EVIDENCE FOR DEPOSITION OF INTERSTELLAR MATERIAL ON THE LUNAR SURFACE.

L. Fimiani[1], D.L. Cook[2], T. Faestermann[1], J.M. Gómez Guzmán[1], K. Hain[1], G.F. Herzog[3], K. Knie[1,4], G. Korschinek[1], B. Ligon[3], P. Ludwig[1], J. Park[3], R.C. Reedy[5], and G. Rugel[1,6]. [1]Fakultät für Physik, TU-München, D-85748 Garching, Germany; [2]Institut für Geochemie und Petrologie, ETH, 8092 Zurich, Switzerland; [3]Dept. Chem. & Chem. Biol., Rutgers U., Piscataway, NJ 08854 USA; [4]GSI, D-64291 Darmstadt , Germany; [5]Planetary Science Institute, Los Alamos, NM 87544-3826 USA; [6]Forschungszentrum Dresden-Rossendorf, D-01314 Dresden, Germany.

Introduction: Astronomical observations indicate that one or more supernovae (SN) ocurred in the vicinity of our solar system in the recent past (~10Myr) [1,2]. One possible indication of the arrival of SN (or perhaps AGB) debris locally was the detection of ^{60}Fe/Fe ($T_{1/2}$ = 2.62 Myr [3]) excesses in a ferromanganese crust from the Pacific Ocean [4,5]. Another indication came from the Moon. In a previous study [6] we reported a ^{60}Fe/Fe depth profile constructed with 2 samples of the Apollo 12 core 12025, 4 samples of the Apollo 15 core 15008, 2 samples known as 'skim', 'scoop' and 'under boulder' soil collected near the shade of a small boulder in Station 9 during the Apollo 16 mission (shaded samples), and 5 samples of the deep drill core 60007/6, sampled during the same mission. We complete the previous work by reporting new measurements of ^{53}Mn ($T_{1/2}$ = 3.7 Myr [7]) in the same samples, including deeper samples of the 12025 core, and by using those measurements for a critical assessment of the ^{60}Fe results. We also determined the activities of ^{60}Fe and ^{53}Mn of 7 samples from 4 iron meteorites; these activities were used to establish reference levels for local production due to galactic cosmic rays.

Experimental Methods: To all samples (60 to 190 mg) we added 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. The rest (main sample) was evaporated and re-dissolved in 8M HCl from which iron was extracted with di-isopropyl 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 by anion exchange. Mn was precipitated from the Mn eluate with $KClO_3$ as MnO_2(s). We used ICP-MS to determine the elemental compositions of the sample aliquots, and accelerator mass spectrometry to measure ^{53}Mn/Mn ratios (in the same samples as reported in [6]) at the Beschleunigerlaboratorium der Ludwig-Maximilians-Universität und Technischen Universität München in Garching, Germany [8].

Results and discussion:

^{53}Mn. Our results are summarized in Fig. 1. All results agree with the previous published results (all measured via neutron activation analysis) [9-12]. Depths are expressed in g/cm^2 using the bulk densities for each sample set: 1.92 g/cm^3 for 12025, 1.65 g/cm^3 for 60007, 1.5 g/cm^3 for 15008 and for the shaded samples.

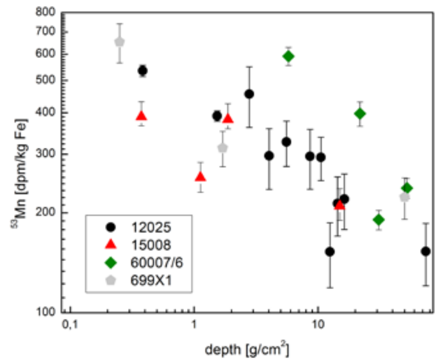

Fig. 1: ^{53}Mn measurements. Black circles correspond to core 12025; red triangles to core 15008; green diamonds to core 60007/6 and grey hexagons to the set of 'skim', 'scoop' and 'under boulder' samples.

^{60}Fe. Preliminary results were shown in [6]; final results are summarized in Table 1 and Fig. 2. First measurements by Cook et al. [13] are also included. Iron and nickel contents for this work are summarized as well. For a complete elemental composition, refer to [5].

^{60}Fe is synthesized not only in stars but also in spallation processes in extraterrestrial matter by cosmic rays. For this reason, the contribution of local, galactic cosmic ray (GCR) production of ^{60}Fe was estimated from measurements in a set of iron meteorites. These meteorites are composed mainly of iron and nickel and serve as reference for the cosmogenic production of ^{53}Mn and ^{60}Fe. The expected contribution of solar cosmic rays (SCR) to production in the lunar samples can be neglected [6, 13].

Fig. 2 shows the ^{60}Fe depth profile constructed with all data made up to this date. The expected contribution of cosmogenic production of ^{60}Fe has been subtracted. From the integrated deposition of about 10^7 at/cm^2 we infer a local interstellar fluence of ^{60}Fe of 4×10^7 at/cm^2.

