RARE GAS STUDIES OF TWENTY-FOUR ANTARCTIC CHONDRITES

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***Abstract*:** The concentrations of rare gases and isotopic compositions of He, Ne and Ar were determined in twenty-four antarctic meteorites by rare gas mass spectrometry. No significant difference is found in cosmic-ray irradiation and thermal histories between antarctic and non-antarctic chondrites, except a discovery of extremely long irradiation age of 92 m.y. for the Yamato-74035 (L6) chondrite. The Yamato-75028 chondrite contains high concentrations of solar-type rare gases. On the basis of rare gas data, two groups of paired meteorites were identified; they are Yamato-75097, -75102, -75108 and -75271, and Allan Hills-77015, -77167 and -77260.

1. Introduction

A great number of meteorites have been collected in Antarctica since the 10th Japanese Antarctic Research Expedition found nine meteorites at the south-eastern end of the Yamato Mountains in 1969 (*e.g.* YANAI, 1979). From circumstancial evidence that large groups of meteorites were found in ablated ice areas, most of them are supposed to have been accumulated there by some mechanism working with glacier movement. The meteorites collected in the accumulation areas may contain individuals of various orgin such as a single fall and shower formation or fragmentation at the time of fall.

Rare gas concentrations and isotopic compositions are basic data for meteorite research. We have accumulation of rare gas data for non-antarctic meteorites. They give wide information on the history of meteorites including the cosmic-ray irradiation, and a useful clue for identifying fragments or shower of the same fall.

2. Experimental Procedures and Results

Meteorites studied in this work are twenty-four antarctic chondrites. They are ten H chondrites and fourteen L chondrites, of which five are unequilibrated (type 3) chondrites. Meteorite samples chosen were the ones whose ^{53}Mn and ^{40}K data were available. The following meteorite samples were strongly weathered: ALH-77015, -77167 and -77260, and Y-74459 and -75028. Bulk samples between 40 and 220 mg were analyzed with conventional rare gas mass spectrometry (TAKAOKA, 1976).

The concentrations of five rare gases and isotopic ratios of He, Ne and Ar are listed in Table 1. Errors cited for the isotopic ratios are statistical errors (1σ) calculated from sample and calibration measurements. Uncertainty for the concentration is estimated to be about 10%. However, samples were chips of meteorites between 40 and 220 mg and most of them used in this work were more or less weathered. Thus scattering of the concentration may result from the weathering of samples.

The Y-75028 chondrite contains large amounts of solar-type trapped gases. In other chondrites the cosmogenic and radiogenic components were predominant for He and Ne. Argon is a mixture of three components; cosmogenic, radiogenic and trapped. Except for Y-75028, all of ^3He determined was regarded as cosmogenic. Four Allan Hills chondrites and two Yamato chondrites (Y-74094 and -75028) contain trapped Ne. To calculate quantities of cosmogenic, radiogenic and trapped gases, the following isotopic ratios were assumed: for cosmogenic gases, $(^3He/^4He)_c=0.2$, $(^{20}Ne/^{22}Ne)_c=0.85$, $(^{21}Ne/^{22}Ne)_c=0.92$ and $(^{38}Ar/^{36}Ar)_c=1.55$, and for trapped gases, $(^4He/^{20}Ne)_t=330$, $(^{20}Ne/^{22}Ne)_t=8.2$, $(^{21}Ne/^{22}Ne)_t=0.03$ and $(^{38}Ar/^{36}Ar)_t=0.187$. The $^4He/^{20}Ne$ ratio for the trapped component is a mean value of Pesyanoe (ZÄHRINGER, 1962) and Orgueil (MAZOR *et al.*, 1970). The concentrations of cosmogenic and radiogenic isotopes are listed in Table 2.

3. Discussion

3.1. Cosmic-ray exposure age

Figure 1 shows a correlation plot between the $^3He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios of cosmogenic gases. The least squares fit gives a line represented by the equation

$$^3He/^{21}Ne=22.7\cdot{}^{22}Ne/^{21}Ne-20.0\,.$$

Variation of cosmic-ray energy spectrum in the different shielding depth is responsible for such a correlation. The $^3He/^{21}Ne$ vs. $^{22}Ne/^{21}Ne$ correlation lines have been reported for non-antarctic chondrites (EBERHARDT *et al.*, 1966; NISHIIZUMI *et al.*, 1980a). As shown in Fig. 1, the correlation line for the antarctic chondrites is in good agreement with that for non-antarctic ones. Hence we suppose no difference in the shielding effect on the production of cosmogenic nuclides between the antarctic and non-antarctic meteorites. On this basis, we correct the ^{21}Ne production rate for the shielding effect by using the following relation

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

Table 1. Rare gas concentrations and isotopic ratios of He, Ne and Ar.

