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# Rumuruti chondrites: Noble gases, exposure ages, pairing, and parent body history

Ludolf SCHULTZ*, Hartwig W. WEBER, and Luitgard FRANKE

Max-Planck-Institut für Chemie (Otto-Hahn-Institut) D-55020 Mainz, Germany
*Corresponding author. E-mail: schultz@mpch-mainz.mpg.de

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**Abstract**–In this paper, we present concentration and isotopic composition of the light noble gases He, Ne, and Ar as well as of $^{84}$Kr, $^{132}$Xe, and $^{129}$Xe in bulk samples of 33 Rumuruti (R) chondrites. Together with previously published data of six R chondrites, exposure ages are calculated and compared with those of ordinary chondrites. A number of pairings, especially between those from Northwest Africa (NWA), are suggested, so that only 23 individual falls are represented by the 39 R chondrites discussed here. Eleven of these meteorites, or almost 50%, contain solar gases and are thus regolithic breccias. This percentage is higher than that of ordinary chondrites, howardites, or aubrites. This may imply that the parent body of R chondrites has a relatively thick regolith. Concentrations of heavy noble gases, especially of Kr, are affected by the terrestrial atmospheric component, which resides in weathering products. Compared to ordinary chondrites, $^{129}$Xe/$^{132}$Xe ratios of R chondrites are high.

## INTRODUCTION

Since 1969, more than 30,000 meteorite specimens have been recovered from Antarctica. During recent years, hot deserts like the Sahara have also become the source of many new meteorite finds. The vast increase in the number of meteorites available for scientific investigations led to the discovery of several meteorite groups or grouplets that had not been established before in modern meteorite classification schemes. We report here noble gas measurements on most members of such a group, the so-called rumurutiites, or R chondrites.

Kallemeyn et al. (1996) summarized the available information on the nine R chondrites known at that time. Meteorites that belong to this group have a basically chondritic chemical composition, a high modal abundance of olivine (70 ± 8 wt%), and a high degree of oxidation (39 ± 2 mol% Fa; almost no metallic FeNi). R chondrites form a distinct group in the standard three-isotope plot of oxygen with the highest $\Delta^{17}$O values so far. Many of these stones exhibit light/dark structures indicating that they are regolith breccias.

The first meteorite in this group, Carlisle Lakes, was discovered on the Nullarbor Plain in Australia (Binns and Pooley 1979). Rubin and Kallemeyn (1989) noted the similarity of this meteorite to the Antarctic stone Allan Hills (ALH) 85151; Weisberg et al. (1991) recognized the relationship of Carlisle Lakes and ALH 85151 to Yamato (Y-) 75302 and termed these meteorites "Carlisle Lakes-type" chondrites. Subsequently, additional members of this group were found and described: Y-793575 (Yanai 1992), Y-82002 (Nakamura et al. 1993), Acfer 217 (Bischoff et al. 1994), and two paired Antarctic stones, Pecora Escarpment (PCA) 91002 and 91241 (Rubin and Kallemeyn 1994). The first and only witnessed fall of this group, Rumuruti, occurred in 1934 but remained unstudied until 1993 (Schulze and Otto 1993; Schulze et al. 1994). Its name is now adopted for this new chondrite group (rumurutiite). Since then, more R chondrites have been detected, primarily in hot deserts, including Dar al Gani (DaG) 013 (Jäckel et al. 1996; Palme et al. 1996), DaG 417, Hammadah al Hamra (HaH) 119 (Grossmann 1997), Hughes 030 (Bischoff et al. 1998), and Sahara 98248, as well as the three (possibly paired) stones Sahara 99527, 99531, and 99537 (Grossman 1999, 2000). Other finds from the Sahara are Ouzina (Grossman 2000) and several Northwest Africa specimens (Grossman and Zipfel 2001; Russell et al. 2002, 2003, 2004). From the Antarctic, five new R chondrites are described: the four paired specimens Mount Prestrud (PRE) 95404, 95410, 95411, and 95412 (Rubin and Kallemeyn 1994; Kallemeyn 1998), Asuka (A-) 881988, and Y-881988 and 791827 (Yanai et al. 1995). The latter specimen is probably paired with Y-75302 (Nagao et al. 1999). Recently, LaPaz Ice Field (LAP) 02238 was recovered (Russell et al. 2004).

The Antarctic chondrite Elephant Moraine (EET) 96026 is also described as an R chondrite (*Antarctic Meteorite Newsletter* 21, February 1998), however, it has an oxygen

Table 1. Characteristic data of R chondrites measured in this study. The abbreviations of meteorite names are given in brackets.

| Meteorite | Find/fall | Weight (grams) | Type[a] (matrix) | Shock group | Weathering group[b] | Pair |
|---|---|---|---|---|---|---|
| Acfer 217 | 1991 | 174 | R3.8-5 | S2 | W5/6 | |
| Allan Hills (ALH) 85151 | 1985 | 14 | R.3.6 | S2 | W2/3 | |
| Asuka (A-) 881988 | 1988 | 172 | R4 | | | |
| Carlisle Lakes | 1977 | 50 | R3.8 | S3 | W3/4 | |
| Dar al Gani (DaG) 013 | 1995 | 205 | R3.5-6 | S1 | W4 | |
| Dar al Gani (DaG) 417 | 1998 | 171 | R3-4 | S2 | W3 | |
| Hammadah al Hamra (HaH) 119 | 1995 | 352 | R4 | S3 | W4 | |
| Hughes 030 | 1991 | 100 | R3-6 | | | |
| LaPaz Ice Field (LAP) 02238 | 2002 | 27 | R | | | |
| Mt. Prestrud (PRE) 95404 | 1995 | 40 | R3 | | | 1 |
| Mt. Prestrud (PRE) 95410 | 1995 | 42 | R3 | | | 1 |
| Mt. Prestrud (PRE) 95411 | 1995 | 44 | R3 | | | 1 |
| Mt. Prestrud (PRE) 95412 | 1995 | 15 | R3 | | | 1 |
| Northwest Africa (NWA) 053 | ? | 390 | R4 | S2 | W2 | |
| Northwest Africa (NWA) 753 | 2001 | 12000 | R3.9 | S2 | W2 | 2 |
| Northwest Africa (NWA) 755 | 2001 | 352 | R3.7 | S2 | W4 | 3 |
| Northwest Africa (NWA) 845 | 2001 | 36 | R4 | | W1 | 3 |
| Northwest Africa (NWA) 851 | 2001 | 695 | R4 | | W4 | 3 |
| Northwest Africa (NWA) 978 | 2001 | 722 | R3.8 | S3 | W2 | 3 |
| Northwest Africa (NWA) 1471 | 2001 | 53 | R3/4 | S3 | W3/4 | 3 |
| Northwest Africa (NWA) 1472 | 2001 | 108 | R3/4 | S3 | W3/4 | 2 |
| Northwest Africa (NWA) 1476 | 2001 | 21 | R3 | S3 | W1 | 2 |
| Northwest Africa (NWA) 1477 | 2001 | 35 | R3 | S3 | W3/4 | 2 |
| Northwest Africa (NWA) 1478 | 2001 | 28 | R3 | S3 | W1/2 | 2 |
| Northwest Africa (NWA) 1566 | 2001 | 159 | R3.8 | S2 | W4 | 2 |
| Northwest Africa (NWA) 1583 | 2002 | 78 | R3.9 | S2 | W1/2 | |
| Northwest Africa (NWA) 1585 | 2002 | 77 | R5 | S2 | W1 | |
| Ouzima | 1999 | 642 | R4 | S2 | W4 | |
| Pecora Escarpment (PCA) 91002 | 1991 | 210 | R3.8-6 | S2 | W2/3 | 4 |
| Pecora Escarpment (PCA) 91241 | 1991 | 75 | R3.8-6 | S2 | | 4 |
| Rumuruti | 1934 | >67 | R3.8-6 | S2 | W0/1 | |
| Sahara 98248 | 1998 | 39 | R4 | S2 | W2 | |
| Sahara 99527 | 1999 | 19 | R5 | S3 | W4 | 5 |
| Sahara 99531 | 1999 | 31 | R3-5 | S3 | W3/4 | 5 |
| Sahara 99537 | 1999 | 27 | R3-6 | S3 | W3/4 | 5 |
| Yamato (Y-) 75302 | 1976 | 4 | R3.8 | S4 | W3/4 | 6 |
| Yamato (Y-) 791827 | 1979 | 9 | R4 | | | 6 |
| Yamato (Y-) 793575 | 1979 | 25 | R3.8 | S2 | W3/4 | |
| Yamato (Y-) 82002 | 1982 | 7 | R3.9 | S2 | W4/5 | |

[a] Many R chondrites contain fragments of different type.

[b] Weathering group according to Wlotzka (1993).

isotopic composition that does not confirm this classification (Clayton and Mayeda 2003). This meteorite is therefore not included in this paper.

Some general information on all R chondrites, mainly taken from Koblitz (2003), is given in Table 1.

