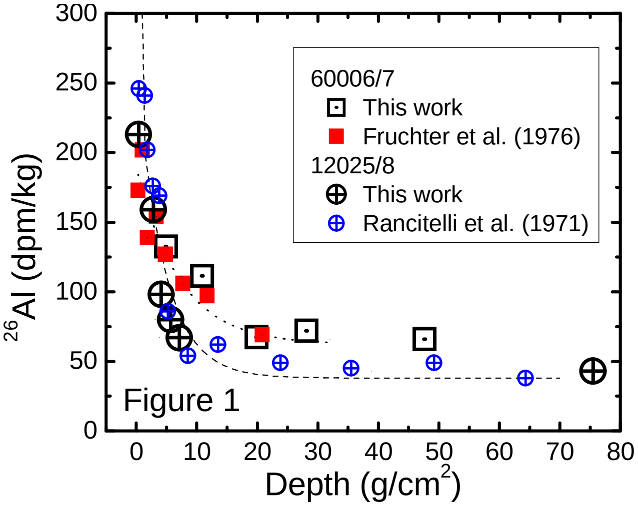
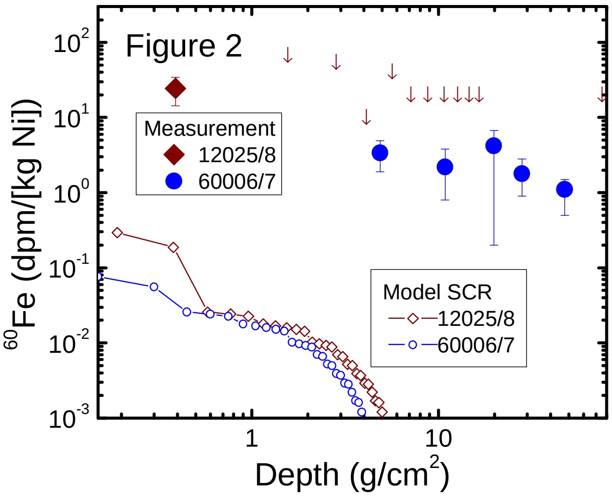
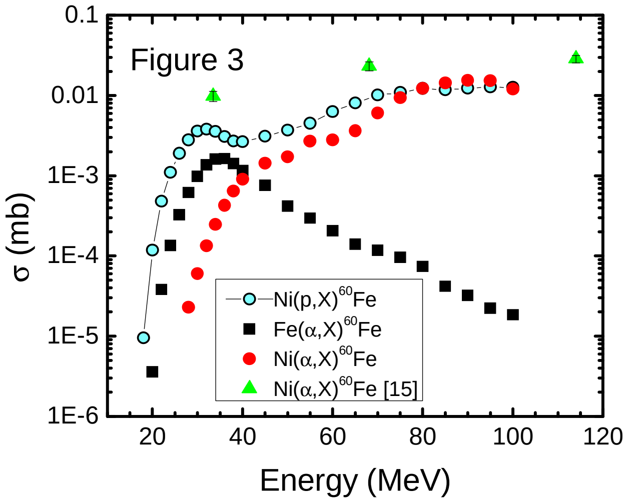
^{60}Fe, ^{10}Be, AND ^{26}Al IN LUNAR CORES 12025/8 AND 60006/7: SEARCH FOR A NEARBY SUPERNOVA.

D.L. Cook[1,2], E. Berger[1,3], T. Faestermann[4], G.F. Herzog[1], K. Knie[4,5], G. Korschinek[4], M. Poutivtsev[4], G. Rugel[4], and Serefiddin F.[1,6] [1]Chem. & Chem. Biol., Rutgers U., Piscataway, NJ 08854, [2]Earth Sci., U. Oxford, Oxford, OX1 3PR, UK, <davec@earth.ox.ac.uk>, [3]U. Arizona, Tucson, AZ, USA, [4]Fakultät für Physik, TU-München, D-85748, Garching, Germany, [5]GSI, Darmstadt, Germany, [6]Div. Phys. Sci., Cuesta College, San Luis Obispo, CA 93403.







Introduction: We searched two lunar cores for ^{60}Fe produced by a supernova event. Ref. [1] attributed a spike of ^{60}Fe ($T_{1/2}$=1.49 Ma) found in a narrow layer milled from a deep-sea FeMn crust to supernova debris deposited ~ 2 Ma ago. Ref. [2] confirmed these results for the crust but found no evidence for a ^{60}Fe spike in North Atlantic sediment. We reasoned that the lunar surface deserved consideration as a supernova debris collector because on the Moon 1) the net sedimentation rate is negligible (sedimentation dilutes the ^{60}Fe signal in terrestrial deposits); and 2) concentrations of the Ni isotopes responsible for interfering, spallogenic production of ^{60}Fe are low. On the other hand, stochastic impacts garden the lunar surface (*e.g.*, [3]). We sought to minimize gardening effects by choosing soil cores with smooth ^{53}Mn profiles, namely 12025/8 and 60006/7 [4,5].

