Noble Gases in Ten Stone Meteorites from Antarctica

Hartwig W. Weber and Ludolf Schultz
Max-Planck-Institut für Chemie, Mainz

Dedicated to Prof. H. Hintenberger on the occasion of his 70th birthday

Z. Naturforsch. **35a**, 44–49 (1980); received October 18, 1979

The concentrations and isotopic composition of noble gases have been determined in all ten stone meteorites recovered in Antarctica during 1976–1977 by a U.S.-Japanese expedition. From a comparison of spallogenic and radiogenic gas components it is concluded that the chondrites Mt. Baldr (a) and Mt. Baldr (b) belong to the same fall but that all other stone meteorites are individual finds.

Introduction

During the austral summer 1976–1977 a joint U.S.-Japanese party recovered eleven new meteorites from South Victoria Land in Antarctica [1, 2]. These meteorites are part of more than 1500 others detected up to now in Antarctica since the first discovery in 1969 of nine meteorites near the Yamato Mountains in East Antarctica [3].

The importance of these meteorite finds in Antarctica can be summarized as follows: (a) The amount of the most primitive solar material (carbonaceous chondrites Type I) available for scientific investigations is very small. Additional material could improve such important data as cosmic (solar) abundances. (b) Sampling in non-Antarctic areas may bias the distribution of different meteorite classes as well as their size distribution. Antarctic meteorites may represent the true distribution because small samples can also be detected [4]. (c) Unusual meteorite finds — like ALHA 77081 [5] — bear evidence of hitherto unknown planetary evolution processes.

The relatively high concentration of meteorites in specific localities of the Antarctic continent seems to be the result of several fortunate circumstances: (a) The lifetime of stone meteorites against erosion is enhanced in areas with temperatures permanently below the freezing point of water. (b) The flow of ice from the interior of Antarctica to the margins of the continent provides a mechanism for transportation and collection. (c) The existence of places where strong winds strip the ice bare of snow and where evaporation of the ice takes place, provides a mechanism for excavating buried meteorites.

Reprint requests to Prof. Dr. L. Schultz, Max-Planck-Institut für Chemie, Postfach 3060, D-6500 Mainz, Western Germany.

In a mineralogical-chemical investigation of the eleven meteorites Mt. Baldr (a) and (b) and Allan Hills A 76001 to 009 (ALHA 77002 is an iron meteorite), Olsen et al. [6] classified the 10 stone meteorites to be one eucrite, one LL-3 group chondrite, four H 6 and four L 6 chondrites. The close similarity with respect to mineralogy and chemistry between some of these chondrites suggests that paired finds among the chondrites of the same petrological group cannot be excluded. This is the case for Mt. Baldr (a) and (b) as well as for 76003 and 76007, respectively [6].

A method to detect paired finds is the analysis of cosmic-ray irradiation effects. If two meteorites were, during their flight in space, part of the same body (meteoroid) their cosmic-ray exposure age must be the same. Furthermore, if the temperature history of the meteoroid is the same for all of its material, the gas retention ages calculated from radiogenic ^{4}He and ^{40}Ar should be the same. Thus, paired falls can be recognized among Antarctic chondrites from the analyses of the noble gas concentration in these meteorites.

Fireman et al. [7] have determined the terrestrial ages of four of these meteorites to be between 30,000 and 1.5 million years, while the terrestrial ages from other than Antarctic stone meteorites are smaller [8, 9]. Using meteorites from Antarctica, therefore, the influence of terrestrial age on the noble gas concentrations of stone meteorites can been investigated.

Experimental Procedures and Results

We have analysed the concentration and isotopic composition of He, Ne and Ar as well as the concentration of ^{84}Kr and ^{132}Xe in all ten stone

0340-4811 / 80 / 0100-0044 $ 01.00/0. — Please order a reprint rather than making your own copy.

Tab. 1. Concentrations of noble gas isotopes in samples of Antarctic stone meteorites.

