AL-26, BE-10, and MN-53 IN SIX LUNAR METEORITES.

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Introduction: Few ^{53}Mn activities have been reported for lunar meteorites. They can help to identify the effects of solar-cosmic-ray (SCR) irradiation and to improve estimates of cosmic-ray exposure (CRE) ages longer than 3 Ma. We report the activities of the cosmogenic radionuclides (CRN) ^{26}Al ($T_{1/2}$=0.7 Ma), ^{10}Be ($T_{1.2}$=1.39 Ma), and ^{53}Mn ($T_{1/2}$~3.7 Ma) in six lunar meteorites. From these activities and published results we construct cosmic-ray exposure (CRE) histories.

Experimental methods and results: ^{26}Al, ^{10}Be, and ^{53}Mn were separated chemically by precipitation and ion exchange. Activities were measured by accelerator mass spectrometry, ^{26}Al (dpm/kg) and ^{10}Be (dpm/kg) at Purdue University, and ^{53}Mn (dpm/[kg Fe]) at TU-München (Table 1).

Discussion: We fit CRN data to various exposure models by finding combinations of parameters that minimize $\chi^2 = \frac{1}{n-p}\sum_{i=1}^{n}\frac{\left(O_i - E_i\right)^2}{O_i}$. Here O_i is the i^{th} of n measurements, E_i is the estimate of O_i predicted by an exposure model, and p is the number of parameters allowed to vary for each calculation. Our general model has six parameters, a lunar burial depth $D_{2\pi}$ and exposure time $T_{2\pi}$, a radius $R_{4\pi}$, a depth $D_{4\pi}$, and exposure time $T_{4\pi}$ for the meteoroid in transit to Earth, and a terrestrial age T_{terr}. We have

$$E = P_{2\pi}\left(D_{2\pi}\right)\left(1-\exp\left[-\lambda T_{2\pi}\right]\right)\exp\left(-\lambda\left[T_{4\pi}+T_{Terr}\right]\right)+$$
$$P_{4\pi}\left(R_{4\pi},D_{4\pi}\right)\left(1-\exp\left[-\lambda T_{4\pi}\right]\right)\exp\left(-\lambda T_{Terr}\right)$$

For all CRN in meteoroids, the production rates $P_{4\pi}$ due to galactic cosmic rays are based on [1]; in the Moon, we adapt $P_{2\pi}$(GCR) from [2] except for ^{41}Ca. Thermal neutron capture dominates lunar ^{41}Ca production at depths > ~20 g/cm^2. We therefore made the approximation that $P_{2\pi}$(^{41}Ca) in dpm/[g Ca] is equal to the (depth-dependent) values for the Apollo 15 core [3], independent of matrix effects. Most elemental compositions are taken from the literature; in a few cases we measured Fe by ICP-MS. In some lunar meteorites, the effects of solar cosmic rays (SCR) are also important. We calculated SCR production rates for the meteorites studied following [4].

As we had too few measurements to determine all parameters in the general model, we chose certain values (indicated by ≡ in Table 2) and then, by iterating the Microsoft Excel routine Solver, found the values of the others that minimized χ^2 (Table 2).

MAC 88104/5 – For fitting, we adopted the following activities (TW=this work): ^{41}Ca = 15.5; ^{36}Cl=4.4; ^{26}Al=15.3; ^{10}Be=2.0 [5]; ^{53}Mn=56.2 [TW]. The best fitting results indicate burial on the Moon at 370 g/cm^2, a transit time of ~ 40 ka, and a terrestrial age of ~15 ka. The calculations overestimate the ^{10}Be activity, 2.9 *vs.* 2.1. Overall, the new results agree fairly well with those of [6-9]: T_{terr}, = 0.2-0.25 Ma; and $T_{4\pi}$ = 0.04-0.1 Ma. CRN data and the ^{131}Xe/^{136}Xe ratio indicate different lunar burial depths, 360-500 g/cm^2 and 85 g/cm^2, respectively, the latter for >500 Ma [7]. MAC 88104/5 probably was exposed at several different depths on the Moon.

Dhofar 081 (paired with *MAC 88104/5*?) - For fitting, we took weighted averages of [TW] and [10]: ^{36}Cl=7.2; ^{26}Al=31.6; ^{10}Be=5.0; ^{53}Mn=88.3. Our fit with $T_{4\pi}\equiv 0$ gives T_{terr}=100 ka and $D_{2\pi}$=310 g/cm^2 *vs.* 200 ka and 200 g/cm^2 from [10]. Fits with finite $T_{4\pi}$ give better results with $T_{4\pi}$=170 ka being best. The ejection ages ($T_{4\pi}$ + T_{terr}) of Dhofar 081, ~0.4 Ma, and MAC 88104/5, ~0.2 Ma, do not agree, but the uncertainties are appreciable.