Meteorite	^{3}He*	^{4}He*	^{3}He/^{4}He#	^{21}Ne*	^{22}Ne/^{21}Ne#	^{20}Ne/^{22}Ne#	^{36}Ar*	^{40}Ar*	^{38}Ar/^{36}Ar#	^{40}Ar/^{36}Ar	^{84}Kr*	^{132}Xe*
H chondrite												
Y-74094 (H6)	1.48	2460	0.600±0.019	0.348	1026±15	1099±27	0.956	7110	218±2	7440 ±240	3.1	1.4
Y-74115 (H6)	20.1	1870	10.8 ±0.3	3.21	1142±11	854±11	0.923	5810	681±4	6290 ±110	0.52	1.1
Y-74155 (H4)	13.0	2100	6.08 ±0.28	2.10	1122±6	848±4	2.0	5800	306±4	2900 ±30	2.1	3.9
Y-74193 (H5)	12.0	1800	6.55 ±0.18	1.20	1236±8	841±8	0.72	6700	424±4	9300	1.3	—
Y-74364 (H?)	14.7	1500	9.80 ±0.17	2.04	1284±8	840±8	2.21	4840	328±2	2190 ±80	5.3	2.5
Y-74371 (H6)	18.6	1390	13.4 ±0.2	2.64	1188±35	800±27	1.06	4710	542±35	4440 ±70	0.34	0.18
Y-74418 (H6)	17.6	1230	14.3 ±0.2	2.36	1183±10	778±13	0.881	6800	624	7720 ±160	2.2	1.3
Y-74459 (H6)	69.6	1430	48.8 ±1.2	13.4	1076±8	842±5	1.84	4680	1137±5	2540 ±40	0.63	0.59
Y-75028 (H3 or L3)	19.0	30000	0.623±0.015	1.80	15700±150	11350±60	35.0	2300	187±1	66.6±0.2	4.5	3.6
ALH-77003 (H3)	39.0	2400	16.4 ±0.4	4.30	1287±7	1183±6	130	2600	193±1	19.4±0.3	76	61
L chondrite												
Y-74035 (L6)	185	2790	66.2 ±0.9	38.1	1125±5	817±4	3.65	7080	1112±5	1940 ±10	2.2	1.3
	235	3320	70.8 ±2.0	40.5	1144±12	811±12	6.82	9490	673±2	1390 ±10	3.1	3.1
Y-74077 (L?)	72.1	1600	45.1 ±1.1	16.3	1110±7	838±6	1.77	5230	1114±7	2950 ±40	0.9	1.0
Y-74080 (L6)	150	1500	104.0 ±3	16.0	1203±4	820±3	1.3	3100	1050±60	2200 ±10	2.7	1.0
	103	916	112.0 ±2	15.4	1214±12	808±9	1.71	5230	1191±5	3060 ±30	1.4	1.1
	120	1080	112.0 ±3	17.5	1206±7	806±9	1.65	4890	1293±8	2970 ±30	0.7	0.7
Y-74116 (L?)	11	820	13.5 ±0.5	3.3	1092±6	929±8	0.90	6000	1020	6700	2.1	0.8
Y-74362 (L6)	25.7	653	39.3 ±0.5	6.43	1126±9	834±5	1.18	6390	685±35	5420	1.6	0.06
Y-74454 (L5)	18.6	1560	12.0 ±0.2	3.20	1099±25	872±19	0.984	8360	721±6	8490	7.6	1.9
Y-74605 (L?)	55.9	470	119.0 ±3	11.9	1107±11	837±5	1.98	716	793±4	362 ±4	0.4	0.7

Table 1. (Continued).