We have reported concentration and isotopic composition of noble gases in Acfer 217 and Carlisle Lakes (Bischoff et al. 1994). Nagao et al. (1999) have provided noble gas data of R chondrites from the Japanese Antarctic meteorite collection. Here we report analyses of 33 other R chondrites and discuss the results with respect to pairing, thermal events, irradiation stages, and implications for the thermal history of these stones. For completeness, this report also includes the earlier measurements from this laboratory as well as those of Nagao et al. (1999). This paper is an expanded and updated version of several abstracts (Bischoff et al. 1998, 2001; Schultz and Weber 2001; Weber and Schultz 1995, 1996, 1998a, 1998b, 2001; Weber et al. 1997).

## EXPERIMENTAL PROCEDURES AND RESULTS

Two different systems were used for the measurement of these samples, but the applied procedures were similar (e.g., Schultz and Weber 1996; Loeken et al. 1992). Bulk samples were taken from matrix parts of the meteorite at least 2 mm apart from the fusion crust. If possible, they were wrapped as chunks in Fe or Ni foil and stored in vacuo for at least 24 hours at about 100 °C to reduce the amount of adsorbed atmospheric noble gases. The samples were then heated to about 1700 °C for 30 minutes in a W-crucible of a resistance heated double-vacuum Ta oven. Ti and Zr-Al getter performed purification of the noble gas mixture. He and Ne were separated from the heavy noble gases using an activated charcoal trap at the temperature of boiling nitrogen. After an additional cleaning step, He and Ne were admitted into the all-metal magnetic sector field mass spectrometer. After analyses, this fraction was pumped off and Ar, Kr, and Xe were desorbed and then admitted to the mass spectrometer.

Mass peaks and their corresponding gas amounts were determined by peak height comparison, extrapolated back to the time of gas inlet. Magnetic peak jumping was controlled by a Hall probe and a desktop computer was used to determine the peak heights using an electron multiplier for Ne, Kr, and Xe and a Faraday cup for He and Ar measurements. Measuring known amounts of atmospheric gases determined the sensitivity and mass discrimination of the mass spectrometer; for He an artificial mixture ($^3$He/$^4$He = 0.978) was used. The sensitivities of each system remained constant to better than ±10% during the course of these measurements. Corrections for doubly charged $^{40}$Ar at mass 20 were ≤3%. Our laboratory standard Lakewood was measured at intervals of about two months. The results of these measurements are shown in Fig. 1 (the data are given in Schultz and Franke 2004). No systematic trend from mean values is observed and it is therefore assumed that over the period of these measurements (about six years) the experimental settings have not been changed significantly.

The results of all individual measurements of R chondrites are compiled in Table 2.

The measured noble gases are mixtures of different components. For the partitioning into individual fractions, the following assumptions were made (indices are s = solar; c = cosmogenic; r = radiogenic; t = trapped):

$^3$He$_c$ in solar gas containing meteorites was calculated taking $^4$He$_r$ = 1.5 · 10$^{-5}$cm$^3$STP/g and ($^4$He/$^3$He)$_s$ = 3500. For meteorites with very high solar $^4$He (ALH 85151 and PRE 95410/1/2), the correction is large. Less than 10% of the total $^3$He is cosmogenic, and for these samples a significant concentration of $^3$He$_c$ cannot be given.

Neon is mostly cosmogenic for meteorites without solar gases. Small corrections of $^{22}$Ne$_c$ have been made for measurements with $^{20}$Ne/$^{22}$Ne > 0.82, assuming that these higher values are caused by the addition of atmospheric Ne.

($^{22}$Ne/$^{21}$Ne)$_c$ is an important parameter for shielding corrections of production rates of cosmogenic nuclides, but this ratio is difficult to obtain for meteorites containing solar gas. However, it is possible if several bulk samples with varying mixing ratios of cosmogenic and solar gas are measured or a stepwise heating experiment is carried out. Figure 2 shows a 3 isotope plot of neon for ALH 85151, DaG 417 (heating steps), Hughes 030, and Sahara 99531/537. A linear fit of the samples of each individual meteorite allows the estimation of ($^{22}$Ne/$^{21}$Ne)$_c$ from the cosmogenic $^{20}$Ne/$^{22}$Ne = 0.82. For samples with small solar gas contributions, $^{21}$Ne$_c$ is calculated from the measured $^{21}$Ne, assuming ($^{22}$Ne/$^{21}$Ne)$_s$ = 32 and ($^{22}$Ne/$^{21}$Ne)$_c$ = 1.11. Furthermore, to calculate $^{38}$Ar$_c$, values of ($^{36}$Ar/Ar$^{38}$)$_t$ = 5.32 and ($^{36}$Ar/$^{38}$Ar)$_c$ = 0.67 are used.

## Production Rates and Cosmic Ray Exposure Ages

Production rates of cosmogenic nuclides are dependent on the chemical composition of the target material. Usually, these production rates are given for L-chondrite chemistry; for other chondrite groups, a chemical correction factor F is introduced (Eugster 1988). We have calculated F values for $^3$He, $^{21}$Ne, and $^{38}$Ar for R chondrites from the mean concentrations of their main target elements (in wt%): Mg (13.03 ± 0.63); Al (1.26 ± 0.36); Si (16.46 ± 0.60); S (4.1 ± 0.1); K (0.080 ± 0.011); Ca (1.29 ± 0.21); Ti (0.061 ± 0.014); Cr (0.328 ± 0.059); Mn (0.219 ± 0.024); Fe (24.43 ± 0.71); and Ni (0.96 ± 0.48) (Bischoff et al. 1994; Schulze et al. 1994; Yanai et al. 1995; Kallemeyn et al. 1996; Palme et al. 1996; Merchel 1998).

### *Helium*

Eugster (1988) calculates the production rate of $^3$He in L chondrites P(3)$_L$ (in units of 10$^{-8}$cm$^3$STP/gMa) as a function of the shielding parameter ($^{22}$Ne/$^{21}$Ne)$_c$:

$$P(3)_L = [2.09 - 0.43 \cdot (^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_c] \qquad (1)$$

For mean shielding, ($^{22}$Ne/$^{21}$Ne)$_c$ = 1.11, a value of 1.61 × 10$^{-8}$cm$^3$STP$^3$He/gMa is determined.

The production rate of R chondrites P(3)$_R$ is calculated according to Cressy and Bogard (1976) with the chemical composition of this meteorite group given above: P(3)$_R$ = 1.60 · 10$^{-8}$cm$^3$STP$^3$He/gMa, very similar to P(3)$_L$. A somewhat higher value of (1.75 ± 0.05) · 10$^{-8}$cm$^3$STP$^3$He/gMa is obtained for ($^{22}$Ne/$^{21}$Ne)$_c$ = 1.11 if the model by Leya et al. (2000) is used for meteoroids with different radii.

### *Neon*

The production rate of $^{21}$Ne is given by Eugster (1988) to

$$P(21)_L = 1.61 \cdot [21.77 \cdot (^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_c - 19.32]^{-1} \qquad (2)$$

For mean shielding, P(21)$_L$ = 1.61 × 10$^{-8}$cm$^3$STP$^3$He/gMa is the result. For R chondrites, P(21)$_R$ is calculated using a formula given by Schultz and Freundel (1985). For average shielding, a value of 0.294 · 10$^{-8}$cm$^3$STP$^{21}$Ne/gMa is obtained. The smaller production rate of R chondrites

