NOBLE GASES IN TEN, SMALL YAMATO CHONDRITES

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***Abstract*:** Concentrations of noble gases and isotopic compositions of He, Ne and Ar were determined for small Yamato chondrites. Five of the ten specimens studied showed high $(^{22}Ne/^{21}Ne)_c$ ratios, suggesting hard cosmic-ray irradiation in small bodies in space or near surfaces of meteoroids. Among them, Y-74447 (H) shows a cosmogenic $^{22}Ne/^{21}Ne$ ratio as high as 1.306 ± 0.040, which suggests a very hard cosmic-ray irradiation in a small body. The preatmospheric size of this chondrite may be as small as inferred from its recovered mass (14.3 g). No significant difference was found in cosmic-ray irradiation history between antarctic and non-antarctic chondrites.

Cosmic-ray irradiation ages and U/Th-He and K-Ar ages are given. While Y-74138(H) was found to contain appreciable amounts of trapped, solar-type gases, Y-74060(H) shows complete loss of radiogenic ^4He and radiogenic ^{40}Ar as low as found in shocked L chondrites. The Y-74060 chondrite is one of those rare cases in which H chondrites lost radiogenic gases by shock or other metamorphic events. Trapped planetary gases are discussed in relation with petrologic types.

1. Introduction

In noble gas studies of antarctic meteorites, we have determined the concentrations and isotopic compositions of noble gases in more than thirty meteorites, and have shown several significant results. Such examples are a very long age ($T_{1/2}=92$ Ma) of cosmic-ray irradiation for Yamato-74035 (L6) (hereafter abbreviated as Y-74035), enrichment in solar-type gases for Y-75028 (H3), the first "gas-rich" chondrite from Antarctica (TAKAOKA *et al.*, 1981), and remarkable enrichment in neutron-capture products ^{80}Kr, ^{82}Kr and ^{128}Xe and the high Br content (11.2 ppm) for Y-74191 (L3) (TAKAOKA and NAGAO, 1980). Distributions of cosmic-ray irradiation ages for H and L chondrites from Antarctica resemble those for the non-antarctic chondrites (TAKAOKA *et al.*, 1981).

Most meteorites studied in the previous works were of normal size, more than 500 g in weight. In the Yamato meteorite collection, there are many small meteorites that have never been studied. They are valuable because such small specimens are difficult to recover in other regions of the earth. Many studies have been made for cosmic-ray effects in both falls and finds of normal size, but few in meteorites of small size. In the present work we report the isotopic study of noble gases in small Yamato chondrites.

2. Samples

Samples used in this work are ten chondrites of small meteorites with fusion crusts selected for studies of the cosmic-ray effects in small objects in space. ^{53}Mn contents were determined for the nearby samples by NISHIIZUMI *et al.* (1982). The recovered masses, classification and descriptions of meteorites are shown in Table 1. The recovered masses of chondrites studied range from 7.9 g for Y-74652 to 84.6 g for Y-74372, and are mostly less than 30 g. Y-74065 (probably paired with Y-74066), -74074, -74104, -74447, -74652 and -75270 are described as complete individuals. Y-74372, the only specimen found buried in ice, is described as a nearly complete individual with a corner broken-off (YANAI, 1979). The small meteorites studied have not been examined in detail either chemically or mineralogically. Therefore the meteorite class shown in Table 1 is only tentative and may be changed by further investigations.

Table 1. Meteorites used in this work. Recovered mass, classification and description were according to YANAI (1979). Classification shown in parentheses is given by NISHIIZUMI et al. (1982).