In Fig. 3 we compare the activities of ^{53}Mn and ^{60}Fe in all our lunar samples with our measurements of iron meteorites. Cook et al. [13] had already concluded that samples from the 60007/6 core had activities consistent with being of local, cosmogenic origin. We found that samples (1,2,4,5,6,7) have a significant ^{60}Fe activity (1σ to 2σ above the estimated GCR contribution, respectively) [6].

The elevated ^{60}Fe activities of the lunar samples are inconsistent with the production by GCR, SCR or meteoritic contamination. However we cannot exclude cosmogenic production alone for the corresponding ^{53}Mn activities. Supernovae produce appreciable quantities of both ^{60}Fe and ^{53}Mn whereas AGB stars produce ^{60}Fe but little ^{53}Mn. Thus, we infer that interstellar material from either or both sources may be present on the lunar surface.

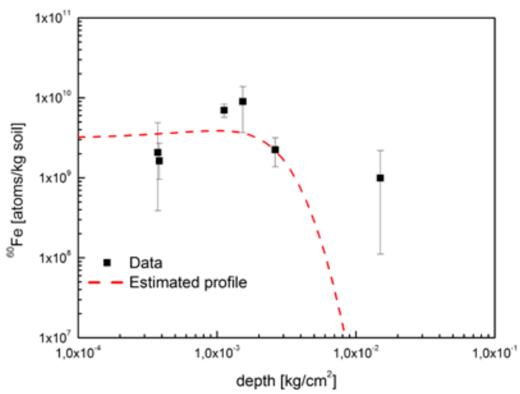

Fig. 2: ^{60}Fe depth profile. The dashed red line is an estimated profile used to integrate the data up to a depth of ~3 cm in the lunar surface.

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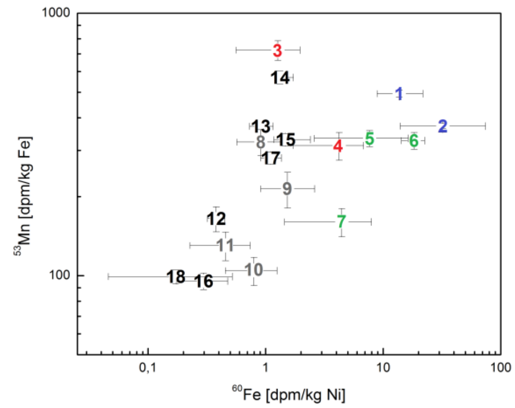

Fig. 3: ^{53}Mn vs ^{60}Fe. 1: 12025,14, 2: 12025,23 (blue); 3: 69921 (‘skim’), 4: 69941 (‘scoop’) (red); 5: 15008,1050, 6: 15008,1051, 7: 15008,1053 (green); 8-11: samples from Apollo16 60007/6 core (grey); 12 to 18: iron meteorites (black) 12 and 13: Dermbach and Emery, respectively [14], 14-18 [15].

Table 1: Compilation of all ^{60}Fe measurements in lunar samples. Data taken from previous work by our group [6, 13].

Sample	Depth	Fe	Ni	^{60}Fe/Fe	^{60}Fe
	[g/cm²]	wt%	[ppm]	[10⁻¹⁵]	[dpm/kg Ni]
12025,14	0.4	12.6±0.3	128±3	$3.1^{+1.9}_{-1.1}$	$13.7^{+8.1}_{-4.8}$
12025,23	1.5	12.5±0.3	145±5	$4.6^{+9.4}_{-3.1}$	$32.1^{+16.1}_{-18.2}$
15008,1050	0.4	9.42±0.21	154±4	$2.3^{+2.6}_{-1.5}$	$7.6^{+8.7}_{-5.1}$
15008,1051	1.1	8.61±0.19	144±4	$7.8^{+1.3}_{-1.3}$	$25.3^{+4.1}_{-4.0}$
15008,1052	1.9	8.24±0.18	159±5	$0.0^{+1.3}_{-0.0}$	$0.0^{+3.8}_{-0.0}$
15008,1053	15	9.20±0.19	213±5	$1.6^{+1.3}_{-1.1}$	$3.7^{+2.9}_{-2.5}$
60007,517	5.8			$1.4^{+0.7}_{-0.5}$	$1.6^{+0.8}_{-0.6}$
60007,516				$1.5^{+1.1}_{-0.9}$	$1.7^{+1.3}_{-1.1}$
60007,515	21.9	4.1 [16]	272 [16]	$2.3^{+1.6}_{-1.0}$	$2.7^{+1.9}_{-1.1}$
60007,514	30.9			$1.2^{+0.7}_{-0.6}$	$1.4^{+0.8}_{-0.6}$
60006,418	52.4			$0.7^{+0.4}_{-0.3}$	$0.8^{+0.5}_{-0.4}$
69921	0.3			$5.9^{+3.2}_{-3.3}$	$3.7^{+2.9}_{-2.5}$
69941	1.7	4.82±0.12	1211±27	$8.2^{+5.1}_{-4.9}$	$8.4^{+2.6}_{-2.5}$
69961	under boulder			$0.0^{+1.3}_{-0.0}$	$0.0^{+0.8}_{-0.0}$