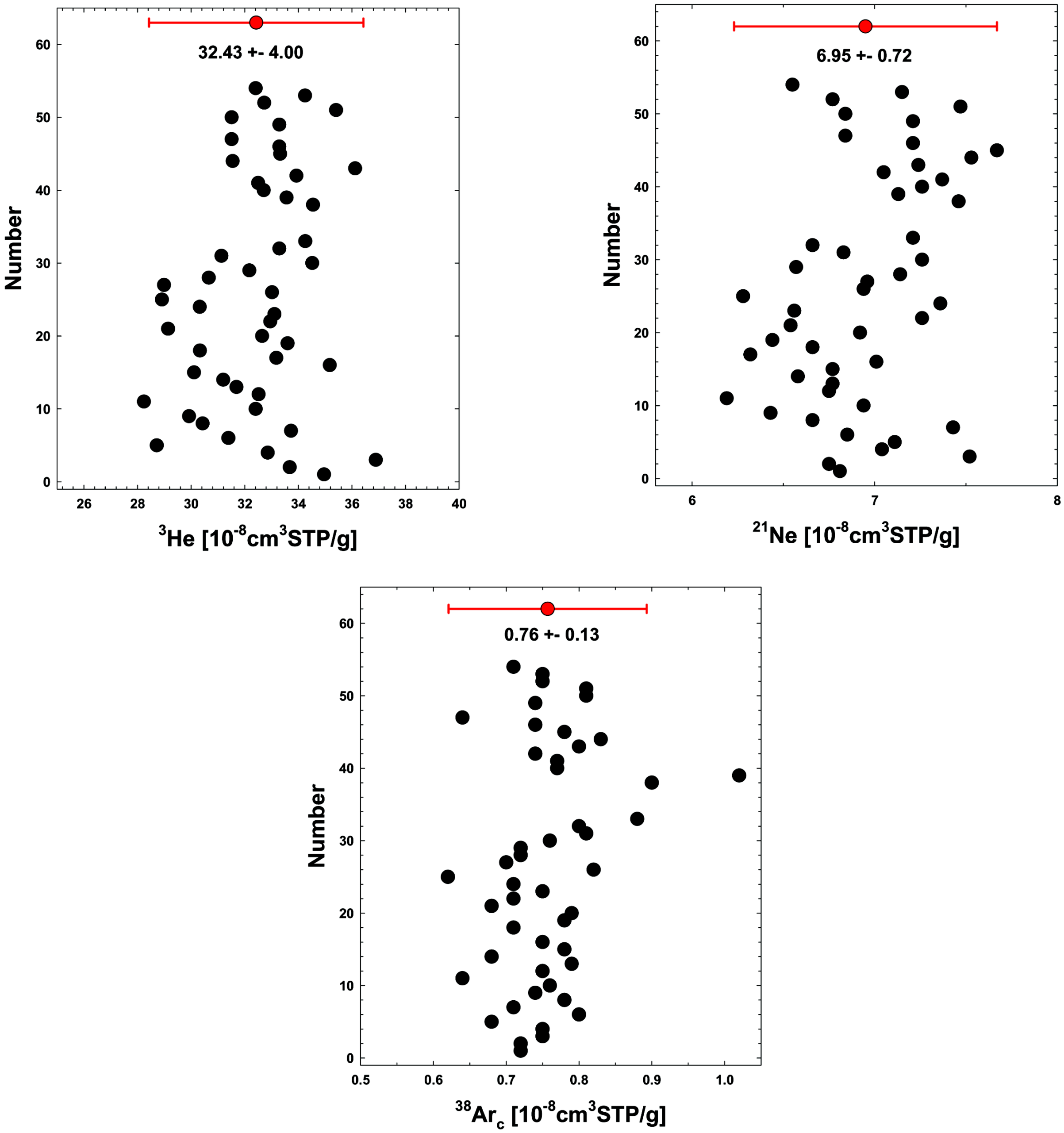

Fig. 1. Concentrations of cosmogenic $^3$He, $^{21}$Ne, and $^{38}$Ar in bulk samples of Lakewood (sample weights are about 100 mg). This meteorite was used as a laboratory standard to check the performance of the analysis system before the measurement of each new sample suite. The data given are results of measurements during the recent six years. They show that no significant change in the quality of data took place during the time where R chondrites were measured. The uncertainty given with the mean values are 2 $\sigma$.

compared to L chondrites is mainly due to the lower Mg content of R chondrites. This production rate, however, is in perfect agreement with the rate calculated using the formulas of Leya et al. (2000).

### *Argon*

The shielding dependence of the production rate of $^{38}$Ar (Eugster 1988) is given by:

$$P(38)_L = [0.109 - 0.062 \cdot (^{22}Ne/^{21}Ne)_c] \quad (3)$$

with a reduction of 13% according to Schultz et al. (1991). For calculating $P(38)_R$, we use

$$P(38)_R = 1.58 \cdot [Ca] + 0.086 \cdot [Fe + Ni] + 0.33 \cdot [Ti + Cr + Mn] + 2.6 \cdot [K] \quad (4)$$

Table 2. Noble gas concentrations (in $10^{-8}$cm$^{3}$STP/g) of R chondrites.

| Meteorite | Source[a] | Weight (mg) | $^{3}$He | $^{4}$He | $^{20}$Ne | $^{21}$Ne | $^{22}$Ne | $^{36}$Ar | $^{38}$Ar | $^{40}$Ar | $^{84}$Kr | $^{132}$Xe | $^{129}$Xe/$^{132}$Xe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ALH 85151 | H | 2.35 | 136.00 | 307000 | 908.00 | 9.76 | 78.60 | 35.20 | 7.55 | 1673 | 0.097 | 0.036 | 1.55 |
| | | 2.45 | 41.70 | 5810 | 23.61 | 7.85 | 10.19 | 8.60 | 2.33 | 1930 | 0.088 | 0.059 | 2.35 |
| | | 2.66 | 143.70 | 336000 | 1021.00 | 9.73 | 87.42 | 38.41 | 8.19 | 2387 | 0.081 | 0.046 | 2.41 |
| | | 2.61 | 161.90 | 390000 | 1158.00 | 10.28 | 98.29 | 41.90 | 8.74 | 2468 | 0.064 | 0.044 | 2.46 |
| DaG 013 | M | 85.30 | 11.72 | 1284 | 2.76 | 2.48 | 2.88 | 6.79 | 1.55 | 2924 | 0.305 | 0.092 | 1.51 |
| DaG 417 | Mz | 6.31 | 32.40 | 32700 | 114.60 | 4.64 | 14.38 | 11.90 | 2.90 | 6029 | 0.508 | 0.120 | 1.35 |
| Step 1 | | 27.9 | 20.05 | 20600 | 23.72 | 0.55 | 2.50 | 12.02 | 9.13 | 6537 | | | |
| Step 2 | | | 9.57 | 7840 | 37.63 | 1.33 | 4.45 | 1.21 | 0.33 | 1525 | | | |
| Step 3 | | | 1.49 | 1015 | 24.72 | 0.85 | 2.95 | 0.82 | 0.21 | 117 | | | |
| Step 4 | | | 0.34 | 70 | 17.48 | 0.80 | 2.37 | 1.48 | 0.41 | 78 | | | |
| Step 5 | | | 0.05 | 3 | 3.75 | 1.00 | 1.44 | 1.28 | 0.47 | 105 | | | |
| Sum | | | 31.50 | 29530 | 107.30 | 4.54 | 13.71 | 16.81 | 10.55 | 8362 | | | |
| HaH 119 | M | 108.1 | 2.50 | 626 | 0.67 | 0.69 | 0.77 | 1.22 | 0.32 | 3710 | 0.079 | 0.036 | 1.60 |
| | | 108.0 | 2.35 | 630 | 0.67 | 0.66 | 0.76 | 1.57 | 0.38 | 4140 | 0.139 | 0.048 | 1.47 |
| | | 114.5 | 2.41 | 596 | 0.68 | 0.68 | 0.77 | 1.63 | 0.42 | 4035 | 0.190 | 0.055 | 1.44 |
| Hughes 030 | G | 2.49 | 33.70 | 9614 | 130.00 | 13.60 | 24.80 | 10.15 | 3.49 | 3037 | 0.219 | 0.074 | 1.38 |
| | | 25.99 | 36.90 | 12150 | 155.60 | 13.70 | 26.90 | 7.69 | 3.21 | 2654 | 0.120 | 0.052 | 1.47 |
| | | 28.20 | 39.70 | 16910 | 214.60 | 13.60 | 31.80 | 7.40 | 3.11 | 3368 | 0.073 | 0.031 | 1.47 |
| LAP 02238 | H | 103.55 | 34.90 | 73120 | 176.50 | 8.19 | 22.60 | 10.83 | 2.90 | 4968 | 0.065 | 0.059 | 3.22 |
| | | 20.09 | 63.00 | 57060 | 104.90 | 7.49 | 16.37 | 10.78 | 3.00 | 5720 | 0.067 | 0.061 | 3.66 |
| NWA 053 | M | 25.60 | 0.19 | 981 | 0.095 | 0.046 | 0.059 | 1.88 | 0.38 | 4790 | 0.145 | 0.028 | 1.53 |
| | | 96.90 | 0.20 | 967 | 0.085 | 0.042 | 0.051 | 2.19 | 0.42 | 5148 | 0.205 | 0.037 | 1.67 |
| NWA 753 | Mz | 82.60 | 17.90 | 1422 | 4.01 | 4.32 | 4.69 | 3.26 | 1.01 | 3473 | 0.039 | 0.042 | 2.24 |
| NWA 755 | Mz | 90.60 | 13.50 | 1157 | 3.22 | 3.45 | 3.75 | 3.61 | 1.04 | 4065 | 0.272 | 0.076 | 1.28 |
| NWA 845 | Mz | 102.71 | 13.22 | 1227 | 3.50 | 3.63 | 3.94 | 3.63 | 1.03 | 3829 | 0.041 | 0.033 | 2.32 |
| NWA 851 | Mz | 100.63 | 15.13 | 1186 | 3.61 | 3.80 | 4.06 | 1.49 | 0.63 | 3686 | 0.021 | 0.019 | 1.87 |
| NWA 978 | LA | 102.41 | 13.11 | 1297 | 3.51 | 3.11 | 3.52 | 20.63 | 4.21 | 4645 | 0.840 | 0.200 | 1.14 |
| | | 106.77 | 12.75 | 1237 | 3.74 | 3.13 | 3.59 | 17.38 | 3.62 | 3375 | 0.717 | 0.212 | 1.11 |
| NWA 1471 | M | 84.20 | 13.26 | 1138 | 2.68 | 2.97 | 3.22 | 1.97 | 0.73 | 3990 | 0.067 | 0.034 | 1.45 |
| | | 78.75 | 13.45 | 1138 | 2.91 | 3.13 | 3.41 | 1.92 | 0.74 | 4373 | 0.076 | 0.031 | 1.43 |
| NWA 1472 | M | 84.86 | 17.65 | 1380 | 3.60 | 3.93 | 4.24 | 6.12 | 1.56 | 3335 | 0.324 | 0.062 | 1.38 |
| | | 79.22 | 17.26 | 1332 | 3.84 | 4.25 | 4.59 | 5.31 | 1.44 | 3040 | 0.304 | 0.062 | 1.36 |
| NWA 1476 | M | 81.11 | 19.52 | 1431 | 4.62 | 4.35 | 4.87 | 15.51 | 3.45 | 798 | 0.120 | 0.094 | 1.73 |
| NWA 1477 | M | 84.24 | 19.14 | 1476 | 4.82 | 4.77 | 5.28 | 7.75 | 1.89 | 1542 | 0.077 | 0.080 | 3.29 |
| NWA 1478 | M | 79.78 | 20.72 | 1483 | 4.04 | 4.36 | 4.73 | 3.87 | 1.23 | 2451 | 0.036 | 0.037 | 2.02 |
| | | 53.50 | 19.99 | 1591 | 4.78 | 5.27 | 5.70 | 3.86 | 1.25 | 2385 | 0.025 | 0.031 | 2.23 |
| NWA 1566 | M | 80.81 | 15.83 | 1351 | 5.12 | 4.05 | 4.58 | 22.01 | 4.57 | 7504 | 0.900 | 0.187 | 1.17 |
| | | 69.07 | 16.45 | 1342 | 5.03 | 4.70 | 5.28 | 13.32 | 2.87 | 4235 | | | |
| NWA 1583 | B | 103.89 | 18.35 | 632 | 6.66 | 7.35 | 7.66 | 2.24 | 1.03 | 1706 | 0.007 | 0.007 | 2.20 |
| | | 99.51 | 18.49 | 629 | 6.73 | 7.34 | 7.71 | 2.37 | 1.21 | 1755 | 0.011 | 0.005 | 2.76 |
| NWA 1585 | W | 101.26 | 4.20 | 17 | 7.76 | 8.30 | 9.00 | 3.32 | 2.40 | 89 | 0.004 | 0.004 | 2.88 |

