EXPOSURE HISTORIES OF SEVEN ORDINARY CHONDRITES WITH HELIUM-3 LOSSES.

P. Ma[1], G.F. Herzog[1], T. Faestermann[2], K. Knie[2], G. Korschinek[2], G. Rugel[2], A. Wallner[2], L. Schultz[3], J. Johnson[4], A.J.T. Jull[4], and D. Fink[5]. [1]Dept. Chemistry & Chemical Biology, Rutgers Univ., New Brunswick, NJ 08854-8087, [2]Fakultät für Physik, Technische Universität München, 85748 Garching, Germany, [3]Max-Planck-Institut fur Chemie, Postfach 3060, D-55020 Mainz, Germany, [4]NSF-Arizona AMS Lab., U. Arizona, Tucson, AZ 85721, [5]ANSTO, PMB 1, Menai NSW 2234, Australia. <pma@rutchem.rutgers.edu>

Introduction: Many stony meteorites have lost both cosmogenic and radiogenic He. Some of the losses may have begun when collisions on m-sized meteoroids (rather than on parent bodies) launched fragments into Earth-crossing orbits that passed close to the Sun. Complex exposure histories would follow naturally in this picture. Among meteorites with He losses, complex histories appear to be fairly common for low cosmogenic ^{21}Ne contents [10^{-8} cm^3 STP/g], ^{21}Ne$_c$ <1 [1], but rare for larger ones [2]. The cosmogenic nuclide data needed to test for complex exposures are relatively scarce. To investigate further the possible link between complex exposures and helium losses, we have measured cosmogenic nuclides in seven ordinary chondrites with $0.53 < {}^{21}\mathrm{Ne}_c < 1.17$, one of them -- Staelldalen -- a fall.

Experimental Methods: For radionuclide measurements, we separated silicate-rich material with a hand magnet. Procedures for the isolation of Be, Al, and Cl from the silicates followed [3] and [4]. We analyzed sample aliquots for elemental Mn, Fe, and Ni by ICP-MS.

We measured the samples' ^{26}Al/^{27}Al and ^{10}Be/^{9}Be ratios at ANSTO, and their ^{36}Cl/Cl ratios at PRIME Lab of Purdue University. Procedural blanks were negligible. The ^{53}Mn/^{55}Mn ratios were measured by AMS at the Technische Universität München [5]. A procedural blank gave $^{53}\mathrm{Mn}/^{55}\mathrm{Mn} \leq 1 \times 10^{-12}$ (atom/atom). Noble gas measurements for *bulk* samples of ALH 88004 and Markovka followed [6].

Results: Results appear in Table 1. We calculated one-stage cosmic-ray exposure (CRE) ages [7] from ^{22}Ne/^{21}Ne ratios and ^{3}He, ^{21}Ne, and ^{38}Ar contents (this work and [8]). These ages are often too low for ^{22}Ne/^{21}Ne <1.08. We also calculated CRE ages from the measured radionuclide activities by using compositions from [9] and production rates from both experiment [10] and modeling [11].

ALH 88004 - Exposure for 2-3 My or a complex history: The ^{36}Cl activity of 5.9 dpm/kg suggests a terrestrial age less than 0.3 My. The measured ^{22}Ne/^{21}Ne ratio of 1.17 implies 20%-below-normal production rates for ^{21}Ne and ^{26}Al. Lower bounds on CRE ages calculated from normal LL-chondrite production rates (^{22}Ne/^{21}Ne~1.11), are: T_{26}>2.5 My; T_{10}>2.5±0.2; T_{53}>3.1±0.3. Based on the actual ^{22}Ne/^{21}Ne ratio and approximate CRE ages we expect ^{26}Al to have reached saturation at ~0.8×60 = 50 dpm/kg. The higher (LL-chondrite-normalized) ^{26}Al activity of 66 dpm/kg contradicts this conclusion. Loss of ^{21}Ne – an interesting if speculative possibility for this meteorite, which retains only 18% of its ^{3}He – or experimental error might resolve the paradox. The alternative is a two-stage irradiation.

Daraj 115 - Simple exposure for 6-7 My: The ^{22}Ne/^{21}Ne ratio of 1.31 implies shallow burial, <1 cm. It also suggests a small preatmospheric size and raises hopes for finding SCR effects. The nominal ^{21}Ne age of ~7.3 My would seem to place the meteorite in the main cluster of H-chondrite exposure ages. The H-chondrite-normalized ^{10}Be and ^{26}Al activities (dpm/kg) of 11.4 and 40, however, are somewhat lower than saturation values for small meteorites such as Udaipur (R=11.5 cm; P_{10}=17±1; and P_{26}=44±3

Table 1. Cosmogenic nuclide contents, production rates (P), and cosmic ray exposure ages (T, My).