	Class (6)	Sample weight mg	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{84}Kr	^{132}Xe
			in 10^{-8} cm^3 STP/g								in 10^{-10} cm^3/g	
Mt. Baldr (a)	H 6	157	8.8	1250	(2.17)	2.55	2.76	0.73	0.42	6040	0.48	0.29
			.3	50		.15	.13	.05	.03	300	.12	.03
		130	9.3	1920	3.63	2.55	2.87	0.93	0.45	5660	1.4	1.1
			.5	80	.16	.09	.13	.04	.02	250	.2	.1
Mt. Baldr (b)	H 6	158	8.2	1450	2.37	2.18	2.43	1.57	0.59	5330	2.3	1.6
			.4	70	.20	.09	.10	.12	.04	240	.9	.6
		131	9.1	1690	3.42	2.26	2.56	1.11	0.45	4710	1.3	2.0
			.5	80	.44	.08	.09	.05	.03	200	.4	.7
Allan Hills A 76001	L 6	140	74.1	1800	15.1	16.8	18.5	1.92	2.08	6040	1.0	1.0
			2.9	80	.5	.7	.7	.08	.11	300	.2	.2
		122	73.3	1560	14.7	16.5	18.1	1.74	1.87	6430	0.9	1.6
			3.0	70	.6	.6	.6	.08	.08	300	.1	.1
Allan Hills A 76003	L 6	191	77.7	810	16.5	18.1	19.6	3.58	2.35	3680	1.3	1.0
			2.8	30	.6	.6	.7	.21	.11	170	.2	.2
		151	81.5	840	17.2	19.4	21.0	3.83	2.55	3910	0.6	0.6
			3.1	40	1.0	.7	.7	.16	.10	180	.2	.2
Allan Hills A 76004	LL 3	163	24.2	1030	9.0	8.0	9.0	37.9	7.76	4000	34	33
			.9	40	.5	.3	.3	1.3	.26	190	3	2
		126	24.6	1000	9.4	8.33	9.6	37.6	7.74	4320	39	37
			.9	50	.5	.30	.3	1.3	.28	200	3	3
Allan Hills A 76005	Euc	102	11.3	1410	1.74	1.99	2.28	1.68	2.12	1900	1.2	1.9
			.4	60	.07	.07	.09	.08	.08	80	.2	.2
		104	12.1	1350	2.00	2.15	2.53	1.44	1.89	1570	0.9	0.7
			.5	50	.15	.10	.11	.07	.07	60	.2	.1
Allan Hills A 76006	H 6	125	41.1	1280	8.0	9.4	10.2	1.82	1.35	5900	2.9	1.7
			1.9	60	.4	.4	.4	.15	0.7	300	.7	.4
		129	38.9	1790	7.9	8.9	9.7	2.00	1.71	5260	3.2	2.0
			1.8	100	.4	.4	.3	.12	.08	300	.4	.4
Allan Hills A 76007	L 6	132	51.3	361	8.9	9.4	10.6	1.26	1.27	235	2.3	1.1
			1.9	14	.4	.4	.4	.05	.04	14	.2	.1
		178	51.2	352	8.6	9.2	10.4	1.46	1.46	270	1.3	1.5
			2.0	15	.4	.3	.4	.12	.07	15	.2	.2
Allan Hills A 76008	H 6	166	3.02	1350	—	0.81	0.89	1.00	0.35	5930	2.2	1.2
			.13	70		.03	.03	0.6	.06	230	.5	.4
		120	3.10	1510	0.66	0.81	0.88	0.82	0.24	5660	1.8	1.3
			.15	70	.03	.03	.03	.05	.02	280	.2	.2
Allan Hills A 76009	L 6	153	23.0	860	6.7	7.0	7.6	1.38	0.68	6090	0.6	
			.9	40	.3	.3	.3	.08	.06	290	.2	
		129	22.7	640	6.1	6.6	7.2	1.16	0.72	5600	0.7	0.6
			1.1	30	.7	.2	.3	.05	.03	300	.3	.1

meteorites found 1976/77 in South Victoria Land, Antarctica. All samples analysed were bulk samples, with weights between 100 and 200 mg. The procedures of gas extraction, purification, mass spectrometry and calibration have been described earlier [10]. The results are given in Table 1. The uncertainties assigned to the concentrations are the sum of the estimated errors of blank correction, of the calibration gas mixture, and the statistical error of the peak height measurement.

