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Comparison of cosmic-ray exposure ages and trapped noble gases in chondrule and matrix samples of ordinary, enstatite, and carbonaceous chondrites

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Abstract–We performed a comprehensive study of the He, Ne, and Ar isotopic abundances and of the chemical composition of bulk material and components of the H chondrites Dhajala, Bath, Cullison, Grove Mountains 98004, Nadiabondi, Ogi, and Zag, of the L chondrites Grassland, Northwest Africa 055, Pavlograd, and Ladder Creek, of the E chondrite Indarch, and of the C chondrites Hammadah al Hamra 288, Acfer 059, and Allende. We discuss a procedure and necessary assumptions for the partitioning of measured data into cosmogenic, radiogenic, implanted, and indigenous noble gas components. For stone meteorites, we derive a cosmogenic ratio ^{20}Ne/^{22}Ne of 0.80 ± 0.03 and a trapped solar ^{4}He/^{3}He ratio of 3310 ± 130 using our own and literature data. Chondrules and matrix from nine meteorites were analyzed. Data from Dhajala chondrules suggest that some of these may have experienced precompaction irradiation by cosmic rays. The other chondrules and matrix samples yield consistent cosmic-ray exposure (CRE) ages within experimental errors. Some CRE ages of some of the investigated meteorites fall into clusters typically observed for the respective meteorite groups. Only Bath's CRE age falls on the 7 Ma double-peak of H chondrites, while Ogi's fits the 22 Ma peak. The studied chondrules contain trapped ^{20}Ne and ^{36}Ar concentrations in the range of 10^{-6}–10^{-9} cm^3 STP/g. In most chondrules, trapped Ar is of type Q (ordinary chondritic Ar), which suggests that this component is indigenous to the chondrule precursor material. The history of the Cullison chondrite is special in several respects: large fractions of both CR-produced ^{3}He and of radiogenic ^{4}He were lost during or after parent body breakup, in the latter case possibly by solar heating at small perihelion distances. Furthermore, one of the matrix samples contains constituents with a regolith history on the parent body before compaction. It also contains trapped Ne with a ^{20}Ne/^{22}Ne ratio of 15.5 ± 0.5, apparently fractionated solar Ne.

INTRODUCTION

This work continues a systematic investigation of the noble gas inventory of chondritic constituents, and of chondrules in particular. This study will provide complementary information on parent body evolution and on the precompaction history of chondrules (Polnau et al. 1999; Polnau et al. 2001). We did not find suitable chondrules in all meteorites included in this study; however, we present all data, because they provide useful comparisons with contradicting literature data and basic information in cases where noble gases were previously not analyzed. Previous studies have shown that excess spallation concentrations from pre-irradiation can preferentially be observed in chondrites with short exposure ages (Polnau et al. 2001). However, pre-irradiation histories of individual chondrules may differ and chondrule-melting processes were operative over currently unknown time scales. We include in this work some individual chondrules from different classes of chondrites.

For each sample studied in this work, we calculate a cosmic-ray exposure (CRE) age based on the cosmogenic noble gas concentrations and appropriate production rates. The abundances of the relevant target elements for the production of the cosmogenic noble gases were determined for most of the samples. Helium, Ne, and Ar isotopic abundances in some gas-rich meteorites allow us to determine the isotopic ratios of the solar type gases in bulk chondrites. In particular, ^{4}He/^{3}He and ^{20}Ne/^{22}Ne ratios differ from ratios reported in the solar wind (SW) (Geiss et al. 2004). Knowing these ratios in bulk chondrites is important for partitioning the different noble gas components: implanted solar, trapped or indigenous Q type (e.g., OC-Xe for ordinary chondrites) (Lavielle and Marti 1992), cosmogenic, and radiogenic. Thus, an added overview for the adopted isotopic ratios of He, Ne, and Ar of the different components in chondrites appears useful.

It is not a priori clear whether a meteorite contains solar or Q type trapped gases. The proportions of these components can only be derived with proper assumptions for the isotopic ratios in mixtures of solar and Q type gases. Therefore, we discuss a procedure for the evaluation of the noble gas components in chondrites where solar and Q type gases are present.

INVESTIGATED SAMPLES

Table 1 lists the samples investigated in this work, their sources, and specific reasons for selection. Bulk noble gas data already exist in the literature for many meteorites studied here (Schultz and Franke 2004), but in all but two cases either no chondrules were analyzed or the results of the earlier studies yield contradicting CRE ages. The two cases where chondrule data have been reported are Dhajala (Gopalan et al. 1977 and Fredriksson et al. 1985) and Allende (Vogel et al. 2004). For Dhajala, Gopalan et al. (1977) obtained agreement within experimental errors between the CRE ages of bulk and chondrules based on ^{21}Ne and ^{38}Ar. The reason we selected Dhajala for this work is that considerable differences exist among the reported CRE ages. For Allende samples listed in Schultz and Franke (2004), we calculate average ^{3}He and ^{21}Ne concentrations of 7.8 and 1.84×10^{-8} cm^3 STP/g for bulk and matrix samples, respectively, whereas the average concentrations in chondrules are higher by 15% and 30%, respectively. We decided to investigate the matrix/chondrule differences more thoroughly by deriving noble gas production rates and CRE ages for individual matrix separates and chondrules using measured target element concentrations. No noble gas data on chondrules exist for all other meteorites studied here. Furthermore, for Bath, Nadiabondi, Pavlograd, and Indarch, large differences in the reported CRE ages exist and we wanted to clarify the situation. Two meteorites, Northwest Africa (NWA) 005 and Hammadah al Hamra (HaH) 280, have not been studied before. Schultz and Franke (2004) report our preliminary data (Lorenzetti et al. 2004; personal communication).

Nadiabondi

This meteorite consists of a single mass of 3.665 kg recovered shortly after the fall in 1956 and sent to the Natural History Museum in Paris. Later, approximately 1000 smaller fragments with a combined mass of 11.5 kg were collected during several expeditions to the fall site in 1997–1999 (Heinlein 1999). The matrix and chondrule separates of sample #2370 studied here were given to Kurt Marti (UCSD) in 1980 by Paul Pellas (NHM, Paris). These separates yield concentrations of cosmogenic noble gases similar to those published by Zähringer (1960) and Kirsten et al. (1963). Sample #2659 was obtained by Rainer Wieler (ETH, Zürich) in 1988, also from Paul Pellas. Some data are cited as private communication by Schultz and Franke (2004). We obtained a split of sample #2659 from Rainer Wieler.

The concentrations of the cosmogenic noble gases in sample #2370 are about a factor of three higher than those in sample #2659. On the other hand, trapped ^{36}Ar in sample #2370 is a factor of about three lower than in sample #2659. According to the classification by Marti (1967) sample #2370 corresponds to a type 5 chondrite and sample #2659 to a type 4 chondrite. As both samples were obtained before more recent collections (1997–1999), they originate from the main mass of 3.665 kg. Either this meteorite is brecciated with some clasts showing pre-irradiation histories or a mislabeling has occurred.

Pavlograd

Our sample of Pavlograd (L6) with the label "Bachmut (L6)" is from the Natural History Museum in Vienna, where chondrule J2659 was separated. Preliminary data for "Bachmut" separates, cited as Lorenzetti et al. (2004), are reported by Schultz and Franke (2004) and the concentrations of cosmogenic noble gases are about a factor of three higher than those in the Bachmut bulk samples studied by Hintenberger et al. (1965), Zähringer (1968), and Ganapathy and Anders (1970). The latter authors also studied bulk samples of Pavlograd (L6) and reported concentrations of cosmogenic noble gases that are a factor of three higher than those of Bachmut. They state that a mixup of samples from Bachmut (fall 1814) and Pavlograd (fall 1826), both collected in the Ukraine, could have occurred. Therefore, the preliminary data (Lorenzetti et al. 2004) listed for "Bachmut" in Schultz and Franke (2004) and the data reported here apparently concern the L(6) chondrite Pavlograd.

EXPERIMENTAL PROCEDURE AND RESULTS

Chondrule Separation

The matrix sample and individual chondrules of Dhajala, Nadiabondi sample #2370, and Allende (except for chondrules A38 and SHE) were prepared at the University of California in San Diego. Bath and Indarch were obtained from the Field Museum of Chicago, but the chondrules were separated in Bern. The Bath sample was crushed and the matrix and chondrules were obtained by handpicking. The

Table 1. Investigated chondrites.

Meteorite	Type	Fall/find	Recovered mass (kg)	Reason for selection	CRE age from literature in Ma (Reference)	Source of sample
Dhajala	H3.8	Fall 1/28/1976	45	CRE age matrix and 3 chondrules	4.6(1), 7(2), 5.5(3),14.5(23), 4.2(31)	Univ. of California, San Diego
Bath	H4	Fall 8/29/1892	21	CRE age matrix/chondrules	7.62(4), 7.46(5), 0.75(6), 5.6(28), 5.5(29), 7.9(31)	Field Museum, Chicago
Cullison	H4	Find 1911	10	CRE age matrix/chondrules, complex exposure history	1.7(7), 1.22(8), 1.1(9), 1.64(31)	Smithsonian Inst., Washington
GRV 98004	H5	Find 1999	0.155	CRE age matrix/chondrules	0.052(10)	Inst. Geochem. Guangzhou, China
Nadiabondi sample #2370	H5	Fall 7/27/1956	3.665	Check CRE age, comparison matrix and 2 chondrules	67(32), 60(69), 65(31) see text	Nat. Hist. Museum, Paris
Nadiabondi sample #2659	H4	Fall 7/27/1956	3.665	Check CRE age, comparison matrix/chondr.	20(11), 20.3(31) see text	Nat. Hist. Museum, Paris
Ogi	H6	Fall 6/8/1741	14.2	Check CRE age	19(12), 34(13), 23.5(31)	Nat. Hist. Museum, London
Zag	H3–6	Fall 8/5/1998	175	CRE age matrix/chondrules	5(14), 5.6(15), 4.3(16), 66(17)	J. Nauber, Zürich
Grassland	L 4	Find 1964	4.4	CRE age of magn.and non-magn. silicates	7.5(18), 8.8(19)	American Meteorite Lab., Denver, CO
NWA 055	L4	Find 1998	42	Determination of CRE age	21.9(31)	J. Nauber, Zürich
Pavlograd	L6	Fall 5/19/1826	40	Check CRE age CRE age matrix/chondrule	54(20), 54(33), 54.5 (31) see text	Nat. Hist. Museum, Vienna
Ladder Creek	L6	Find 1937	35.1	CRE age matrix/chondrules	0.89(7), 0.95(8), 0.7(9), 0.87(21), 0.98(22), 0.97(31)	American Meteorite Lab., Denver, CO
Indarch	EH4	Fall 4/7/1891	27	CRE age matrix/chondrules	6.5(6), 16.2(24), 11.6(25), 16.3(26), 14.7(27), 11.4(31)	Field Museum, Chicago
Hammadah al Hamra 280	CK4	Find 2000	26.5	Determination of CRE age	4.7(31)	M. Friebel and S. Haberer, Germany
Acfer 059	CR2	Find 1989	0.281	CRE age matrix/chondrules	Paired Acfer 097: 5.8(30) Paired El Djouf 001: 6.0(30) 8.8(31)	Museum für Naturkunde, Berlin
Allende	CV 3	Fall 2/8/1969	~2000	CRE age matrix and 5 chondrules	See text	Univ. of California, San Diego

