^{10}BE, ^{26}AL, AND ^{53}MN IN MARTIAN METEORITES.

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Introduction: Cosmic-ray exposure ages of martian meteorites help determine how many separate events brought meteorites from Mars to Earth. The activities, A, of cosmogenic radionuclides give cosmic-ray exposure (CRE) ages (T) when we know 1) the terrestrial age, t, of the meteorite; 2) the production rate, P, of the nuclide; and 3) that the period of exposure did not last more than ~3 half-lives of the nuclide measured. We then have $T = -\mathrm{Ln}\,(1-Ae^{\lambda t}/P)/\lambda$, where λ is the decay constant. The CRE ages of many martian meteorites [1,2] approach or exceed the bound of ~3 half-lives for the radionuclides most commonly determined. With its longer half-life of 3.7 My, ^{53}Mn records irradiation times up to ~11 My. Advances in accelerator mass spectrometry (AMS) now allow the measurement of ^{53}Mn/^{55}Mn ratios as low as 5×10^{-14} [3], thus reducing the mass of sample needed for analysis and making a survey of ^{53}Mn in SNC meteorites feasible.

Experimental Methods: We analyzed 100-to-200-mg samples of six SNC meteorites (Table 1) and 10-to-30 mg samples of several control samples, namely, Dhurmsala (LL6) for ^{26}Al and ^{10}Be; and Allende (CV3), Bogou (IA), ALH 77250 (IA), and Grant (IIIB) for ^{53}Mn.

After the addition of appropriate carriers stony material was dissolved in HF, HNO_3, and $HClO_4$ and irons in dilute HNO_3. To separate the elements of interest, we evaporated the solution, took up the residue in 1 M HCl, took an aliquot for chemical analysis, added a few drops of 3% H_2O_2, and evaporated the solution to dryness. We dissolved this residue in 10.2 M HCl, loaded the solution on an anion exchange column, and eluted two fractions: Al + Be + Ni and most Cr^{3+} with 10.2 M HCl; and Mn^{2+} and any remaining Cr^{3+} with 7.1 M HCl. To minimize Cr^{3+}, which interferes in subsequent AMS, we purified the Mn-bearing fraction by repeating the foregoing procedure. After evaporation, the residue from the Mn fraction was dissolved in 7 M HNO_3 (ultra pure) and Mn was precipitated as MnO_2 on addition of $KClO_3$. The MnO_2 was redissolved and precipitated, and dried, first at 110°C and then at 250°C. Procedures for the separation of Be and Al followed [4].

We used AMS to measure ^{53}Mn/^{55}Mn ratios at the Technische Universität München [3]. Initially, results were normalized to those for a laboratory standard in which the ^{53}Mn had been produced by a nuclear reaction and its concentration determined by an inbeam measurement of the deexcitation gamma rays of ^{53}Mn [5]. A procedural blank gave ^{53}Mn/^{55}Mn $\leq 1 \times 10^{-12}$ (atom/atom).

The ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios were measured at PRIME Lab of Purdue University. We also analyzed several sample aliquots for elemental Mn, Fe, and Ni by ICP-MS.

Results: Elemental Mn and/or Fe contents (mass %) follow: ALH 77005, --, 15.4±0.8; ALH 84001, 0.369, 14.4±0.7; EET 79001A, 0.414, 14.9±0.7; LEW 88516, 0.360, 14.8±0.5; QUE 94201, 0.354%, 13.8±0.9; Zagami, --, 17.0±0.9. The results agree within ~10% with literature values [6] except for Fe in Zagami (17.0 *vs.* 14.1 [6]). We also measured the Ni and Fe contents (mass %) of Bogou, 7.01±0.35 and 89.6±4.5, and of Grant Bar I, 8.71±0.44 and 88.8±4.4.

Analyses of ^{53}Mn in control samples gave the following results: ALH 77250, 347±39, 395±26; Bogou (USNM 2245) 351±71, 412±41; Bogou (KN) 368±37, 364±30 all in [dpm/[kg (Fe+1/3Ni)]; Allende [dpm/(kg Fe)], 260±54, 184±65; Grant [dpm/kg], 367±70, 431±43. Literature values in the same units [see 6] are as follows: ALH 77250, 565±22; Allende (3529), 330±31; Bogou, 471±20; Grant, 373±10 (bar I). Except in Grant, our ^{53}Mn activities are systematically lower than published results by a factor of 1.33±0.12 (2σ; weighted average; 8 measurements). A review of results for an internal laboratory standard for AMS, Sikhote-Alin (IIB), gave a similar factor of 1.27±0.13. We therefore apply a provisional factor of 1.33 to normalize all ^{53}Mn activities. Recalculated values for the meteorites above are as follows (normalization uncertainty not included): ALH 77250, 493±34; Bogou (USNM 2245), 507±55; Bogou (KN), 487±40; Allende, 295±72; and Grant, 531±57. Two separate Dhurmsala samples each contained 21.2±0.3 dpm ^{10}Be/kg and 67.6±3.3 and 73.7±2.2 dpm ^{26}Al/kg. Results for ^{53}Mn, ^{10}Be, and ^{26}Al in SNC meteorites appear in Table 1. The ^{26}Al and ^{10}Be activities agree well with published results [8-10].

