Cosmic-ray exposure and gas retention ages of the Guangmingshan (H5) chondrite

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Abstract **Isotopic compositions of noble gases from the Guangmingshan chondrite were analyzed. Based on the analyses of cosmogenic nuclei, cosmic-ray exposure age of the meteorite is (65±10.0) Ma (^{3}He), (80±12) Ma (^{21}Ne) and (65±10.0) Ma (^{38}Ar), with an average of 70 Ma. This is the highest exposure age of H-group ordinary chondrites. Gas retention ages of K-Ar and U, Th-^{4}He are (4230±100) Ma and (3300±60) Ma, respectively. The smaller ages of ^{3}He than ^{21}Ne and ^{4}He than ^{40}Ar suggest that both ^{3}He and ^{4}He lost together. This is probably related to a solar heating effect of a meteorite with a small perihelion during the last exposure period.**

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

Cosmic-ray exposure ages of meteorites are determined from abundances of stable cosmogenic nuclei and activities of radioactive ones[1]. The stable nuclei integrated cosmic-ray flux during the exposure age of a meteorite in the space, and the radioactive nuclei recorded intensity of the flux in a meteorite. In order to determine the exposure ages of a meteorite, it is required to have contents of certain noble gas isotopes and activities of radioactive cosmogenic nuclei (e.g. ^{3}He, ^{10}Be, ^{22}Na, ^{26}Al, ^{36}Cl, ^{39}Ar, ^{40}K, ^{41}Ca, ^{53}Mn, ^{60}Co and ^{81}Kr)[1, 2]. Chondrites are the most primitive and complicated meteorites of the solar system. They experienced varies of events in the solar nebula (e.g. formations of chondrules, fine-grained matrix, interstellar grains in the matrix, Ca-Al-rich inclusions and mafic inclusions), and secondary processes in their asteroidal parent bodies (aqueous alteration, thermal and shock metamorphisms)[3]. Up to date, cosmic-ray exposure ages of a large number of meteorites have been determined[4]. The exposure ages of stony meteorites are less than 100 Ma. Among them, H-group has two peaks around 7 Ma and 33 Ma, L-group varies between 20—30 Ma, and LL-group shows a peak of 15 Ma. Exposure ages of stone-iron meteorites are within 10—100 Ma, and those of iron meteorites are the highest (100—1000 Ma). The exposure age peaks of chondrites probably indicate primary breakup events of their parent bodies. In addition, the exposure ages also give hints for burial depths of the meteorites in their parent bodies. Studies of noble gas isotopes and exposure ages of meteorites will clarify thermal histories and shock metamorphism of their parent bodies, and hint at early evolution of the solar system. On the basis of petrological and mineral chemical study of the Guangmingshan chondrite[5,6], here we report its cosmic-ray exposure ages and gas retention ages.

This meteorite fell in Guangmingshan Village, Zhunghe City, Liaoning Province (39°48′15″N, 122°45′50″E) at about 08:00 am (Beijing time) on December 30, 1996. The stone broke into three pieces with a total mass of 2.91 kg. According to its petrography and mineral chemistry[5,6], the Guangmingshan chondrite consists mainly of olivine (average Fa of 19.5 mol%), low-Ca pyroxene (average Fs of 17.3 mol%), plagioclase (average An of 12.1 mol%), kamacite (0.39%—0.55% Co). Minor minerals are troilite, diopside, apatite, whitlockite, taenite and chromite. Observation of the polished thin sections indicated that the chondrules are less abundant, but readily delineated. No glass was found in the chondrules. Silicate matrix is well recrystallized. The sample shows weak shock metamorphism, and only some grains of olivine and low-Ca pyroxene exhibit undulose extinction. Accordingly, the shock grade was referred to as S1. Based on the taxonomic parameters of olivine-kamacite compositions (olivine: 16.9—20.4 mol% Fa; kamacite: 0.40%—0.52% Co)[7], the Guangmingshan meteorite was classified as H5 ordinary chondrite.