Noble gases in meteoritic samples are a mixture of three components with different isotopic composition: *Spallogenic* (cosmogenic) isotopes which were produced by cosmic rays, *radiogenic* ^{4}He and ^{40}Ar from natural radioactive decay of K, U and Th, and *trapped* primordial or solar gas. To calculate the radiogenic ^{4}He and the spallogenic ^{21}Ne, ^{22}Ne, and ^{38}Ar from the noble gas mixture of the sample, the following assumptions for the isotopic composition of trapped and spallogenic gases were made:

Table 2. Spallogenic and radiogenic noble gas nuclides and some important spallogenic nuclide ratios. The quoted uncertainties in the spallogenic concentrations are only the experimental errors.

	Spallogenic					Radiogenic	
	^{3}He in 10^{-8} ccSTP/g	^{21}Ne	^{38}Ar	^{3}He/^{21}Ne	^{22}Ne/^{21}Ne	^{4}He in 10^{-8} ccSTP/g	^{40}Ar
Mt. Baldr (a)	9.0	2.55	0.31	3.53	1.078	1200	6040
	.3	.09	.01	.16	.018	1870	5660
Mt. Baldr (b)	8.6	2.22	0.31	3.87	1.083	1410	5330
	.3	.06	.02	.18	.010	1650	4710
Allan Hills A 76001	73.7	16.7	1.86	4.41	1.099	1430	6040
	2.1	.5	.07	.21	.007	1200	6430
Allan Hills A 76003	79.6	18.8	1.98	4.23	1.083	420	3680
	2.1	.5	.06	.15	.006	440	3910
Allan Hills A 76004	24.4	8.15	0.74	2.99	1.110	910	3910
	.6	.20	.02	.11	.006	880	4000
Allan Hills A 76005	11.7	2.07	1.90	5.65	1.159	1350	1900
	.3	.06	.06	.08	.010	1290	1570
Allan Hills A 76006	40.0	9.15	1.33	4.37	1.087	1080	5900
	1.3	.25	.09	.19	.009	1590	5620
Allan Hills A 76007	51.2	9.30	1.21	5.51	1.129	105	235
	1.4	.24	.06	.21	.008	96	270
Allan Hills A 76008	3.06	0.81	0.14	3.78	1.094	1330	5930
	.10	.02	.04	.15	.009	1490	5660
Allan Hills A 76009	22.9	6.78	0.52	3.38	1.088	740	6090
	.7	.17	.05	.14	.008	520	5600

Trapped: ^{20}Ne/^{22}Ne = 9.8;
^{36}Ar/^{38}Ar = 5.32;

Spallogenic: ^{4}He/^{3}He = 5;
^{20}Ne/^{21}Ne = 0.9;
^{36}Ar/^{38}Ar = 0.65.

^{3}He and ^{21}Ne are almost entirely spallogenic and ^{40}Ar entirely radiogenic.

Table 2 shows the concentrations of spallogenic ^{3}He, ^{21}Ne, and ^{38}Ar, as well as the ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios. The values given are the mean of two individual measurements. In addition, the radiogenic ^{4}He and ^{40}Ar are shown for each individual measurement.

Discussion

Radiogenic Gases

^{4}He and ^{40}Ar in samples from the one and the same Antarctic meteorite show large variations, up to 40% for ^{4}He and up to 20% for ^{40}Ar. Such large variations within a single meteorite are not seen in radiogenic gases from the Bruderheim Berkeley Standard [11]. One explanation for this effect might be weathering of the U, Th, and K bearing minerals of the meteorite and the loss of radiogenic gases from these minerals. Gibson et al. [12] have recently analysed samples with different degrees of weathering from the Holbrook chondrite. They observe a 10% loss of radiogenic gases from the more weathered samples. The much longer terrestrial age of the Antarctic meteorites may therefore be responsible for variations in the content of radiogenic noble gas nuclides in these meteorites.

