EXPOSURE-AGE-INITIATING EVENTS FOR MARTIAN METEORITES: THREE OR FOUR?

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Based on cosmogenic He and Ne, it was concluded earlier that at least three, and probably only three distinct impact events (now dated at ~0.6 Myr, ~3 Myr, and ~12 Myr) were required to explain the cosmic ray exposure histories of the nine SNC, or martian meteorites then known (1, 2). Three groups have concluded that the the tenth recognized martian meteorite, ALH84001 (3), has an exposure age of ~14-16 Myr and that this is longer than any other SNC exposure (4, 5, 6). This conclusion, if correct, would require a total of four impact events, either in space or on Mars, and would imply that ejection of solid objects from Mars is a more common process than previously imagined (e.g. 7). This abstract reexamines requirements for a fourth impact event.

Meteorites with diverse chemical compositions and self-shielding will have quite different production rates of cosmogenic noble gases. Generally, the calculation of cosmic ray exposure ages requires normalization to chondrite composition and average shielding, usually $[^{22}Ne/^{21}Ne]_c = 1.11$, in order to use production rates derived from chondrites. Exposure ages for ALH84001 and the other SNCs were determined from cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar by using more than one chondrite-normalized production rate, different assumed compositions, and slightly different methods of correcting for variations in shielding and composition. To compare exposure ages for Nakhla, Chassigny, and ALH84001, I considered cosmogenic data measured in several laboratories and applied self-consistent corrections for differences in composition and shielding. This analysis indicates that Nakhla and Chassigny have very similar, if not identical exposure ages, whereas the ages based on ^{21}Ne and ^{38}Ar appear longer for ALH84001. Considering the large corrections applied, however, this conclusion cannot be considered definitive.

I used six analyses each of Nakhla and Chassigny (Table 1) made in five laboratories and summarized by (8). For ALH84001, I used five analyses made in three laboratories (4, 5, 6). The considerable variation in ^{3}He shown by Nakhla is likely due to diffusive loss from feldspar, which is more abundant in Nakhla and is known to show major losses of ^{3}He in eucrites (9). Thus, those higher ^{3}He values of Nakhla and Chassigny, which are similar to ^{3}He concentraions for ALH84001, may be more accurate. Cosmogenic ^{3}He requires essentially no adjustment for compositional differences among these meteorites and apparently little adjustment for shielding differences (10). Thus ^{3}He exposure ages could be identical for these three meteorites.

For a given meteorite, various analyses of cosmogenic ^{21}Ne and ^{38}Ar show significant variations and range over factors of 1.15-1.36 and 1.3-2.3, respectively. For Nakhla I considered averages of all five analyses; discarding an older analysis with higher $[^{21}Ne]$ changed the average modestly (column 3 of Table 1). Concentrations of ^{21}Ne for six Chassigny samples tend to correlate with the considerable variation in $^{22}Ne/^{21}Ne$ (Table 1, $^{22}Ne/^{21}Ne$-meas.), suggesting a shielding trend. Thus, I considered, in addition to the average ^{21}Ne, also ^{21}Ne values corresponding to $^{22}Ne/^{21}Ne$ ratios of 1.115 (two analyses) and 1.155 (four analyses; Table 1). Corrections for shielding (discussed below) largely erase these variations in ^{21}Ne for Chassigny (column 8). For ALH84001 I considered both the average of all five ^{21}Ne values and the average by omitting the analysis with the lowest $^{22}Ne/^{21}Ne$ of 1.17 (Table 1). For each meteorite I used the average of all available cosmogenic ^{38}Ar values (Table 1). Omitting the smallest and largest ^{38}Ar value for Nakhla gives an identical average ^{38}Ar, but a smaller uncertainity (Table 1). Observed variations in cosmogenic abundances among samples could be due to several factors, including analytical uncertainties, shielding differences, and heterogeneties in sample composition. However, all uncertainties shown in Table 1 are derived only as one-sigma of the simple means and do not include additional uncertainties due to corrections for shielding and composition discussed below.

Corrections to cosmogenic ^{21}Ne and ^{38}Ar for differences in target element abundances were made using the relative element production factors given by (10) and chemical analyses of Nakhla, Chassigny (11, 12), and ALH84001 (13), all made in the same laboratory. These composition factors are shown in Table 1 as "corrections-comp" and serve to normalize cosmogenic production rates to L-chondrite target composition. Composition factors show a total range of almost a factor of two for ^{21}Ne (from 1.56 to 0.85) and a factor of six for ^{38}Ar (from 1.61 to 0.266). For comparison, I also calculated compositional correction factors using the older equations of (14). In all cases these older factors were within a few percent of those calculated from the equations of (10). The magnitude of compositional corrections required for ^{21}Ne and especially ^{38}Ar suggests significant additional uncertainty when comparing exposure ages of these martain meteorites.

The effect of different chemical compositions on the $[^{22}Ne/^{21}Ne]_c$ ratio must be determined prior to its use for shielding corrections, a consideration apparently not made in previous reports. To make this correction, I examined a plot of cosmogenic $^{22}Ne/^{21}Ne$ vs. [Mg]/[Si+Al] from measurements of mineral separates of three chondrites made in two laboratories (14, 15). These separates show a range in [Mg]/[Si+Al], the major target elements for cosmogenic Ne production, that is comparable to that shown by Nakhla, Chassigny, and ALH84001. From the trend defined by these separates, I estimate that relative to L-chondrite composition, cosmogenic $^{22}Ne/^{21}Ne$ needs to be multiplied by factors of ~0.97 for Nakhla, ~1.02 for Chassigny, and 0.99 for ALH84001. Composition-corrected ratios are shown in Table 1 as "$^{22}Ne/^{21}Ne$-corr". Corrected ratios act to decrease the shielding corrections required for Nakhla and ALH84001 and increase that for Chassigny.