Meteorite	^{3}He*	^{4}He*	^{3}He/^{4}He#	^{21}Ne*	^{22}Ne/^{21}Ne#	^{20}Ne/^{22}Ne#	^{36}Ar*	^{40}Ar*	^{38}Ar/^{36}Ar#	^{40}Ar/^{36}Ar	^{84}Kr*	^{132}Xe*
L chondrite												
Y-75097 (L4)	42.8	349	123.0 ±2	9.41	1087±5	836±5	1.80	220	649±4	122.4±0.9	0.4	0.5
Y-75102 (L6)	45.3	287	158.0 ±2	9.42	1079±8	845±17	1.75	220	714±14	125.7±1.5	0.4	0.1
Y-75108 (L4)	39.2	386	102.0 ±2	9.83	1089±7	843±13	2.93	246	438±4	84.0±0.3	0.4	0.4
Y-75271 (L?)	47.3	413	115.0 ±3	10.0	1095±7	835±4	2.30	240	557±5	104.3±1.1	0.1	0.1
ALH-77015 (L3)	4.7	1300	3.55 ±0.10	0.96	1355±4	2380±20	87.0	3700	189±1	42.9±0.3	59	42
ALH-77167 (L3)	4.4	1200	3.79 ±0.14	0.81	1408±16	2650±30	96.0	3300	187±1	34.0±0.1	46	24
ALH-77260 (L3)	3.5	890	3.90 ±0.10	0.55	1323±16	2600±40	90.0	3100	189±1	34.3±0.1	68	45
Bruderheim	63.0	590	106.0 ±6	12.0	1098±11	839±8	1.4	1000	1056±15	744 ±8	0.7	0.7

* Concentrations of He, Ne and Ar are gives in unit of 10^{-8} cm^3 STP/g.
** Concentrations of Kr and Xe are given in unit of 10^{-10} cm^3 STP/g.
# Isotopic ratios except ^{40}Ar/^{36}Ar are shown in per mill.
Classification of meteorites is referred to YANAI (1979) and MARVIN and MASON (1980).

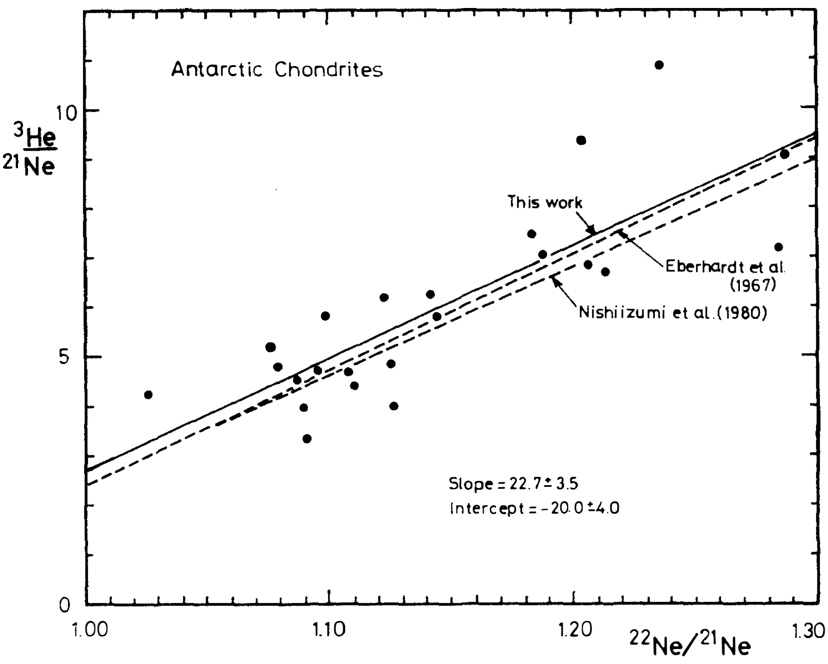

Fig. 1. Correlation plot between $^3He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ for antarctic chondrites. The correlation line is a least squares fit to all data points given in the diagram.

where $P_{21}(5.3)$ is the ^{21}Ne production rate for $(^3He/^{21}Ne)_c=5.3$, given by HERZOG and ANDERS (1971). $P_{21}(5.3)$ is 0.433×10^{-8} cm^3 STP/g m.y. for H chondrites and 0.466×10^{-8} cm^3 STP/g m.y. for L chondrites. Since the correlation line shown in Fig. 1 gives $(^{22}Ne/^{21}Ne)_c=1.114$ for $(^3Ne/^{21}Ne)_c=5.3$, our shielding correction is normalized to the $(^{22}Ne/^{21}Ne)_c$ ratio of 1.114. CRESSY and BOGARD (1976) have given a similar rate and a complicated method of correction for shielding. The concentrations of cosmogenic ^3He, ^{21}Ne and ^{38}Ar, and the exposure age T_{21} calculated with the cosmogenic ^{21}Ne isotope are listed in Table 2. For comparison, the exposure age T_3 calculated with cosmogenic ^3He is given in Table 2. The production rate of ^3He is assumed to be 2.48×10^{-8} cm^3 STP/g m.y. for both H and L chondrites (HERZOG and ANDERS, 1971).