Table 2. *Continued.* Noble gas concentrations (in $10^{-8}$cm$^3$STP/g) of R chondrites.

| Meteorite | Source[a] | Weight (mg) | $^3$He | $^4$He | $^{20}$Ne | $^{21}$Ne | $^{22}$Ne | $^{36}$Ar | $^{38}$Ar | $^{40}$Ar | $^{84}$Kr | $^{132}$Xe | $^{129}$Xe/$^{132}$Xe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ouzina | M | 113.20 | 11.47 | 1092 | 1.70 | 1.65 | 1.99 | 9.52 | 2.06 | 8445 | 0.812 | 0.095 | 1.34 |
| PRE 95404 | H | 18.30 | 150.70 | 472100 | 2970.00 | 10.79 | 241.00 | 97.90 | 18.96 | 5053 | 0.104 | 0.076 | 2.64 |
| | | 6.68 | 447 | 1519000 | 10120.00 | 29.80 | 815.00 | 321.00 | 62.40 | 5770 | 0.236 | 0.100 | 1.84 |
| PRE 95410 | H | 3.28 | 299.00 | 977000 | 8660.00 | 26.10 | 697.00 | 272.00 | 52.70 | 6763 | 0.412 | 0.104 | 1.97 |
| | | 3.02 | 331.00 | 1061000 | 9136.00 | 29.00 | 738.00 | 280.00 | 54.40 | 5822 | 0.181 | 0.065 | 2.49 |
| | | 3.60 | 404.00 | 131500 | 11410.00 | 33.70 | 918.00 | 352.90 | 68.20 | 6579 | 0.323 | 0.085 | 2.55 |
| PRE 95411 | H | 3.34 | 395.00 | 1352000 | 4437.00 | 16.40 | 387.00 | 184.20 | 36.50 | 5223 | 0.229 | 0.100 | 1.51 |
| | | 2.79 | 487.00 | 1622000 | 6443.00 | 23.10 | 548.00 | 247.10 | 48.70 | 5900 | 0.310 | 0.143 | 1.89 |
| | | 3.57 | 331.00 | 1110000 | 3975.00 | 15.10 | 347.00 | 154.20 | 30.40 | 5565 | 0.194 | 0.083 | 1.73 |
| PRE 95412 | H | 4.18 | 396.00 | 1332000 | 9051.00 | 27.10 | 731.00 | 274.80 | 53.30 | 6235 | 0.201 | 0.074 | 4.21 |
| | | 3.21 | 478.00 | 1644000 | 10680.00 | 31.20 | 865.00 | 328.60 | 64.10 | 6321 | 0.252 | 0.075 | 3.11 |
| | | 3.09 | 153.10 | 496000 | 2944.00 | 11.10 | 242.00 | 96.80 | 18.94 | 6103 | 0.118 | 0.074 | 2.66 |
| PCA 91002 | H | 84.20 | 66.70 | 60030 | 924.00 | 14.10 | 83.30 | 33.90 | 7.44 | 4640 | 0.088 | 0.093 | 3.19 |
| PCA 91241 | H | 67.90 | 65.20 | 59900 | 990.00 | 14.60 | 88.70 | 36.90 | 8.09 | 4160 | 0.088 | 0.092 | 3.17 |
| Rumuruti | B | 117.00 | 25.60 | 2084 | 22.60 | 4.60 | 6.62 | 4.71 | 1.53 | 7890 | 0.034 | 0.035 | 2.84 |
| Sahara 98248 | M | 8.30 | 25.20 | 1590 | 4.31 | 2.74 | 3.69 | 21.51 | 4.55 | 12830 | 0.950 | 0.121 | 1.30 |
| | | 13.23 | 23.00 | 1488 | 5.85 | 2.47 | 3.48 | 38.04 | 7.73 | 18190 | 1.400 | 0.155 | 1.23 |
| Sahara 99527 | M | 6.67 | 38.00 | 921 | 8.81 | 8.52 | 9.56 | 12.10 | 3.22 | 6200 | 0.461 | 0.044 | 1.43 |
| | | 70.90 | 35.00 | 923 | 10.30 | 8.14 | 9.23 | 19.95 | 4.79 | 9186 | 0.759 | 0.074 | 1.34 |
| Sahara 99531 | M | 9.01 | 34.00 | 19090 | 275.90 | 9.69 | 32.8 | 27.95 | 6.35 | 6623 | 0.793 | 0.119 | 1.26 |
| | | 11.30 | 48.90 | 24340 | 266.60 | 10.62 | 33.10 | 20.99 | 5.08 | 6020 | 0.465 | 0.080 | 1.36 |
| Sahara 99537 | M | 5.60 | 49.40 | 34800 | 253.00 | 10.10 | 31.50 | 20.98 | 5.24 | 5737 | 0.320 | 0.063 | 1.42 |
| | | 70.00 | 45.80 | 25190 | 187.00 | 9.80 | 25.70 | 18.64 | 4.51 | 5327 | 0.413 | 0.079 | 1.41 |
| Y-793575 | T | 82.00 | 11.26 | 1433 | 1.61 | 1.62 | 1.99 | 1.29 | 0.46 | 5560 | 0.019 | 0.017 | 3.26 |
| | | 6.33 | 11.20 | 1330 | 1.54 | 1.58 | 1.92 | 0.96 | 0.34 | 5200 | 0.009 | 0.008 | 3.50 |

[a] B = Museum für Naturkunde, Berlin, Germany.
G = R. Bartoschewitz, Gifhorn, Germany.
H = Meteorite Working Group and JSC Houston, Texas, USA.
LA = Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, California, USA.
M = Institut für Planetologie, Universität Münster, Münster, Germany.
Mz = Max-Planck-Institut für Chemie, Mainz, Germany.
T: National Institute of Polar Research, Tokyo, Japan.
W: Smithsonian Institution, Washington D. C., USA.

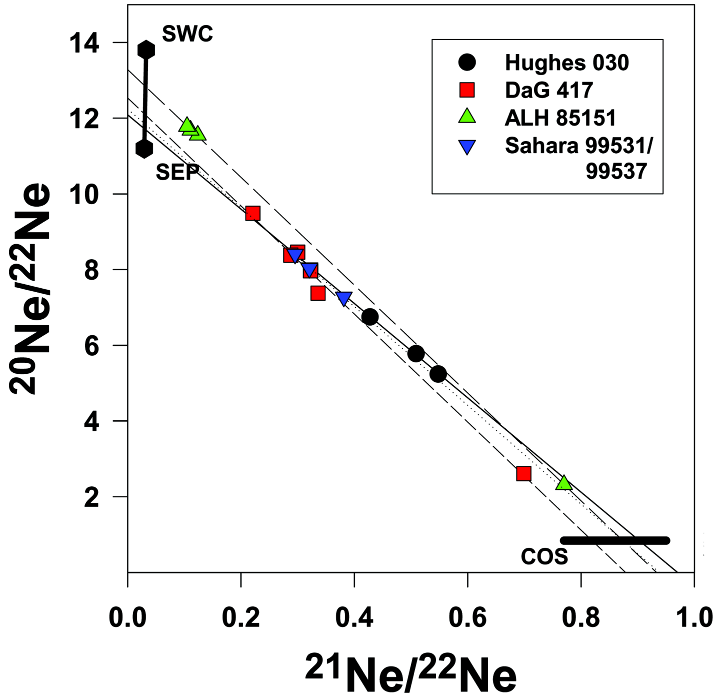

Fig. 2. Ne three-isotope plot with end-member values of solar wind (SWC), solar energetic particles (SEP) and the range of cosmogenic neon (COS). Shown are the results of measured samples of four regolith breccias with large amounts of solar gas. The shielding parameter of cosmogenic $(^{22}Ne/^{21}Ne)_c$ is obtained from regression lines and a $(^{20}Ne/^{22}Ne)_c = 0.82$.

and obtain $P(38)_R = 0.0412 \cdot 10^{-8} cm^3 STP^{38}Ar/gMa$. This production rate is considerably lower than that calculated according to Leya et al. (2000), which results in values between 0.06 and 0.07 (in units of $10^{-8} cm^3 STP^{38}Ar/gMa$).