Corrections for differences in shielding between martian meteorites and the L-chondrite value of $^{22}Ne/^{21}Ne = 1.11$ were made using equations reported by (10), and are shown in Table 1 as "corrections-shield". Use of the shielding trends of (16) gives slightly larger corrections. The ^{21}Ne and ^{38}Ar shielding factors are greatest for ALH84001, but are rather modest for Nakhla. Although corrections for shielding differences are less than those for compositional differences, especially for ^{38}Ar, they can be expected to add some additional uncertainty in the comparison of exposure ages.

Composition- and shielding-corrected concentrations for ^{21}Ne and ^{38}Ar are given in the next-to-last column of Table 1. Exposure ages (last column) were calculated using the chondrite-normalized production rates given by (10). Although the uncertainity in production rates adds an additional uncertainty in age, age differences among meteorites calculated from a single nuclide (e.g., ^{21}Ne) cannot be due to the production rate assumed. These differences must reflect cumulative uncertainties in measurements, sample heterogeneity, corrections for differences in composition and shielding, or actual differences in exposure ages themselves. The He, Ne, and Ar exposure ages for Nakhla and Chassigny appear identical within uncertainties associated with measurements alone. The ^{21}Ne and ^{38}Ar exposure ages for ALH84001 differ from those of Nakhla and Chassigny by amounts greater than measurement uncertainties. If we arbitrarily assume that corrections applied to ^{21}Ne and ^{38}Ar for differences in composition and shielding are accurate to $\pm 10\%$, these corrections would contribute <u>additional</u> uncertainties to the ^{21}Ne ages of all three meteorites of ~1.8-2.1 Ma. Similar or greater uncertainties would be produced in ^{38}Ar ages.

Whether we conclude that these three meteorites have the same or different exposure ages depends upon the accuracy of the various corrections applied to normalize the production rates. If we consider all uncertainties deriving from measurements and applied corrections, then the three cosmic ray exposure ages could be the same, and it may be possible for all three exposures to have been initiated by a common impact event. On the other hand, the fact that Nakhla and Chassigny appear to have identical exposure ages, in spite of very large corrections applied for compositional differences, may indicate that these corrections are accurate. In this case ALH84001 would have an exposure age distinctly older than those for Nakhla and Chassigny. Still a third possibility is that each meteorite has a distinct age, and that at least five SNC impact events are required.

References: (1) Bogard et al., GCA 48, 1723, 1984; (2) Treiman et al., Meteoritics 29, 581-592, 1994; (3) Mittlefehldt, Meteoritics 29, 214, 1994; (4) Eugster, Meteoritics 29, 464, 1994; (5) Swindle, Meterorites, submitted, 1994; (6) Miura et al., GCA, submitted, 1994; (7) McSween, Meteoritics 29, 757-779, 1994; (8) Schultz & Kruse Meteoritics 24, 155, 1989; (9) Heymann et al., GCA 8, 1241, 1968; (10) Eugster, GCA 52, 1649, 1988; (11) Dreibus et al, LPSC XIII, 186, 1982; (12) Burghele et al., LPSC XIV, 80, 1983; (13) Dreibus et al., Meteoritics 29, 461, 1994; (14) Bogard & Cressy, GCA 37, 527, 1973; (15) Bochsler et al., Meteorite Research, 857, 1969; (16) Graf et al., GCA 54, 2521, 1990.

Table 1. All concentrations in units 10^{-8} cm^3STP/g.

Meteorite	No. analyses	^{21}Ne meas.	$^{22}Ne/^{21}Ne$ meas.	$^{22}Ne/^{21}Ne$ corr.	corrections comp.	corrections shield	^{21}Ne corr.	AGE Ma
Nakhla	5	2.53+.33	1.142	1.112	1.56	1.01	3.99+.53	12.0+1.6
Nakhla	4	2.39+.21	1.145	1.115	1.56	1.02	3.82+.19	11.5+.6
Chassigny	6	3.85+.37	1.141	1.161	0.85	1.23	4.04+.39	12.2+1.2
Chassigny	2	4.17	1.115	1.135	0.85	1.11	3.96	11.9
Chassigny	4	3,69+.35	1.155	1.175	0.85	1.29	4.07+.39	12.3+1.2
ALH84001	5	3.87+.21	1.20	1.19	0.997	1.36	5.24+.25	15.8+.9
ALH84001	4	3.96+.08	1.21	1.20	0.997	1.40	5.54+.10	16.7+.3

Meteorite	No. analyses	^{3}He meas.	^{38}Ar meas.	corrections comp.	corrections shield	^{38}Ar corr.	AGE Ma
Nakhla	6	17.5-24.2	1.90+.50	0.266	1.01	0.510+.134	11.0+2.9
Nakhla	4		1.90+.21	0.266	1.01	0.510+.056	11.0+1.2
Chassigny	4	19.5-24.2	0.255+.042	1.61	1.08	0.442+.073	9.6+1.6
ALH84001	5	23.4-24.9	0.515+.066	1.42	1.13	0.829+.107	17.9+2.3