1 Sample and experiments

Analyses of noble gases of the whole rock were conducted in Institute of Physics, University of Bern, Switzerland, following a method described by refs. [8, 9]. Sample of the meteorite (2—3 g) without fusion crust was crushed in a stainless steel martor to a grain size of <1 mm (usually 750 μm). The whole analysis system was pre-heated and vacuumized. The sample, standard of Mocs chondrite (L6) and an aluminium-slice were installed in the sample frame, and the system was heated to 300℃ and vacuumized again. After that, the sample was heated in vacuum to 100℃ to desorb any atmospheric gases, and backgrounds of ^{4}He and ^{40}Ar were checked. Before loading the sample, the molybdenum crucible was heated by a heatronic furnace at 1700℃. Mocs standard was first loaded in the molybdenum crucible and heated at 1700℃. Extracted He, Ne and Ar were analyzed using mass spectrometers, and the results were compared with the recommended values to check the measurement. The sample of the meteorite was then treated and analyzed under an identical condition as the standard. Extraction and measurement of the noble gases were carried out using two different systems of A and B. System A has two 60° sector-type mass spectrometers and a Faraday cup. It was used to analyze He, Ne and Ar. System B consists of a noble gas extracting part and two metal-tube mass spectrometers equipped with secondary electron multipliers.

One of the mass spectrometers is used to analyze He and Ne, and the other for Ar. Analytical results of noble gas isotopes of the Guangmingshan chondrite are given in table 1. Analysis errors correspond to a confidence level of 95%.

Table 1 Isotopic compositions of He, Ne and Ar of the Guangmingshan chondrite (cm^3/g(CSTP))

^{4}He	^{20}Ne	^{40}Ar	$^{4}He/^{3}He$	$^{20}Ne/^{22}Ne$	$^{22}Ne/^{21}Ne$	$^{36}Ar/^{38}Ar$	$^{40}Ar/^{36}Ar$
$1750\pm80\times10^{-8}$	$21.4\pm0.8\times10^{-8}$	$5150\pm100\times10^{-8}$	17.10	0.863	1.143	0.923	1650.6

^{3}He 102.3 ± 5.0, ^{21}Ne 21.7 ± 0.8, ^{22}Ne 24.8 ± 0.8, ^{36}Ar 3.12 ± 0.2, ^{38}Ar 3.38 ± 0.2.

2 Exposure ages

Cosmic-ray exposure ages of meteorites are determined based on abundances of the cosmogenic unclei produced by reactions between meteorites and galactic cosmic ray. They can be calculated using the following equation:

$$T_s = C^s/P^s, \quad (1)$$

where T_s is the exposure age, C^s is the concentration of stable cosmogenic nuclide s (s can be ^{3}He, ^{21}Ne, or ^{38}Ar, cm^3 S/g (STP)), P^s is the production rate ($cm^3/g \cdot Ma$ (STP)).

First, the measured concentrations of noble gas isotopes were deconvolved into cosmogenic (c), trapped (tr) and radiogenic (r) components, using the following experiential ratios[9]: $He_r = 0$, $(^{4}He/^{3}He)_c = 5$, $(^{20}Ne/^{21}Ne)_c = 1$, $(^{20}Ne/^{22}Ne)_c = 0.8$, $(^{36}Ar/^{38}Ar)_c = 0.65$ and $(^{40}Ar/^{38}Ar) = 0.2$. Concentrations of cosmogenic $^{22}Ne_c$ and $^{38}Ar_c$ can be calculated based on the following equations, respectively.