The K-Ar gas retention ages — calculated using the mean K concentrations of their respective class — are between 3.6 and 4.4 AE with the exception of 76007. This meteorite has a K-Ar ages of about 0.6 AE, a value which is typical for a number of black L-group chondrites [13]. U, Th-^{4}He ages (assuming mean U concentrations and a Th/U = 3.6) are lower than the K-Ar ages. In particular, the eucrite 76005 has an U, Th-He age of only 0.4 AE, which can be explained by diffusive loss of ^{4}He from feldspars.

Trapped Gases

While none of these meteorites show evidence for the presence of solar-type primordial gases, all of them contain trapped planetary noble gases which

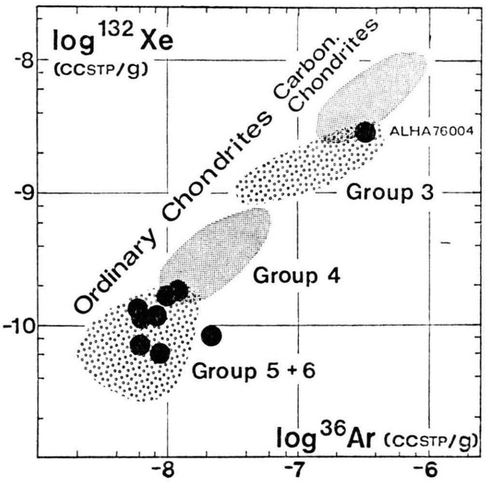

Fig. 1. Different petrological-chemical groups of chondrites contain variable amounts of trapped planetary noble gases. All the chondrites studied here plot in or close to the field of their group.

correlate with the petrological-chemical group of the chondrite [14, 15]: Type 3 chondrites contain most and type 6 the least planetary gas. In a diagram of trapped ^{132}Xe (or ^{84}Kr) versus ^{36}Ar a linear correlation is observed and different groups occupy specific areas (Figure 1). Except for 76004, all Antarctic chondrites investigated in this study plot in or close to the field of group 5 and 6 chondrites, in accordance with their petrological classification. The LL-chondrite 76004, however, has much larger concentrations of trapped planetary noble gases and lies in the field of group 3 chondrites.

Exposure Ages

From the spallogenic noble gas concentrations, the exposure age of the meteorites can be calculated, if the production rates for the spallogenic nuclides are known. Using the production rates given by Cressy and Bogard [16] and their method of shielding correction with the spallogenic ^{22}Ne/^{21}Ne ratio, we calculate exposure ages which are given in Table 3. Most of the Antarctic meteorites have ^{22}Ne/^{21}Ne values close to the "mean" ratio of 1.11. The shielding corrections are therefore small (^{3}He: $<5\%$, ^{21}Ne: $<18\%$, ^{38}Ar: $<19\%$). The exposure ages range from about 1 million years to about 35 million years and are in the range of exposure ages observed for other chondrites.

For some of the investigated stones, however, the exposure ages calculated from the different

Tab. 3. Noble gas exposure ages. The exposure ages are calculated with production rates given by Cressy and Bogard (1976). The ^{22}Ne/^{21}Ne has been used to correct for shielding effects. The uncertainties assigned to exposure ages include a 10% error for production rates. Exposure ages calculated from corrected ^{3}He take into account diffusive losses of ^{3}He.

	Exposure age (in 10^6 years) calculated from			
	^{3}He	^{3}He$_{corr}$	^{21}Ne	^{38}Ar
Mt. Baldr (a)	3.6 .5	4.9	4.9 .7	3.6 .6
Mt. Baldr (b)	3.5 .5	4.4	4.3 .6	3.7 .6
Allan Hills A76001	29.7 3.8	34.0	33.1 4.3	24.4 3.5
Allan Hills A76003	31.5 4.0	36.4	34.4 4.4	24.7 3.3
Allan Hills A76004	10.0 1.3	17.7	17.4 2.2	11.6 1.5
Allan Hills A76005	4.4 .6	8.4	7.1 1.0	9.2 1.2
Allan Hills A76006	16.2 2.2	18.1	18.2 2.3	16.2 2.7
Allan Hills A76007	21.4 2.7	21.4	21.0 2.7	19.4 2.9
Allan Hills A76008	1.3 .2	1.7	1.7 .2	1.8 .7
Allan Hills A76009	9.1 1.2	13.2	12.7 1.6	6.7 1.4