References: (1) Evans et al. (1982), (2) Gopalan et al. (1976), (3) Gopalan et al. (1977), (4) Leya et al. (2001), (5) Graf et al. (2001), (6) calculated from Kirsten et al. (1963), (7) Hintenberger et al. (1964), (8) Cressy and Bogard (1976), (9) Herzog et al. (1997), (10) Lorenzetti et al. (2003), (11) calculated from data of Wieler (1996), in Schultz and Franke (2004), (12) calculated from data of Padia et al. (1984), (13) Takaoka et al. (1989), (14) calculated from data of Wieler et al. (1999), (15) Murty and Mahajan (2002), (16) Whitby et al. (2000), (17) asteroid regolith preexposure time (Whitby et al. 2000), (18) Zähringer (1968), (19) Polnau et al. (2001), (20) calculated from data of Ganapathy and Anders (1970), (21) Srinivasan (1977), (22) Zähringer (1966), (23) Vogt et al. (1992), (24) Crabb and Anders (1981), (25) Patzer et al. (2001), (26) Schaeffer et al. (1965), (27) Zähringer (1962), (28) Ganapathy and Anders (1973), (29) Hintenberger et al. (1965), (30) Bischoff et al. (1973), (31) calculated from data of Lorenzetti et al. (2004), in Schultz and Franke (2004), (32) Zähringer and Gentner (1960), (33) calculated from data of Vinogradov and Zadorozhnyi (1964).

sample of Indarch was cut into slices 2 mm thick and the matrix and chondrule material was obtained with a 0.9 mm dentist drill. The Cullison sample was obtained from the Smithsonian Institution in Washington, D.C. The chondrule material was prepared by a dental drill. The study of Grassland is a continuation of the work on this meteorite by Polnau et al. (2001). Magnetic separations were performed to further investigate the observation in previous work, where the magnetic chondrules showed the strongest evidence for precompaction exposure. A bulk sample was separated, using a hand magnet, into an Fe/Ni- and a silicate fraction.The density separations for the silicate fraction were performed using sodium polytungstate. Only about 2% of the bulk sample had density of <3 g/cm^3. The density separations were followed by a separation into magnetic and nonmagnetic fractions using a hand magnet. The large Pavlograd (L6) chondrule J2659 and the Allende chondrules A38 and SHE were supplied by Gero Kurat (Natural History Museum, Vienna). The matrix/chondrule separation for Ladder Creek was performed by us by handpicking and the matrix/chondrule samples were obtained from Ansgar Greshake (Museum für Naturkunde, Berlin). Finally, no chondrules were separated from Grove Mountains (GRV) 98004, Ogi, Zag, NWA 055, and HaH 280 either because no sufficiently large chondrules were found or because the CRE ages were considered to be too high for a determination of a precompaction exposure age.

Noble Gas Analyses

All samples were heated in vacuum at 90 °C for several days in the storage arm of the extraction system to remove adsorbed terrestrial atmospheric gases. The noble gases were extracted in a single step by RF induction heating at 1700 °C and measured in our system B mass spectrometer. The technical details, blank, and background corrections are described by Eugster et al. (1993). The results are given in Table 2.

Chemical Analyses

For the chemical analyses, aliquots were taken of samples used for the noble gas measurements. The digestion of the samples was performed using concentrated high-purity HF, $HClO_4$, and HNO_3. For complete dissolution, the samples were heated by microwave excitation in Teflon pressure bombs. The concentrations of the target elements relevant for our work were measured either by inductively coupled plasma–optical emission spectroscopy or by inductively coupled plasma mass spectrometry. BHVO-1 and BCR-1 standard samples were analyzed as reference material; good agreement with literature data was obtained. Silicon was not measured but calculated under the assumption that all elements, except for iron and sulfur, are present as their oxides. All S was assumed to be in FeS. Of the remaining Fe, two-thirds is found as metal and one-third as Fe_2O_3. With the same assumptions for BHVO-1 and BCR-1, we get for SiO_2 values of 48.2% and 58.5%, which is in reasonable agreement with the literature values of 49.9% and 54.3%, respectively.

Table 3 gives the concentrations of the elements, with typical experimental errors of ±10% (2σ). Except where indicated, these samples were analyzed by us, and in several cases data represent averages of duplicate measurements. Small sample sizes, in particular for some of the chondrules, account for the relatively large experimental uncertainties. For some meteorites we observe significant differences in chemical composition between matrix and chondrule samples. For example, chondrules show low Fe abundances in Dhajala, Bath, Nadiabondi, Pavlograd, Ladder Creek, Indarch, Acfer 059, and Allende (except for chondrule A1). Low Fe abundances and correspondingly high Si- and/or Mg concentrations are observed in most of these meteorites. The chondrule A1 of Allende shows about the same Fe abundance as the matrix in contrast to other chondrule samples.

CALCULATION OF NOBLE GAS COMPONENTS

The isotopic abundances of He, Ne, and Ar in chondrites are mixtures of cosmogenic (c), radiogenic (r), and trapped (tr) components. For the calculation of CRE ages based only on stable noble gas nuclides, of ^{4}He and ^{40}Ar gas retention ages, and of the abundances of the trapped noble gases, the measured data have to be partitioned into three components. Certain assumptions have to be made for their quantitative assessment.

The signatures of the trapped noble gases in a chondritic sample are not a priori clear: they typically represent mixtures of implanted solar gases and of primitive (Q type) trapped or indigenous gases. In the separation procedure described below, we do not consider other minor trapped gas components such as Ne-E because their contribution to total Ne is negligibly small.

Isotopic Composition of Solar and Q Type Noble Gases

Table 4 gives the generally adopted isotopic ratios of He, Ne, and Ar in the different trapped and cosmogenic components: for solar type gases (Wieler 2002a), for Q gases (Ott 2002), and for cosmogenic gases (Wieler 2002b).

We attempt here to further characterize the observed solar type He and Ne isotopic composition in some of the meteorites. To do this we use two approaches: 1) we calculate from the most gas-rich meteorites (^{4}He × 10^{-3} cm^3 STP/g) in the compilation of Schultz and Franke (2004) the ^{4}He/^{3}He ratios after correction of cosmogenic ^{3}He, based on CRE ages given in the original literature. The resulting ratios are listed in Table 5. An average solar ^{4}He/^{3}He ratio of 3310 ± 130 is

Table 2. Results of He, Ne, and Ar measurements.

Meteorite (type) collection no.	Sample type and weight (mg) of analyzed sample	^{4}He	^{20}Ne	^{40}Ar	^{4}He/^{3}He	^{20}Ne/^{22}Ne	^{22}Ne/^{21}Ne	^{36}Ar/^{38}Ar	^{40}Ar/^{36}Ar
			10^{-8} cm^{3} STP/g						
H chondrites									
Dhajala (H3.8)	Matrix (20.8)	1270	2.21	4990	169	1.128	1.125	5.08	203
BE–752	Chondrule 1 (20.1) nm	1690	2.46	19200	253	0.908	1.077	2.68	8879
	Chondrule 2 (14.3) nm	1940	10.5	20100	279	3.189	1.298	3.08	11,300
	Chondrule 3 (11.0) wm	1550	3.96	5050	197	1.486	1.151	3.76	1900
Bath (H4)	Matrix (19.8)	1140	2.11	4980	104	0.850	1.050	1.84	4020
BE–721	Chondrules (20.3)	n.d.	n. d.	8830	n. d.	n. d.	n. d.	1.25	14,750
Cullison (H4)	Matrix 1 (9.9)	266	1.15	1890	392	1.489	1.122	5.06	454
BE–4	Matrix 2 I (7.1)	310	20.3	1970	460	10.33	2.863	5.38	499
	Matrix 2 II (31.3)	290	1.24	1650	438	1.614	1.133	4.96	504
	Matrix A (30.9)	311	1.06	1730	447	1.405	1.110	4.82	485
	Chondrules (5.1)	343	1.25	2290	392	1.454	1.126	4.36	1089
	Fe, Ni (51.5)	209	0.90	973	342	2.088	1.227	4.73	348
GRV 98004,2 (H5)	Bulk (53.4)	1430	0.0682	6270	15640	2.500	1.390	5.83	6780
BE–697									
Nadiabondi (H5)	Matrix (20.2)	1980	21.7	8330	18.8	0.872	1.129	1.27	1760
Sample # 2370	Chondrule 1 (14.6) sm	2230	31.0	9730	19.0	1.110	1.148	1.00	2660
	Chondrule 2 (9.7) sm	1710	26.2	11900	15.5	0.895	1.131	0.92	3260
Nadiabondi (H4)	Bulk (22.9)	1420	11.2	8130	36.4	1.527	1.202	4.14	680
Sample # 2659									
Ogi (H6)	Bulk (21.4)	1740	6.06	7060	47.1	0.920	1.180	1.14	5100
BE–712									
Zag (H3–6)	Bulk (31.4)	1250	3.50	6640	172	1.675	1.133	2.56	5540
BE–695	Light phase								
L chondrites									
Grassland (L4)	<3 g/cm^{3}, mag (40.0)	6280	18.3	10680	572	4.74	1.70	4.82	614
BE–343	<3 g/cm^{3}, nm (42.3)	5460	15.3	10020	496	4.04	1.59	4.54	940
	>3 g/cm^{3}, mag (41.5)	7790	24.1	6280	484	4.39	1.62	4.37	842
	>3 g/cm^{3}, nm(40.7)	6610	20.0	6630	386	3.69	1.48	3.96	1240
	Fe,Ni (41.2)	9910	15.9	6750	408	3.73	1.49	4.50	830
NWA 055 (L4)	Bulk (20.3)	978	49.5	3440	32.2	3.96	1.51	2.88	624
BE–723									
Pavlograd (L6)	Matrix (20.1)	781	18.9	5070	8.40	1.069	1.138	0.84	1910
BE–581	Chondrule J2689 (11.8)	1900	29.2	7770	18.8	1.208	1.171	0.90	2670
Ladder Creek (L6)	Matrix (21.4)	660	0.34	3370	437	0.900	1.20	3.83	8800
BE–137	Chondrules (22.3)	813	0.58	5100	481	0.990	1.20	3.13	32,500
E chondrite									
Indarch (EH4)	Matrix (20.2)	552	4.6	6260	36.4	1.01	1.12	3.67	1078
BE–722	Chondrules (19.9)	524	5.87	3940	30.8	0.97	1.11	4.16	811

Table 2. *Continued.* Results of He, Ne, and Ar measurements.

Meteorite (type) collection no.	Sample type and weight (mg) of analyzed sample	^{4}He	^{20}Ne	^{40}Ar	^{4}He/^{3}He	^{20}Ne/^{22}Ne	^{22}Ne/^{21}Ne	^{36}Ar/^{38}Ar	^{40}Ar/^{36}Ar
		10^{-8} cm^{3} STP/g							
C chondrites									
HaH 280 (CK4)	Bulk (20.1)	995	1.75	1980	152	0.89	1.06	1.91	2650
BE–710									
Acfer 059 (CR2)	Matrix (20.2)	84,500	235	576	2816	11.14	8.62	5.31	2.9
BE–760	Chondrules (20.4)	28,600	74.3	330	2398	9.43	4.44	4.68	4.48
Allende (CV3)	Matrix (30.2)	3420	5.86	5480	370	2.105	1.317	4.82	357
BE–761	Chondrule A1 (42.0) wm	2190	2.43	1940	239	0.954	1.079	2.97	1488
	Chondrule B1 (20.6) nm	3950	2.71	8760	447	1.046	1.141	3.86	3709
	Chondrule K100(20.5) nm	4760	3.02	1950	458	0.939	1.087	1.79	1414
	Chondrule A38 (41.3) nm	2790	2.86	5500	311	0.937	1.080	2.81	4650
	Chondrule SHE (40.3) nm	3480	2.87	6310	398	0.970	1.082	2.73	4050
Typical experimental error (2σ mean)		4%	4%	4%	3%	2%	1%	2%	3%

mag = magnetic; nm = nonmagnetic; sm = strongly magnetic; wm = weakly magnetic.

Table 3. Concentration of elements[a] relevant for this work (wt%).