As shown in Table 2, the Y-74035 chondrite (L6) has a very long exposure age of 92 m.y., the longest of chondrites known to date. Hence, this meteorite seems to have traveled space along an orbit different in orbital parameters from most other chondrites of short exposure ages. We know that an achondrite Norton County has a long exposure age equal to that of the Y-74035. These two stones seem to have experienced long travels in space as relatively small meteoroids. Y-74080 (L6) also has a long exposure age of 49 m.y. This chondrite has high $^3He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios and seems to have been exposed to the cosmic-ray irradiation in a shallow depth of the meteoroid. A very short exposure age of 0.50 m.y. for Y-74094 (H6) contrasts with the long age for the Y-74035. ^{53}Mn radioactivity in the Y-74094 is also very

Table 2. Concentrations of cosmogenic and radiogenic isotopes and cosmic-ray exposure and gas retention ages.

Meteorite	$^{3}He_{c}$	$^{21}Ne_{c}$	$^{38}Ar_{c}$	T_{3} (m.y.)	T_{21} (m.y.)	$^{4}He_{r}$	$^{40}Ar_{r}$	T_{4} (b.y.)	T_{40} (b.y.)
H chondrite									
Y-74094	1.48	0.348	0.034	0.597	0.499	2410	7110	4.9	4.62
Y-74115	20.1	3.21	0.518	8.10	8.10	1770	5810	4.2	4.29
Y-74155	13.0	2.1	0.27	5.2	5.0	2.40	5800	4.5	4.28
Y-74193	12.0	1.1	0.19	4.8	3.9	1740	6700	4.2	4.52
Y-74364	14.7	2.04	0.354	5.93	8.13	1430	4840	3.7	3.99
Y-74371	18.6	2.64	0.428	7.50	8.02	1300	4710	3.5	3.95
Y-74418	17.6	2.36	0.438	7.10	7.05	1140	6800	3.2	4.55
Y-74459	69.6	13.4	1.99	28.1	25.8	1080	4680	3.1	3.94
Y-75028	—	1.0	—	—	—	—	2300	—	2.85
A-77003	39	4.3	0.9	16.	15.	1360	2600	3.6	3.03
L chondrite									
Y-74035	210	39.3	3.81	84.7	91.7	2010	8290	4.0	4.86
Y-74077	72.1	16.3	1.87	29.1	34.3	1240	5230	2.9	4.12
Y-74080	124	16.3	2.0	50.0	48.9	550	4410	1.5	3.81
Y-74116	11	3.3	0.85	4.4	6.4	770	6000	2.0	4.34
Y-74362	25.7	6.43	0.668	10.4	14.5	525	6390	1.4	4.44
Y-74454	18.6	3.20	0.597	7.5	6.41	1470	8360	3.3	4.89
Y-74605	55.9	11.9	1.36	22.5	24.7	191	716	0.6	1.43
Y-75097	42.8	9.41	0.946	17.3	17.8	135	220	0.4	0.57
Y-75102	45.3	9.42	1.05	18.3	17.1	61	220	0.2	0.57
Y-75108	39.2	9.83	0.836	15.8	18.8	190	246	0.6	0.62
Y-75271	47.3	10.0	0.968	19.1	19.7	177	240	0.5	0.61
ALH-77015	4.7	0.95	0.2	1.9	1.8	550	3700	1.5	3.57
ALH-77167	4.4	0.77	0.0	1.8	1.3	419	3300	1.2	3.39
ALH-77260	3.5	0.55	0.2	1.4	0.7	411	3100	1.1	3.29

Decay constants given by STEIGER and JÄGER (1977) were used for calculation of gas retention ages.

low (31 dpm/kgFe), less than a tenth of saturation level (NISHIIZUMI *et al.*, 1981).