For calculating $^3$He, $^{21}$Ne, and $^{38}$Ar exposure ages of R chondrites, the shielding Equations 1 to 3 for L chondrites and the production rates $P(3)_R$, $P(21)_R$, and $(P38)_R$ as given above are used.

### *Exposure Ages*

Concentrations of cosmogenic $^3$He, $^{21}$Ne, $^{38}$Ar and $(^{22}Ne/^{21}Ne)_c$ ratios are given in Table 3. Included are earlier published values from our laboratory (Bischoff et al. 1994) as well as measurements of R chondrites by Nagao et al. (1999). Table 3 also includes measured $^{20}$Ne/$^{22}$Ne ratios, which indicate meteorites with solar gases where this ratio is substantially larger than 1. For the meteorites containing solar gas, ALH 85151, DaG 417, Hughes 030, and Sahara 99531/37, the cosmogenic $^{22}$Ne/$^{21}$Ne ratios are determined from a fit of measured samples in three-isotope plots of Ne, assuming $(^{20}Ne/^{22}Ne)_c = 0.82$ (Fig. 2). For other R chondrites with solar gas and only one measurement, a mean value of $(^{22}Ne/^{21}Ne)_c = 1.11$ is used.

For samples with high shielding characterized by $(^{22}Ne/^{21}Ne)_c < 1.08$, the relation between the $^{21}$Ne production rate and $(^{22}Ne/^{21}Ne)_c$ becomes invalid, resulting in an overestimation of the production rate (e.g., Jentsch and Schultz 1996). This may effect some of the calculated exposure ages (e.g., NWA 1583).

Exposure ages $T_3$, $T_{21}$, and $T_{38}$ are given together with a mean exposure age in Table 3. HaH 119 and NWA 1583 and 1585 have low $^4$He contents as well as a low $^3$He/$^{21}$Ne of approximately 3, suggesting loss of helium during the flight of the meteoroids (e.g., Schultz and Weber 1997). For calculating the mean exposure age, the lower $^3$He-age was not taken into account.

## DISCUSSION

### Pairing

The majority of stony meteorite falls produce several specimens because many meteoroids tend to fragment during their flight through the atmosphere. In such cases, these paired fragments distribute themselves on the ground in an ellipse-shaped strewn field. If find locations are carefully mapped, the individual pieces of one meteorite fall can be easily recognized. Find locations are given for many finds recovered from the Dar al Gani region (Libya). In cases such as these, strewn fields can be recognized if the classification of these meteorites is also known (e.g., Schlüter et al. 2002). However, for many meteorites this is not the case because the coordinates of the find locations are not given or withheld by the finder (for several Sahara samples relative coordinates are

Table 3. Radiogenic $^{40}$Ar (in $10^{-8}$cm$^3$STP/g), the measured $^{20}$Ne/$^{22}$Ne as indicator of solar gas, the cosmogenic shielding parameter $^{22}$Ne/$^{21}$Ne, and exposure ages $T_3$, $T_{21}$, and $T_{38}$ (in Ma) calculated from the cosmogenic nuclides $^3$He, $^{21}$Ne, and $^{38}$Ar, respectively.

| Meteorite | $^{40}$Ar | $^{20}$Ne/$^{22}$Ne | ($^{22}$Ne/$^{21}$Ne)$_c$ | $T_3$ | $T_{21}$ | $T_{38}$ | Mean age | References[a] |
|---|---|---|---|---|---|---|---|---|
| Acfer 217 | 5500 | 2.53 | (1.110) | 32.2 | 32.2 | 31.9 | 32.1 ± 0.2 | (a) |
| ALH 85151 | 1670 | 11.55 | 1.143 | 30.7 | 29.5 | 23.8 | | |
| | 1930 | 2.32 | 1.143 | 25.5 | 30.4 | 18.2 | | |
| | 2390 | 11.68 | 1.143 | 30.4 | 28.3 | 24.7 | | |
| | 2470 | 11.78 | 1.143 | 32.1 | 29.1 | 22.0 | | |
| | | | | | 29.3 ± 0.9 | | 27.1 ± 4.2 | |
| Asuka-881988 | 5940 | 0.79 | 1.228 | 17.6 | 24.3 | 14.6 | 19.5 ± 4.8 | (b) |
| Carlisle Lakes | 3970 | 0.86 | 1.077 | 5.3 | 7.1 | 6.4 | 6.3 ± 0.7 | (a) |
| DaG 013 | 2920 | 0.96 | 1.143 | 7.4 | 9.7 | 7.0 | 8.0 ± 1.2 | |
| DaG 417 | 6029 | 7.97 | 1.22 | 15.0 | 20.1 | 18.3 | | |
| | 8062 | 7.83 | 1.22 | 15.0 | 19.7 | 14.5 | | |
| | | | | | 19.9 ± 0.3 | | 17.1 ± 2.6 | |
| HaH 119 | 3710 | 0.87 | 1.121 | 1.6 | 2.4 | 2.2 | | |
| | 4140 | 0.88 | 1.138 | 1.5 | 2.5 | 2.2 | | |
| | 4040 | 0.88 | 1.131 | 1.5 | 2.5 | 2.7 | | |
| | | | | | 2.5 ± 0.1 | | 2.4 ± 0.2[c] | |
| Hughes 030 | 3040 | 5.24 | 1.107 | 19.6 | 44.5 | 38.1 | | |
| | 2650 | 5.78 | 1.107 | 21.1 | 44.7 | 42.4 | | |
| | 3370 | 6.75 | 1.107 | 22.0 | 43.8 | 41.3 | | |
| | | | | | 44.3 ± 0.5 | | 42.5 ± 2.5[c] | |
| LAP 02238 | 4970 | 7.81 | (1.110) | 21.4 | 25.2 | 20.6 | | |
| | 5720 | 6.41 | (1.110) | 29.7 | 23.5 | 23.3 | | |
| | | | | | 24.3 ± 1.8 | | 24.0 ± 1.5 | |
| NWA 053 | 4790 | 1.60 | (1.110) | 0.12 | 0.18 | (0.57) | | |
| | 5150 | 1.66 | (1.110) | 0.13 | 0.15 | 0.16 | | |
| | | | | | 0.17 ± 0.02 | | 0.15 ± 0.03 | |
| NWA 753 | 3470 | 0.86 | 1.081 | 11.1 | 12.8 | 9.2 | 11.0 ± 1.8 | |
| NWA 755 | 4065 | 0.86 | 1.082 | 8.4 | 10.3 | 8.4 | 9.3 ± 0.9 | |
| NWA 845 | 3830 | 0.89 | 1.077 | 8.2 | 10.5 | 8.0 | 9.3 ± 1.2 | |
| NWA 851 | 3690 | 0.89 | 1.060 | 9.3 | 10.0 | 7.8 | 8.9 ± 1.1 | |
| NWA 978 | 4645 | 1.00 | 1.110 | 8.2 | 10.5 | 8.0 | | |
| | 3375 | 1.04 | 1.120 | 8.0 | 11.1 | 8.7 | | |
| | | | | | 10.8 ± 0.4 | | 9.1 ± 1.4 | |
| NWA 1471 | 3990 | 0.83 | 1.080 | 8.2 | 8.7 | 8.3 | | |
| | 4370 | 0.85 | 1.084 | 8.3 | 9.4 | 8.7 | | |
| | | | | | 9.1 ± 0.5 | | 8.6 ± 0.5 | |
| NWA 1472 | 3335 | 0.85 | 1.076 | 10.9 | 11.3 | 9.3 | | |
| | 3040 | 0.84 | 1.078 | 10.7 | 12.4 | 10.2 | | |
| | | | | | 11.9 ± 0.8 | | 10.8 ± 1.0 | |
| NWA 1476 | 798 | 0.95 | 1.103 | 12.2 | 14.3 | 12.7 | 13.5 ± 0.8 | |
| NWA 1477 | 1542 | 0.91 | 1.094 | 11.9 | 15.0 | 10.1 | 12.6 ± 2.4 | |
| NWA 1478 | 2451 | 0.85 | 1.081 | 12.9 | 12.8 | 11.5 | | |
| | 2385 | 0.84 | 1.078 | 12.4 | 15.3 | 12.1 | | |
| | | | | | 14.1 ± 1.8 | | 12.8 ± 1.3 | |
| NWA 1566 | 7500 | 1.12 | 1.094 | 9.9 | 12.8 | 10.3 | | |
| | 4235 | 0.95 | 1.107 | 10.3 | 15.7 | 8.7 | | |
| | | | | | 14.3 ± 2.1 | | 11.2 ± 2.5 | |
| NWA 1583 | 1710 | 0.87 | 1.037 | 11.3 | 16.7 | 13.2 | | |
| | 1760 | 0.87 | 1.043 | 11.4 | 17.4 | 16.8 | | |
| | | | | | 17.1 ± 0.5 | | 14.5 ± 2.8 | |
| NWA 1585 | 89 | 0.86 | 1.085 | 1.1 | 18.3 | 31.3 | 24.4 ± 6.5[c] | |
| Ouzina | 8450 | 0.86 | 1.201 | 7.3 | 7.9 | 7.6 | 7.6 ± 0.2 | |
| PRE 95404 | 5050 | 12.32 | (1.110) | 10.2 | 11.5 | (3.2) | | |
| | 5770 | 12.42 | (1.110) | 8.4 | 15.6 | 16.2 | | |

