SOURCES OF LIVE ^{60}Fe, ^{10}Be, AND ^{26}Al IN LUNAR CORE 12025, CORE 15008, SKIM SAMPLE 69921, SCOOP SAMPLE 69941, AND UNDER-BOULDER SAMPLE 69961.
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Summary: Relatively high concentrations of live ^{60}Fe ($T_{1/2}$ = 2.62±0.04 Ma [1]) in lunar surface samples [2 and this study] confirm earlier work [3,4] and suggest the arrival of supernova (SN) debris on the Moon about 2 Ma ago.

Introduction: Refs. [3,4] presented evidence for the recent arrival of SN dust in Earth's neighborhood: Two independent ^{60}Fe profiles through a terrestrial deep-sea Mn crust each peaked in a narrow layer deposited ~2.1±0.4 Ma ago. If interpreted as originating in a SN, the ^{60}Fe excesses correspond to a fluence to Earth of ≤1.4×10^8 atom ^{60}Fe(SN) cm^{-2}. Assuming a lunar-soil density of ~2 g/cm^3 and uniform mixing to a depth of 2 cm, and allowing for radioactive decay, one might expect to find up to ~$1.4\times10^8/(2\times2)\times0.57 = 2\times10^7$ atom ^{60}Fe(SN)/(g soil) ≤ 0.010 dpm ^{60}Fe/[kg soil].

Although [4] confirmed the ^{60}Fe spike of [3] in the original Mn crust, they found no evidence for elevated ^{60}Fe in a sediment core deposited during the same period. They discussed possible explanations for the lack of ^{60}Fe.

Cook et al. [2] searched for SN debris on the lunar surface by analyzing ^{60}Fe in 11 samples from core 12025/8 and 5 samples from core 60006/7. In 12025/8, all measurements but one gave upper limits. The ^{60}Fe activity (14^{+9}_{-6} dpm/[kg Ni]) of the topmost sample of 12025 was greater than that predicted for ^{60}Fe production due to galactic or solar cosmic rays, suggesting a SN contribution. With only 4 counts of ^{60}Fe detected, however, the activity was not far above blank. Further, the argument against meteoritic contamination [see 5] relied on nickel or noble metal measurements made on different samples of 12025.

The main aims of this work were to reproduce the report of excess live ^{60}Fe in 12025 [4], this time supported by compositional measurements, and to look for excess ^{60}Fe in other samples from the lunar surface.

Experimental methods: *Samples* – Through the courtesy of CAPTEM and the Astromaterials Laboratory of the Johnson Space Center we obtained: 1) two near-surface samples from core 12025; four samples from core 15008; and one sample each from the 'skim' soil 64421, the underlying 'scoop' soil 64441, and the under-boulder soil 64461.

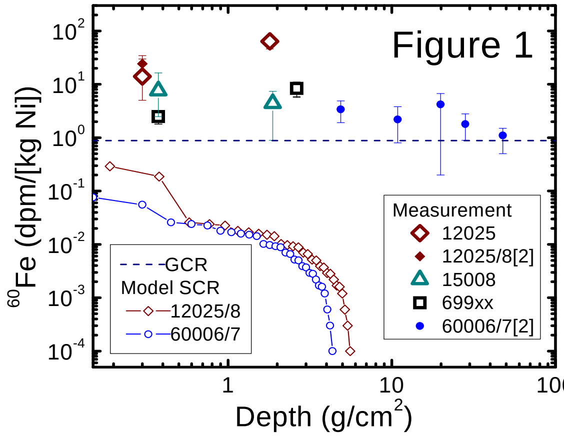
To all samples (60 to 190 mg) we added 8 mg Be carrier and 10 mg Mn carrier. After digestion in 5 mL 7M HNO_3, 5 mL conc. HF, and 1 mL conc. $HClO_4$, an aliquot (5 wt%) of the resulting solution was taken for elemental analysis by ICP-MS. After addition of 8 mg Al carrier to samples 12025,14 and 23 only, the rest (main sample) was evaporated and re-dissolved in 8M HCl from which iron was extracted with diisopropyl ether and then back extracted into 1M HCl. The main sample (minus iron) was evaporated once again and dissolved in 9M HCl for separation of Mn from Be and Al by anion exchange. Mn was precipitated from the

Table 1. Elemental concentrations[a] in lunar soils.

Sample	Mg	Al	Ca	Ti	Fe	Ni[b]
12025,14,365	5.35±0.16	6.41±0.13	6.98±0.33	1.55±0.02	12.6±0.3	128±3
12025,23,366	5.67±0.17	6.45±0.13	7.22±0.33	1.57±0.03	12.5±0.3	145±5
12028[8]	5.61	6.08	7.35	1.65	12.9	
15008,1004,1050	5.86±0.19	9.65±0.24	8.77±0.40	0.77±0.02	9.42±0.21	154±4
15008,1005,1051	5.63±0.16	8.90±0.17	8.69±2.00	0.74±0.01	8.61±0.19	144±4
15008,1006,1052	5.46±0.16	8.89±0.19	7.99±0.36	0.70±0.01	8.24±0.18	159±4
15008,1026,1053	6.18±0.18	9.51±0.20	8.62±0.38	0.76±0.01	9.20±0.19	213±5
15007 [7]	3.6±2.1	11.4±4.1	9.8±3.2	0.9±0.1	5.1±3.1	
69921,0,31	3.50±0.11	13.14±0.31	11.45±0.49	0.37±0.01	4.82±0.12	1211±27
Avg. [9]	3.80	13.92	10.79	0.37	4.43	480

Notes: a) wt % except Ni [ppm]. b) blank correction ~25%

Mn eluate with $KClO_3$ as MnO_2(s). Be and Al were separated by cation exchange, precipitated with NH_3(aq), and ignited to make the oxides.