	ALH	Daraj	HaH	IR	Mark	Stael	Ybbs
IR	LL4	H6	H4	H6	H4	H5	H4
Mass (kg)	0.31	0.42	0.38	1.5	8.80	3.40	1.50
^{36}Cl	5.9 ±0.3	3.9 ±0.1	1.8 ±0.1	7.9 ±0.2	7.4 ±0.3	6.2 ±0.2	5.9 ±0.2
^{26}Al	67.0 ±1.0	44.2 ±0.8	48.8 ±0.9	75.5 ±1.3	40.5 ±0.9	65.0 ±1.8	46.4 ±1.2
^{10}Be	12.0 ±0.4	13.4 ±0.5	9.4 ±0.5	15.3 ±0.5	6.6 ±0.2	15.4 ±0.6	9.2 ±0.7
^{53}Mn	192 ±11	188 ±24	182 ±19	209 ±12	149 ±16	190 ±43	156 ±33
^{3}He	0.80	5.68	1.91	4.1	1.01	3.60	1.61
^{4}He	188	546	162	674	154	69	868
^{21}Ne$_c$	0.680	1.17	0.638	1.03	0.530	0.979	0.620
^{36}Ar	1.47	0.73	9.93	1.98	0.65	2.04	2.03
^{38}Ar$_c$	0.131	0.197	0.106	0.15	0.055	0.157	0.071
^{40}Ar$_r$	368	3599	5630	615	1316	650	3680
^{22}Ne/^{21}Ne	1.172	1.317	1.132	1.13	1.053	1.098	1.067
^{3}He/^{21}Ne	1.18	4.85	2.99	3.95	1.91	3.68	2.60
T_3	>0.5	>3.8	>1.2	>2.6	>0.6	>2.3	>1.0
T_{21}	2.7	7.5	2.3	3.7	>1.3	3.1	>1.7
T_{38}	3.1	5.6	2.1	3.1	>1.0	3.0	>1.3

Meteorites: ALH=ALH 88004; Daraj=Daraj 115; HaH=Hammada al Hamra 002; IR=Indio Rico; Mark=Markovka; Stael=Staelldalen; Ybbs=Ybbsitz. **Units:** ^{36}Cl, ^{26}Al, ^{10}Be in dpm/(kg silicate); ^{53}Mn in dpm/[kg Fe]; noble gas contents in 10^{-8} cm^3 STP/g.

[12]). Additional discordances at the 10-20% level are the lower CRE ages based on ^{53}Mn/^{26}Al, 5±1 My, and on ^{38}Ar, 5.6 My. With T>5 My, the ^{26}Al/^{10}Be activity ratio of 3.5±0.5 should approximate P_{26}/P_{10}. For GCR production only, modeling [11] gives a smaller value, $P_{26}/P_{10}=2$, indicating SCR effects. An unusual complex history with two periods of near-surface exposure is possible but seems farfetched.

HaH 002 - 2-3 My of exposure and long terrestrial age: From [7], we have $T_{21}=2.3$ and $T_{38}=2.1$ My. As the ^{22}Ne/^{21}Ne ratio of 1.13 indicates production rates depressed by only ~10%, the low ^{36}Cl activity of 1.8 dpm/kg suggests an appreciable terrestrial age, $0.1\leq T_{terr}\leq 0.45$ My. The particular choices T=2.3 My and $T_{terr}=0.2$ My can account for the ^{26}Al activity but a larger value of T_{terr}, 0.6±0.3 My, is needed to explain the ^{10}Be activity if $P_{10}=17.9$ dpm/kg. With $T_{terr}=0.2$ My, itself an extraordinarily large value for desert meteorites [13], we calculate $T_{53}=3.7\pm0.6$ and $T_{26\text{-}53}=3.6\pm1.1$ My for $P_{53}=378$ dpm/[kg Fe]. Our best estimate of the CRE age for this scattered data set is 2.5±0.5 My.

Indio Rico - Simple exposure for 3.5 My? Correction for a small amount of atmospheric/trapped neon reduces the measured ^{22}Ne/^{21}Ne ratio from 1.183 to 1.128/1.142, values that correspond to production rates ~10% below normal. The corresponding CRE ages $T_{21}=3.7$ My and $T_{38}=3.1$ My agree fairly well with an age of 4.1 My calculated from ^{53}Mn. A ^{10}Be age estimated with $P_{10}=0.9\times19.6$ is 2.8±0.3 My. As in ALH 88004, however, the normalized ^{26}Al activity of 64.0 dpm/[kg H-chondrite] is inconsistent with the cosmogenic ^{22}Ne/^{21}Ne ratio. With a liberal allowance for experimental error, a one-stage irradiation lasting about 3.5 My under near normal shielding has some plausibility. The alternative is a two-stage irradiation.