Table 3. *Continued.* Radiogenic $^{40}$Ar (in $10^{-8}$cm$^3$STP/g), the measured $^{20}$Ne/$^{22}$Ne as indicator of solar gas, the cosmogenic shielding parameter $^{22}$Ne/$^{21}$Ne, and exposure ages $T_3$, $T_{21}$, and $T_{38}$ (in Ma) calculated from the cosmogenic nuclides $^3$He, $^{21}$Ne, and $^{38}$Ar, respectively.

| Meteorite | $^{40}$Ar | $^{20}$Ne/$^{22}$Ne | ($^{22}$Ne/$^{21}$Ne)$_c$ | $T_3$ | $T_{21}$ | $T_{38}$ | Mean age | References[a] |
|---|---|---|---|---|---|---|---|---|
| PRE 95410 | 6760 | 12.42 | (1.110) | 12.7 | 15.4 | 21.6 | | |
| | 5820 | 12.38 | (1.110) | 17.7 | 21.2 | 11.6 | | |
| | 6580 | 12.43 | (1.110) | 17.9 | 18.0 | 23.8 | | |
| PRE 95411 | 5220 | 11.47 | (1.110) | 5.7 | 16.9 | 17.8 | | |
| | 5900 | 11.76 | (1.110) | 15.0 | 22.7 | 17.5 | | |
| | 5565 | 11.46 | (1.110) | 8.9 | 16.4 | 11.0 | | |
| PRE 95412 | 6235 | 12.38 | (1.110) | 9.9 | 15.4 | 11.0 | | |
| | 6320 | 12.35 | (1.110) | 5.4 | 15.3 | 22.0 | | |
| | 6100 | 12.17 | (1.110) | 7.4 | 12.7 | 7.9 | | |
| | | | | | 15.8 ± 3.3 | | 15.3 ± 4.0[c] | |
| PCA 91002 | 4640 | 11.09 | (1.110) | 31.1 | 40.5 | 25.8 | | |
| PCA 91241 | 4160 | 11.16 | (1.110) | 30.3 | 41.6 | 27.9 | | |
| | | | | | 41.1 ± 0.8 | | 32.8 ± 6.6 | |
| Rumuruti | 7890 | 3.41 | (1.110) | 16.0 | 15.5 | 15.6 | 15.7 ± 0.2 | |
| Sahara 98248 | 12830 | 1.17 | 1.297 | 16.6 | 17.0 | 17.2 | | |
| | 18190 | 1.68 | 1.277 | 16.5 | 14.5 | 18.8 | | |
| | | | | | 15.8 ± 1.8 | | 16.8 ± 1.4 | |
| Sahara 99527 | 6200 | 0.922 | 1.092 | 23.8 | 29.2 | 22.9 | | |
| | 9186 | 1.116 | 1.085 | 21.8 | 26.3 | 24.6 | | |
| Sahara 99531 | 6623 | 8.41 | (1.110) | 18.2 | 30.5 | 26.5 | | |
| | 6020 | 8.05 | (1.110) | 26.6 | 33.8 | 27.4 | | |
| Sahara 99537 | 5737 | 8.03 | (1.110) | 25.1 | 32.1 | 31.3 | | |
| | 5327 | 7.28 | (1.110) | 24.5 | 31.7 | 24.2 | | |
| | | | | | 30.6 ± 2.6 | | 26.7 ± 4.1 | |
| Y-75302 | 5620 | 7.18 | (1.110) | 22.0 | 21.5 | 21.1 | | (b) |
| Y-791827 | 4370 | 6.89 | (1.110) | 19.0 | 23.8 | 20.1 | | (b) |
| | | | | | 22.7 ± 1.6 | | 21.3 ± 1.6 | |
| Y-793575 | 5560 | 0.81 | 1.220 | 7.3 | 8.5 | 6.5 | | |
| | 5200 | 0.80 | 1.233 | 7.2 | 7.8 | 4.6 | | |
| | | | | | 8.2 ± 0.5 | | 7.0 ± 1.3 | |
| Y-82002 | 4580 | 5.88 | (1.110) | 21.4 | 17.4 | 18.0 | 18.9 ± 2.2 | (b) |

[a] (a) Bischoff et al. (1994); (b) Nagao et al. (1998).

[c] $^{21}$Ne and $^{38}$Ar age.

given only). Pairing in particular is a major problem for NWA meteorites listed as individual meteorites. The present situation on mineral markets makes it even possible that NWA meteorites are paired with other Saharan rumurutiites like Ouzina or those from DaG.

If find locations are unknown, then the confirmation of paired samples is difficult, especially for those of similar petrologic type and shock classification. In such cases, the confirmation of the pairing of samples must involve laboratory tests; the determination of cosmogenic nuclides is a promising approach. In some cases, however, even with such measurements, a clear decision concerning pairing cannot be made.

Kallemeyn (1998) suggested the pairing of four PRE samples on the basis of similar chemical compositions and the close proximities of their finds. Indeed, their similar noble gas records confirm this. Satterwhite and Mason (1993) suggested pairing of PCA 91002 and 91241. As both specimens have similar amounts of solar gases as well as similar exposure ages, pairing of these stones is corroborated.

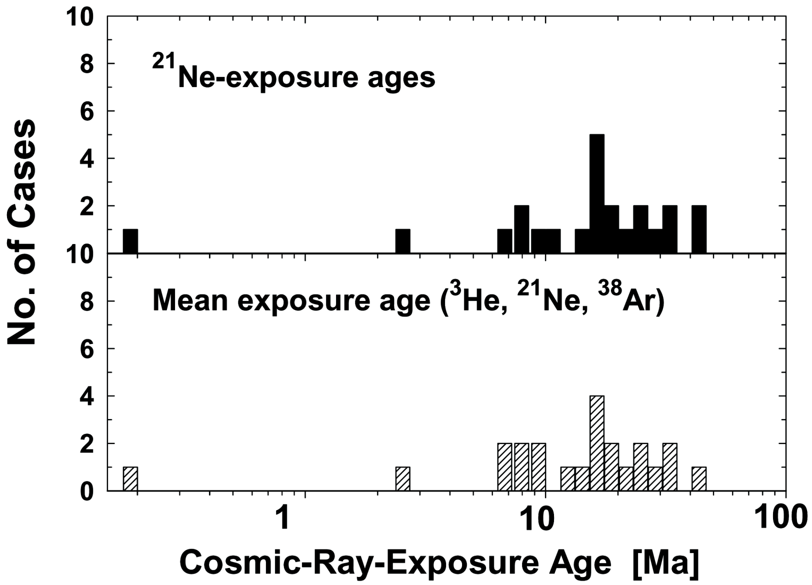

Fig. 3. A comparison of pairing corrected exposure ages calculated from cosmogenic $^{21}$Ne alone and the mean of $^3$He-, $^{21}$Ne-, and $^{38}$Ar-ages. The bar width corresponds to the uncertainty of age, which is estimated to 15%.

Based on the noble gases, Nagao et al. (1999) also concluded that Y-75302 and Y-791827 are probably paired.

The noble gas record of the 23 meteorite specimens from North Africa (Acfer, DaG, HaH, NWA, Ouzina, and Sahara) must be discussed in more detail concerning pairings. Here the exposure age, the shielding parameter $^{22}$Ne/$^{21}$Ne, the presence of solar gases, the concentration of radiogenic $^4$He and $^{40}$Ar, the loss of cosmogenic $^3$He, and the classification parameters are considered.

Trusting the relative find coordinates of Sahara 99527/31/37 as given by Grossman (2000) (all three stones were found within <1 km distance), pairing is suggested. Sahara 99527 has no solar gases but a similar exposure age to Sahara 99531 and 99537, which have large amounts of solar gas. It is therefore assumed that all three specimens are paired. The small sample of Sahara 99527 probably represents a solar gas-free inclusion of this regolithic breccia.

Sahara 98248 has a shorter exposure age of about 17 Ma and a rather large $^{22}$Ne/$^{21}$Ne of about 1.29, indicating a small preatmospheric mass. This meteorite is probably not paired with any of those under discussion.

HaH 119 and NWA 053 are not paired with any other measured meteorite because their exposure ages of 2.4 and 0.2 Ma, respectively, do not match any other R chondrite from the Sahara. Also, DaG 417 can be excluded from further pairing discussions because of the presence of solar gases but a different exposure age.

