(^{36}Ar/^{38}Ar)_{tr} = 5.32$; $(^{40}Ar/^{36}Ar)_c = 0.2$; $(^{40}Ar/^{36}Ar)_{tr} = 2.9 \times 10^{-4}$. $(^{22}Ne/^{21}Ne)_c$ ratio is not sensitive to trapped Ne component, because of its low concentration and nearly constant $(^{20}Ne/^{36}Ar)_{tr}$ for many chondrites.

In addition, $^{22}Ne_c$, $^{21}Ne_c$ and $^{20}Ne_{tr}$ can be calculated below[1)]:

$$^{22}Ne_c = {}^{22}Ne_m \times [1-(^{20}Ne/^{22}Ne)_m/(^{20}Ne/^{22}Ne)_{tr}]/[1-(^{20}Ne/^{22}Ne)_c/(^{20}Ne/^{22}Ne)_{tr}], \tag{2}$$

$$^{21}Ne_c = {}^{21}Ne_m-(^{21}Ne/^{22}Ne)_{tr}[^{22}Ne_m-{}^{22}Ne_c], \tag{3}$$

$$^{20}Ne_{tr} = {}^{20}Ne_m-{}^{22}Ne_c(^{20}Ne/^{22}Ne)_c, \tag{4}$$

here, m is the measurement of the isotopes of He, Ne and Ar, and their ratios. For $(^{20}Ne/^{36}Ar)_{tr} < 1$, $(^{20}Ne/^{36}Ar)_{tr} > 1$ and terrestrial Ne, sets of values of $^{22}Ne_c$, $^{21}Ne_c$ and $^{20}Ne_{tr}$ can be calculated based on eqs. (2)—(4) and using the data of table 2. Values of $^{38}Ar_c$ and $^{36}Ar_{tr}$ are calculated below:

For $(^{36}Ar/^{38}Ar)_c=0.65$, $^{38}Ar_c = {}^{38}Ar_m[1.1392 - 0.2141(^{36}Ar/^{38}Ar)_m]$; $^{36}Ar_{tr} = 0.65 \times {}^{38}Ar_c$.

For $(^{36}Ar/^{38}Ar)_c=0.63$, $^{38}Ar_c = {}^{38}Ar_m[1.1343 - 0.2132(^{36}Ar/^{38}Ar)_m]$; $^{36}Ar_{tr} = 0.63 \times {}^{38}Ar_c$.

Besides concentrations of the cosmogenic nuclides calculated above, production rates of ^{3}He, ^{21}Ne and ^{38}Ar are required in order to determine the exposure ages. Because H, L, LL groups of chondrites have different concentrations of the target elements of the cosmogenic nuclides, a chemical factor (F) is introduced during calculating the production rates. The production rates of ^{3}He, ^{21}Ne and ^{38}Ar (hereafter called p^3, p^{21} and p^{38}, respectively) are functions of the shielding parameter $(^{22}Ne/^{21}Ne)_c$, which can be calculated below[3]:

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1) Eugster, personal communication, 2001.

$$p^{3} = F[2.09 - 0.43(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{c}], \qquad F_{\mathrm{H}} = 0.98;\ F_{\mathrm{L,LL}} = 1.00,$$

$$p^{21} = 1.61F[21.77(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{c} - 19.32]^{-1}, \qquad F_{\mathrm{H}} = 0.93;\ F_{\mathrm{L,LL}} = 1.00,$$

$$p^{38} = F[0.125 - 0.071(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{c}], \qquad F_{\mathrm{H}} = 1.08;\ F_{\mathrm{L,LL}} = 1.00.$$

The gas retention ages of ^{4}He and ^{40}Ar are calculated from

$$T_{4} = {}^{4}\mathrm{He}_{r} = 75200[^{238}\mathrm{U}](e^{0.155[t]} - 1) + 474[^{235}\mathrm{U}](e^{0.985[t]} - 1) + 56400[^{232}\mathrm{Th}](e^{0.0492[t]} - 1), \quad (5)$$

$$T_{40} = 1.805\ln[^{40}\mathrm{Ar}_{r}/0.701 \times \mathrm{K}+1], \quad (6)$$

here, $t = T_4$; K, ^{238}U, ^{235}U and ^{232}Th are average concentrations of the bulk meteorites (μg/g, or $\times 10^{-6}$); radiogenic $^{4}\mathrm{He}_{r}$ and $^{40}\mathrm{Ar}_{r}$ are measured values (10^{-8} cm^3 STP/g). For H-group, K 782×10^{-6}, Th 0.04×10^{-6} and U 0.013×10^{-6}; for L-group, K 858×10^{-6}, Th 0.042×10^{-6} and U 0.015×10^{-6}.

2 Results and discussion

The analyses of isotopes of He, Ne and Ar and their ratios are listed in table 3. Table 4 shows the calculated concentrations of the cosmogenic, trapped, and radiogenic nuclides, and table 5 shows the determined production rates of cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar, their exposure ages, and the gas retention ages of ^{4}He(T_4) and ^{40}Ar(T_{40}).