Other chondrites studied showed the exposure ages between 1 and 35 m.y., which are in the range of exposure ages found in non-antarctic ordinary chondrites. Figure 2 illustrates distribution of exposure ages for H and L chondrites. Four of nine H chondrites gather around a 4 m.y. peak which is found for the non-antarctic H chondrites. The exposure age distribution for L chondrites is rather uniform. Clustering around 1.3 and 18 m.y. found in Table 2 is due to paired meteorites, identified as fragments of two independent falls in Subsection 3.4. The uniform distribution of exposure ages is characteristic of the non-antarctic L chondrites. As found in Fig. 2,

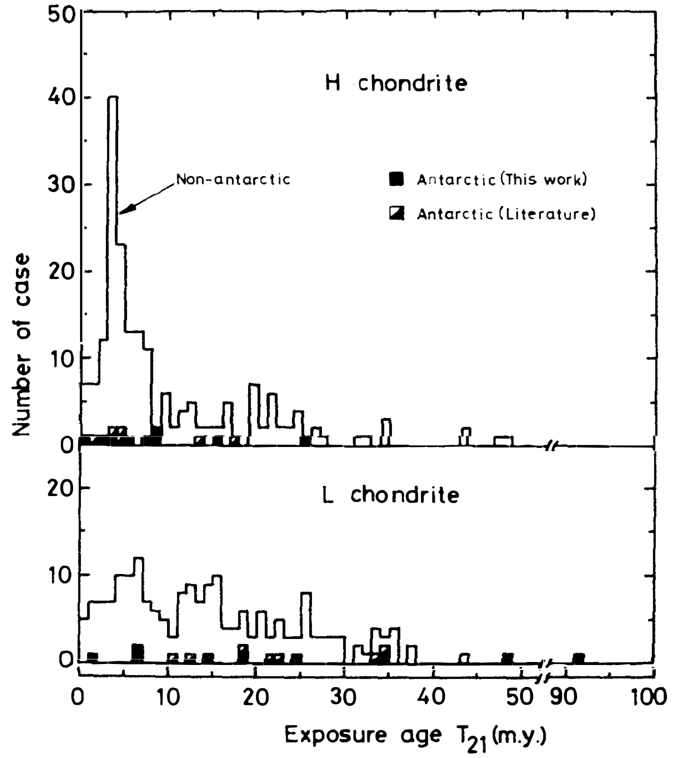

Fig. 2. Distribution of cosmic-ray exposure ages of antarctic H and L chondrites. Exposure ages of antarctic chondrites given by TAKAOKA *and* NAGAO *(1978),* NAGAO *and* TAKAOKA *(1979) and* WEBER *and* SCHULTZ *(1980) as well as this work are plotted. Note that the Y-74035 chondrite has the exposure age as long as 92 m.y. This is the longest age observed for chondrites known to date. The exposure age (49 m.y.) of Y-74080 is also longer than the longest one of non-antarctic chondrites.*

the cosmic-ray irradiation history of the antarctic H and L chondrites seems to be not significantly different from that of the non-antarctic ones.

Recently NISHIIZUMI *et al.* (1980a) have reported that the ^{21}Ne production rate calibrated based on ^{26}Al age deviates systematically from the production rates calibrated with other methods such as ^{53}Mn age, ^{81}Kr-^{83}Kr and ^{22}Na-^{22}Ne methods, and they recommend a new ^{21}Ne production rate of $P_{21}=0.31\times10^{-8}$ cm^3 STP/g m.y. for L chondrites of $^{22}Ne/^{21}Ne=1.11$, though the reason for the discrepancy is not yet settled. The same result has also been reported by MÜLLER *et al.* (1981). If we adopt the new ^{21}Ne production rate recommended by NISHIIZUMI *et al.*, the exposure ages listed in Table 2 become longer by a factor of 1.5.

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

The concentrations of radiogenic ^4He and ^{40}Ar and the gas retention ages are listed in Table 2. Radiogenic ^4He was corrected by the following equation

$$^{4}He_{r}={}^{4}He_{m}-5\cdot{}^{3}He_{c}-330\cdot{}^{20}Ne_{t}\ ,$$

where r, m, c and t mean radiogenic, measured, cosmogenic and trapped components, respectively. ^{40}Ar determined is mostly radiogenic, and no correction was made for the cosmogenic and trapped components. In calculation of U/Th-He and K-Ar ages, mean concentrations of U (12 ppb for the H chondrite and 15 ppb for the L chondrite) and K (850 ppm for both H and L chondrites) and Th/U=3.6 were assumed (MORGAN, 1971). In most cases, He ages are shorter than Ar ages. This is attributed mainly to diffusive loss of radiogenic ^{4}He. Especially, the He loss is significant for L chondrites. A group of L chondrites is found to reveal very short ages. It includes Y-74605, -75097, -75102, -75108 and -75271. Their K-Ar ages are about 0.6 b.y., close to a typical age for black L-group chondrites reported by HEYMAN (1967). According to HEYMAN, such chondrites suffered collisional degassing about 0.53 b.y. ago. The U/Th-He and K-Ar ages for the antarctic chondrites are in the range of those for the non-antarctic chondrites. There is no significant difference in the gas retention age distribution between them.