		Na	Mg	Al	Si	S	K	Ca	Cr	Mn	Fe
H chondrites											
Dhajala	Matrix	0.54	21.1	1.06	11.0	2.0[d]	0.11	1.26	0.37[d]	0.41	41.1
(H 3.8)	Chondrule 1	0.64[d]	17.8	1.89	25.8	2.0[d]	0.29	2.02	0.37[d]	0.23[d]	3.9
	Chondrule 2	0.64[d]	14.5	1.28	27.2	2.0[d]	0.29	1.40	0.37[d]	0.23[d]	7.2
	Chondrule 3	0.64[d]	10.3	0.66	30.5	2.0[d]	0.29	0.77	0.37[d]	0.23[d]	10.4
Bath (H4)	Matrix	0.55	11.6	0.91	15.7	2.0[d]	0.08	1.07	0.34	0.21	32.0
	Chondrules	0.88	19.6	1.45	20.5	1.5	0.14	2.87	0.36	0.36	12.0
Cullison	Matrix	0.64[d]	13.8	1.02	26.3	2.0[d]	0.04	1.44	0.37[d]	0.23[d]	10.6
(H4)	Chondrules	0.64[d]	18.0	1.24	21.7	2.0[d]	0.05	1.32	0.37[d]	0.23[d]	10.6
Nadiabondi	Matrix	0.64[d]	16.2	1.00	9.6	2.0[d]	0.10	1.21	0.37[d]	0.48	35.7
(H5)	Chondrule 1	0.64[d]	16.0	1.21	23.9	2.0[d]	0.11	2.28	0.37[d]	0.23[d]	10.8
Sample # 2370	Chondrule 2	0.64[d]	14.5	1.19	26.8	2.0[d]	0.09	1.93	0.37[d]	0.23[d]	9.2
L chondrites											
Pavlograd (L6)	Matrix	0.62	16.5	1.08	15.5	2.2[d]	0.08	1.04	0.39[d]	0.54	25.9
	Chondrule	0.876[e]	15.4	1.27	24.6	2.2[d]	0.149[e]	1.99	0.39[d]	0.26[d]	11.2
Ladder	Matrix	0.68	15.7	1.50	16.4	2.2[d]	0.11	1.54	0.34	0.29	24.0
Creek (L6)	Chondrules	1.14	22.5	1.94	14.5	2.2[d]	0.16	2.02	0.82	0.39	17.8
E chondrite											
Indarch	Matrix	0.92	12.3	0.87	14.0	5.8[d]	0.10	0.77	0.36	0.28	36.0
(EH4)	Chondrules	0.95	16.4	1.09	22.2	5.8[d]	0.06	1.54	0.34	0.22	15.0
C chondrites											
Acfer 059	Matrix	0.104[b]	13.2	1.32	20.3	2.2[d]	0.024	2.02	0.37[b]	0.17[b]	23.8
(CR2)	Chondrules	0.104[b]	4.8	11.6	26.3	2.2[d]	0.026	1.40	0.37[b]	0.17[b]	3.8
	Bulk	0.104[b]	13.4[b]	1.17[b]	20.7	2.2[d]	0.05	1.26[b]	0.37[b]	0.17[b]	24.6[b]
HaH 280	Bulk	0.32[c]	14.8[c]	1.61[c]	19.0	2.2[d]	0.028[c]	1.54	0.37[c]	0.15[c]	23.6[c]
(CK4)											
Allende	Matrix	0.33[d]	17.9	3.66	10.6	2.2[d]	0.038	1.9[d]	0.36[d]	0.14[d]	23.6
(CV3)	Chondrule A1	0.33[d]	17.4	1.62	16.8	2.2[d]	0.024	1.69	0.36[d]	0.14[d]	23.1
	Chondrule B1	0.33[d]	24.0	2.06	15.0	2.2[d]	0.16	2.46	0.36[d]	0.28	8.4
	Chondrule K100	0.66	25.0	3.45	11.1	2.2[d]	0.02	4.18	0.36[d]	0.14[d]	16.8
	Chondrule A38	0.444	21.4	2.30	21.9	2.2[d]	0.08	2.77	0.36[d]	0.14[d]	5.1
	Chondrule SHE	0.33[d]	22.8	2.67	23.1	2.2[d]	0.16	3.14	0.36[d]	0.14[d]	5.3

Typical Ti concentrations of 0.06% and Fe/Ni ratios of 18 (Wasson and Kallemeyn 1988) adopted. Experimental uncertainties are about ±10% (2σ).

[a] Data from this work, except where indicated. [b] Endress et al. (1994). [c] Kallemeyn et al. (1991), average values for CK chondrites. [d] Wasson and Kallemeyn (1988). [e] G. Kurat, personal communication.

Table 4. Isotopic ratios of trapped and cosmogenic He, Ne, and Ar in meteorites.

	^{4}He/^{3}He	^{20}Ne/^{22}Ne	^{22}Ne/^{21}Ne	^{36}Ar/^{38}Ar	^{40}Ar/^{36}Ar	^{4}He/^{20}Ne	^{20}Ne/^{36}Ar
Trapped gases							
Solar gas-rich metorites	3310 ± 130[a]	12.24 ± 0.30[b]	30.5 ± 0.5[d]	5.58 ± 0.03[d]	[n]	120–600[a]	47 ± 3[e]
	3100 ± 30[g]	12.16 ± 0.30[c]		5.77 ± 0.07[d]			
	3200 ± 300[m]						
Q gas in primitive meteorites	8130 ± 180[e]	10.67 ± 0.02[e]	34.0 ± 1.2[e]	5.34 ± 0.02[e]	0.00029 ± 0.00017[f]	117 ± 30[e]	0.042 ± 0.008[e]
		10.11 ± 0.02[e]					
Cosmogenic gases							
Stone meteorites	6.2 ± 0.2[h]	0.80 ± 0.03[j]	1.05–1.25[k]	~0.65[k]	0.3[l]	–	–
	6.1 ± 0.3[i]						
Iron meteorites	3.2–4.4[k]	–	–	0.58–0.65[o]	0.31[l]	–	–

[a] This work, Table 5. [b] Ngawi LL 3 chondrite bulk (Eugster et al. 1993). [c] This work, Fig. 2. [d] Solar wind in moon and meteorites (Wieler 2002a). [e] Ott (2002). [f] Dyalpur ureilite (Goebel et al. 1978). [g] This work; Fig. 1. [h] Welten et al. (2003). [i] Alexeev et al. (1998). [j] This work; see text. [k] Wieler (2002b). [l] Measured for iron meteorites by Kaiser and Zähringer (1969). For stone meteorites, the same ratio is adopted. [m] Ngawi LL3 chondrite (Eugster et al. 1993). [n] For discussion of $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{tr}$ in meteorites see Ott (2002). [o] This ratio is shielding dependent (Lavielle and Marti, personal communication).

Table 5. Solar ^{4}He/^{3}He and ^{4}He/^{20}Ne ratios[a] in ordinary and R chondrites and in the Pesyanoe aubrite. Concentrations in 10^{-8} cm^{3} STP/g.

	Measured		Cosmogenic[b]	Solar[c]	
Meteorite	^{3}He	^{4}He	^{3}He	^{4}He/^{3}He	^{4}He/^{20}Ne
Acfer 111	881	2,705,700	60	3296	580
(H3–6 chondrite)	696	2,109,300	60	3317	580
	783	2,411,670	60	3336	570
	668	2,022,220	60	3326	600
	1028	2,877,780	60	2973	540
	885	2,712,570	60	3288	540
	795	2,403,110	60	3270	560
			Average	3258	
Fayetteville	745	2,027,000	50	2917	400
(H4 chondrite)	657	2,050,000	50	3377	390
	970	3,000,000	50	3261	480
	600	2,100,000	50	3818	400
			Average	3383	
Weston	574	1,600,000	55	3083	390
(H4 chondrite)	657	2,050,000	55	3377	390
	970	3,000,000	55	3261	480
	600	2,100,000	55	3818	400
			Average	3343	
Mt. Prestrup 95404 (R chondrite)	47	1,519,000	15	3516	390
Mt. Prestrup 95410 (R chondrite)	331	1,061,000	26	3490	150
Mt. Prestrup 95411	395	1,352,000	16	3567	310
(R chondrite)	487	1,622,000	16	3444	250
	331	1,110,000	16	3524	280
			Average	3512	
ALH 85151 (R3.6 chondrite)	450	1,321,000	40	3222	240
Pesyanoe (aubrite)	426	1,068,000	80	3087	300
Average for all meteorites				3310 ± 130	
Range for all meteorites					120–600

[a] Calculated from the most solar gas-rich meteorites (^{4}He > 1,000,000 × 10^{-8} cm^{3} STP/g) measured by Schultz et al. (1972), Wieler et al. (1989), and Pedroni and Begemann (1994) and listed in Schultz and Franke (2004).

[b] As measured in samples of low ^{4}He of the respective meteorite or as calculated from the CRE age given in the original literature.

[c] Cosmogenic and radiogenic ^{4}He are neglected, cosmogenic ^{3}He and ^{20}Ne are subtracted.

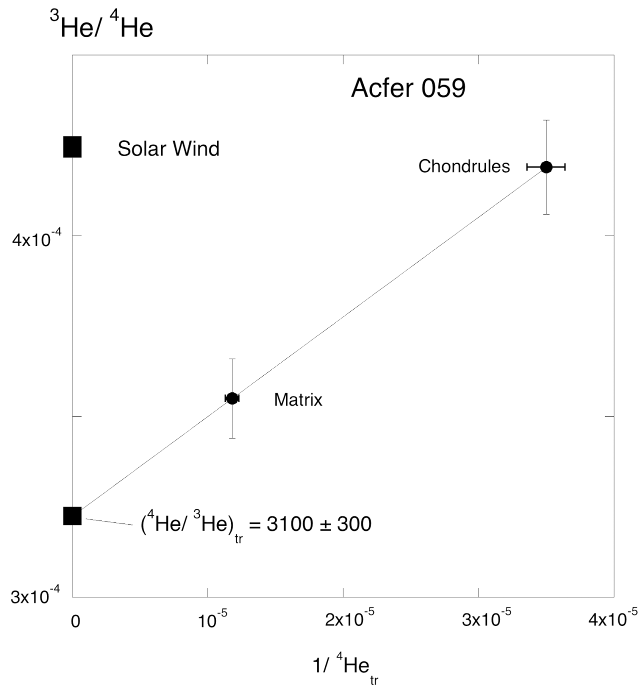

Fig. 1. ^{3}He/^{4}He versus 1/^{4}He$_{tr}$ diagram for the Acfer 059 chondrite. The ordinate intercept yields a ^{4}He/^{3}He ratio of 3100 ± 300 for the trapped solar He component. For correction of ^{4}He$_r$ and ^{4}He$_c$ see text. For comparison, He in the solar wind has ^{4}He/^{3}He = 2350 ± 50 (average for SWC foils) (Geiss et al. 2004).

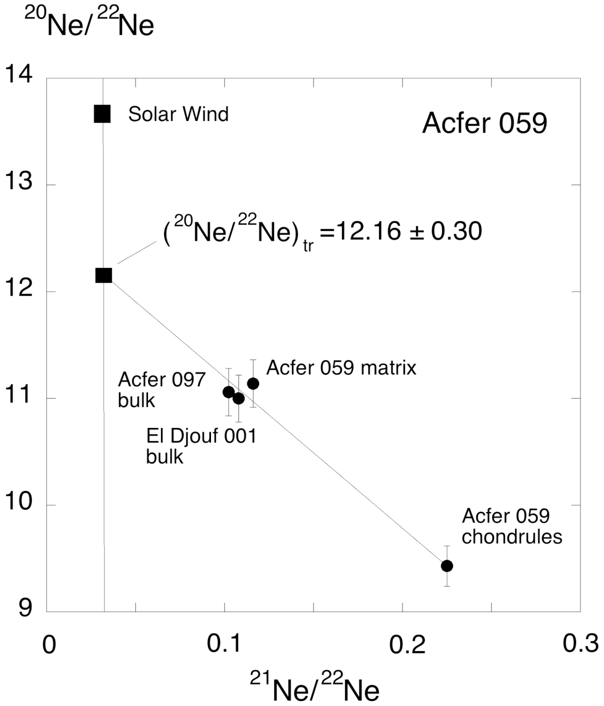

Fig. 2. ^{20}Ne/^{22}Ne versus ^{21}Ne/^{22}Ne diagram for Acfer 059 and paired Acfer 097 and El Diouf 001 (Bischoff et al. 1993). Extrapolation of the correlation line yields a ^{20}Ne/^{22}Ne ratio of 12.16 ± 0.30 for the trapped Ne component of this meteorite. The value of solar wind Ne of 13.7 ± 0.3 is from Geiss et al. (2004).

obtained. 2) The ordinate intercept of the He ratios of the gas-rich chondrite Acfer 059 (Table 2) yields a trapped ^{4}He/^{3}He ratio of 3100 ± 300 (Fig. 1). In this plot we consider ^{4}He$_c$ and ^{4}He$_r$ to be negligibly small relative to the large concentration of total ^{4}He. ^{4}He$_r$ is assumed to be mostly lost, as the K-Ar gas retention age is low (see below). Here we compare this result with that of 3200 ± 300 for the gas-rich Ngawi (LL3) chondrite (Eugster et al. 1993) using the same method. Inspecting the data in Table 5, we conclude that the ^{4}He/^{3}He ratios for trapped solar He in gas-rich meteorites are in the range of 3100–3400.

