Indication for Supernova Produced ^{60}Fe Activity on Earth

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In a deep ocean ferromanganese crust an excess of ^{60}Fe radioactivity was measured by means of high sensitivity accelerator mass spectrometry. The enhanced concentrations measured in the first two of three layers (corresponding to a time span of 0–2.8 Myr and 3.7–5.9 Myr, respectively) suggest the deposition of supernova produced ^{60}Fe on earth. There is even a weak indication that the flux into the crust was higher about 5 Myr ago.

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The possibility of a supernova explosion near the solar system has been discussed for a long time and, among other things, its consequences on the terrestrial biosphere [1–3]. From the number of supernova explosions observed in spiral galaxies [4], one can conclude that an explosion within 30 pc from the sun is rather unlikely, with a probability of only a few in 10^8 yr. But indirect evidence seems to indicate that such violent events did happen during the geological and biological history. Recently, a very near ($\sim$200 pc) and young ($\sim$680 yr) supernova remnant has been discovered [5]. The observation of radioactivities on earth, which cannot be produced by other processes, would be a clear indication of such an event in the past [6,7].

Several long-lived radioisotopes are possible diagnostic tools to identify their origin from supernovae. We believe that the most promising isotope for this purpose is ^{60}Fe. It is predicted to be produced in significant amounts by supernovae (discussed in a very early publication [8] and, later, in self-consistent supernova calculations [9]). Because of the absence of other significant production channels, the natural abundance is far below the expected supernova induced signal. Other long-lived isotopes, which are nearly free of background (e.g., ^{146}Sm, ^{182}Hf, ^{244}Pu, ^{247}Cm), are produced in supernovae in much smaller quantities. ^{60}Fe has a half-life of (1.49 ± 0.27) Myr [10], long enough to survive the transport to earth. Finally, we have the accelerator mass spectrometry (AMS), a very sensitive method to measure minute concentrations of ^{60}Fe [11].

The measurement of the isotope of interest is most promising if the natural sample has a low accumulation rate as this would cause a relatively high concentration of the isotope under consideration. Therefore we chose a hydrogenetic ferromanganese crust [12] with a growth rate of only a few mm Myr^{-1}. Our sample originates from Mona Pihoa in the South Pacific (19° S, 149° W) at a depth of about 1300 m. An ^{60}Fe depth profile of three layers has been measured, corresponding to an age span of 0–2.8, 3.7–5.9, and 5.9–13 Myr estimated by cobalt dating. It is based on the finding that the cobalt concentration C_{Co} in ferromanganese crusts belonging to the same group as our crust is related to their growth rates R: $R[\text{mm/Myr}] = 1.28/(C_{\text{Co}}[\%] - 0.24)$ [13]. A ^{53}Mn profile ($T_{1/2} = 3.7$ Myr) has also been measured in the same samples. This isotope is dominantly produced by spallation of cosmic rays on iron in solar system dust, which is accreted by the earth. Details of the samples are given in Table I.

Before the AMS measurement, iron (manganese) has been chemically separated from the ferromanganese crust by means of Fe extraction with diisopropyl ether and ion exchange chromatography with a Dowex AG1 resin. From this iron (manganese) negative FeO^- (MnO^-) ions have been produced in a sputter ion source and accelerated by the Munich tandem accelerator as Fe^{11+} (Mn^{11+}) ions up to an energy of 155 MeV. At the end of the beam transport system, tuned to mass number 60 (53) and charge state 11^+, the interfering stable isobar ^{60}Ni (^{53}Cr) was separated by means of a 135° magnet, filled with 6 mbar of nitrogen. Because of the interactions with the gas, the ions assume an average charge state depending on their nuclear charge. Therefore isobaric ions exit the magnet at different positions [14]. Afterwards the ions enter an ionization chamber, where the ^{60}Fe (^{53}Mn) ions can be identified by their position, residual energy, differential energy loss, and angle.

Possible background rates due to different ion species have been determined by means of a 13-Myr-old crust sample (^{60}Fe) and artificial samples, which have been chemically treated in the same way as the crust samples (^{60}Fe and ^{53}Mn).