Meteorite	Recovered mass (g)	Classification	Description
Y-74060	17.1	Chondrite (H)	Fragment
Y-74065	12.1	L3	Almost half. Probably paired with Y-74066. Many chondrules
Y-74072	29.0	Chondrite (H)	Fragment
Y-74074	54.2	Chondrite (H)	Complete individual
Y-74104	21.8	Chondrite (H)	Complete individual
Y-74138	22.9	Chondrite (H)	Fragment. Loose aggregate of chondrules
Y-74372	84.6	Chondrite (L)	Nearly complete individual. Found buried in ice
Y-74447	14.3	Chondrite (H)	Complete individual. Very well rounded
Y-74652	7.9	Chondrite (L)	Complete individual. Very well rounded
Y-75270	26.9	Chondrite (L)	Almost complete rounded piece

The samples delivered to us consisted of 0.1 to 0.2 g chips taken from near the meteorite surface. They are more or less weathered. Among them, Y-74060 and -74072 were highly weathered, and Y-74065, -74447, -74652 and -75270 were relatively less weathered. Fusion crusts were removed. Bulk samples between 70 and 190 mg were analyzed with a conventional technique of noble gas mass spectrometry (TAKAOKA, 1976).

3. Results and Discussion

The concentrations of five noble gases and isotopic ratios of He, Ne and Ar determined are listed in Table 2. Errors cited for the isotopic ratios include statistical errors (1σ) of sample measurements and errors due to corrections for both mass discrimination and blank. Uncertainties for the concentrations are estimated to be 5% for He, Ne and Ar, and 8% for Kr and Xe.

Table 2. Noble gas concentrations and isotopic ratios of He, Ne and Ar. Concentrations are given in units of 10^{-8} cm^3 STP/g for He, Ne and Ar, and 10^{-10} cm^3 STP/g for Kr and Xe. Isotopic ratios except ^{40}Ar/^{36}Ar are given in per mill.

Meteorite	^{3}He	^{4}He	^{3}He/^{4}He	^{21}Ne	^{22}Ne/^{21}Ne	^{20}Ne/^{22}Ne
Y-74060	2.35	13.5	174±5	0.837	1097±11	948±11
Y-74065	27.6	1360.	20.3 ±0.5	6.04	1122±6	821±6
Y-74072	4.17	339.	12.3 ±0.3	1.55	1098±6	859±7
Y-74074	4.32	369.	11.7 ±0.3	1.81	1074±8	839±6
Y-74104	3.47	227.	15.3 ±0.4	1.70	1068±9	872±9
Y-74138	35.5	8588.	4.13±0.11	4.15	1706±12	4406±24
Y-74372	18.3	499.	36.7 ±1.4	3.66	1155±8	856±4
Y-74447	6.14	882.	6.96±0.20	0.762	1362±17	1166±17
Y-74652	21.8	605.	36.1 ±1.0	3.18	1170±7	814±11
Y-75270	31.9	763.	41.8 ±1.1	5.10	1160±4	821±5
Meteoirte	**^{36}Ar**	**^{40}Ar**	**^{38}Ar/^{36}Ar**	**^{40}Ar/^{36}Ar**	**^{84}Kr**	**^{132}Xe**
Y-74060	1.22	315.	347±9	258±7	1.47	1.12
Y-74065	2.07	7100.	423±7	3432±78	0.656	1.05
Y-74072	2.02	3610.	336±6	1790±30	1.95	2.84
Y-74074	0.758	3180.	507±16	4197±140	1.05	1.31
Y-74104	1.70	2200.	331±10	1291±29	2.01	2.50
Y-74138	18.2	6730.	239±5	370±7	10.5	10.6
Y-74372	1.96	4820.	389±12	2459±58	1.12	0.756
Y-74447	1.02	4240.	370±11	4155±192	1.41	0.887
Y-74652	0.698	5190.	834±36	7433±360	1.04	1.30
Y-75270	1.12	4660.	903±29	4158±130	1.30	1.60