From a ^{20}Ne/^{22}Ne versus ^{21}Ne/^{22}Ne correlation for Acfer 059 and the paired chondrites Acfer 097 and El Djouf 001 (Bischoff et al. 1993) in Fig. 2 we obtain a trapped ^{20}Ne/^{22}Ne ratio of 12.16 ± 0.30, which is similar to that reported by Eugster et al. (1993) for the Ngawi chondrite (12.24 ± 0.30).

There are two reported trapped ^{36}Ar/^{38}Ar ratios for gas-rich meteorites, 5.58 ± 0.03 (Benkert et al. 1993) and 5.36 ± 0.10 (Pepin et al. 1999). Acfer 059 yields a ratio of 5.36 ± 0.10 (Fig. 3).

The ^{4}He/^{20}Ne ratio in solar gas-rich meteorites is quite variable and the compilation in Table 5 shows a range of 120–600. The depletion of He in certain meteorites may relate to diffusion loss processes. For comparison, reported SW values are 650 ± 50 and 400 ± 25, respectively (Wieler 2002a).

Cosmogenic ^{20}Ne/^{22}Ne in Chondrites

A ratio that has never been determined experimentally is that of the cosmogenic ^{20}Ne/^{22}Ne. Many workers adopt a ratio close to 0.8 without an experimental determination. We performed a thorough evaluation of this isotopic ratio. Several thousand Ne measurements for chondrites were compiled by Schultz and Franke (2004). As mentioned above, the ^{20}Ne/^{22}Ne ratio of trapped Ne in chondrites is about 12. There are about 30 chondrites in which the contribution of trapped Ne to total Ne is extremely small and that show measured ^{20}Ne/^{22}Ne ratios of <0.80. These chondrites were analyzed after 1965 and therefore the ^{20}Ne/^{22}Ne ratios are calibrated on the new atmospheric ^{20}Ne/^{22}Ne ratio. Allowing for some experimental uncertainty in measured values ≤0.80, we adopt a cosmogenic ratio ^{20}Ne/^{22}Ne in chondrites of 0.80 ± 0.03. We also find no apparent dependence of the measured ^{20}Ne/^{22}Ne ratio on cosmic ray shielding.

Determination of the Type of Trapped (Implanted and Indigenous) Gases and Calculation of the He, Ne, and Ar Components

The best distinction between solar and Q type trapped gases is observed for the ratio ^{20}Ne/^{36}Ar. This ratio is

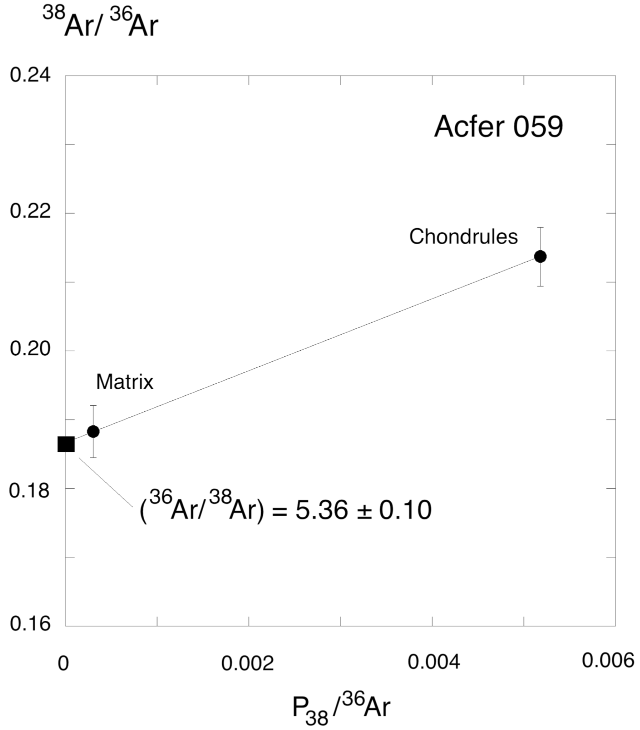

Fig. 3. ^{38}Ar/^{36}Ar versus P_{38}/^{36}Ar diagram for the Acfer 059 chondrite. The ordinate intercept yields a ^{36}Ar/^{38}Ar ratio of 5.36 ± 0.10 for the trapped component of this meteorite.

diagnostic for the proportions of solar and Q type gases that make up the trapped gases of a chondritic sample. The ratio of solar ^{20}Ne ($^{20}Ne_S$) to Q type ^{20}Ne ($^{20}Ne_Q$) and of Q type ^{36}Ar ($^{36}Ar_Q$) to solar ^{36}Ar ($^{36}Ar_S$) as a function of $(^{20}Ne^{20}Ne/^{36}Ar)_{tr}$ are given by:

$$^{20}Ne_S/^{20}Ne_Q = [(^{36}Ar/^{20}Ne)_Q \times (^{20}Ne/^{36}Ar)_{tr} - 1]/ [1 - (^{36}Ar/^{20}Ne)_S \times (^{20}Ne/^{36}Ar)_{tr} \tag{1}$$

$$^{36}Ar_Q/^{36}Ar_S = [(^{20}Ne/^{36}Ar)_S - (^{20}Ne/^{36}Ar)_{tr}]/ [(^{20}Ne/^{36}Ar)_{tr} - (^{20}Ne/^{36}Ar)_Q] \tag{2}$$

where $(^{36}Ar/^{20}Ne)_Q = 23.8$ and $(^{36}Ar/^{20}Ne)_S = 0.0213$ (Table 4).

In Fig. 4 these dependencies are shown graphically. In order to calculate the ratio $(^{20}Ne/^{36}Ar)_{tr}$, we have to proceed in an iterative way.

Step 1. Calculation of $^{20}Ne_{tr}$ in a First Approximation

We adopt $(^{20}Ne/^{22}Ne)_{tr} = 11.4$, the average of the ratios for Ne_S and Ne_Q, as given in Table 4. This value is the best choice in a first approximation, as we do not know yet what the correct value for the trapped Ne in a particular meteorite is. Furthermore, for $(^{20}Ne/^{22}Ne)_c$, we adopt 0.80 (Table 4). The concentration of $^{22}Ne_c$ is calculated from:

$$^{22}Ne_c = {}^{22}Ne_m\,[1 - (^{20}Ne/^{22}Ne)_m/(^{20}Ne/^{22}Ne)_{tr}]/ [1 - (^{20}Ne/^{22}Ne)_c/(^{20}Ne/^{22}Ne)_{tr}] \tag{3}$$

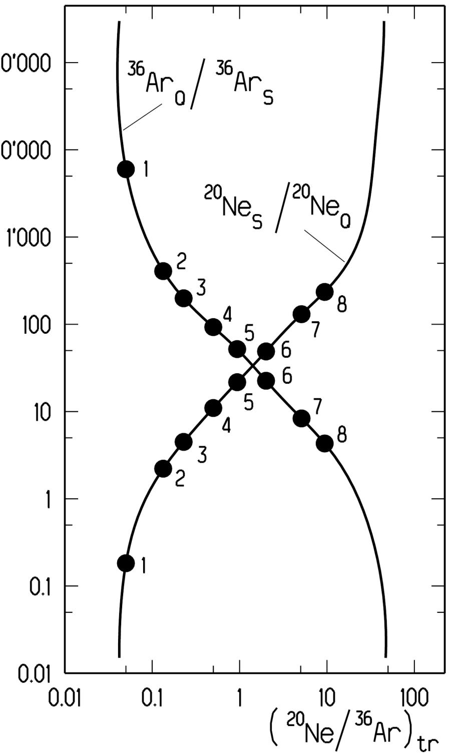

Fig. 4. Ratio of $^{20}Ne_s/^{20}Ne_Q$ and $^{36}Ar_Q/^{36}Ar_s$ as a function of the $(^{20}Ne/^{36}Ar)tr$ ratio. This graph allows us to calculate, in a first approximation, the proportions of solar (*S*) and Q type gases in a chondrite based on the $(^{20}Ne/^{36}Ar)tr$ ratio. 1 = GRV 98004 (bulk); 2 = Ladder Creek (matrix); 3 = Cullison (matrix 2II); 4 = Nadiabondi (bulk); 5 = Grassland (<3); 6 = Zag (bulk); 7 = Cullison (matrix 2I); 8 = Ogi (bulk).

where *m* stands for measured, as given in Table 2. With the above values we obtain:

$$^{22}Ne_c = {}^{22}Ne_m\,[1 - (^{20}Ne/^{22}Ne)_m/11.4]/0.9298 \tag{4}$$

$^{20}Ne_{tr}$ is then obtained from:

$$^{20}Ne_{tr} = {}^{20}Ne_m - 0.80 \times {}^{22}Ne_c \tag{5}$$

Step 2. Calculation of $^{36}Ar_{tr}$ in a First Approximation

We adopt $(^{36}Ar/^{38}Ar)_{tr} = 5.51$, that is, the average value for Ar_Q and Ar_S, as given in Table 4. For $(^{36}Ar/^{38}Ar)_c$, we adopt 0.65 (Table 4). The concentration of $^{38}Ar_c$ is calculated from:

$$^{38}Ar_c = {}^{38}Ar_m\,[1 - (^{36}Ar/^{38}Ar)_m/(^{36}Ar/^{38}Ar)_{tr}]/ [1 - (^{36}Ar/^{38}Ar)_c/(^{36}Ar/^{38}Ar)_{tr}] \tag{6}$$

or, with the above values:

$$^{38}Ar_c = {}^{38}Ar_m\,[1 - (^{36}Ar/^{38}Ar)_m/5.51]/0.882 \tag{7}$$

$^{36}Ar_{tr}$ is then obtained from:

$$^{36}Ar_{tr} = {}^{36}Ar_m - 0.65 \times {}^{38}Ar_c \tag{8}$$

The ratio $(^{20}Ne/^{36}Ar)_{tr}$ from Equations 5 and 8 is inserted into Equations 1 and 2 to calculate the mixing ratios of solar and Q type Ne and Ar.