We have to distinguish between two kinds of background: background from other isotopes, e.g., ^{60}Ni, mimicking ^{60}Fe in the AMS measurement, as mentioned above, and background from ^{60}Fe nuclei in the samples, which are not produced in supernovae. ^{59}Fe is not stable and ^{58}Fe has a natural abundance of only 0.28%. Therefore the ^{60}Fe production by neutron capture can be neglected. Production by cosmic rays is expected to be the main

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TABLE I. Chemical composition and AMS results of the ferromanganese crust samples. The ^{60}Fe/Fe background has not been subtracted, since the one count still could have been due to a real ^{60}Fe ion. The blank sample originates from the ferromanganese crust VA 13-2 [32]. During the ^{53}Mn blank measurements, no background events were detected. Considering the well-known efficiency of the measurement, we have calculated the ^{60}Fe/Fe and ^{53}Mn/Mn ratios. The fluxes $\phi_{^{60}\mathrm{Fe}}$ and $\phi_{^{53}\mathrm{Mn}}$ in the crust are already corrected for the radioactive decay, assuming a constant flux during that interval. The errors (1σ) include the statistical error and the error due to uncertainties of the growth rates and the half-life of ^{60}Fe. Because of the reduced uptake of iron (~1%) and manganese (~5%) from the water into the crust the flux into the ocean is higher.

	Layer 1	Layer 2	Layer 3	Blank
Depth (mm)	0–3	5–10	10–20	38
Fe	15.2%	16.7%	17.9%	24.4%
Mn	17.7%	17.7%	16.5%	17.3%
Co	1.48%	0.84%	1.12%	^{10}Be dated
Growth rate (mm Myr^{-1})	1.0 ± 0.3	2.2 ± 0.7	1.5 ± 0.5	3.75
age (Myr)	0–2.8	3.7–5.9	5.9–13	13
^{60}Fe counts	14	7	2	1
$^{60}\mathrm{Fe/Fe} \times 10^{-15}$	$2.1^{+0.7}_{-0.6}$	$1.4^{+0.8}_{-0.5}$	$0.45^{+0.6}_{-0.3}$	0.25
$\phi_{^{60}\mathrm{Fe}}$ (10^6 $\mathrm{cm}^{-2}\,\mathrm{Myr}^{-1}$)	$1.0^{+0.5}_{-0.3}$	8^{+11}_{-5}	$10^{+22}_{-8.5}$	300
^{53}Mn counts	26	6	7	0[a]
$^{53}\mathrm{Mn/Mn} \times 10^{-13}$	6.6 ± 1.3	$4.0^{+2.4}_{-1.6}$	$2.2^{+1.2}_{-0.8}$	<0.3[a]
$\phi_{^{53}\mathrm{Mn}}$ (10^8 $\mathrm{cm}^{-2}\,\mathrm{Myr}^{-1}$)	$2.6^{+1.2}_{-0.8}$	$6.4^{+5.8}_{-3.4}$	$4.4^{+3.6}_{-2.2}$	...

[a] A chemical blank was used for the ^{53}Mn measurements instead of the "crust blank."

background source of nonsupernova ^{60}Fe in our samples and will be discussed in more detail.

One natural production channel of ^{60}Fe is the spallation of cosmic rays on krypton in the earth's atmosphere. Using ^{36}Cl data, one can estimate the atmospheric ^{60}Fe production. Measurements of the ^{36}Cl content in different Greenland drill core samples yielded ^{36}Cl flux rates of $\sim 6 \times 10^{10}$ $^{36}\mathrm{Cl\,cm^{-2}\,Myr^{-1}}$, which were nearly constant during the whole measured time span of 60 kyr [15]. At the geographical latitude, where our samples have been collected, one has to expect a 1.7 times higher flux rate than in Greenland [16], i.e., $\sim 1 \times 10^{11}$ $^{36}\mathrm{Cl\,cm^{-2}\,Myr^{-1}}$. Contrary to ^{60}Fe, ^{36}Cl is mainly produced on argon, which is 8500 times more abundant in the atmosphere than krypton, the most abundant element in air heavier than iron. The maximum cross section for the $^{84}\mathrm{Kr}(p, 11p14n)^{60}\mathrm{Fe}$ reaction has been computed to 150 μbarn at 800 MeV, whereas it was measured for $^{40}\mathrm{Ar}(p, 2p3n)^{36}\mathrm{Cl}$ to be 64 mbarn already at about 90 MeV [17], so one can exclude a flux rate much higher than 10^4 $^{60}\mathrm{Fe\,cm^{-2}\,Myr^{-1}}$ due to this process.