Y-74060 (H) chondrite is notable for complete depletion in radiogenic ^{4}He and the low concentration of radiogenic ^{40}Ar. This chondrite suffered severe outgassing by collisional shock or other metamorphic events. Y-74138 (H) contains appreciable amounts of trapped He and Ne. The ^{4}He concentration, the $(^{20}\mathrm{Ne}/^{36}\mathrm{Ar})_t$ ratio and its Ne isotopic composition satisfy requirements for "gas-rich" meteorites (CRABB and SCHULTZ, 1981). This is the second discovery of a gas-rich meteorite in the Yamato meteorite collection. In other chondrites, the cosmogenic and radiogenic components are predominant for He and Ne. Argon is a mixture of the cosmogenic, radiogenic and trapped components. Except for Y-74138, all ^{3}He found was regarded as cosmogenic. Y-74447 contains a small amount of trapped Ne. To distinguish the cosmogenic, radiogenic and trapped components, the following isotopic ratios are assumed: for cosmogenic gases $(^3\mathrm{He}/^4\mathrm{He})_c=0.2$, $(^{20}\mathrm{Ne}/^{22}\mathrm{Ne})_c=0.85$ and $(^{38}\mathrm{Ar}/^{36}\mathrm{Ar})_c=1.55$; for trapped gases $(^4\mathrm{He}/^{20}\mathrm{Ne})_t=330$, $(^{20}\mathrm{Ne}/^{22}\mathrm{Ne})_t=8.2$, $(^{21}\mathrm{Ne}/^{22}\mathrm{Ne})_t=0.03$ and $(^{38}\mathrm{Ar}/^{36}\mathrm{Ar})_t=0.187$ except for Y-74138. For Y-74138, $(^{20}\mathrm{Ne}/^{22}\mathrm{Ne})_t=13.0$ was assumed.

3.1. *Cosmic-ray irradiation age*

Figure 1 shows a correlation plot between the ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios of cosmogenic gases. Most small meteorites except Y-74060, -74072, -74074 and -74104 fit the correlation line defined by antarctic chondrites of larger size (TAKAOKA *et al.*,

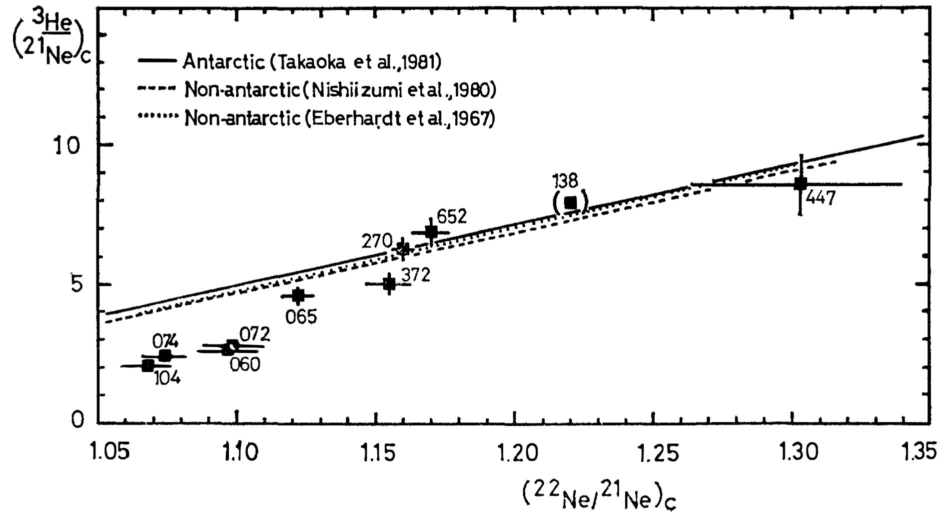

Fig. 1. Correlation plot between cosmogenic $^3He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios.

1981). Among them, the Y-74447 chondrite shows very high $(^{22}Ne/^{21}Ne)_c$ and $(^3He/^{21}Ne)_c$ ratios. The error bars are relatively large because of corrections for blank and trapped Ne. The high $^{22}Ne/^{21}Ne$ and $^3He/^{21}Ne$ ratios found in Y-74447 indicate cosmic-ray irradiation in a small object or at an extremely shallow depth in the meteoroid. The chondrite was irradiated by high-energy (or hard) cosmic-ray flux. The preatmospheric size of Y-74447 might be as small as inferred from the recovered mass. A similar case of very hard cosmic-ray irradiation has been reported for the Allan Hills A77081(H) chondrite (SCHULTZ *et al.*, 1980).