Step 3. Calculation of the Final Values of Cosmogenic and Trapped Ne and Ar

The values for $(^{20}Ne/^{22}Ne)_{tr}$, $(^{22}Ne/^{21}Ne)_{tr}$, and $(^{36}Ar/^{38}Ar)_{tr}$, respectively, can be derived from the measured data given in Table 4, and inserted into Equations 3 and 6, respectively, to obtain the final values of $^{22}Ne_c$, $^{38}Ar_c$, $^{20}Ne_{tr}$, and $^{36}Ar_{tr}$. $^{21}Ne_c$ is calculated from:

$$^{21}Ne_c = {}^{21}Ne_m - (^{21}Ne/^{22}Ne)_{tr}\,[^{22}Ne_m - {}^{22}Ne_c] \qquad (9)$$

Step 4. Calculation of Cosmogenic, Trapped, and Radiogenic He

a) Chondrites with $^4He_m > 2000 \times 10^{-8}$ cm^3 STP/g: we assume that these chondrites contain a negligibly small contribution of $^4He_{tr}$. Thus, $^3He_{tr}$ and $^4He_{tr}$ are assumed to be 0 and $^3He_c = {}^3He_m$. For the calculation of ^4He_c, we adopt $(^4He/^3He)_c = 6.2 \pm 0.2$ (Table 4). Consequently:

$$^4He_r = {}^4He_m - {}^3He_c\,(^4He/^3He)_c \qquad (10)$$

b) Chondrites with $^4He_m > 2000 \times 10^{-8}$ cm^3 STP/g: first, the contribution of ^4He_r from U and Th decay is calculated. The upper limit of ^4He_r is obtained adopting a gas retention age of 4.56 Ga. For O and C chondrites we use 12 ppb U and 43 ppb Th and for E chondrites 9.5 ppb U and 32 ppb Th (Wasson and Kallemeyn 1988). For O and C chondrites $\leq 2000 \times 10^{-8}$ cm^3 STP/g are calculated, and for E chondrites $\leq 1600 \times 10^{-8}$ cm^3 STP/g ^4He_r are calculated. Furthermore, as mentioned above, a ratio $(^4He/^3He)_{tr} = 3310 \pm 130$ (Table 5) is adopted. ^3He_c is then obtained from:

$$^3He_c = [(^4He/^3He)_{tr}\,{}^3He_m - {}^4He_m + {}^4He_r]/$$
$$[(^4He/^3He\,)_{tr} - (^4He/^3He)_c] \qquad (11)$$

and $^4He_{tr}$ from:

$$^4He_{tr} = {}^4He_m - {}^4He_r - {}^3He_c(^4He/^3He)_c. \qquad (12)$$

Table 6 gives the He, Ne, and Ar components of the investigated meteorites. For some ratios the experimental errors are the same for all measurements; where this is not the case, they are given individually.

CRE AGES

Calculation of Production Rates

Production rates for stone meteorites must take into account both the abundances of the target elements for the production of cosmogenic noble gases and the shielding characteristics within the meteoroid. The sensing for shielding during exposure to cosmic rays can be based on the ratio $^{22}Ne/^{21}Ne$. For all meteorites for which the chemical composition was determined in this work (Table 3), we used the production rate calculation method derived by Eugster and Michel (1995). This method is appropriate for chondrule and matrix samples, as their chemical compositions differ from that of bulk chondrites. The ^{21}Ne production rate (P_{21}) formula for diogenites (Table 6 in Eugster and Michel 1995) was applied, except for the Acfer 059 chondrule sample, where the formula for eucrites was used. This sample shows ratios of Mg/Al and Mg/Si close to those of eucrites, whereas these ratios in the other samples studied in this work are closer to those in diogenites. For GRV 98004, Ogi, Zag, Grassland, and NWA 055, we adopted the method for average L chondrites and H chondrites, respectively, (Eugster 1988) because we lack chemical composition data. The cosmogenic $^{22}Ne/^{21}Ne$ ratios (Table 6) are suitable for shielding corrections ≥1.08 (Leya et al. 2001; Masarik et al. 2001), and we used a value of 1.08 whenever a ratio of <1.08 was measured. The calculated production rates are listed in Table 7.

CRE Ages

The CRE age (T) of a meteorite measures the integral time of exposure to galactic cosmic rays. In this work we calculate the CRE using three different nuclides: $T_i = C_i/P_i$, where i represents ^3He, ^{21}Ne, and ^{38}Ar. The concentrations C_i are given in Table 6 and production rates P_i in Table 7. The average values for the CRE ages, T_{av}, based on ^3He (T_3), ^{21}Ne (T_{21}), and ^{38}Ar (T_{38}) are also given in Table 7.

We show below that a loss of cosmogenic ^3He can be explored in a T_3/T_{21} versus T_4/T_{40} diagram (Fig. 5), where T_4 and T_{40} are the U,Th-^4He and ^{40}K-^{40}Ar gas retention ages, respectively. For samples with ^3He loss, as indicated by an extremely low T_3/T_{21} ratio, the T_3 ages in Table 7, given in parentheses, are not used for calculating T_{av}. This is the case for Cullison and Acfer 059, the latter not shown in Fig. 5 because no T_4 could be calculated. In the following we will discuss the CRE ages of each meteorite individually. In cases of high Cl concentrations (Indarch) or of known large mass (Allende), we are aware of the possibility that neutron-produced ^{36}Ar is present and did not calculate an ^{38}Ar age.

Dhajala

Our age for the matrix sample of 4.2 ± 0.8 Ma (Table 7) is at the low end of bulk sample ages reported by previous workers, ranging from 4.6 Ma (Evans et al. 1982) to 14–15 Ma (Vogt et al. 1992). The ages obtained by Vogt et al. (1992) were calculated based on $^{10}Be/^{21}Ne$ and $^{26}Al/^{21}Ne$. These authors also obtained different pre-atmospheric sizes of the meteorite as estimated from different radionuclides. This could indicate that the meteorite has a complex exposure history. These authors note that Dhajala had a large pre-atmospheric size. However, the numerous data compiled by

Table 6. Cosmogenic and trapped noble gases. Concentrations in 10^{-8} cm^3 STP/g.

		Cosmogenic				Trapped		
Meteorite	Sample	^{3}He	^{21}Ne	^{38}Ar	^{22}Ne/^{21}Ne	^{4}He	^{20}Ne	^{36}Ar
Dhajala	Matrix	7.5	1.74	0.27 ± 0.10	1.087 ± 0.02	–	0.70	24.4
(H3.8)	Chondrule 1	6.7	2.52	0.46 ± 0.03	1.066 ± 0.02	–	0.62	1.9
	Chondrule 2	7.0	2.25	0.28 ± 0.02	1.038 ± 0.03	–	8.41	1.6
	Chondrule 3	7.9	2.31	0.24 ± 0.02	1.085 ± 0.02	–	1.95	2.5
Bath (H4)	Matrix	11.0	2.36	0.50 ± 0.03	1.045 ± 0.02	–	0.13	0.91
	Chondrules	–	–	0.42 ± 0.03	–	–	–	0.33
Cullison	Matrix 1	0.68	0.69	0.049 ± 0.018	1.054 ± 0.02	–	0.57	4.1
(H4)	Matrix 2I	0.67	0.63	–	–	–	20.0	3.9
	Matrix 2II	0.66	0.68	0.053 ± 0.014	1.053 ± 0.02	–	0.67	3.2
	Matrix A	0.70	0.68	0.082 ± 0.017	1.049 ± 0.02	–	0.49	3.5
	Chondrules	0.88	0.76	0.101 ± 0.010	1.064 ± 0.02	–	0.60	2.0
	Fe,Ni	0.61	0.35	0.077 ± 0.013	1.092 ± 0.03	–	0.56	2.8
GRV 98004 (H5)	Bulk	0.091	0.020	–	1.154 ± 0.03	–	0.05	0.92
Nadiabondi	Matrix	105	22.0	3.24 ± 0.20	1.122 ± 0.02	–	1.9	3.2
Sample #2370	Chondrule 1	117	24.3	3.39 ± 0.20	1.118 ± 0.02	–	9.3	3.4
(H5)	Chondrule 2	110	25.9	3.74 ± 0.25	1.122 ± 0.02	–	3.0	3.7
Nadiabondi Sample #2659 (H4)	Bulk	39	6.0	0.74 ± 0.07	1.126 ± 0.02	–	5.7	11.4
Ogi (H6)	Bulk	36.9	5.58	1.09 ± 0.06	1.168 ± 0.02	–	6.1	0.68
Zag (H3-6)	Bulk	7.3	1.84	0.28 ± 0.02	1.051 ± 0.02	–	2.0	1.02
Grassland	<3, mag	9.4	2.23	0.40 ± 0.08	1.141 ± 0.03	5200 ± 1000	16.3	17.1
(L4)	<3, nm	9.7	2.35	0.40 ± 0.05	1.160 ± 0.03	4400 ± 1000	13.1	10.4
	>3, mag	14.1	3.33	0.35 ± 0.04	1.134 ± 0.03	6700 ± 1000	21.1	7.2
	>3, nm	15.5	3.62	0.40 ± 0.03	1.123 ± 0.03	5500 ± 1000	16.8	5.1
	Fe,Ni	21.6	2.82	0.20 ± 0.03	1.126 ± 0.03	8800 ± 1000	13.4	8.0
NWA 055 (L4)	Bulk	30.4	8.17	1.02 ± 0.06	1.111 ± 0.03	–	42.2	4.8
Pavlograd	Matrix	93.0	15.5	3.03 ± 0.20	1.112 ± 0.02	–	5.1	0.68
(L6)	Chondrule	101.1	20.6	3.06 ± 0.20	1.131 ± 0.02	–	10.5	0.92
Ladder Creek	Matrix	1.51	0.32	0.032 ± 0.003	1.190 ± 0.02	–	0.04	0.36
(L6)	Chondrules	1.69	0.49	0.024 ± 0.002	1.180 ± 0.02	–	0.12	0.14
Indarch	Matrix	15.2	4.06	0.56 ± 0.04	1.100 ± 0.02	–	1.0	5.4
(EH4)	Chondrules	17.0	5.45	0.29 ± 0.03	1.094 ± 0.02	–	1.1	4.7
HaH 280 (CK4)	Bulk	6.6	1.85	0.29 ± 0.02	1.051 ± 0.02	–	0.19	0.56
Acfer 059	Matrix	4.8	1.83	–	1.191 ± 0.03	83,500 ± 4000	233	198
(CR2)	Chondrules	3.6	1.58	–	1.258 ± 0.03	27,600 ± 2000	73	72
Allende	Matrix	8.5	2.10	0.35 ± 0.07	1.170 ± 0.03	–	3.89	15.1
(CV3)	Chondrule A1	8.8	2.36	0.22 ± 0.02	1.064 ± 0.02	–	0.42	1.16
	Chondrule B1	8.0	2.27	0.19 ± 0.02	1.116 ± 0.02	–	0.68	2.24
	Chondrule K100	9.3	2.96	0.58 ± 0.03	1.075 ± 0.02	–	0.48	1.00
	Chondrule A38	8.4	2.82	0.23 ± 0.02	1.068 ± 0.02	–	0.45	1.04
	Chondrule SHE	8.0	2.73	0.32 ± 0.02	1.066 ± 0.02	–	0.54	1.35
Typical experimental error (2σ mean)		4%	5%	–	–	–	5%	5%

Table 7. Production rates and CRE ages.