Except for NWA 053, NWA 1585 (classified as an R5 chondrite and with very low concentrations of radiogenic $^4$He and $^{40}$Ar) and NWA 1583, (which has a very low cosmogenic $^{22}$Ne/$^{21}$Ne of 1.04 and a $^{21}$Ne exposure age of about 17 Ma), all other NWA meteorites have similar classification parameters (except the weathering grade). However, a closer inspection reveals two separate groups:

1. NWA 753, 1472, 1476, 1477, 1478, and 1566
2. NWA 755, 845, 851, 978, and 1471

The mean $^4$He concentrations of group (1) and (2) are (1336 ± 65) and (1127 ± 54) × $10^{-8}$cm$^3$STP/g, respectively, and the $^{21}$Ne exposure ages are (13.7 ± 1.2) and (10.1 ± 0.7) Ma, respectively. Therefore, it is assumed that these two groups probably represent two separate meteorite showers.

Ouzina, also a meteorite from Morocco, is probably an individual fall.

Table 1 lists the proposed pairings among R chondrites. The total number of individual falls is reduced to 23.

## Regolith Breccias

Many R chondrites are breccias with a light/dark structure (e.g., Kallemeyn et al. 1996), which is sometimes obscured in desert meteorites due to limonitic staining. The presence of solar noble gases in these samples show that they are regolithic breccias. This is also observed in stony meteorites from other classes, but the percentage of gas-rich members varies. Bischoff and Schultz (2004) have shown that about 15% of all H chondrites are regolith breccias, while the percentage of solar-gas containing L, LL, and E chondrites is only about 3%, 5.5%, and 9.6%, respectively. For achondrites, 30% of the aubrites and 38% of howardites are regolith breccias. Considering the pairings discussed in the previous section, 11 out of 23 R chondrites contain solar gases and thus about 48% are regolith breccias. This is the highest percentage observed in all meteorite classes with the exception of lunar meteorites.

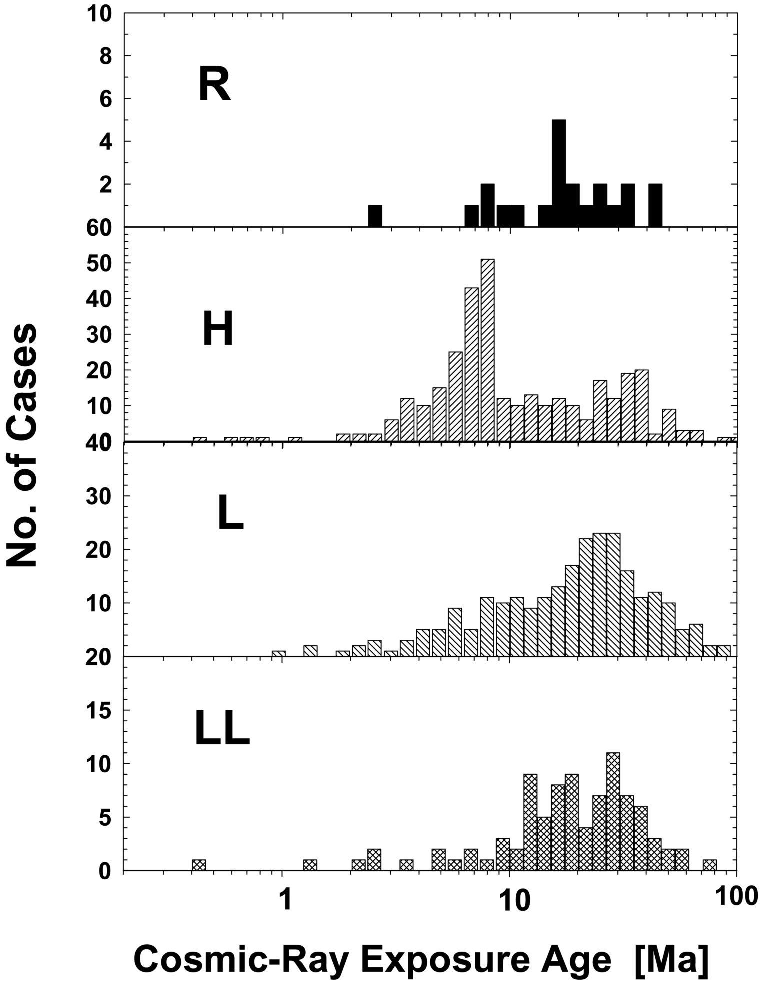

Fig. 4. Comparison of $^{21}$Ne-exposure age distributions of R chondrites and ordinary chondrites (Lipschutz and Schultz 1998, updated using data from Schultz and Franke 2004). For ordinary chondrites, only data with ($^{22}$Ne/$^{21}$Ne)$_c$ > 1.08 are used to avoid additional uncertainties of production rates due to extreme shielding.

The measured irradiation records of individual regolithic meteorites are difficult to reconcile with the general models of asteroidal regolith formation (e.g., Pedroni 1989). However, the varying percentage of regolith breccias in individual classes indicates that the surface layers of their parent bodies are different in their irradiation properties and/or gardening effects.

## Cosmic Ray Exposure Ages

Exposure ages are calculated from the three cosmogenic noble gas nuclides $^3$He ($T_3$), $^{21}$Ne ($T_{21}$), and $^{38}$Ar ($T_{38}$) (Table 3). $T_{21}$ is in many cases the most reliable age because cosmogenic $^3$He is occasionally influenced by diffusive loss (Hintenberger et al. 1966) and cosmogenic $^{38}$Ar has proven to be difficult to deduce due to high concentrations of trapped gas. In the case of R chondrites, the high amount of solar gases in many of these meteorites causes additional uncertainties. In Fig. 3, the distributions of $^{21}$Ne-exposure ages $T_{21}$ and the mean of $T_3$, $T_{21}$, and $T_{38}$ are compared. $T_{21}$ is in most cases somewhat higher with a difference in mean values of approximately 8%. For a comparison of exposure age histograms, this difference is not significant because the estimated uncertainties of the exposure ages are about 15%.

The majority of stony meteorites have cosmic ray exposure ages between 5 and 50 Ma. Exposure ages less than 1 Ma are rare (e.g., Marti and Graf 1992; Wieler and Graf 2001). This distribution is explained by a model assuming that most stony meteoroids accumulate the major part of their stable cosmogenic nuclides within the main asteroid belt before the meteoroids enter a resonance and are brought to Earth within a few million years (Gladman et al. 1997; Morbidelli and Gladman 1998). Only a small number of meteorites are rather rapidly delivered from the main asteroid belt or produced from parent bodies already on Earth-crossing orbits (Patzer et al. 1999). NWA 053 is such a meteorite, with an exceptionally low exposure age of <0.2 Ma.

A comparison of exposure age distributions of R, H, L,

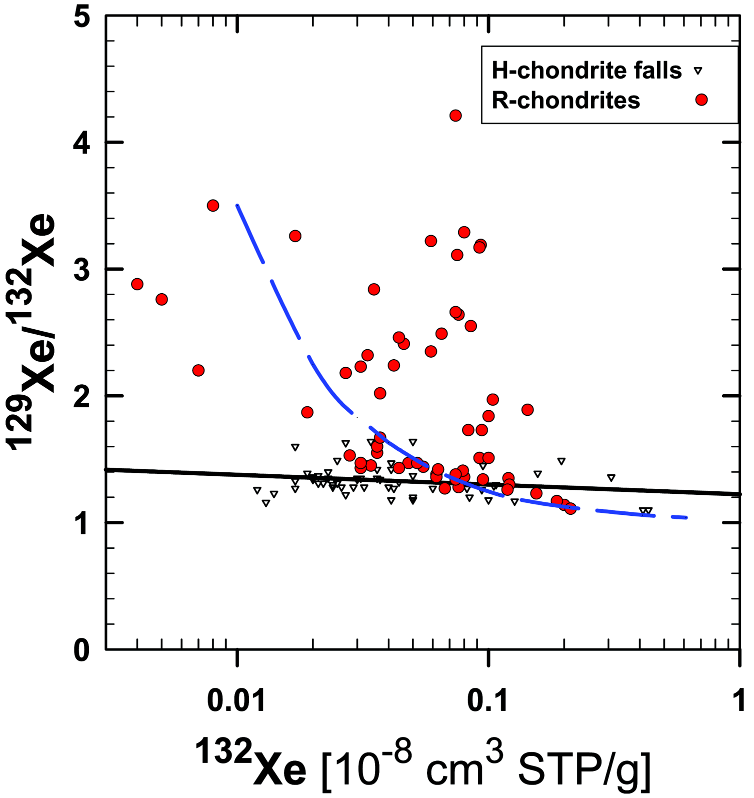

Fig. 5. A comparison of $^{129}Xe/^{132}Xe$ as a function of $^{132}Xe$ concentrations in H chondrite falls and R chondrites. The H chondrites show the $^{129}Xe/^{132}Xe$ values in a rather narrow range of 1.35 ± 0.20 (Schultz et al. 1990). The R chondrites, however, exhibit larger values. For desert meteorites, weathering will lower the $^{129}Xe/^{132}Xe$. This is indicated by the dashed line, which shows the effect of increasing addition of atmospheric Xe of a meteorite originally containing $1 \times 10^{-10}$cm$^3$STP/g $^{132}Xe$ with $^{129}Xe/^{132}Xe = 3.5$.

and LL chondrites is given in Fig. 4. For ordinary chondrites, the $^{21}Ne$-ages are evaluated from the data collection of Schultz and Franke (2004). To avoid possible additional uncertainties in the production rate of $^{21}Ne$ due to corrections for high shielding, these diagrams only include data with $^{22}Ne/^{21}Ne > 1.08$.