3.3. Trapped gas

The Y-75028 chondrite contains high concentrations of solar-type trapped gases. This chondrite has been classified as H3 or L(?)3 including H5 clasts (YANAI, 1979). More than fifty stones of non-antarctic meteorites contain solar-type rare gases (WASSON, 1974). The solar-type gases found in such meteorites have been supposed to originate from solar particle implantation into grain surfaces. The $^{20}Ne/^{22}Ne$ ratio for trapped Ne in these meteorites is more than eleven, close to a value found for solar wind Ne, and generally Ne is more enriched relative to trapped Ar (Fig. 3). Carbonaceous chondrites have large amounts of planetary-type gases. However, the planetary-type gases are depleted in Ne compared with Ar, and the $^{20}Ne/^{22}Ne$ ratio is around eight.

Figure 3 represents a ^{20}Ne vs. $^{20}Ne/^{36}Ar$ plot. Most meteorites enriched in the solar-type gas are plotted on the right side of the diagram. Carbonaceous chondrites fall along a correlation line ranging from the left bottom to the right middle in the diagram. A few carbonaceous chondrites overlap both correlation fields. These include high concentrations of solar-type gases. The Y-75028 chondrite is located close to the center of the field of solar-gas-rich meteorites and the right upper end of the field of carbonaceous chondrites.

It is well known that the meteorites containing the solar-type rare gases often show a light-dark texture and include xenolithic fragments (WASSON, 1974). The Y-75028 includes H5 clasts in the H3 or L(?)3 host. However, the light-dark texture has not been observed in it. Since this meteorite is badly weathered (YANAI, 1979), it might be difficult to find such a structure.

ZÄHRINGER (1966) and MARTI (1967) have shown a correlation between the con-

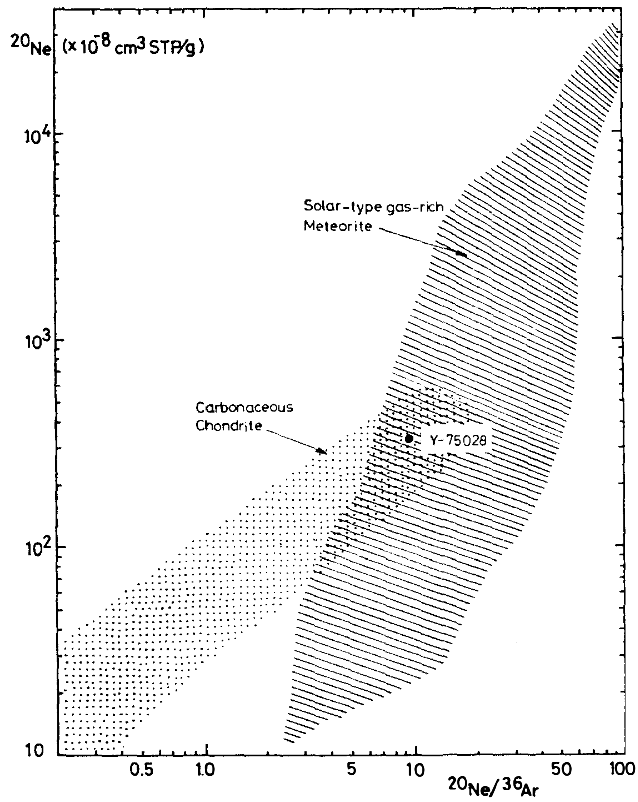

Fig. 3. ^{20}Ne *vs.* $^{20}Ne/^{36}Ar$ *plot for solar-type gas-rich meteorites and for carbonaceous chondrites. Data were taken from* WASSON *(1974) and* SCHULTZ *and* KRUSE *(1978).*