Y-74138 also shows a high $(^3He/^{21}Ne)_c$ ratio (approximately 7.9), though estimate of the cosmogenic $^{22}Ne/^{21}Ne$ ratio is associated with a large uncertainty because this chondrite contains an appreciable amount of trapped Ne. The $^{22}Ne/^{21}Ne$ ratio corrected for trapped solar Ne is as high as 1.22. This indicates that the Y-74138 chondrite was also irradiated by hard cosmic-rays in a small body or extremely near the meteoroid surface.

High $^{22}Ne/^{21}Ne$ and $^3He/^{21}Ne$ ratios for Y-74652, -75270 and -74372 are also suggestive of hard cosmic-ray irradiations in small bodies or meteoroid surface. These five chondrites are regarded as small meteorites or as surface samples of meteoroids.

Y-74060, -74072, -74074 and -74104, all H chondrites, are depleted in cosmogenic ^3He, probably due to diffusive He loss, and have $^{22}Ne/^{21}Ne$ ratios less than 1.10, suggesting cosmic-ray irradiation at moderate shielding depth such as is found in meteorites of normal size.

TAKAOKA *et al.* (1981) have reported that the correlation between $^3He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ for antarctic chondrites is in good agreement with that for non-antarctic chondrites, as shown in Fig. 1. This indicates no significant difference in the shielding effect on the production rates of cosmogenic isotopes between antarctic and non-antarctic chondrites. We correct the ^{21}Ne production rate for the shielding depth by the following relation (TAKAOKA *et al.*, 1981),

$$P_{21}=\frac{5.30\cdot P_{21}(5.3)}{22.7(^{22}Ne/^{21}Ne)_c-20.0}, \tag{1}$$

Table 3. Concentrations of cosmogenic and radiogenic isotopes, and cosmic-ray irradiation and gas retention ages.

Meteorite	$^{3}He_c$	$^{21}Ne_c$	$^{38}Ar_c$	$(^{22}Ne/^{21}Ne)_c$	$^{4}He_r$	$^{40}Ar_r$	T_{21} (Ma)		T_{38}† (Ma)	T_4 (Ga)	T_{40}(Ga)
Y-74060	2.35	0.837	0.222	1.097±0.011	1.8	315.	1.79	1.75†	2.85	0.01	0.77
Y-74065	27.6	6.04	0.556	1.122±0.006	1220.	7100.	13.4	13.3†	8.59	2.9	4.6
Y-74072	4.17	1.55	0.342	1.098±0.006	318	3610.	3.33	3.32†	4.42	1.1	3.5
Y-74074	4.32	1.81	0.276	1.074±0.008	347	3180.	3.45	3.48†	3.22	1.2	3.3
Y-74104	3.47	1.70	0.278	1.068±0.009	210	2200.	3.14	3.26†	3.24	0.75	2.8
Y-74138	33.	4.09	1.08	(1.22)	—	6730.	13.7	11.3†	12.6	—	4.5
Y-74372	18.3	3.66	0.450	1.155±0.008	408	4820.	9.22	8.99†	8.05	1.1	4.0
Y-74447	6.14	0.761	0.212	1.306±0.040	732	4240.	3.20	2.11†	4.04	2.3	3.8
Y-74652	21.8	3.18	0.514	1.170±0.007	496	5190.	8.45	8.07†	9.68	1.3	4.1
Y-75270	31.9	5.10	0.912	1.160±0.004	604	4660.	13.1	12.7†	16.6	1.6	3.9

Decay constants used for calculation of ages are those given by STEIGER and JÄGER (1977).

† Cosmic-ray irradiation ages calculated with CRESSY and BOGARD's formulation (CRESSY and BOGARD, 1976).