		Production rates (10^{-8} cm^3 STP/g, Ma)			CRE ages (Ma)			
Meteorite	Sample	P_3	P_{21}	P_{38}	T_3	T_{21}	T_{38}	T_{av}
Dhajala (H3.8)	Matrix	1.494	0.453	0.0714	5.0 ± 0.6	3.8 ± 0.6	3.8 ± 1.5	4.2 ± 0.8
	Chondrule 1	1.735	0.463	0.0533	3.9 ± 0.5	5.4 ± 0.7	8.6 ± 1.2	6.0 ± 2.6
	Chondrule 2	1.714	0.401	0.0454	4.1 ± 0.5	5.6 ± 0.7	6.2 ± 0.8	5.3 ± 1.2
	Chondrule 3	1.691	0.317	0.0374	4.7 ± 0.6	7.3 ± 0.9	6.4 ± 0.9	6.1 ± 1.4
Bath (H4)	Matrix	1.555	0.305	0.0571	7.1 ± 0.8	7.7 ± 0.9	8.8 ± 1.1	7.9 ± 1.0
	Chondrules	–	–	0.0714	–	–	5.9 ± 0.8	5.9 ± 0.8
Cullison	Matrix 1	1.692	0.383	0.0407	(0.40)	1.80 ± 0.25	1.20 ± 0.50	1.50 ± 0.30
	Matrix 2I	1.692	0.383	–	(0.40)	1.64 ± 0.25	–	1.64 ± 0.25
	Matrix 2II	1.692	0.383	0.0407	(0.39)	1.78 ± 0.25	1.30 ± 0.40	1.54 ± 0.24
	Matrix A	1.692	0.383	0.0407	(0.41)	1.78 ± 0.25	2.01 ± 0.50	1.90 ± 0.12
							Av. matrix	1.64 ± 0.25
	Chondrules	1.692	0.448	0.0386	(0.52)	1.70 ± 0.25	2.60 0.40	2.15 ± 0.45
GRV 98004 (H5)	Bulk	1.562	0.258	–	0.058 ± 0.007	0.078 ± 0.010	–	0.068 ± 0.010
Nadiabondi (H5) sample #2370	Matrix	1.514	0.294	0.0652	69.4 ± 8.0	74.8 ± 8.0	49.7 ± 7.0	65 ± 15
	Chondrule 1	1.673	0.337	0.0581	69.9 ± 8.0	72.1 ± 8.0	58.3 ± 7.0	67 ± 9
	Chondrule 2	1.682	0.315	0.0496	65.4 ± 8.0	82.2 ± 9.0	75.4 ± 9.0	74 ± 9
Nadiabondi (H4) sample #2659	Bulk	1.574	0.288	0.0487	24.8 ± 3.0	20.8 ± 2.5	15.2 ± 2.5	20.3 ± 5.0
Ogi (H6)	Bulk	1.556	0.245	0.0454	23.7 ± 3.0	22.8 ± 3.0	24.0 ± 3.0	23.5 ± 2.0
Zag (H6)	Bulk	1.593	0.357	0.0522	4.6 ± 0.5	5.2 ± 0.6	5.4 ± 0.7	5.1 ± 0.5
Grassland (L4)	<3, mag	1.599	0.292	0.0440	5.9 ± 1.0	7.6 ± 1.0	9.1 ± 1.5	7.5 ± 1.6
	<3, nm	1.591	0.271	0.0426	6.1 ± 1.0	8.7 ± 1.0	9.4 ± 1.5	8.1 ± 2.0
	>3, mag	1.602	0.300	0.0445	8.8 ± 1.0	11.1 ± 1.3	7.9 ± 1.1	9.3 ± 1.8
	>3, nm	1.607	0.314	0.0453	9.6 ± 1.1	11.5 ± 1.4	8.8 ± 1.1	10.0 ± 1.5
							Average	8.7 ± 1.3
NWA 055 (L4)	Bulk	1.612	0.331	0.0461	18.9 2.0	24.7 ± 3.0	22.1 ± 3.0	21.9 ± 3.0
Pavlograd (L6)	Matrix	1.579	0.331	0.0523	58.9 ± 7.0	46.8 ± 7.0	57.9 ± 8.0	54.5 ± 8.0
	Chondrule	1.666	0.309	0.0546	60.7 ± 7.0	66.7 ± 8.0	56.0 ± 7.0	61.1 ± 6.0
Ladder Creek (L6)	Matrix	1.559	0.229	0.0585	0.97 ± 0.11	1.40 ± 0.16	0.55 ± 0.08	0.97 ± 0.40
	Chondrules	1.599	0.315	0.0555	1.06 ± 0.12	1.56 ± 0.20	0.43 ± 0.07	1.02 ± 0.60
Indarch (EH4)	Matrix	1.521	0.286	–	10.0 ± 1.1	14.2 ± 1.6	–	12.1 ± 2.5
	Chondrules	1.658	0.393	–	10.2 ± 1.1	13.9 ± 1.8	–	12.0 ± 2.5
HaH 280 (CK4)	Bulk	1.610	0.383	0.0553	4.1 ± 0.5	4.8 ± 0.6	5.2 ± 0.7	4.7 ± 0.6
Acfer 059 (CR2)	Matrix	1.567	0.209	–	(3.1 ± 0.4)	8.8 ± 1.0	–	8.8 ± 1.0
	Chondrules	1.653	0.200	–	(2.2 ± 0.3)	7.9 ± 1.0	–	7.9 ± 1.0
Allende (CV3)	Matrix	1.571	0.272	–	5.4 ± 0.6	7.7 ± 1.0	–	6.6 ± 1.2
	Chondrule A1	1.613	0.425	–	5.5 ± 0.6	5.6 ± 0.7	–	5.6 ± 1.0
	Chondrule B1	1.690	0.444	–	4.7 ± 0.5	5.1 ± 0.6	–	4.9 ± 1.0
	Chondrule K100	1.653	0.563	–	5.6 ± 0.6	5.3 ± 0.6	–	5.4 ± 1.0
	Chondrule A38	1.728	0.522	–	4.9 ± 0.6	5.4 ± 0.7	–	5.2 ± 1.0
	Chondrule SHE	1.727	0.557	–	4.6 ± 0.5	4.9 ± 0.6	–	4.8 ± 1.0

Schultz and Franke (2004) for this meteorite show a considerable spread in cosmogenic noble gas concentrations and ^{22}Ne/^{21}Ne ratios, indicating that samples from various depths within the meteorite were studied, making the determination of the production rates and CRE age difficult. The three chondrules yield average CRE ages of 6.0, 5.3, and 6.1 Ma, respectively, but if we exclude the ^{3}He ages in our list, the CRE ages of chondrules are 7.2, 6.4, 7.1 Ma, respectively. Since measured ^{3}He/^{21}Ne ratios are very low, we cannot exclude the possibility that ^{3}He from the pre-irradiation was lost at the time of compaction into the meteorite. This would not affect the ^{4}He concentration. Varying pre-irradiations of chondrules and of fragments thereof may also explain in part the very large range of reported CRE ages in the literature. We conclude that all chondrules of this meteorite appear to have been pre-irradiated. This conclusion and the presence of trapped Ne in the chondrule 2 will be discussed below.

Bath

For this meteorite, we obtain a matrix CRE age of 7.9 ± 1.0 Ma, which is similar to the CRE data reported in the determinations by Leya et al. (2001) and Graf et al. (2001), whereas the older data show considerably lower ages (Table 1). For our chondrule separates we could only calculate a ^{38}Ar age of 5.9 ± 0.8 Ma, slightly lower than the matrix age, which is outside experimental errors. Since only one CRE age was determined for the chondrules, we do not consider this difference to be significant.

Cullison

As mentioned above, we did not calculate a T_3 age. The average CRE age of 1.64 ± 0.35 Ma based on seven determinations is within the range of 1.1–1.7 Ma obtained by other workers for bulk samples (Table 1). Our chondrule separates yield a T_{21} of 1.70 ± 0.25 Ma, which is close to that of our matrix samples. Also, the average CRE age of 2.15 ± 0.45 Ma of the chondrules is not outside experimental errors, but little higher than the average matrix age. For this meteorite we also measured an Fe/Ni fraction. The noble gas production rates of pure Fe/Ni differ strongly from those of silicate material, but we have doubts about the purity of the Fe/Ni separates and have not calculated a CRE age. Herzog et al. (1997) interpret their Cullison data to represent a complex exposure history with a stage of low production rates for 5–15 Ma, followed by an irradiation lasting 0.4–0.5 Ma with high production rates. Perhaps such a recent break-up event was responsible for the ^{3}He loss.

GRV 98004

In our earlier study (Lorenzetti et al. 2003), we obtained a CRE age of 0.052 ± 0.008 Ma, which makes this chondrite a suitable candidate for the study of a chondrule precompaction exposure. In this work we tried to prepare chondrule separates, but were not successful in finding sufficient chondrule material for studying the matrix/chondrule relationship. The excess of cosmogenic ^{38}Ar was too low to calculate a T_{38}; the average value for T_3 and T_{21} of 0.068 ± 0.010 Ma is close to that of our earlier work.

Nadiabondi

In the Investigated Samples section, we outlined that the two samples #2370 and #2659 studied in this work originate from the same mass at the MNH in Paris. The resulting CRE ages of the two samples as well as the concentrations of trapped Ar differ strongly. Sample #2370 yields a CRE age of 65 ± 15 Ma (matrix) and a concentration of ^{36}Ar$_{tr}$ of 3.2 × 10^{-8} cm^{3} STP/g, consistent with a H5 classification (Marti 1967). From the data of Zähringer (1960) and of Kirsten et al. (1963) we calculate CRE ages of 67 and 60 Ma, respectively, and a ^{36}Ar$_{tr}$ concentration of about 1.5 × 10^{-8} cm^{3} STP/g. On the other hand, sample #2659 shows a CRE age of 20.3 ± 5.0 Ma and ^{36}Ar$_{tr}$ = 11.4 × 10^{-8} cm^{3} STP/g, which corresponds to an H4 classification. This sample (from Rainer Wieler) yields data that agree with their results (Schultz and Franke 2004), within errors. We conclude that either Nadiabondi contains type 4 and type 5 material, and the type 5 material was pre-exposed by cosmic rays, or alternatively, the differences between the two samples are due to erroneous labelling.

Chondrule 1 and chondrule 2 of Nadiabondi #2370 investigated here yield consistent results. The six determinations of CRE ages give an average CRE age of 70 ± 4 Ma for the two chondrules, which is in agreement with the matrix age of 65 ± 15 Ma.

Ogi

Two disagreeing CRE ages are reported in the literature (Table 1) and the present age of 23.5 ± 2.0 Ma lies between the previous results. This age falls on a CRE age cluster of the H chondrites of 22 Ma (see below). Insufficient chondrule material was found to study the matrix/chondrule relation.

Zag

We obtain a CRE age of 5.1 ± 0.5 Ma, and the three individual ages agree well. Earlier results (Table 1) are also around 5 Ma. This meteorite would be suited for a study of a possible chondrule pre-exposure, but no chondrules were found.

Grassland

This meteorite was studied by Polnau et al. (2001) who found (based on T_3, T_{21}, and T_{38}) consistently higher CRE ages for the chondrules compared to the matrix, although just outside experimental errors. Here we continued this investigation by analyzing magnetic and non-magnetic silicates with densities <3 g/cm^{3} (mainly feldspar) and >3 g/cm^{3} (mainly pyroxene). These samples were available from the relatively difficult separation of the chondrules from the matrix (Polnau et al. 2001). We did not observe a systematic age difference between the various separates, although there is a tendency for slightly lower ages of the <3 g/cm^3 fraction. The average CRE age for all samples of Grassland studied here is 8.7 ± 1.3 Ma, which is in good agreement with the ages previously reported (Table 1).

NWA 055

No previous noble gas analyses for this meteorite exist. We obtained a CRE age of 21.9 ± 3.0 Ma that falls on a broad cluster in the range of 20–30 Ma (see below). Having determined a relatively high age, we consider NWA 055 to not be well-suited for the study of a possible difference between matrix and chondrules.

Pavlograd

Our concentrations of the cosmogenic noble gases are in good agreement with those of the bulk samples reported by Vinogradov and Zadorozhnyi (1964) and by Ganapathy and Anders (1970). T_{av} for the chondrule is 61.1 ± 6.0 Ma, which is about 12% higher than that of our matrix sample, but the difference is not outside experimental errors.

Ladder Creek

For this meteorite, CRE ages in the range of 0.7 to 0.98 Ma have been reported (Table 1). This young age makes Ladder Creek suited for the study of a possible chondrule precompaction age. Our matrix age of 0.97 ± 0.40 Ma agrees with previously determined ages, and the chondrules yield essentially the same value.

Indarch

The CRE ages obtained by other workers lie within a rather large range between 6.5 and 16.3 Ma. We investigated this chondrite in order to clarify the situation and to investigate the matrix/chondrule relationship. Our matrix CRE age is 12.1 ± 2.5 Ma, and a chondrule age of 12.0 ± 2.5 Ma is well within this range.