For H group chondrites, the common cluster at about 7 Ma dominates the distribution and approximately 54% have exposure ages less than 10 Ma. However, only 23% of L chondrites and 16% of LL chondrites have exposure ages <10 Ma. The exposure ages of R chondrites are between 0.2 and 42 Ma falling well in the range of the other chondrites. However, the distributions look different if major breakup events are concerned. With only 23 different R chondrite ages available, a discussion about possible age cluster is speculative, but six R chondrites fall into a range of 16.6 ± 1.1 Ma and may suggest a common breakup event on their parent body.

### $^{129}$Xe

Weber and Schultz (1995, 1998a) noted that several R chondrites have ratios $^{129}Xe/^{132}Xe > 2$. Figure 5 shows the $^{129}Xe/^{132}Xe$ ratio of all R chondrite bulk samples measurements as a function of the concentration of trapped $^{132}Xe$. For comparison, data of H3 and H4 chondrite falls are also plotted (Schultz et al. 1990). While the $^{129}Xe/^{132}Xe$ ratios of H chondrites have a small range of 1.35 ± 0.20 and are independent from the amount of trapped Xe, many samples of R chondrites have elevated $^{129}Xe/^{132}Xe$ ratios. There is also a clustering along the H chondrite line, but this is at least partly due to the fact that many of the desert meteorites contain some atmospheric Xe with a $^{129}Xe/^{132}Xe = 0.98$, which would lower the measured value. The influence of such atmospheric contamination is shown in Fig. 5. The decrease of $^{129}Xe/^{132}Xe$ with increasing atmospheric contribution of an original sample with a $^{132}Xe$ concentration of $1 \times 10^{-10}$ cm$^3$STP/g and a $^{129}Xe/^{132}Xe = 3.5$ is shown as a dashed line.

The higher $^{129}Xe/^{132}Xe$ ratios in R chondrites are probably due to relative higher concentrations of now extinct $^{129}I$ compared to H chondrites that contain metal, because iodine is located in the silicate phase and increased metal contents reduce its concentration in bulk samples.

### Weathering Effects and Noble Gas Concentrations

Most meteorites recovered from hot deserts have terrestrial ages of several thousand years. During this time,

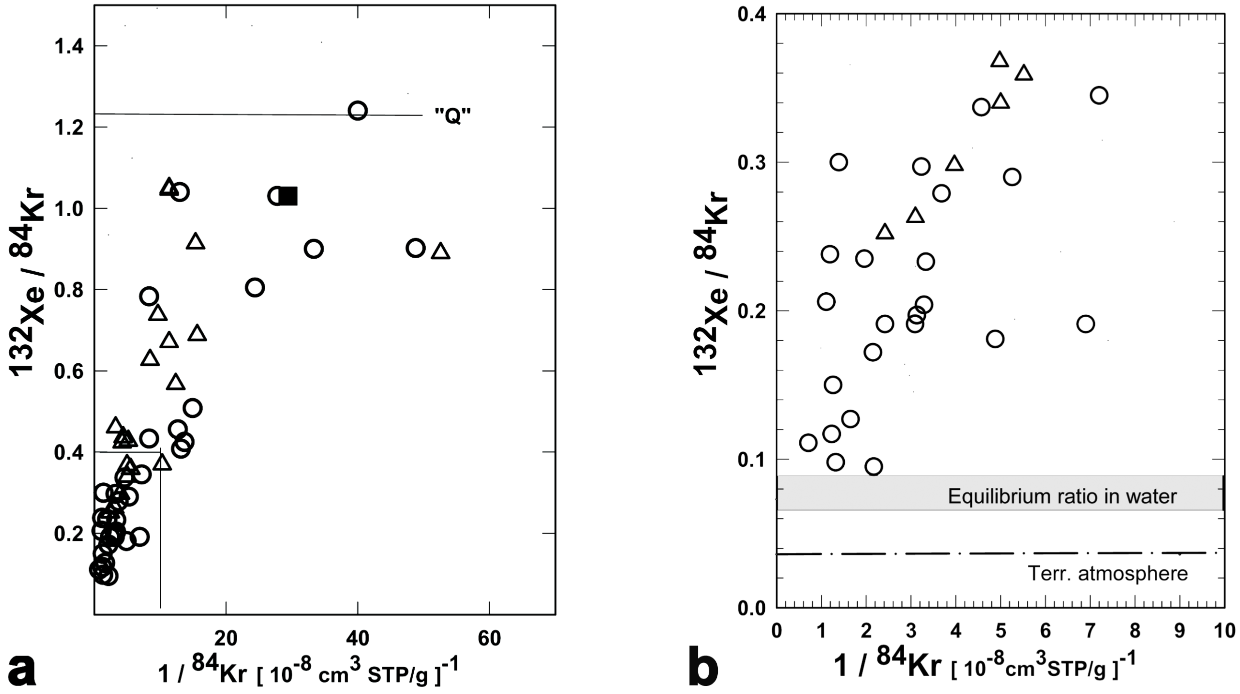

Fig. 6. a) $^{132}$Xe/$^{84}$Kr versus 1/$^{84}$Kr in all individual R chondrite samples from hot deserts (circles), Antarctica (triangles), and Rumuruti (square). Heavily weathered stones, mostly from hot deserts, with large amounts of atmospheric contamination have low $^{132}$Xe/$^{84}$Kr ratios. Shown is also the ratio of the planetary component Q. b) Enlargement of the inset box in (a). The range of observed equilibrium concentrations of $^{132}$Xe/$^{84}$Kr in water and that of the terrestrial atmosphere. The highly contaminated meteorites approach the water value. This could be due to the incorporation of the gases into the meteorites via dissolved gases in water or by a fractionation of atmospheric gas during adsorption.

terrestrial weathering products are built within the meteorite and heavy noble gases from the terrestrial atmosphere are also incorporated. This terrestrial contribution is mainly seen in the Kr concentrations because the $^{84}$Kr/$^{132}$Xe ratio in trapped meteoritic gases (Q) is around unity, while that of the atmosphere is 28. Scherer et al. (1994) studied the trapped noble gases in chondrites from hot deserts and Antarctica and concluded that this component probably was transported into the meteorite via water, because the measured elemental ratios approach the range of that found in water.

A similar observation is made for R chondrites (Figs. 6a and 6b). For meteorites with large concentrations of $^{84}$Kr (small 1/$^{84}$Kr), the $^{84}$Kr/$^{132}$Xe values approach the range of equilibrium ratios in water (Kipfer et al. 2002) but not that of the terrestrial atmosphere. However, this could also be due to the fractionation of terrestrial gas during incorporation, favouring the adsorption of Xe. Because R chondrites contain almost no metal, the oxidation of metal to hydroxides is not the main cause of terrestrial atmospheric gases in these meteorites. It should be also noted that Antarctic meteorites are generally less weathered and, consequently, these rocks contain less trapped atmosphere.

## Thermal History

Dixon et al. (2003) have studied the chronology and thermal history of four R chondrites (Carlisle Lakes, Rumuruti, Acfer 217, and PCA 91002) using $^{39}$Ar-$^{40}$Ar ages. Interpretation of these results is complicated due to the brecciated nature of three of these meteorites. The observed ages are between about 4.3 and 4.5 Ga and are therefore older than Ar-Ar ages of most shocked ordinary chondrites.

The $^{40}$Ar concentration of all our measurements is given in Table 3. Because many of these rocks are found in hot deserts, weathering products contain adsorbed atmospheric argon, and only part of the measured $^{40}$Ar is of radiogenic origin. The calculation of conventional K-Ar ages is thus not meaningful, but our data indicate that most R chondrite material was not exposed to a recent thermal event that caused severe loss of radiogenic argon.

Generally, low $^{4}$He and $^{40}$Ar concentrations are likely due to recent thermal events on the parent body. NWA 1585 has a very low $^{40}$Ar concentration of about $9 \times 10^{-7}$cm$^3$STP/g, combined with a similarly low $^{4}$He concentration. However, this meteorite has also a very low $^{3}$He exposure age compared to those calculated from $^{21}$Ne and $^{38}$Ar. This indicates that NWA 1585 suffered significant solar heating after ejection from the parent body due to an orbit with small perihelia distance (e.g., Schultz and Weber 1997).

## CONCLUSIONS

Due to many new finds in hot deserts and Antarctica, the small group of rumurutiites consists now of at least 23 individual falls. Within this group, several pairings have been detected in particular among the North African samples.

About 50% of all members of this group are regolith breccias, as demonstrated by the presence of incorporated solar gases. This is the highest percentage among all other groups of chondrites or achondrites. The distribution of exposure ages is similar to those of L or LL chondrites, but a cluster around 16.6 Ma suggests a major breakup event at this time. The heavy noble gases Kr and Xe are affected by the adsorption of atmospheric gases in terrestrial weathering products. However, for many samples, relatively high $^{129}$Xe/$^{132}$Xe ratios are observed.

Within 25 years, this group has developed from an individual sample (Carlisle Lakes) to a new well-characterized set of more than 23 members. With many new meteorites recovered every year from Antarctica and hot desert regions, it is likely that not only more R chondrites but also material from other new interplanetary bodies are sampled.

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