We used ICP-MS to determine the elemental compositions of the sample aliquots; and accelerator mass spectrometry to measure ^{60}Fe/Fe ratios at the Beschleunigerlaboratorium der Ludwig-Maximilians-Univ. und Technischen Univ. München, Garching, Germany [6], and ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios at PRIMELab of Purdue University.

Results and discussion: Table 1 shows the elemental compositions of the samples. Agreement with literature results is generally good [7-9] except for samples 69941 and 69961, which appear to be low by 40% for unknown reasons. Our Ni measurements are higher than reported, but these differences do not affect our conclusions. We have adopted for 69921, 41, and 61 the composition of 69921, which agrees with results of [9]. The ^{26}Al, ^{10}Be, and ^{60}Fe activities of the samples are shown in Table 2 and a ^{60}Fe (dpm/[kg Ni]) depth profile in Fig. 1. The new ^{10}Be activities for 12025 are about 40% lower than those of [2] and increase slightly with sample depth. Agreement for ^{26}Al activities with measured values is good [10,11]. The ^{53}Mn samples need further purification.

GCR exposure of both lunar surface materials and typical iron meteorites produces ^{60}Fe, mainly from the minor isotopes of Ni, at a rate of ~0.88±0.44 (dpm/[kg Ni]) [6,12]. The use here of the measured Ni concentrations as a normalizing element for the reported ^{60}Fe activities (column 7, Table 2) should correct for the presence of meteoritic contamination in the samples.

We define a ^{60}Fe activity as marginally or significantly elevated if the difference (^{60}Fe-0.88) (dpm/[kg Ni]) is 1σ-2σ or >2σ, respectively, above 0. Accordingly, samples 12025,365 and 15008,1050 have ^{60}Fe activities that are marginally elevated; three others, 12025,366,23, 69921, and 69941 are significantly (>2σ) above blank. Both results for 12025 are consistent with those of [2].

Cook et al. [2] previously evaluated the possibility that solar cosmic ray irradiation produced some of the ^{60}Fe, and concluded that the ^{60}Fe activities expected from SCR (Figure 1) are below detectable levels, although these calculations omit possible small contributions from the reaction ^{58}Fe(α,2p)^{60}Fe.

As the elevated ^{60}Fe activities seem inconsistent with production by GCR and SCR or with meteoritic contamination, and in the absence of any obvious competing hypothesis, we infer that supernova dust may be present in lunar surface samples.

Table 2. Sample activities.

Sample [a]	Depth cm	^{26}Al [b]	^{10}Be [b]	^{60}Fe/Fe [c]	^{60}Fe [d]	^{60}Fe [e]
12x,14,365	0.2	230±18	9.32±0.37	$2.6^{+3.0}_{-1.7}$	$1.8^{+2.1}_{-1.2}$	14^{+16}_{-9}
12x,23,366	0.8	216±18	9.78±0.31	$13.8^{+3.9}_{-3.9}$	$9.4^{+2.7}_{-2.7}$	64^{+18}_{-18}
15x04,1050	0.25	188±10	8.79±0.26	$2.3^{+2.6}_{-1.5}$	$1.2^{+1.3}_{-0.8}$	$7.6^{+8.7}_{-5.1}$
15x05,1051	0.75	139±11	8.56±0.23	$0^{+1.3}_{-0}$	$0^{+0.6}_{-0}$	$0^{+4.3}_{-0}$
15x06,1052	1.25	140±9	9.29±0.24	$1.6^{+1.2}_{-1.1}$	$0.7^{+0.5}_{-0.5}$	$4.4^{+3.5}_{-3.0}$
15x26,1053	11.2	60±5	9.75±0.27	$0^{+1.3}_{-0.0}$	$0^{+0.7}_{-0.0}$	0^{+3}_{-0}
69921,31,0	0.25	244±21	9.32±0.32	$11.8^{+3.3}_{-3.3}$	$3.1^{+0.9}_{-0.9}$	$2.5^{+0.7}_{-0.7}$
69941,138,42	1.7	123±8	8.79±0.71	$16.4^{+5.3}_{-4.9}$	$2.5^{+0.8}_{-0.8}$	$8.4^{+2.7}_{-2.5}$
69961,146,38	>50	67±6	10.8±0.2	$0^{+1.3}_{-0}$	$0^{+0.2}_{-0}$	$0^{+0.7}_{-0}$

$T_{1/2}$ (Ma): ^{10}Be = 1.36; ^{26}Al = 0.705. [a] 12x=12025; 15x=15008,10. [b] dpm/kg. [c] 10^{-15} atom ^{60}Fe/[atom Fe]. [d] (10^{-3} dpm ^{60}Fe)/(kg soil); Fe this work. [d] dpm ^{60}Fe/(kg Ni); Ni this work.

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