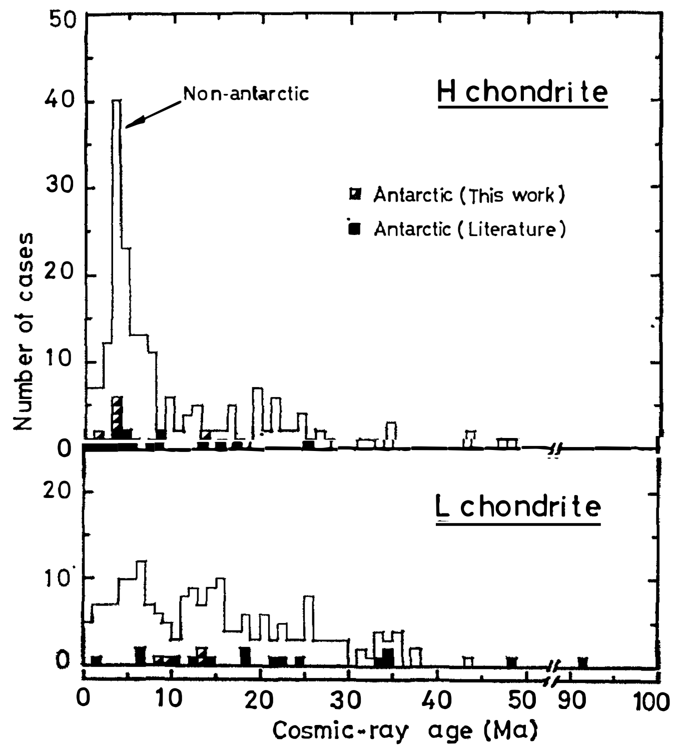

Fig. 2. Distributions of cosmic-ray irradiation ages calculated from cosmogenic ^{21}Ne. For comparison, antarctic and non-antarctic H and L chondrites are also plotted. Data sources are given in TAKAOKA et al. (1981). Note that a great part of antarctic H chondrites including the present ones fall in a 4 Ma cluster, the dominant distribution of cosmic-ray irradiation ages for non-antarctic H chondrites. L chondrites don't show such clustering.

where $P_{21}(5.3)$ is the ^{21}Ne production rate for $^{3}He/^{21}Ne=5.30$, deduced from recent falls of short cosmic-ray age. $P_{21}(5.3)=0.433\times10^{-8}$ cm^3 STP/g·Ma for H chondrites and 0.466×10^{-8} cm^3 STP/g·Ma for L chondrites (HERZOG and ANDERS, 1971). CRESSY and BOGARD (1976) have given similar production rates and shielding corrections. The cosmic-ray irradiation ages calculated from eq. (1) are listed in Table 3, along with ages calculated using CRESSY and BOGARD's values for comparison. The ^{21}Ne cosmic-ray ages given by both formulations are in excellent agreement except for Y-74138 and -74447. These two showed very high $^{22}Ne/^{21}Ne$ ratios and thus large shielding corrections. There is fairly good agreement between the ^{21}Ne ages and ^{38}Ar ages.

The cosmic-ray irradiation ages range from 1.8 to 14 Ma. Figure 2 illustrates the distributions of cosmic-ray ages. Five of the six specimens classified as H chondrites, fall in a 4 Ma cluster also found for non-antarctic H chondrites (CRABB and SCHULTZ, 1981), as shown in Fig. 2. In contrast, the cosmic-ray ages of L chondrites show rather uniform distribution compared with H chondrites.

Similarities in the $^{3}He/^{21}Ne$ *vs.* $^{22}Ne/^{21}Ne$ correlation and in the distribution of cosmic-ray irradiation ages strongly suggest that the cosmic-ray irradiation history of the antarctic H and L chondrites is not greatly different from that for non-antarctic falls and finds.

3.2. U/Th-He and K-Ar ages

Radiogenic ^{4}He was corrected by the following relation,

$$^4He_r = {}^4He_m - 5 \cdot {}^4He_c - 330 \cdot {}^{20}Ne_t, \qquad (2)$$

where r, m, c and t mean radiogenic, measured, cosmogenic and trapped, respectively. For Y-74138, which contains trapped He, the trapped He correction by eq. (2) results in a negative value and no radiogenic ^{4}He is given in Table 3. This suggests preferential ^{4}He loss. ^{40}Ar determined is mostly radiogenic, and no correction was applied for the cosmogenic and trapped components. Since no data for U, Th and K contents were available for the meteorites studied, mean concentrations of U (12 ppb for H chondrites and 15 ppb for L chondrites) and K (850 ppm for both H and L chondrites) and Th/U=3.6 were assumed (MORGAN, 1971; GOLES, 1971). The U/Th-He and K-Ar ages are summarized in Table 3 along with the concentrations of radiogenic ^{4}He and ^{40}Ar.