Experimental methods: For ^{60}Fe, 17 carrier-free samples were dissolved in HF. Iron was extracted into diisopropyl ether, back extracted with HCl, and precipitated twice as the hydroxide**.** A subset of twelve samples were also analyzed for ^{10}Be and ^{26}Al; separate sample masses of 9-20 mg were dissolved after the addition of Be (~2.5 mg) and Al (~9 mg) carriers. Be and Al were separated by ion exchange, precipitated as the hydroxides, and ignited to the oxides. We used accelerator mass spectrometry to measure isotope ratios, ^{60}Fe/Fe at the Beschleunigerlaboratorium der Ludwig-Maximilians-Universität und Technischen Universität München in Garching, Germany [6], and ^{10}Be/^{9}Be and ^{26}Al/^{27}Al at PRIMELab of Purdue U.

Results and discussion: The ^{26}Al, ^{10}Be, and ^{60}Fe activities of the samples are shown in Table 1 and Figs. 1 and 2. The ^{26}Al activities agree fairly well with literature values (Fig. 1; [7-9]). Except for 60007,515 the ^{10}Be activities (dpm/kg) of both cores lie in the range 11.7-14.1 with an average of 13.5±1.0, which may be compared with a surface activity of 11.5 for 68815 [10], or of 11.8 for 74275 after corrections of 1.8 for pre-exposure and a factor of 1.38 for undersaturation [9].

Fitoussi et al. [2] estimated a maximum local fluence of 1×10^8 (atom ^{60}Fe) cm^{-2} at the time that supernova debris passed through the solar system ~2 Ma ago. With diameters of 2 cm, the cores studied would have collected at most 3×10^8 atom ^{60}Fe while on the Moon. Were all the ^{60}Fe to have been mixed uniformly down to the bottoms of the topmost samples 12025,358 (0.4 cm; 2.4 g; 13.3 wt% Fe) and 60007,517 (3.3 cm, 15.6 g; 3.3 wt% Fe), respectively, then we calculate ^{60}Fe/Fe ratios expected today, *i.e.*, after 2.1 Ma of decay, of 3.4×10^{-14} and 2.1×10^{-14}. These values are about 9 to 15 times larger than observed (Table 2).

We compared the measured ^{60}Fe concentrations with values expected from cosmic-ray activation. In iron meteorites, galactic cosmic-rays (GCR) produce ^{60}Fe at a rate, $P_{60\text{-GCR}}$, of ~ 1.5 dpm/[kg Ni], primarily through reactions of secondary protons and neutrons with the less abundant isotopes of Ni [6,11,12]. This estimate omits possible GCR contributions from ^{58}Fe(α,X)^{60}Fe. All five 60006/7 samples have ^{60}Fe activities comparable to (within 95% confidence limit (CL)) the GCR value. Eleven of the 12025/8 samples have an activity of zero but are within the CLs of the GCR value. However, the topmost sample (12025,358) has significantly higher activity than expected for GCR.

We evaluated the possibility that solar cosmic ray irradiation produced some of the ^{60}Fe observed in surface samples 60007,517 and 12025,358. With the TALYS code we calculated cross sections for the nuclear reactions ^{nat}Fe(α,X)^{60}Fe, ^{nat}Ni(p,X)^{60}Fe, and ^{nat}Ni(αX)^{60}Fe (Fig. 3). We adopted a proton flux (p/cm^2 s^{-1}) of $J_p(R)$ (p/cm^2) = $3.5\exp(-R/R_o)$ with the rigidity $R(\text{MV}) \approx 43.3\sqrt{E_p(\text{MeV})}$, R_o = 100 MV, and $J_\alpha(R) = 0.037J_p(E_p/4)$. The results for the production of ^{60}Fe by particles for $1\leq E_p \leq 100$ MeV, from the surface down to depths where production reaches zero, are shown in Fig. 2. No measurable ^{60}Fe production from SCR is predicted at the depth of sample 60007,517. Although production of ^{60}Fe by SCR is greatest at the surface, it apparently cannot account for the observed activity in sample 12025,358 which exceeds the predicted SCR value by a factor of ≈ 54.