Cosmic rays also produce ^{60}Fe in extraterrestrial matter which is not shielded by the earth's atmosphere and its magnetic field. It can settle gravitationally on earth and contribute to the ^{60}Fe flux. Unlike in the atmosphere the main target nuclei are ^{62}Ni and ^{64}Ni. In two iron meteorites, as well as in the metallic fractions of two stony iron meteorites, we have measured ^{60}Fe/Ni ratios in the order of 10^{-13} [18]. Extraterrestrial dust has a chemical composition similar to that of CI chondrites: 1.077% Ni, and 18.23% Fe [19]. Taking this ratio into account, one expects an $^{60}\mathrm{Fe}/^{53}\mathrm{Mn}$ ratio of $\sim 5 \times 10^{-4}$ in dust. In addition, most ^{60}Fe in meteorites is produced by secondary galactic neutrons since the cross sections for production by protons are about 1 order of magnitude lower up to energies of about 100 MeV, which is not the case for ^{53}Mn. In interplanetary dust, however, there is no secondary neutron flux, and most of the protons are of solar origin with low energy. Therefore the $^{60}\mathrm{Fe}/^{53}\mathrm{Mn}$ ratio in dust should be reduced to $\sim 10^{-4}$. In the crust, however, we have measured $^{60}\mathrm{Fe}/^{53}\mathrm{Mn}$ ratios of the order of 10^{-2} (see Table I), so cosmogenic ^{60}Fe from interplanetary dust, the dominating source of extraterrestrial matter on earth, cannot explain our findings.

Because of the shielding of the atmosphere, and the low abundance of the main target elements in the earth's crust, the ^{60}Fe/Fe ratio due to cosmic ray production can be expected to be orders of magnitude lower in terrestrial material than in a meteorite and could not have influenced the measured ^{60}Fe signal. Additionally, the crust was shielded with 1300 m of water.

Table I and Fig. 1(a) show the measured ^{60}Fe/Fe (and ^{53}Mn/Mn) ratios. In layers 1 and 2 a clear signal above the background, determined from blank measurements, can be seen. In Fig. 1(b) the implication of these ^{60}Fe concentrations is illustrated. Even the low flux into layer 1 is more than 1 order of magnitude above the expected terrestrial and cosmogenic background. Although the errors are very large, the mean ^{60}Fe flux into layer 2 appears, if corrected for radioactive decay, significantly higher than that of layer 1. Additionally, the $^{60}\mathrm{Fe}/^{53}\mathrm{Mn}$ ratios are too high to be explained by solar system sources (see also Table I).

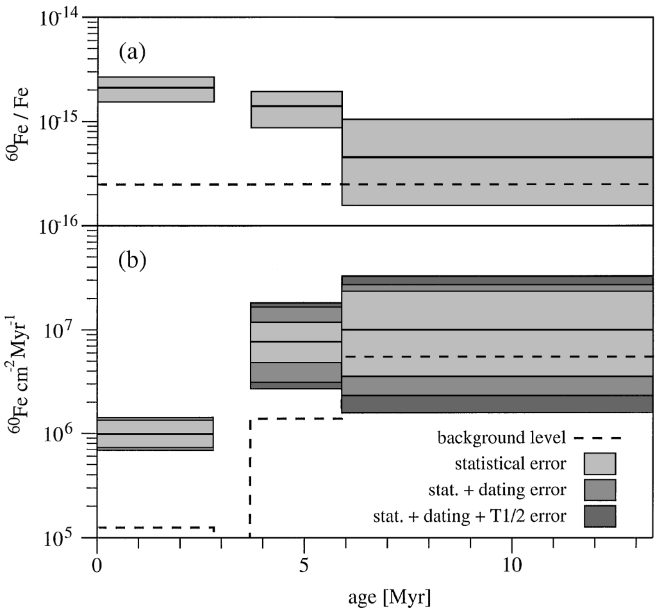

FIG. 1. ^{60}Fe/Fe ratios in the ferromanganese crust and resulting fluxes. In [13], thirteen encrustations with $C_{Co} > 0.5\%$ were dated with the Co method and with the alternative ^{10}Be method [33]. A comparison of both methods yields a mean difference of 33%, which we have used as an estimate for the error of our growth rate determinations. All errors are 1σ. (a) The ^{60}Fe/Fe ratios as measured from the different layers corresponding to different time spans. The signals of the first two layers are clearly above the background. (b) The ^{60}Fe flux (^{60}Fe cm^{-2} Myr^{-1}) in the crust. Here a constant flux during the respective time interval is assumed. The decay of ^{60}Fe is taken into account. Light gray indicates only the statistical errors of the measurements, medium gray includes the error due to the uncertainty of the growth rate, and dark gray also includes the error of the half-life.