As mentioned earlier, Y-74060(H) has lost radiogenic ^{4}He completely and most of its ^{40}Ar. The K-Ar age is 0.77 Ga, a characteristically low value found for shocked L chondrites which lost radiogenic ^{40}Ar by collisional shock about 0.53 Ga ago (HEYMANN, 1967). However, Y-74060 is one of rare cases in which H chondrites lost radiogenic ^{4}He and ^{40}Ar by collisional shock or other metamorphic events. That He ages are lower than Ar ages in all chondrites studied is the usual trend attributed to long-term preferential diffusive loss of He.

3.3. Trapped gases and petrologic type

As found in Table 2, the Y-74138(H) chondrite contains appreciable amounts

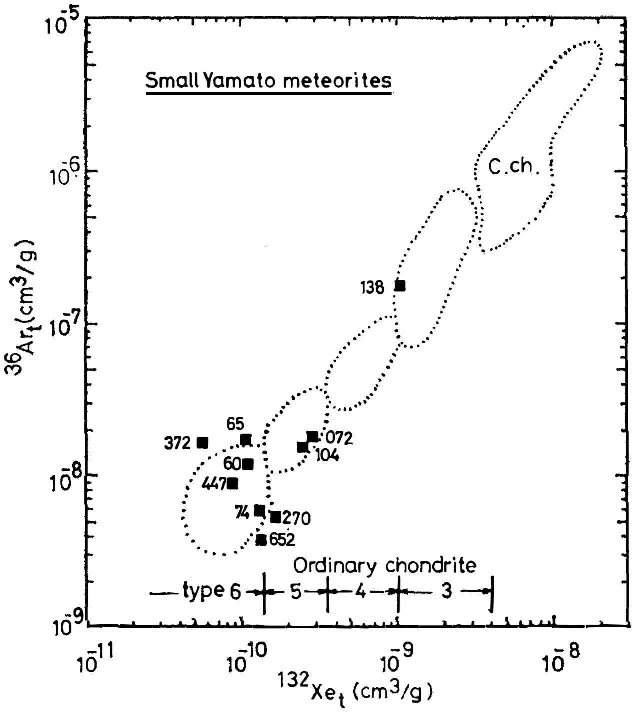

Fig. 3. Plot of trapped ^{36}Ar vs. ^{132}Xe. Relation of trapped ^{132}Xe concentration with petrologic classification is shown.

of trapped gases. From the isotopic composition of Ne, trapped Ne and probably He are considered to be solar-type. However, the ratio of trapped ^{20}Ne to ^{36}Ar is not as high as found in the typical solar gases. This is thought to reflect mixing of solar type gases and planetary Ar, since the latter is commonly present in chondrites and in significantly high amounts in primitive chondrites. From this, the concentrations of trapped ^{132}Xe and ^{84}Kr and from the petrologic description that this chondrite consists of a loose aggregate of chondrules (YANAI, 1979), we conclude that Y-74138 is an H chondrite of petrologic type 3, as discussed later. According to YANAI (1979), Y-74065 is classified as an L chondrite of type 3. However, the trapped gas concentrations in this chondrite are not as high as observed in type 3 chondrites, but are as low as in type 6. A microscopic examination of the nearby sample shows no chondrules but only whitish crystalline grains and black magnetite. The sample used in this work may be an equilibrated portion of the chondrite.

Figure 3 is a plot of trapped ^{36}Ar *vs.* ^{132}Xe. The relation between the trapped ^{132}Xe and the petrologic type of ordinary chondrites is also illustrated (MARTI, 1967). From this relation and trapped ^{132}Xe in Y-74138, it can be classified tentatively as H3. Y-74072, -74104 and -75270 can be classified as H5, H5 and L5, respectively. The other chondrites studied here can be grouped into type 6. These classification must be confirmed by the usual mineralogic and petrologic techniques.

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