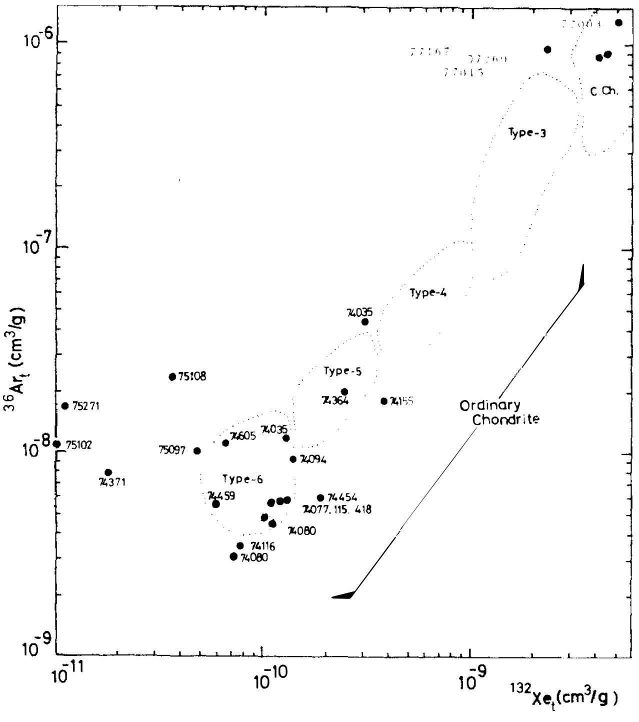

Fig. 4. Plot of planetary-type ^{36}Ar *and* ^{132}Xe.

centrations of trapped planetary-type gases and the petrological classification of chondrites. Trapped ^{36}Ar and ^{132}Xe in the antarctic chondrities studied are plotted in Fig. 4. Most meteorites fall in or close to the fields of petrological types 3, 5 and 6 with several exceptions. The exceptions are: Y-75028 which contains much solar-type primordial gases; Y-75102, -75108 and -75271 which have suffered severe degassing by collisional heating about 0.5 b.y. ago; ALH-77003 which contains much higher concentrations of planetary-type primordial gases as found in carbonaceous chondrites; Y-74362 and -74371 which are greatly depleted in trapped ^{132}Xe for unknown reason.

3.4. *Paired meteorites*

We find in Table 1 two groups of meteorites in which the rare gas concentrations and isotopic ratios are practically equal to each other. One group consists of Y-75097, -75102, -75108 and -75271. These Yamato meteorites are all classified as L chondrite and are characterized by very low contents of radiogenic ^{4}He and ^{40}Ar. As given in Table 2, their K-Ar ages are about 0.6 b.y., a typical age for the L chondrite having the thermal history of collisional metamorphism (HEYMAN, 1967). We can regard these four specimens as fragments of a single fall. The irradiation history deduced from the ^{53}Mn radioactivity (NISHIIZUMI *et al.*, 1980b) as well as cosmogenic rare gas isotopes is compatible with the interpretation as paired meteorites.

Another group consists of ALH-77015, -77167 and -77260. These Allan Hills meteorites are L chondrites of type 3. As shown in Fig. 4, they contain large amounts of planetary-type rare gases. Their cosmic-ray and gas retention ages are in accordance with each other. From the field evidence and petrographic observation, CASSIDY has stated that these are members of a large family consisting of nine paired specimens (MARVIN and MASON, 1980). We regard ALH-77015, -77167 and -77260 as fragments of the same fall based on the rare gas data. The Y-75097 and ALH-77015 groups respectively are doubtless paired meteorites. Y-74605 has the rare gas concentrations and isotopic ratios similar to the Y-75097 group. But the agreement is not so good as found in the group. The Y-74605 is more enriched in both cosmogenic and radiogenic nuclides than the Y-75097 group. However, the ^{53}Mn radioactivity for Y-74605 is equal to that for the Y-75097 group, supporting paired meteorite (NISHIIZUMI *et al.*, 1981). It is not so common for meteorites experienced collisional degassing to show wide variation in the radiogenic ^{40}Ar content exceeding a factor of three. If the Y-74605 chondrite pairs with the Y-75097 group, the mother stone of this group might be a meteorite inhomogeneous in the rare gas content. Other suspects are found for paired meteorites, such as Y-74155 and -74193 (NAGAO *et al.*, 1981; HONDA, 1981) and Y-74364, -74371 and -74193 (NAGAO *et al.*, 1981). However, the agreement of rare gas concentrations or isotopic ratios among them is not consistent. On the basis of the present rare gas data, it is reasonable to defer entering them in a list of paired meteorites.

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