Compared to these values, the fluxes of ^{60}Fe and ^{53}Mn into the ocean are higher. To give an estimate for these fluxes, we can compare the already measured ^{53}Mn flux in Antarctic snow [20], where all of the extraterrestrial input is collected. Whereas we have measured a flux of 2.6×10^8 ^{53}Mn cm^{-2} Myr^{-1} into layer 1, the flux derived from the snow measurement was about 20 times higher (6×10^9 ^{53}Mn cm^{-2} Myr^{-1}). The ^{60}Fe flux into the crust is smaller by a further factor of about 5, which one can estimate from an Fe/Mn ratio of 4.2 in the deep Pacific water [21] and an Fe/Mn ratio of 0.86 in the crust analyzed.

The only reasonable explanation of our findings is that the crust contains live ^{60}Fe from one or more recent supernova explosions near the solar system. Several arguments support this conclusion.

Supernova explosions of massive stars are the only producers of significant amounts of ^{60}Fe that we know of. For $M \geq 15 M_\odot$, they typically eject about $10^{-5} M_\odot$ of ^{60}Fe [9], corresponding to a surface density of 4×10^9 ^{60}Fe cm^{-2} on a sphere with $R = 30$ pc. This is in very good agreement with our findings, if one takes into account the reduced iron uptake ($\sim$1%) of the crust.

The ejecta from a supernova at this distance (or closer) can penetrate the solar wind at 1 AU, because the pressure of the blast wave is still comparable to that of the solar wind.

Dust grains can be the carrier of the ^{60}Fe. There is strong evidence from Supernova 1987A that dust formed early after the star exploded. About 500 days after the explosion, newly condensed dust grains were observed which, very likely, are iron rich [22]. However, other core-collapse supernovae, e.g., SN 1993J and SN 1994I, did not show evidence of dust formation two years after the explosion, but the data do not have the same high quality as those of SN 1987A. Several measurements support the evidence for the transport of interstellar dust and gas into the solar system. The dust detector on the Ulysses spacecraft has measured 10^{-13} g sized particles which are heavier than solar dust and have retrograde solar orbits [23]. They are believed to be of interstellar origin. Because of their large size, they have the possibility to enter the solar system. This is underlined by the observation of meteoroids of the size between 15 to 40 μm having velocities in excess of 100 km/s, too high for a bound orbit around the sun [24]. Also, ions of possible stellar origin have been found in the earth's magnetosphere by the SAMPEX satellite [25].

There is evidence that the solar system is embedded in hot x-ray emitting gas, the so-called local hot bubble, extending over a radius of about 100 pc. It was suggested that this hot gas was produced (and may have been reheated) by one or several supernovae exploding during the past 20 Myr [26]. The presence of ^{60}Fe on earth strongly supports this idea. Measurements with the COMPTEL telescope on the CGRO satellite have shown a wide distribution of the characteristic 1.8-MeV γ line from the radioactive decay of ^{26}Al in the galactic plane [27]. Its presumed origin is from nucleosynthesis in supernovae. The ^{60}Fe signal is expected to be 15% of the ^{26}Al signal [28] and just below the detection limit of the COMPTEL detector.

Evidence for extinct ^{60}Fe [29], as well as for other extinct radioactive isotopes such as ^{26}Al [30], has been found in primitive meteorites, indicating that fresh products of stellar nucleosynthesis have once been mixed into the early solar system. The determined value for the abundance of live ^{60}Fe in the early solar system is still consistent with the steady-state value expected in the interstellar medium from which the sun is formed [31].

Based on these arguments, we conclude that the high flux rate of ^{60}Fe found in the middle layer of our sample is indicative of at least one supernova that exploded at a distance of $\sim$30 pc from the solar system $\sim$5 Myr ago. The ^{60}Fe flux into the younger layer can indicate that there is a background of radioactive iron in the solar neighborhood which could originate from relatively young supernova dust in the local hot bubble.

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