$$^{22}Ne_c = {}^{22}Ne[1.1053 - {}^{20}Ne/^{22}Ne/7.6], \quad (2)$$

$$^{38}Ar_c = {}^{38}Ar[1.1343 - 0.2132(^{36}Ar/^{38}Ar)], \quad (3)$$

In order to determine the exposure ages, the production rates of given cosmogenic nuclei are also required, which can be determined by isotopic ratios between stable and radioactive nuclide couples. However, the production rates can also be changed by different sizes of the asteroids and shielding depths of meteorites buried in them. Eugster[2] reported that the ratio of $(^{20}Ne/^{21}Ne)_c$ is the most sensitive to the shielding effect, and suggested that the ratio could be used as a shielding parameter or indicator to correct the production rates of cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar. Nishiizumi et al.[10] reported a least squares fit equation with $(^{3}He/^{21}Ne)_c = 21.77(^{22}Ne/^{21}Ne)_c - 19.32$, based on the data of 138 chondrites. This correlation is true within the range of 1.06—1.30 of $(^{22}Ne/^{21}Ne)_c$ ratio. The contents of ^{3}He and ^{21}Ne can be used to calculate the production rates or exposure ages if the analyses are plotted on or close to the above correlative line. Others plotted below the line suggest defusion loss of ^{3}He, complicated exposure histories, or effects of 2π exposure geometry of meteorites.

Using the depth-sensitive $(^{22}Ne/^{21}Ne)_c$ ratio as the shielding parameter and abundances of the target elements, production rates of ^{3}He, ^{21}Ne and ^{38}Ar (i.e. P^3, P^{21} and P^{38} $cm^3/g \cdot Ma$ (STP)) are calculated according to the following equations[1]:

$$P^3 = F_H[2.09 - 0.43(^{22}Ne/^{21}Ne)_c], \quad F_H = 0.98; \quad (4)$$

$$P^{21} = 1.61F_H[21.77(^{22}Ne/^{21}Ne)_c - 19.32]^{-1}, \quad F_H = 0.93; \quad (5)$$

$$P^{38} = F_H[0.125 - 0.071(^{22}Ne/^{21}Ne)_c], \quad F_H = 1.08. \quad (6)$$

The production rates are related to the target compositions, and here F_H is the correction factor for H-group chondrites. The F values vary between 0.67—1.00 for ^{21}Ne and 0.75—1.10 for ^{38}Ar among various chondrite groups (CI, CM, CO, CV, H, L, LL, EH and EL). But, the production rate of ^{3}He is insensitive to the target compositions, with a relatively constant F value (0.97—1.01). In addition, the widely used shielding parameter is $(^{22}Ne/^{21}Ne)_c$ ratio, which is correlated with $(^{3}He/^{21}Ne)_c$. This is based on reactions of $^{24}Mg\ (n, \alpha)^{21}Ne$ and $^{25}Mg\ (n, \alpha)^{22}Ne$. Production of ^{21}Ne increases with the secondary neutron flux, whereas that of ^{22}Ne the is insignificant because relative abundance of ^{25}Mg (10%) is much less in comparison with ^{24}Mg (79%). In case of ordinary chondrites, a high $(^{22}Ne/^{21}Ne)_c$ ratio (>1.20) corresponds to irradiation of a small object with a radius of <10 cm, whereas a low ratio (<1.10) suggests a burial depth of >10 cm in a body with a radius of >30 cm.

Table 2 shows the calculated production rates and exposure ages of ^{3}He, ^{21}Ne and ^{38}Ar, based on eqs. (4)—(6). The exposure age of Guangmingshan is 65, 80, or 65 Ma, according to ^{3}He, ^{21}Ne and ^{38}Ar, respectively, with an average of 70 Ma. This is the highest exposure age of ordinary chondrites. Other ordinary chondrites fallen or collected in China have exposure ages of 2.1—40.9 Ma for 18 H chondrites, 2.58—53.9 Ma for 11 L chondrites and 9.4, 16.8 and 41.3 Ma for three LL chondrites[8,11]. The unusually high exposure age of Guangmingshan is probably related to its larger asteroidal body and resistant of weathering in space. Iron meteorites have the highest exposure ages (100—1000 Ma) of the known meteorites, an example for such correlation between the exposure ages and resistance against weathering.