Table 3 Concentrations and isotopic ratios of He, Ne and Ar (10^{-8}cm^{3}STP/g)

Meteorites	^{4}He	^{20}Ne	^{40}Ar	$\frac{^{4}\mathrm{He}}{^{3}\mathrm{He}}$	$\frac{^{20}\mathrm{Ne}}{^{22}\mathrm{Ne}}$	$\frac{^{22}\mathrm{Ne}}{^{21}\mathrm{Ne}}$	$\frac{^{36}\mathrm{Ar}}{^{38}\mathrm{Ar}}$	$\frac{^{40}\mathrm{Ar}}{^{36}\mathrm{Ar}}$
GRV98002 (L5)	670±20	8.42±0.30	6970±200	26.1±0.3	0.883±0.010	1.047±0.010	2.42±0.03	2336±70
GRV98004 (H5)	1390±50	0.401±0.040	6170±200	17715±700	6.44±0.99	3.31±0.40	4.90±0.20	5723±200
Guangmingshan (H5)	1770±50	21.3±0.6	5150±160	17.12±0.17	0.863±0.009	1.131±0.012	0.928±0.011	1652±40
Zhuanghe (H5)	374±10	1.79±0.05	4600±150	75.9±1.0	0.913±0.030	1.016±0.015	3.64±0.10	2258±100

Table 4 Cosmogenic, trapped and radiogenic noble gases (10^{-8} cm^{3} STP/g)

Meteorites	^{3}He	^{21}Ne	^{38}Ar	^{22}Ne/^{21}Ne	^{20}Ne	^{36}Ar	^{4}He	^{40}Ar
	cosmogenic				trapped		radiogenic	
GRV98002 (L5)	25.7 ±1.0	9.11 ±0.40	0.765 ±0.030	1.037 ±0.010	0.87 ±0.40	2.48 ±0.20	536 ±20	6970 ±200
GRV98004 (H5)	0.078 ±0.005	0.0172 ±0.0035	0.0198 ±0.0100		0.388 ±0.040	1.07 ±0.06	1390 ±50	6170 ±200
Guangmingshan (H5)	103.4 ±3.0	21.8 ±0.9	3.16 ±0.15	1.125 ±0.012	1.72 ±0.60	1.07 ±0.05	1230 ±50	5150 ±200
Zhuanghe (H5)	4.93 ±0.20	1.93 ±0.10	0.202 ±0.020	1.00 ±0.02	0.24 ±0.10	1.91 ±0.10	348 ±10	4600 ±150

Table 5 Production rates, cosmic-ray exposure ages (Ma) and gas retention ages (Ga)

Meteorite	P_3	P_{21}	P_{38}	T_3	T_{21}	T_{38}	$T_{\mathrm{pref.}}$	T_4	T_{40}	T_3/T_{21}	T_4/T_{40}
GRV98002 (L5)$^{a)}$	1.639	0.455	0.0504	15.7	20.0	15.2	17.0 ±2.5	1.6 ±0.1	4.63 ±0.16	0.79	0.35
GRV98004 (H5)$^{b)}$	1.580	0.309	0.0499	0.049	0.056	(0.40)	0.052 ±0.008	3.6 ±0.8	4.53 ±0.15	0.88	0.80
Guangmingshan (H5)	1.574	0.290	0.0487	65.7	75.2	65.9	68.9 ±10	3.3 ±0.7	4.23 ±0.15	0.87	0.78
Zhuanghe (H5)	1.606	0.423	0.0545	3.07	4.56	3.71	3.8 ±0.6	1.1 ±0.1	4.05 ±0.15	0.67	0.27

a) $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{c}$=1.05; b) $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{c}$=1.11.

Fig. 1 shows distribution of the exposure ages of H- and L-group of chondrites, with Zhuanghe (3.8 Ma) and GRV 98002 (17 Ma) plotted within the ranges of H- and L-group, respectively. The exposure age of GRV 98004 is 0.052 Ma, the lowest value of Antarctic meteorites reported to date. It is possible that the meteorite has a very low terrestrial age too. Besides exposure age of a bulk Antarctic meteorite, ALH 76008 (1.72 Ma ± 0.11 Ma), Polnau et al.[10] also reported individual exposure ages for a chondrule fragment and matrix of the meteorite. The present authors found that the ^{3}He, ^{21}Ne and ^{38}Ar ages of the chondrule are higher than those of the bulk meteorite by 31%, 67% and 55% respectively. Based on the current production rates, these excesses translate into a precompaction exposure time of 0.9 Ma, indicative of cosmic-ray exposure of the chondrule under the nebular condition before accretion. This is the first evidence for different exposure histories of a chondrule and the bulk meteorite. GRV 98004 has a very low exposure age, hence supplying the best chance for discovery and study of different exposure histories of chondrules and the bulk meteorite. This project is underway. On the other hand, the exposure age of Guangmingshan is 68.9 Ma, plotted at the higher range of H-group. It is also the highest value of Chinese chondrites of H-group.