HaH 280

The compilation by Schultz and Franke (2004) lists preliminary noble gas data obtained by us. We report a CRE age of 4.7 ± 0.6 Ma for the bulk sample and consistent data for the three different methods. We did not find chondrule material to permit a noble gas analysis.

Acfer 059

Previously obtained noble gas data only exist for two paired specimens, except for our own preliminary results on Acfer 059. Bischoff et al. (1993) reported a CRE age for Acfer 097 and El Djouf 001 of 5.8 Ma and 6.0 Ma, respectively. The determination of the CRE age for these meteorites is problematic: ^{3}He shows strong diffusion loss and we do not use T_3 ages. Also, the three specimens contain quite large concentrations of trapped Ne and Ar, and calculations of the $(^{22}Ne/^{21}Ne)_c$ ratio and of the $^{38}Ar_c$ are not reliable. If we use the ^{21}Ne production rate adopted for Acfer 059 to calculate the CRE ages of Acfer 097 and El Djouf 001, we obtain 9.8 and 9.4 Ma, respectively, similar to our T_{av} of 8.8 ± 1.0 Ma for Acfer 059 matrix. The CRE age of the Acfer 059 chondrules is 7.9 ± 1.0 Ma and agrees within experimental errors.

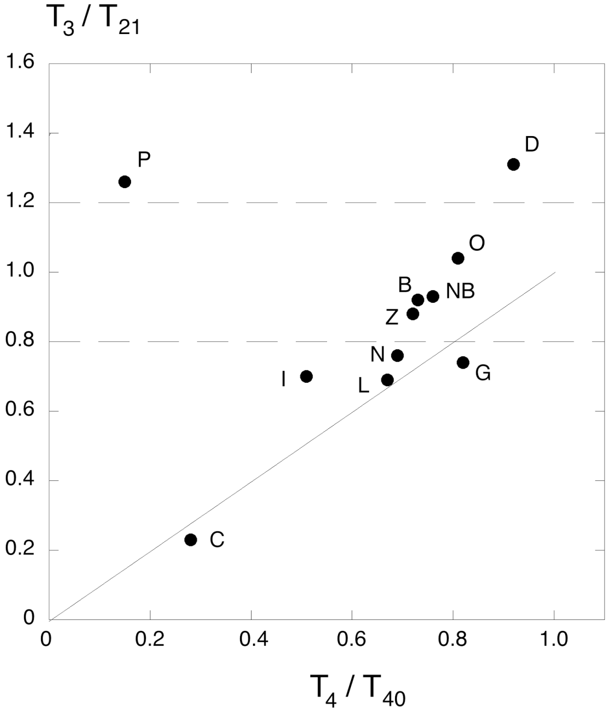

Fig. 5. Ratio of CRE ages T_3/T_{21} versus ratio of gas retention ages T_4/T_{40} for the investigated chondrites. Meteorites following the line with slope 1 lost ^3He_c and ^4He_r during the time they were exposed to CRs. Meteorites lying between the horizontal broken lines and showing a ratio $T_4/T_{40} < 1$ lost ^{4}He before their exposure to CRs, that is, at or before breakup of their parent body. D = Dhajala; B = Bath; C = Cullison; G = GRV 98004; NB = Nadia Bondi; O = Ogi; Z = Zag; N = NWA 055; P = Pavlograd; L = Ladder Creek; I = Indarch; H = HaH 280.

Allende

Numerous analyses were performed for Allende; the noble gas data are given in Schultz and Franke (2004). There are 17 analyses for ^{3}He in bulk or matrix samples with an average ^{3}He concentration of 7.8×10^{-8} cm^3 STP/g and 14 analyses of chondrules that yield a 15% higher average ^{3}He concentration. ^{21}Ne was measured for 26 bulk or matrix samples (average $^{21}Ne = 1.84 \times 10^{-8}$ cm^3 STP/g) and for 15 chondrule separates. The chondrules show on average 30% higher concentrations. In this work we analyzed one matrix and five chondrules. The average ^{3}He concentration for the

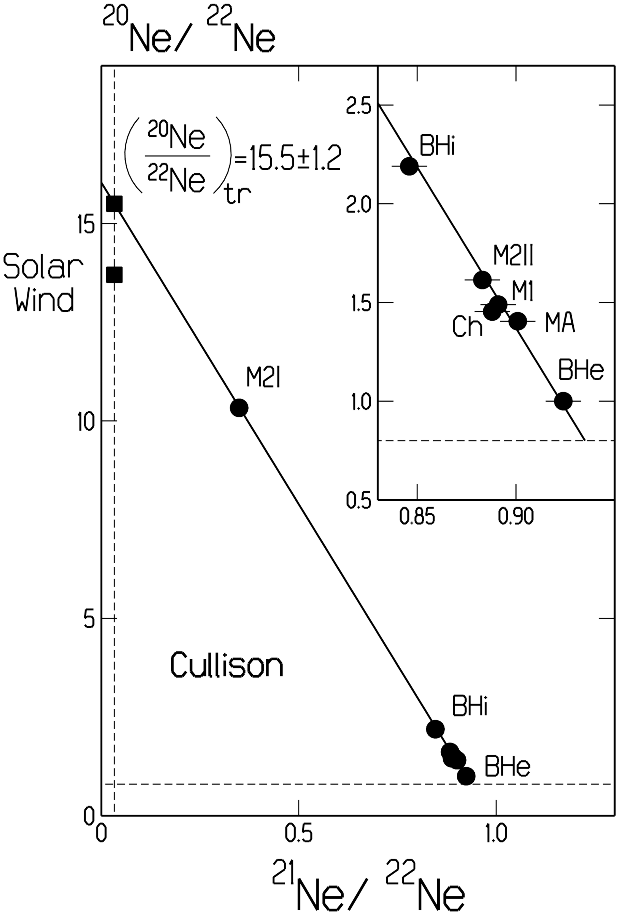

Fig. 6. Ne three-isotope plot for the Cullison chondrite. All available data yield a $(^{20}Ne/^{22}Ne)_{tr}$ ratio of 15.5 ± 1.2, higher than the solar wind value (see caption to Fig. 2). M1 = Matrix 1; M2I = Matrix 2I; M2II = Matrix 2II; MA = Matrix A; Ch = Chondrules; BHe = Bulk (Herzog et al. 1997); BHi = Bulk (Hintenberger et al. 1964).

five chondrules is 8.5×10^{-8} cm^3 STP/g, which is similar to that for the matrix samples, whereas our average ^{21}Ne concentration for the chondrules is 25% higher than that for the matrix. Hence, we have good agreement between literature data and our results. Our Allende matrix sample yields a higher $(^{22}Ne/^{21}Ne)_c$ ratio than the chondrules; this leads to lower production rates for ^{3}He and ^{21}Ne. Consequently, our CRE ages of matrix and chondrules of Allende are the same within experimental errors.

Summary of the CRE Ages

In a review of the CRE histories of ordinary chondrites, Marti and Graf (1992) concluded that H chondrites recorded two major breakup events 7 Ma and 33 Ma ago. In follow-up work, Graf and Marti (1995) and Graf et al. (2001) found that the peak at 7 Ma of the H chondrites represents a double peak for H4/H5 chondrites. In a recent review, Eugster et al. (2006) discussed additional data confirming these clusters and suggest an additional break-up around 22 Ma ago. Of the H chondrites studied here, only Bath (7.9 Ma) falls on the double 7 Ma peaks, whereas Ogi (23.5 Ma) fits the peak of CRE ages around 22 Ma.

For the determination of the precompaction exposure times of chondrules, we realize that production rates differed significantly in the early solar system, when the pre-exposure of the chondrules probably occurred. In previous work (Polnau et al. 2001), we found seven chondrites (ALH 76008, Bjurböle, Bowesmont, Grassland, Hunter, Kalvetta, and Sena) with excesses in the chondrule CRE ages relative to those of matrix samples, although not always outside experimental errors. In the present work, the only chondrite that shows evidence for precompaction exposure of chondrules is Dhajala. The difference in CRE age between a matrix sample and three chondrules is 1.6 ± 1.3 Ma, which is outside experimental errors. This evidence, however, is not very strong due to significant uncertainties in the calculation of the production rates for a meteorite with large pre-atmospheric size. Further evidence for surface exposure comes from the fact that chondrule 2 contains a clear excess of trapped Ne, as demonstrated by the enhanced ratio ^{20}Ne/^{22}Ne of 3.189 (Table 2). This trapped Ne is apparently of solar origin, since the $(^{20}Ne/^{36}Ar)_{tr}$ ratio is 5.26 (Table 6), in contrast to a ratio of <0.8 in the other chondrules and the matrix of Dhajala. In this case, chondrule 2 probably acquired solar gases during its precompaction exposure. Other cases suggesting solar Ne in chondrules (indicated by a $(^{20}Ne/^{36}Ar)_{tr}$ ratio >1) are Nadiabondi and Pavlograd chondrules (Table 6). However, due to their high CRE ages, it is not possible to further assess possible chondrule precompaction exposures. We see no differences in CRE ages for matrix and chondrules for all other chondrites studied here. Based on existing CRE ages, only a few chondrules document pre-exposures to cosmic rays before incorporation into their host material.

RADIOGENIC NOBLE GASES AND GAS RETENTION AGES

The abundances of radiogenic gases ^{4}He and ^{40}Ar, the K, U, and Th concentrations, and the inferred ^{4}He and ^{40}Ar gas retention ages are given in Table 8 (for principles of calculation, see, e.g., Dickin 1995). The ^{4}He ages (T_4) are lower than the ^{40}Ar ages (T_{40}), as is usually observed for chondrites, with a trend for the majority of H chondrite ages $T_4 > 2200$ Ma and a majority for L chondrite ages $T_4 <$ 2200 Ma (Wasson and Wang 1991). There are exceptions, such as the H chondrite Cullison and the L chondrite NWA 055.

Another typical feature of many meteorites, low ^{3}He CRE ages relative to the CRE ages T_{21} and T_{38}, is demonstrated in Fig. 6, where the ratio of the CRE ages T_3/T_{21} is plotted versus the ratio of the gas retention ages T_4/T_{40}.

Table 8. Radiogenic noble gases, K concentrations, and gas retention ages.

		Radiogenic (10^{-8} cm^3 STP/g)		K	Gas retention age (Ma)	
Meteorite	Sample type	^{4}He	^{40}Ar	(ppm)	T_4[b]	T_{40}
Dhajala (H3.8)	Matrix	1220	4990	1100[a]	3300	3600
	Chondrule 1	1650	19,200	2900[a]	–	4200
	Chondrule 2	1900	20,100	–	–	–
	Chondrule 3	1500	5050	–	–	–
Bath (H4)	Matrix	1070	4980	800[a]	3000	4100
	Chondrules	–	8830	1400[a]	–	4200
Cullison (H4)	Matrix 1	260	1890	–	900	–
	Matrix 2I	310	1970	400[a]	1040	3800
	Matrix 2II	290	1650	400[a]	990	3500
	Matrix A	310	1730	–	1040	–
	Chondrules	340	2290	500[a]	–	3600
	Fe,Ni	200	970	–	–	–
GRV 98004 (H5)	Bulk	1430	6270	780[c]	3700	4500
Nadiabondi Sample #2370 (H5)	Matrix	1330	8330	1000[a]	3500	4600
	Chondrule 1	–	9730	1100[a]	–	4700
	Chondrule 2	1020	11,900	900[a]	–	–
Nadiabondi Sample #2659 (H4)	Bulk	1180	8130	780[c]	3200	–
Ogi (H6)	Bulk	1510	7060	780[c]	3800	4700
Zag H6)	Bulk	1200	6640	780[c]	3300	4600
Grassland (L4)	<3, mag	–	10,680	–	–	–
	<3, nm	–	10,020	–	–	–
	>3, mag	–	6280	–	–	–
	>3, nm	–	6630	–	–	–
	Fe,Ni	–	6750	–	–	–
NWA 055 (L4)	Bulk	790	3440	825[c]	2400	3500
Pavlograd (L6)	Matrix	205	5070	800[a]	650	4200
	Chondrule	1270	7770	1490[a]	–	3800
Ladder Creek (L6)	Matrix	650	3370	1100[a]	2000	3000
	Chondrules	800	5100	1600[a]	–	3100
Indarch (EH4)	Matrix	460	6260	1000[a]	2100	4100
	Chondrules	420	3940	600[a]	–	4200
HaH 280 (CK4)	Bulk	950	1980	280[a]	–	4300
Acfer 059 (CR2)	Matrix	–	576	240[a]	–	1800
	Chondrules	–	330	260[a]	–	1900
Allende (CV3)	Matrix	–	5480	3800[a]	–	2000
	Chondrule A1	–	1940	240[a]	–	4560
	Chondrule B1	–	8760	1600[a]	–	3900
	Chondrule K100	–	1950	200[a]	–	4900
	Chondrule A38	–	5500	800[a]	–	4300
	Chondrule SHE	–	6310	1600[a]	–	3400
Typical experimental error (2σ mean)		4%	4%	8%	12%	9%

[a] Table 3. [b] For calculating the U,Th-He gas retention ages, we adopted the following U and Th concentrations (Wasson and Kallemeyn 1988): for H chondrites 0.012 ppm U and 0.042 ppm Th; for L chondrites 0.013 ppm U and 0.043 ppm Th; for the E chondrite 0.009 ppm U and 0.030 ppm Th. [c] Wasson and Kallemeyn (1988).