isotopes do not agree within the limits of error (76004, 76009). Generally the ^{21}Ne age is higher than the ^{3}He and also the ^{38}Ar age. A small ^{3}He exposure age, compared to those calculated from ^{21}Ne and ^{38}Ar, can be explained by a loss of ^{3}He or ^{3}H during the irradiation in space. A deficit of ^{3}He in a meteoritic sample can be detected in a plot of ^{3}He/^{21}Ne vs. ^{22}Ne/^{21}Ne, as first given by Eberhardt et al. [17]. Figure 2 shows the trend lines observed from several chondrites [17] or from depth studies of individual stones [18, 11]. If data points fall below the trend lines of Fig. 2, a diffusive loss of ^{3}He (or ^{3}H) is a plausible explanation, because diffusion would not strongly effect the ^{22}Ne/^{21}Ne ratio. For most of the Antarctic meteorites investigated in this study, the ^{3}He/^{21}Ne is smaller than expected from their ^{22}Ne/^{21}Ne ratio. If the St. Severin line is used for the calculation of the nominal values the deficit of ^{3}He is between 44% and 11%. If this deficit is added to the measured ^{3}He, the sum can be used to calculate a corrected ^{3}He exposure age (Table 3).

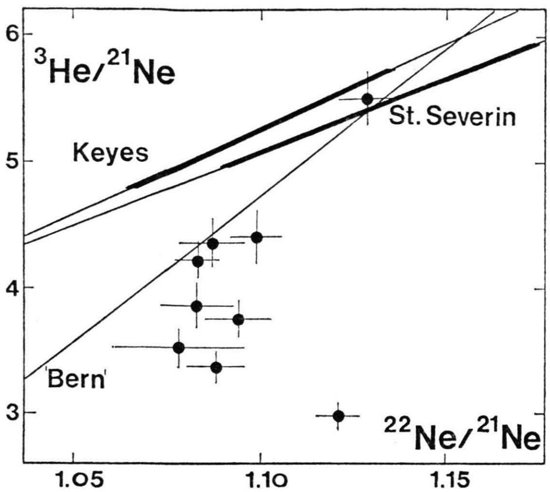

Fig. 2. Relationship between spallogenic $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ for Keyes [18] and St. Severin [11] drill core samples and a number of individual chondrites measured in Bern [17]. Most Antarctic meteorites plot below these trend lines indicating a deficiency of ^{3}He.

These diffusion-loss-corrected ^{3}He exposure ages are in good agreement with the ^{21}Ne exposure ages.

Fireman et al. [7] have given ^{21}Ne ages of 4 of these meteorites: Their values are in good agreement with our ^{21}Ne exposure ages.

The ^{38}Ar exposure ages tend to be lower than the ^{21}Ne ages; this is seen especially for 76001, 76003, 76004 and 76009. All these stones are L- or LL-group chondrites. Only about 12% of the total spallogenic ^{38}Ar is produced in the metallic NiFe of L-chondrites [16]. Loss of ^{38}Ar due to oxidation of the metallic NiFe can only partly account for the relatively low ^{38}Ar exposure ages. Furthermore, Gibson et al. [12] have studied the chemical alteration and loss of noble gases during weathering of the L-ground chondrite Holbrook. These authors observe a comparable loss of all spallogenic gas nuclides and not an enhanced loss of ^{38}Ar. The low ^{38}Ar exposure ages of some of the Antarctic meteorites cannot therefore be explained by a loss of ^{38}Ar caused by this type of terrestrial weathering.

For the LL-3 chondrite 76004 only about 10% of the total ^{38}Ar is of spallogenic origin. This component has been calculated with a trapped $^{36}Ar/^{38}Ar$ of 5.32. If this ratio is raised to 5.50, the $^{38}Ar_s$ concentration would be enlarged and an exposure age is calculated which is comparable to that calculated from $^{21}Ne_s$. However, for the other 3 meteorites with small ^{38}Ar exposure ages compared to those calculated from ^{21}Ne (or corrected ^{3}He), the trapped ^{38}Ar component is small and a possible trapped argon isotope ratio different from 5.32 would not strongly influence the calculated $^{38}Ar_s$. If the production rates used for ^{38}Ar in chondrites are correct, we do not know the mechanism which produces the deviation between ^{21}Ne- and ^{38}Ar-exposure ages in these Antarctic chondrites.