Markovka - Deep exposure for 2-3 My or a two-stage history: If P_{21} and P_{38} are 35% and 9% above normal [7], then we have $T_{21}=1.3$ My and $T_{38}=$ 0.9 My, respectively. The very low ^{22}Ne/^{21}Ne ratio of 1.05, however, suggests a large meteoroid and possibly some reduction of $P_{3,}$ which would lead to an over estimation of ^{3}He loss. By assuming temporarily that shielding factors for the radionuclides are the same as for ^{21}Ne, we arrive at $P_{26}=75$ dpm/kg, $P_{10}=26$ dpm/kg, and $P_{53}=570$ dpm/[kg Fe]. These values translate into ages of 0.7 My, 0.5 My, and 1.6 My, respectively. From the disagreements of T_{26} and T_{10} with T_{21} we infer that the shielding correction of [7] for ^{21}Ne is indeed too large and that T_{21} is too low, as is often the case for such low ^{22}Ne/^{21}Ne ratios. We can fit the activities of ^{26}Al, ^{10}Be, and ^{53}Mn and the concentration of ^{21}Ne within 20% with the production rates of [11] assuming: a meteoroid radius of 1.2 m; a sample depth of 13.2 cm; and a CRE age of 2.2 My. We choose a near-surface location because the measured ^{36}Cl activity indicates low production of ^{36}Cl, <5 dpm/kg, by thermal neutrons. We regard the overall fit to the data as adequate but not compelling. Further analyses of Markovka, and in particular of ^{36}Cl in the metal phase would be useful.

Staelldalen - Simple exposure history: Except for the ^{10}Be activity, which is about 1 dpm/kg lower than expected, the data for this unremarkable fall are consistent with a simple exposure history lasting ~3.0±0.3 My.

Ybbsitz - 2-3 My of deep exposure: Our measured ^{26}Al and ^{10}Be activities agree well with published values [14]. If P_{21} and P_{38} are 20% and 6% higher than normal [7], then we have $T_{21}=1.7$ My and $T_{38}=1.3$ My. The ^{22}Ne/^{21}Ne ratio of 1.067 on which these values depend lies in an ambiguous region where ^{21}Ne production rates vary. With an increase of 20% over H-chondritic values, we would have $P_{26}=67.2$, $P_{10}=23.5$, and $P_{53}=504$, implying $T_{26}=0.89\pm0.06$, $T_{10}=1.1\pm0.5$, and $T_{53}=2.0\pm0.7$, and $T_{26\text{-}53}=3.9\pm1.5$ (all in My). As with Markovka, these ages disagree unacceptably and so we abandon [7] and instead fit the activities of ^{26}Al, ^{10}Be, and ^{53}Mn and the concentration of ^{21}Ne following [11]. For 1.2-m meteoroid at a depth of 14 cm we obtain a CRE age of 2.6 My for Ybbsitz, with all data matched to within 10%. Again, as with Markovka, a relatively low ^{36}Cl activity indicates a location in the outer 20 cm of the meteoroid. Analysis of ^{36}Cl in the metal phase would provide a good test of the proposed exposure history.

Conclusion: Simple exposure histories seem clear or likely for 3 meteorites with He losses and $^{21}\text{Ne}<1\times10^{-8}$ cm^{3} STP/g: Daraj 115, Staelldalen, and Ybbsitz. One-stage histories are ambiguous or unsatisfactory for ALH 88004, Indio Rico, Markovka, and HaH 002. The burden of proof for a two-stage history is not yet clearly met for the latter four meteorites. We conclude that up to 4 of 7 of our "short-lived" meteorites with He losses *may* have had complex histories. Daraj 115 appears to show the effects of irradiation by solar cosmic rays.

References: **[1]** Herzog G. et al. (1997) *MPS, 32*, 413-422. **[2]** Welten K. C. et al. (2001) LPS XXXII, 2148.PDF. **[3]** Vogt S. and Herpers U. (1988) *Fresenius Z. Anal. Chemie, 331*, 186-188. **[4]** Schnabel C. et al. (2001) *LPS XXXII*, 1353. **[5]** Knie K. et al. (2000) *NIM B, 172,* 717-720. **[6]** Schultz L. et al. (1991) *GCA, 55,* 59-66. **[7]** Eugster O. (1988) *GCA, 52,* 1649-1662. **[8]** Schultz L. and Franke (2002) *MPI für Chemie, Mainz.* **[9]** Newsom H. (1995) AGU Ref. Shelf Series, 174. **[10]** Vogt S. et al. (1990) **[11]** Leya I. et al. (2000) *MPS, 35,* 259-286. **[12]** Bhandari N. et al. (1993) *GCA, 57,* 2361-2375. **[13]** Jull A.J.T. et al. (2000) *Radiocarbon, 42,* 151-172. **[14]** Nishiizumi K. (1987) *Nucl. Tracks Radiat. Meas., 13,* 209-273.