As the ^{60}Fe activity in sample 12025,358 seems inconsistent with production by GCR and SCR, the signal may be due to the deposition of debris from a nearby SN, similar to that observed in a terrestrial FeMn crust by [1] and [2]. The discrepancy between the observed and predicted activities discussed above could result from an overestimation of the ^{60}Fe fluence by [2]. Alternatively, sample 12025,837 may not have recorded the full expected signal if the deposition of the SN debris occurred at an angle oblique to the plane of the ecliptic, or we may not have sampled the portion of the core containing the entirety of the debris. Additional analyses of ^{60}Fe in near-surface samples of 12025 and 60007 would be desirable.

References: **[1]** Knie K. et al. (2004) *Phys. Rev. Lett. 93***,** 171103-1 - 117103-4. **[2]** Fitoussi C. et al. (2008) *Phys. Rev. Lett., 101*, 121101. **[3]** McKay D.S. et al., (1991) In: *Lunar Sourcebook* Cambridge Univ. Press, 285-356. **[4]** Nishiizumi K. et al. (1976) *Proc. Lunar Sci. Conf., 7,* 41-54. **[5]** Nishiizumi K. et al. (1979) *EPSL, 44*, 409-414. **[6]** Knie K. et al. (1999) *M&PS, 34,* 729. **[7]** Fruchter J. S. et al. (1976) *Proc. Lunar Sci. Conf., 7,* 27-39. **[8]** Rancitelli L. et al. (1971) *Proc. Lunar Sci. Conf., 2,* 1757-1792. **[9]** Fink et al. (1998) *GCA, 62,* 2389-2402. **[10]** Nishiizumi K. et al. (1988) *Proc. Lunar Sci. Conf. 18*, 79-85. **[11]** Berger E. et al. (2007) *M&PS, 42,* A18. **[12]** Nishiizumi K. and Honda M. (2007) *M&PS, 42,* A118. **[13]** Meyer C. Jr., et al. (1971) *Proc Lunar Sci. Conf. 2*, 393-411. **[14]** Nava D.F. and Philpotts J.A. (1973) *GCA, 37*, 963-973. **[15]** Merchel S. et al. (2000) *NIM B, 172,* 806-811.

Table 1.

Sample	Depth cm	^{26}Al dpm/kg	^{10}Be dpm/kg
12025,358	0.20	213±13	13.4±0.7
12025,359	0.80		12.9±0.7
12025,360	1.45	159±12	13.9±0.8
12025,357	2.10	98±6	12.8±0.6
12025,356	2.90	80±6	14.1±0.8
12025,355	3.65	68±4	13.1±0.7
12028,837	38.7	44±3	11.7±0.7
60007,517	3.3	133±7	13.3±0.4
60007,516	7.3	112±7	13.7±0.7
60007,515	13.3	68±5	16.0±1.0
60007,514	18.3	72±5	13.0±1.1
60006,418	31.8	66±4	13.9±0.8

$T_{1/2}$ ^{10}Be = 1.36 Ma; $T_{1/2}$ ^{26}Al = 0.705 Ma. An apparent switch in the ^{10}Be/^{9}Be ratios of ,355 and ,356 was corrected.

Table 2.

Sample	Depth cm	^{60}Fe/Fe [a]	^{60}Fe [b]	^{60}Fe [c]]
12025,358	0.2	$3.6^{+2.5}_{-1.5}$	$4.6^{+3.2}_{-1.9}$	24^{+17}_{-10}
60007,517	3.3	$1.4^{+0.7}_{-0.5}$	$0.44^{+0.21}_{-0.17}$	$1.6^{+0.8}_{-0.6}$
60007,516	7.3	$1.5^{+1.1}_{-0.9}$	$0.46^{+0.35}_{-0.29}$	$1.7^{+1.3}_{-1.1}$
60007,515	13.3	$2.3^{+1.6}_{-1.0}$	$0.73^{+0.51}_{-0.30}$	$2.7^{+1.9}_{-1.1}$
60007,514	18.3	$1.2^{+0.7}_{-0.6}$	$0.39^{+0.22}_{-0.17}$	$1.4^{+0.8}_{-0.6}$
60006,418	31.8	$0.7^{+0.4}_{-0.3}$	$0.22^{+0.13}_{-0.10}$	$0.8^{+0.5}_{-0.4}$

[a] 10^{-15} atom ^{60}Fe/[atom Fe]. [b] (10^{-3} dpm ^{60}Fe)/(kg soil) with 13.3 wt% Fe for 12025/8 [13] and 3.3 wt% Fe for 60006/7 [14]. [c] dpm ^{60}Fe/(kg Ni) with 189 ppm Ni for 12025/8 and 272 ppm Ni for 60006/7.