Meteorites close to the line with slope 1 apparently lost $^3\mathrm{He}_c$ and $^4\mathrm{He}_r$ during space exposure, presumably either by solar heating or collisional events. Meteorites with normal T_3/T_{21} ratios (between the broken horizontal lines) but ratios $T_4/T_{40} < 1$ have lost $^4\mathrm{He}_r$ at or before meteorite ejection or break-up of the parent body. The H4 chondrite Cullison (matrix and chondrules) lost similar fractions of $^3\mathrm{He}_c$ and $^4\mathrm{He}_r$. A scenario for a small perihelion distance resulting in solar heating has been suggested for many H chondrites by Marti and Graf (1992) and documented by Graf et al. (2001). On the other hand, as already mentioned above, a recent break-up event (Herzog et al. 1997) may explain simultaneous losses of ^{3}He and ^{4}He. Pavlograd matrix material must have lost a large fraction of its ^4He_r at or before break-up from its parent body, while the chondrule J2689 had retained a larger fraction of radiogenic ^{4}He.

The Allende chondrules yield K-Ar gas retention ages about twice as high as the matrix sample. In earlier analyses of ^{4}He, ^{40}Ar, K, and U in chondrules and whole rock samples of Allende, Fireman et al. (1970) observed higher radiogenic gas concentrations in the chondrules and concluded that they are gas-tight and old. It appears that in this meteorite the chondrules are more retentive for ^{40}Ar than the matrix material. For all other meteorites studied here, this retentivity difference is not pronounced, as the ratio T_{40} chondrules/T_{40} matrix is less than 1.2. These data can not be construed as evidence that better retentivity of the chondrules for cosmogenic gases may serve as an explanation for higher CRE ages of chondrules relative to the matrix.

TRAPPED NOBLE GASES

The concentrations of the trapped noble gases are given in Table 6. Trapped gases, shown as excesses on ^{20}Ne and ^{36}Ar, are present in all samples studied in this work. We also observed trapped ^{4}He in Acfer 059 and Grassland. As discussed above, the trapped He in Acfer 059 is of solar origin with a ^{4}He/^{3}He ratio of 3100 ± 300 (Fig. 1). For trapped ^{20}Ne/^{22}Ne, we obtain a ratio of 12.16 ± 0.30 (Fig. 2) and a trapped ^{36}Ar/^{38}Ar ratio of 5.36 ± 0.10 (Fig. 3). Cullison is a special case and we will discuss its trapped noble gases below.

In most chondrites studied here, the trapped Ar is chiefly of Q type, as can be judged from trapped ^{20}Ne/^{36}Ar ratios (Table 4) that are much lower than 47 (the solar ratio), but also larger than 0.042 (for Q type), indicating the presence of some solar Ne. In none of the meteorites studied here do we find evidence for trapped atmospheric contamination (e.g., air ^{40}Ar).

Of special interest is the comparison of trapped gas inventories in chondrules with those of the matrix materials. Some chondrules carry more Ne_{tr} than the respective matrix samples (Dhajala chondrules 2 and 3, Nadiabondi, Pavlograd, Ladder Creek, and Indarch). On the other hand, chondrules are generally depleted in trapped Ar relative to the matrix material. These results are in agreement with earlier data on the ALH 76008 chondrule (Polnau et al. 1999) and with trapped noble gases in chondrules and matrix samples of Bjurböle, Bowesmont, Grassland, Hunter, Kalvesta, Kress, Sena, and St. Germain (Polnau et al. 2001). The only exceptions are Pavlograd and St. Germain, where ^{36}Ar is slightly enhanced. Allende chondrules permit a direct comparison with published data. The trapped ^{20}Ne/^{36}Ar ratios of 0.22 to 0.48 are in agreement with the ratios of 0.28 to 0.50 reported by Vogel et al. (2004).

We conclude that chondrules in the investigated meteorites contain trapped ^{20}Ne and ^{36}Ar concentrations in the range of 10^{-7} to 10^{-9} cm^3 STP/g, except for Acfer 059 (about 7 × 10^{-7} cm^3 STP/g ^{20}Ne and ^{36}Ar). This range is consistent with data obtained by Polnau et al. (2001) for chondrules of eight chondrites as well as by Vogel et al. (2004) for six chondrites; the latter authors overlooked this consistency, which was observed by Polnau et al. (2001). Trapped Ar is predominantly of Q type, whereas in some chondrules, e.g., J2689 of Pavlograd, trapped Ne is dominated by the solar component. It appears that the early history of chondrules included an irradiation stage of components and that the thermal events only partially removed noble gases in chondrule precursor materials.

Trapped Noble Gases in Cullison

The Cullison H4 chondrite is special in several respects: 1) we show that it lost similar fractions of ^3He_c and ^4He_r (Fig. 5) after parent body break-up, either due to solar heating or a catastrophic event; 2) chondrules do not show precompaction exposure relative to its matrix material (Table 7); 3) matrix and chondrule samples show essentially the same chemical composition, in contrast to the other meteorites studied here; and 4) in a two-component analysis, the inferred trapped isotopic ratio ^{20}Ne/^{22}Ne is higher than observed in other meteorites.

The concentrations of trapped ^{36}Ar in the matrix samples of Cullison (Table 6) range from 3.2 to 4.1 × 10^{-8} cm^3 STP/g. Typical type 4 ordinary chondrites have $^{36}Ar_{tr}$ between 3 and 10 × 10^{-8} cm^3 STP/g (Marti 1967). In four matrix samples, the ratio $(^{20}Ne/^{36}Ar)_{tr}$ is 0.16 ± 0.05, which is close to the ratio for Q gas; in contrast, matrix 2I yields 34 times more $^{20}Ne_{tr}$ with a ratio of $(^{20}Ne/^{36}Ar)_{tr} = 5.1$, tending toward a ratio for solar gas-rich meteorites (Table 4). Matrix 2I may contain regolith grains that were irradiated on the surface of the parent body before compaction into the meteorite. The other matrix samples appear to have been heavily shielded during both the parent body residence time and the space irradiation, documented by the low cosmogenic ^{22}Ne/^{21}Ne ratio. Surprisingly, matrix 2I contains essentially no solar ^{4}He: its $(^4He/^{20}Ne)_{tr}$ ratio is <1, as can be estimated from the total ^{4}He concentrations given in Table 2. Total ^{4}He in matrix 2I is 310 × 10^{-8} cm^3 STP/g, whereas the other matrix samples yield an average ^{4}He concentration of 289 × 10^{-8} cm^3 STP/g. This lack of ^{4}He may be explained by the strong He loss discussed above. Obviously, most of Ne_{tr} in matrix 2I is solar type. The origin of Ar_{tr} in this sample is not clear; as matrix 2I contains a similar concentration of $^{36}Ar_{tr}$ as the other matrix samples (Q type gases), Ar_{tr} in matrix 2I may also be Q type gas. However, as matrix 2I probably suffered strong diffusion loss of the light gas component, the low $(^{20}Ne/^{36}Ar)_{tr}$ ratio does not necessarily indicate trapped gas of Q type; it could also be solar type with strong loss of He and Ne. The ratio $(^{20}Ne/^{22}Ne)_{tr} = 15.5 \pm 1.2$ is derived for two-component mixtures (Fig. 6) and assumes identical exposure histories for matrix and chondrules (no pre-irradiation). This Ne ratio is higher than that in solar gas-rich meteorites (Table 4). The question is how solar Ne with a ^{20}Ne/^{22}Ne ratio of 13.8 can be fractionated to a value of 15.5. We do not know the fractionation mechanism of solar wind in the early solar system and we can not exclude implantation from nonsolar sources. From Genesis data (Grimberg et al. 2006), one can estimate that a ^{20}Ne/^{22}Ne ratio of 15.5 corresponds to an implantation depth of about 1 nm. A possible explanation is that solar Ne in Cullison is trapped in nm-sized precursor material.

CONCLUSIONS

The partitioning of the noble gas inventory of chondrites into 1) CR-produced components, 2) radiogenic ^{4}He and ^{40}Ar, and 3) implanted solar and indigenous components, requires the knowledge of certain isotopic ratios of some of these components. Not all of these assumptions are well-founded. Therefore, we adopt a solar ratio ^{4}He/^{3}He = 3310 ± 130 in gas-rich meteorites and a ratio ^{20}Ne/^{22}Ne = 0.80 ± 0.03 for cosmogenic Ne. We outline a procedure for the gas component partitioning process.

In the chondrules of Dhajala (H3.8), there is a suggestion of precompaction exposure. For all other chondrites studied here, the CRE age differences between chondrule and matrix are nonexistent or are just outside experimental errors. The present results and those of Polnau et al. (2001) suggest that some chondrules show precompaction irradiation, but only in few cases excesses are outside error limits: ALH 76008 (H6), Bjurböle (L/LL4), and, by including the ^{3}He CRE age, Bowesmont (L6), Grassland (L4), Kalvesta (H6), Kress (L6), and Sena (H4). Since the production rates are not known, no time scale can be inferred for pre-irradiation in the early solar system. Either individual chondrules or precursor materials thereof could have been exposed in free space or during regolith evolution on the parent objects.

The parent body break-up times, that is, the CRE ages for the recent cosmic irradiation of the meteorites studied in this work, fall within the range of CRE ages typically found for their respective classes and groups. The Allende chondrules show K-Ar gas retention ages that are twice as high as that of the matrix sample, but CRE ages of chondrules and matrix are consistent. The chondrites studied in this work do not show a correlation between pre-exposure time and gas retention age.

We find trapped Ne and Ar in all chondrules, mostly of type Q. Generally, the trapped Ar concentrations are lower in the chondrules than in the corresponding matrix material. In the chondrule samples, the ^{20}Ne and ^{36}Ar concentrations are in the range of about 10^{-7}–10^{-9} cm^{3} STP/g, except for chondrules in the solar gas-rich chondrite Acfer 059 that yield about ten times more trapped noble gases. It appears that the processes that formed the chondrules did not remove all noble gases from precursor materials.

The Cullison H4 chondrite shows two special characteristics: 1) based on the T_3/T_{21} versus T_4/T_{40} diagram, we infer that Cullison lost similar fractions of ^{3}He$_{c}$ and ^{4}He$_{r}$ after its parent body break-up due to solar heating or a catastrophic event, and 2) Ne in one of the matrix samples differs in isotopic composition from Ne in the other trapped gas reservoirs and the concentration is strongly enhanced. The anomalous gases may be an isotopically fractionated solar component.

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