Paired Meteorites

Mt. Baldr (a) and (b) have been found less than one kilometer apart. Both chondrites are very similar with respect to their mineralogy. This suggests that both meteorites belong to the same fall [6]. Within the limits of error, Mt. Baldr (a) and (b) have the same amounts of spallogenic as well as radiogenic gases. Irradiation and thermal history of both meteorites are similar and therefore in agreement with the suggestion that Mt. Baldr (a) and (b) are specimens from the same fall.

Olsen et al. [6] have also discussed the possibility that 76003 and 76007 are paired. The mineralogical and petrological similarities are not so obvious as those of the Mt. Baldr chondrites but a origin from one meteoroid is possible. From the spallogenic and radiogenic gases, however, a paired fall can be excluded. Samples 76003 and 76007 have different exposure ages (Table 3) and their radiogenic ^{40}Ar is different by a factor of more than ten. Both meteorites are definitely separate falls. Taking only the exposure age as criterion, the L-6 chondrites 76001 and 76003 are similar. However, the radiogenic ^{4}He in these meteorites differs by a factor of 3.

In summary, from the noble gas data, it is concluded that all Allan Hills meteorites 76001 to 76009 are individual finds. However, field observation, mineralogy and petrology as well as the noble gas record suggest that Mt. Baldr (a) and (b) constitute a single meteorite.

Acknowledgements

The authors wish to thank Prof. H. Hintenberger for many stimulating discussions and helpful suggestions over a period of several years. We acknowledge the laboratory assistance by Mrs. R. Löhr and help in manuscript preparation by Mrs. S. Link.

We are greatly indebted to Dr. E. J. Olsen, Field Museum of Natural History, Chicago, for supplying us with samples of the Antarctic meteorites.

[1] W. A. Cassidy, E. Olsen, and K. Yanai, Science **198**, 727 (1977).
[2] K. Yanai, Proc. 2. Symp. on Yamato meteorites, Mem. Nat. Inst. Polar Res. Spec. issue No. **8**, 51 (1978).
[3] M. Yoshida, H. Ando, K. Omoto, R. Naruse, and Y. Ageta, Antarctic Rec. **39**, 62 (1971).
[4] G. I. Huss, Meteoritics **12**, 141 (1977).
[5] M. Christophe Michel-Levy, J.-C. Lorin, H. Palme, L. Schultz, B. Spettel, H. Wänke, and H. W. Weber, Meteoritics (in press).
[6] E. J. Olsen, A. Noonan, K. Fredriksson, E. Jarosewich, and G. Moreland, Meteoritics **13**, 209 (1978).
[7] E. L. Fireman, L. A. Rancitelli, and T. Kirsten, Science **203**, 453 (1979).
[8] E. Anders, Rev. Mod. Phys. **34**, 287 (1962).
[9] R. Boeckl, Nature London **236**, 25 (1972).
[10] H. Hintenberger and H. W. Weber, Proc. Lunar Sci. Conf. 4th, 2003 (1973).
[11] L. Schultz and P. Signer, Earth Planet. Sci. Lett. **30**, 191 (1976).
[12] E. K. Gibson and D. D. Bogard, Meteoritics **13**, 277 (1978).
[13] D. Heymann, Icarus **6**, 189 (1967).
[14] J. Zähringer, Earth Planet. Sci. Lett. **1**, 379 (1966).
[15] K. Marti, Earth Planet. Sci. Lett. **2**, 193 (1967).
[16] P. J. Cressy and D. D. Bogard, Geochim. Cosmochim. A **40**, 749 (1976).
[17] P. Eberhardt, O. Eugster, J. Geiss, and K. Marti, Z. Naturforsch. **21a** 414 (1966).
[18] R. J. Wright, L. Simms, M. A. Reynolds, and D. D. Bogard, J. Geophys. Res. **78**, 1308 (1973).