Paired meteorites LAP 02xxx: CRN activities are low in these 5 stones. Nishiizumi et al. [11] inferred $D_{2\pi}$~700 g/cm^2, $T_{4\pi}$=35 ka, and T_{terr}= 20 ka. To obtain production rates at depths > 550 g/cm^2, we extrapolated the composition-adjusted values of [2]. For fitting, we adopted ^{41}Ca = 5.94 and ^{36}Cl=1.95 [11]; ^{26}Al=5.99 and ^{10}Be=0.70 [TW,11]; and ^{53}Mn=22 [TW]. To compare with [11], we first excluded ^{53}Mn. With $R_{4\pi}$=20 cm, we find $D_{2\pi}$=650 g/cm^2, and $T_{4\pi}$=37 ka, but best agreement for T_{terr} ~0. Although the goodness of fit remains acceptable when ^{53}Mn is added, the exposure parameters lead to an overestimate of the measured ^{10}Be activity, 0.7, by ~50%. A three-parameter model with an earlier, long lunar exposure at 50 g/cm^2 followed by burial at 650 g/cm^2 for $T_{2\pi}$=17 Ma, with $T_{4\pi}$=38 ka and T_{terr}=0, i.e. gives a good fit except that the activity predicted for ^{10}Be is ~15% too high.

NWA 032 – CRN activities in NWA 032 are even lower than those in the launch-paired LAP 02xxx stones. Nishii-

Table 1. ^{26}Al, ^{10}Be, and ^{53}Mn activities and Fe concentrations in lunar meteorites.

Sample	^{26}Al^{1}	^{10}Be^{1}	^{53}Mn^{2}	Fe^{3}
Dhofar 081	33.9±2.8	4.36±0.10	88±11	2.38
MAC 88104[5]	11.6±1.2	1.87±0.17		3.43
MAC 88105[5]	14.6±1.2	1.97±0.12	56±7	3.43
LAP 02205,38	6.64±0.38	0.63±0.05	27.2±3.4	17.1
LAP 02205,39	5.48±0.26	0.64±0.05	18.2±1.6	17.1
LAP 02224,13		0.78±0.10	21.1±1.6	17.1
LAP 02226,8	4.99±0.28	0.63±0.04	20.1±1.9	17.1
LAP 02436,10	7.22±0.59			17.1
NWA 032	4.7±0.5	0.33±0.01	2.7	17.6
MET 01210,8	76.7±3.4	6.86±0.49	120±11	13.0
PCA 02007,32	174±5	8.66±0.31	202±22	5.53

1) dpm/kg 2) dpm/[kg Fe] 3) wt% from the literature

zumi and Caffee [10] noted the failure of a one-stage lunar irradiation at any single depth to fit the data well, and called instead for very deep lunar burial followed by a 42 ka trip to Earth as a small ($R_{4\pi}$=5 cm) body that retains SCR effects and that landed <80 ka ago. For fitting we adopted ^{36}Cl=0.78, ^{26}Al=4.0, and ^{10}Be=0.35 [TW,10]; and ^{53}Mn=2.7 [TW]. To evaluate the production rates at lunar depths > 500 g/cm^2 we extrapolated the composition-adjusted production rates of [2] based on constant half-thicknesses (g/cm^2), 134 for ^{36}Cl; 111 for ^{26}Al; 114 for ^{10}Be; 116 for ^{53}Mn. We confirm a poor fit for a single-stage lunar irradiation followed by terrestrial decay. Fits in which $D_{2\pi}$, $T_{4\pi}$, and T_{terr}, all vary converge on large values of $D_{2\pi}$, for which lunar production is small. Ignoring lunar production, therefore, we fit the data by allowing $T_{4\pi}$ and T_{terr} to vary for $1.4<R_{4\pi}<500$ and $D_{4\pi} \leq R_{4\pi}$. Because total activities are so low, we checked for terrestrial contributions based on sea-level P(^{53}Mn) = 0.20 dpm/[kg Fe] [12], which corresponds to a lunar depth of ~1300 g/cm^2, and therefore set P(^{36}Cl) = 0.018; P(^{26}Al) = 0.024; and P(^{10}Be) = 0.0085. The best fit with ^{26}Al=4.0 dpm/kg and without SCR included suggests near-surface exposure in a small meteoroid, $R_{4\pi}$<10 cm. Specifically we find $18 \leq T_{4\pi} \sim\leq 28$ ka and T_{terr}~10±10 ka. CRN activities are reproduced only moderately well, to within 13-36%. With SCR effects included, ^{41}Ca, ^{36}Cl, and ^{53}Mn are matched to within 10% for $T_{4\pi}$=~20 ka and T_{Terr}=<10 ka; ^{10}Be is underestimated, however: 0.2 *vs.* 0.35. The ejection ages of NWA 032 and LAP 02xxx are consistent, but uncertainties are large.