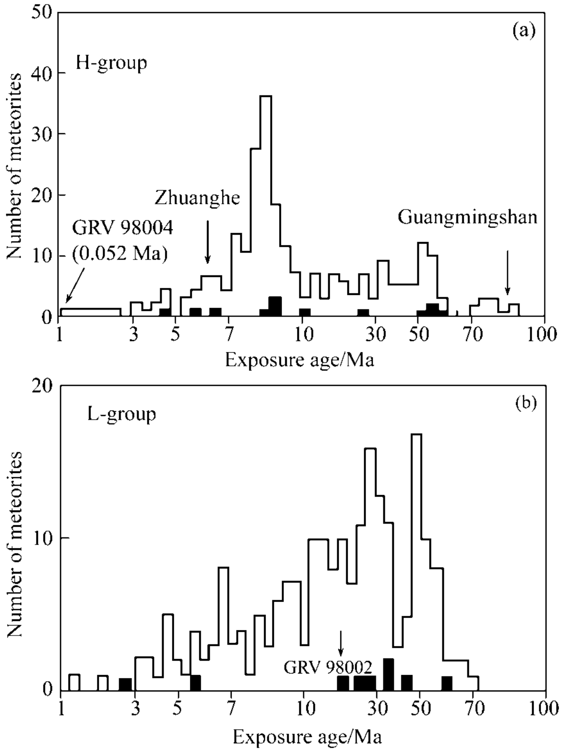

Fig. 1. Distributions of cosmic-ray exposure ages for H-group (a) and L-group (b) of chondrites. Black bars for those of Chinese meteorites, and outlined areas for those of meteorites from other countries[9].

Fig. 2 is plotted using cosmic-ray exposure ages and gas retention ages of Chinese chondrites of various groups. ^{4}He retention ages (T_4) are normally lower than those of ^{40}Ar (T_{40}), because ^{4}He loses more readily than ^{40}Ar. T_4 and T_{40} are calculated according to eqs. (5) and (6), and the results are listed in table 5. The T_{40} of GRV 98002 and GRV 98004 is 4630 Ma and 4530 Ma, respectively. They are close to the formation ages of chondrites, indicative of preservation of all ^{40}Ar. In the diagram of T_3/T_{21}- T_4/T_{40} (fig. 2), there are two types of chondrites. One shows correlated losses of ^{3}He and ^{4}He due to solar heating or catastrophic events, and they are plotted along the dashed line with a slope of 1; the other shows loss of ^{4}He before the exposure ages, i.e. before or during the ejecting events from the asteroidal parent bodies. Their T_3 and T_{21} are consistent with each other within an error of ±15%. The second type of chondrites is plotted between the two dotted and horizontal lines in the figure. Except the above two types, some chondrites lost their He during exposure ages, and the Qidong (QD) meteorite is such an example. Both GRV 98002 and Zhuanghe have a ratio of $T_3/T_{21} < 0.85$, referring to the first type of chondrites. They lost ^4He_r due to solar heating at orbits with small perihelion distances or catastrophic events during their exposure ages, resulting in low ratios of T_4/T_{40}. GRV 98004 and Guangmingshan have a ratio of $T_3/T_{21} > 0.85$, and show nearly correlated losses of ^3He_c and ^4He_r. Summarily, we classify three types of chondrites based on relationship between T_3/T_{21} and T_4/T_{40}: (i) $T_3 = T_{21}$, $T_4 = T_{40}$; (ii) $T_3 < T_{21}$, $T_4 < T_{40}$; (iii) $T_3 = T_{21}$, $T_4 < T_{40}$. Furthermore, it is recognized that chondrites generally show different shock metamorphism[12,13] which caused noble gases incoordinately to be lost.

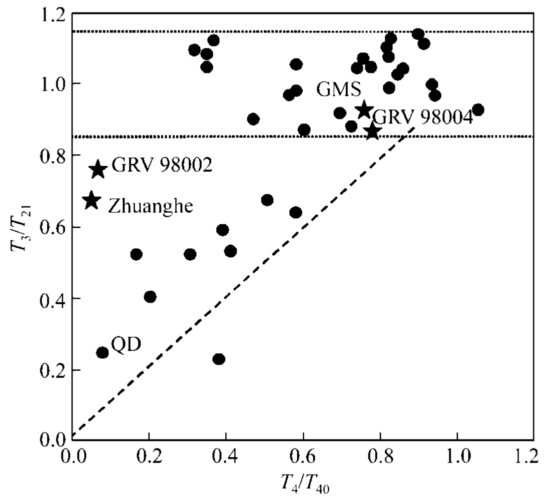

Fig. 2. Exposure age ratio of T_3/T_{21} plots with gas retentions age ratio of T_4/T_{40}. Data of other meteorites (filled circles) are from refs. [4,11]. Abbreviation: Guangmingshan (GMS), Qidong (QD).

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