Discussion: Table 1 shows published ^{3}He and ^{21}Ne CRE ages, T_3 and T_{21} [1], and CRE ages calculated from measured radionuclide activities corrected for terrestrial age [1]. We omit T_{38} from the compilation because these results tend systematically to be about 15% lower than CRE ages based on ^{3}He and ^{21}Ne. Production rates are

Table 1: ^{10}Be, ^{26}Al, (dpm/[kg meteorite]) and ^{53}Mn (dpm/[kg (Fe]) activities and production rates (atom/min/kg or atom/min/[kg Fe]), and CRE ages (T[My]).

Meteorite	EET 79001A	QUE 94201	Zagami	ALH 77005	LEW 88516	ALH 84001
ID	522	48		21	38	339
^{26}Al	33.8±3.7	63.4±6.9	97.7±8.5	47.1±2.4	81.8±5.2	70.2±3.0
^{10}Be	4.99±0.07	11.9±0.2	14.6±0.2[8]	16.2±0.8[8]	16.2±0.2	21.3±0.3
^{53}Mn	30±5	162±11	221±16	170±12	279±20	379±33
T_{terr}[1]	0.2	0.3		0.2		
D, R (cm)	15,15	25,25	25,25	10,10	25,25	25,6
P_{26}	72	100	93	49	77	70
P_{10}	20	21	21	19	22	21
P_{53}	346	451	451	284	451	376
T_{26}	0.86±0.21	1.9±0.9	--	--	--	--
T_{10}	0.70±0.06	2.2±0.3	2.5±0.2	4.2±1.3	3.0±0.3	--
T_{53}	0.51±0.10	2.6±0.3	3.6±0.4	5.2±0.8	5.1±0.8	--
T_3[1]	0.61	2.1	2.9	3.8-4.5	4.3	15
T_{21}[1]	0.65	3.2	3.0	3.2-4.9	4.3	14.2

calculated from elemental compositions [6] and elemental production rates [11].

EET 79001 – CRE ages from noble gases agree at about 0.6 My. Our ^{53}Mn activity, 30±5, is lower than reported values of 60-65 dpm/[kg Fe] (see [7]). Estimates of the preatmospheric radius, R, of EET 79001 range from 10 to 15 cm. Assuming that our sample came from a 15 cm body [12] at a depth, D=15 cm, large enough to preclude SCR production, we obtain CRE ages in fair agreement with those based on noble gases. Smaller depth for fixed radius would increase T_{26}, T_{10}, and T_{53}.

QUE 94201 – Nishiizumi and Caffee [8] report 1) ^{10}Be and ^{26}Al activities similar to ours; and 2) little evidence for the effects of SCR. We assume a sample depth of 25 cm and a meteoroid radius of 25 cm because these choices correspond to normal production rates; smaller depths in bodies with radii of 30 cm to 40 cm give similar results. The various CRE ages are in reasonable agreement.

Zagami – Noble gas CRE ages are close to 3.0 My. Again assuming standard production rates, the ^{10}Be age based on the analysis of [9] gives a similar result; T_{53} is higher.

ALH 77005 - Solar cosmic ray effects and track data combined with an assumed CRE age of 2.5 My originally suggested a very small preatmospheric radius of 4-6 cm [13] for ALH 77005. Absent SCR effects, GCR production rates in such small objects are depressed: $P_{10}<17$ (^{10}Be ~saturated) and $P_{53}<200$ atom/min/[kg Fe] [11]. The ^{53}Mn CRE calculated with $P_{53}=200$, ~12 My, is much larger than values based on noble gases, 3-5 My. We therefore assume a somewhat larger but still small body with R=10 cm. As the low ^{26}Al activity in our sample indicates little or no SCR production, we further assume an interior location. The resulting CRE ages are in the range estimated from the noble gases. A larger radius would raise production rates and lower the CRE ages.

LEW 88516 – Lacking information about size, we adopt production rates for the center of a 25-cm object. T_{53} agrees with the noble gas CRE ages; T_{10} is lower.

ALH 84001 - Noble gas CRE ages of ~14 My imply a 4π irradiation long enough to have saturated ^{10}Be, ^{26}Al and ^{53}Mn. We adopt a radius of 25 cm, which is consistent with the dimensions of the recovered mass, and a depth of 6 cm based on a comparison of ^{10}Be contents measured by us and by [9]. These choices lead to production rates that agree with the measured activities.

Conclusion: CRE ages of SNC meteorites based on ^{53}Mn activities generally agree with CRE ages based on other cosmogenic nuclides. Shergottite basalts QUE 94201 and Zagami came from a more recent ejection event than did lherzolites ALH 77005 and LEW 88516.

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