MET 01210 –Variations in ^{26}Al suggest SCR irradiation of this 23-g anorthositic breccia, perhaps throughout the stone [11]. For building a CRE history we adopted ^{41}Ca=4.1 and ^{36}Cl=14.2 [11]; ^{26}Al=80.2 and ^{10}Be=7.7 [11,TW], and ^{53}Mn=120 [TW]. With $P_{2\pi}$=0 but without inclusion of SCR effects the best fit obtained had an unconvincing χ^2=0.8. With inclusion of SCR effects the best fits are obtained for near-surface samples (1-1.5 cm) for $R_{4\pi}$ = 3, 10 and 150 cm (χ^2=0.25, 0.25, and 0.09). All three gave $T_{4\pi}$~1.7 Ma. The corresponding values of T_{Terr} were 20, 40 and 0 ka. These fits predict all CRN to within 10% on average, but consistently overestimate ^{10}Be in order to match ^{53}Mn. Nishiizumi et al. [11] also inferred T_{terr}~0, but reported a lower (^{10}Be) CRE age of 0.8±0.2 Ma.

Table 2. CRE exposure histories of lunar meteorites.

	$D_{2\pi}$	$T_{2\pi}$	$R_{4\pi}$	$D_{4\pi}$	$T_{4\pi}$	T_{terr}	χ^2
	g/cm^2	Ma	cm	cm	Ma	Ma	
Dho	310	≡>10	≡20	≡5.5	0.23	0.22	0.06
	210	≡>10			≡0	0.08	0.34[a]
	290	≡>10	≡20	≡5.5	0.17	0.17	0.004[a]
MAC	370	≡>10	≡10	≡5.5	0.05	0.13	0.17
	370	≡>10	≡20	≡5.5	0.04	0.16	0.16
	370	≡>10	≡30	≡5.5	0.04	0.14	0.16
	370	≡>10	≡30	≡10.5	0.03	0.14	0.16
LAP	650	≡>10	≡30	≡10.5	0.037	0.0	0.015[b]
	530	≡>10	≡30	≡10.5	0.03	0.1	0.09
	650	17	≡30	≡10.5	0.04	0.0	0.015[c]
NWA	530	≡>10			≡0	0.15	0.56
	>1500	-	<10	<1	0.023	<0.02	0.07
MET	>1200	-	<150	0.5	1.2-1.6	<0.03	0.08-0.3
PCA	>1200	-		<2	~1.5	0.24	3
	0.75	2			≡0	0.24	0.7
	150	≡>10	<10	<1	0.20	0.25	0.12

a) Excludes ^{53}Mn for comparison with [10]. b) Excludes poorly fit ^{53}Mn. c) Assumes an early lunar burial at 50 g/cm^2.

PCA 02007 - Unusually high ^{26}Al activities in 4 samples of this 23-g anorthositic breccia are evidence for SCR exposure [11,TW]. One proposed CRE history [11] has $T_{4\pi}$=0.95 Ma. For fitting, we adopted 41Ca=6.7 and ^{36}Cl=16.5 [11]; ^{26}Al=176 and ^{10}Be=8.5 [11,TW], and ^{53}Mn=202 [TW]. With $T_{2\pi} \equiv 0$, our fitting procedures for $T_{4\pi}$ and T_{terr} give poor results, χ^2>2, primarily because ^{41}Ca is underestimated. Our maximum modeled value of $P_{4\pi}$(^{10}Be,GCR) for $D_{4\pi}$< 2.5 cm and $R_{4\pi}$<10 cm is ~18 dpm/kg, implying $T_{4\pi}$~1.4 Ma or 1.1 Ma if $P_{4\pi}$(^{10}Be,SCR) is as high as 2 dpm/kg. With $T_{4\pi}$=1.4 Ma we estimate P(^{26}Al,SCR)=154 and P(^{53}Mn, SCR) ~ 600. Fitting with $T_{4\pi} \equiv 0$ (i.e., lunar irradiation only) gives a better fit for $D_{2\pi}$=0.75 g/cm^2 (χ^2=0.7). Lunar pre-irradiation at a depth of 150 g/cm^2 followed by Earth transit with $R_{4\pi}$<5 cm with $T_{4\pi}$=0.20 Ma and T_{Terr}=250 ka gives a good fit (χ^2=0.12; ^{36}Cl=13%; others <5%).

Conclusions: Of the 6 lunar meteorites studied, two have transit times of 1-2 Ma and four of <0.3 Ma, reaffirming the general conclusion that most meteoroids launched from the Moon arrive at Earth soon or not at all [13]. As is well known, SCR effects occur in an appreciable fraction of lunar meteorites, suggesting that lunar meteoroids tend to be small. Relatively low launch and Earth arrival velocities [13,14] may help reduce the ablation of lunar meteoroids and thereby aid in the preservation of near-surface material.

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