U, Th-^{4}He and ^{40}K-^{40}Ar gas retention ages are calculated from concentrations of radiogenic $^{4}He_r$ ($1238.5\times10^{-8} cm^3/g$ (STP)) (by subtracting cosmogenic ^{4}He) and $^{40}Ar_r$ ($5150\times10^{-8} cm^3/g$ (STP)), and average bulk abundances of K (780 μg/g)[12], U (0.013 μg/g) and Th (0.04 μg/g)[13] of H chondrites. The gas retention ages of $^{4}He_r$ (T_4) and $^{40}Ar_r$ (T_{40}) are calculated using the following equations[14]:

$$T_4 = {}^4\mathrm{He_r}(1238.5) = 75200[{}^{238}\mathrm{U}](e^{0.155[t]}-1) + 474[{}^{235}\mathrm{U}](e^{0.985[t]}-1)+56400[{}^{232}\mathrm{Th}](e^{0.0492[t]}-1) \quad (7)$$

$$T_{40} = 1.805\ln[{}^{40}\mathrm{Ar_r}/0.701\times \mathrm{K}+1], \quad (8)$$

where $t = T_4$. Using the data of the Guangmingshan chondrite, gas retention ages are 4230 Ma±100 Ma (T_{40}) and 3300 Ma±60 Ma (T_4). The smaller age of T_4 than T_{40} is usually due to a faster loss of ^{4}He than ^{40}Ar during heating. The concentrations of cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar, their production rates, corresponding exposure ages, and the gas retention ages ($^4\mathrm{He_r}$, $^{40}\mathrm{Ar_r}$) are given in table 2.

Table 2 Concentrations of cosmogenic nuclides (cm^3/g (STP)), production rates (cm^3/g • Ma (STP)) and cosmic-ray exposure ages (Ma)

$^3\mathrm{He_c}$	$^{21}\mathrm{Ne_c}$	$^{38}\mathrm{Ar_c}$	^{22}Ne/^{21}Ne	P^3	P^{21}	P^{38}	T_3	T_{21}	T_{38}	T_{av}
102.3×10^{-8}	21.7×10^{-8}	3.17×10^{-8}	1.143	1.566	0.269	0.0486	65.3	80.7	65.2	70.4

$^4\mathrm{He_c} = 511.5\times10^{-8}$, $^4\mathrm{He_r} = 1750\times10^{-8}-511.5\times10^{-8} = 1238.5\times10^{-8}$, $T_4 = (3300\pm60)$ Ma, $T_{40} = (4230\pm100)$ Ma; errors of T_3, T_{21} and T_{38} are 15%; T_{av} average cosmic-ray exposure age.

3 Discussion and conclusion

In the previous study of cosmic-ray exposure ages and gas retention ages of 33 chondrites[14], we found that some meteorites have T_3 ages on the low side of the analysis errors and the lower than exposure ages determined using other cosmogenic nuclei. The lower T_3 ages indicate the loss of $^3\mathrm{He_c}$, and their T_4 ages are smaller than T_{40}. Some other meteorites show lower T_4 than T_{40}. But, their T_3 ages are consistent with exposure ages of other cosmogenic nuclei within analysis errors (±15%). On the T_3/T_{21}–T_4/T_{40} diagram[8], analyses cluster into two groups: (ⅰ) meteorites with loss of both $^3\mathrm{He_c}$ and $^4\mathrm{He_r}$ plotted on or close to a dotted line with a slope of 1. These meteorites lost comparative fractions of $^3\mathrm{He_c}$ and $^4\mathrm{He_r}$ together, probably due to degassing by the solar heating in the case of their small perihelions or intensive impact events within their exposure ages. (ⅱ) Those with identical T_3 and T_{21} within the analysis error (±15%), but the radiogenic ^{4}He lost significantly. They are plotted within two horizontal dotted lines on the T_3/T_{21}–T_4/T_{40} chart. Losing the radiogenic ^{4}He from the meteorites probably took place before breakup of the asteroidal parent bodies.

Summarily, the Guangmingshan chondrite has a T_3/T_{21} ratio of 0.80 and T_4/T_{40} ratio of 0.78, and it is close to the dotted line with a slope of 1 on the T_3/T_{21}–T_4/T_{40} diagram. In addition, this meteorite has a relationship of $T_3<T_{21}$ and $T_4<T_{40}$. Accordingly, we refer to Guangmingshan as a meteorite of type (1). Furthermore, the Guangmingshan chondrite shows no significant shock effects. We suggest that the loss of both $^3\mathrm{He_c}$ and $^4\mathrm{He_r}$ may be due to its small perihelion that makes it heated by the sun within the exposure age of 70 Ma.

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