^{60}Fe Anomaly in a Deep-Sea Manganese Crust and Implications for a Nearby Supernova Source

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A nearby supernova (SN) explosion in the past can be confirmed by the detection of radioisotopes on Earth that were produced and ejected by the SN. We have now measured a well resolved time profile of the ^{60}Fe concentration in a deep-sea ferromanganese crust and found a highly significant increase 2.8 Myr ago. The amount of ^{60}Fe is compatible with the deposition of ejecta from a SN at a distance of a few 10 pc. The well defined time of the SN explosion makes it possible to search for plausible correlations with other events in Earth's history.

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Several observations indicate that one or even more supernova (SN) explosions occurred rather close to the solar system during the past several millions of years. Such hints originate from different fields in science, like studies of the local interstellar matter [1], analyses of the extreme ultraviolet radiation in the solar vicinity [2], observations of the composition of cosmic rays [3], or even paleobiology [4,5]. Such events can be confirmed by the detection of SN produced material in a terrestrial reservoir [6]. Because of the low terrestrial background, only long-lived radionuclides are capable for this purpose.

The radionuclide ^{60}Fe ($T_{1/2} = 1.49$ Myr [7]) is produced inside the solar system only in minute amounts. Because of spallation reactions with cosmic rays (CRs), ^{60}Fe/Fe ratios in the order of only 10^{-14} have been reported for meteorites [8]. On Earth, a much smaller concentration has to be expected because of the atmospheric shielding from CRs. Naturally occurring nuclear fission cannot produce ^{60}Fe in significant amounts, neither as a fission product [9] nor via fission neutrons, since the target nuclei to be considered are not stable. However, large amounts of ^{60}Fe are produced by stellar nucleosynthesis, as recently confirmed by the detection of the decay of ^{60}Fe in our galaxy by the RHESSI satellite [10].

Although asymptotic giant branch (AGB) stars [11] and (the very rare) carbon deflagration supernovae (SNe) [12] are suggested to produce ^{60}Fe, type II SNe can be considered as the dominant source of ^{60}Fe in the galaxy. Typically, they produce ^{60}Fe in the order of 10^{-5}–10^{-4} solar masses [13,14]. The ejected debris (containing the bulk of ^{60}Fe) can travel 50 pc and even beyond, depending on the density of the interstellar medium (ISM). In case of a SN sufficiently close to our solar system, this material can be directly deposited on Earth, leaving a ^{60}Fe signal far above the natural terrestrial level [6,15]. The half-life of ^{60}Fe is long enough to search for such a signal during the past several millions of years, and we have an ultra sensitive method [accelerator mass spectrometry, (AMS)] to determine ^{60}Fe/Fe ratios down to a level of 10^{-16} [16]. Thus, we believe that ^{60}Fe is a unique indicator for the detection of SN debris on Earth [15,17]. Other long-lived radioisotopes are formed in SNe only in much smaller quantities (e.g., the p-process nuclide ^{146}Sm and the r-process nuclides ^{182}Hf and ^{244}Pu) that make their detection even more difficult [18], or, the natural background on Earth might be too high to obtain a clear and unique signal (e.g., ^{26}Al, ^{53}Mn).

In a previous measurement we have found already an indication for excess ^{60}Fe which can be attributed to a nearby SN [15]. However, a quantification of the deposited material and a dating of the event(s) would allow a determination of the SN's distance as well as a search for plausible correlations with other occurrences in Earth's history.

Ideal reservoirs for detecting such a signature are hydrogenous deep-ocean ferromanganese crusts. We chose a crust (237KD from the cruise VA13/2 [19]) originating from the equatorial Pacific (position 9 °18′ N, 146 °03′ W) at a depth of 4830 m. This crust has a very flat and uniform surface and no indications of inhomogeneous growth. Therefore, a time resolution in the order of a few 0.1 Myr is achievable. Its growth rate was determined by the decrease of the concentration of the cosmogenic radionuclide ^{10}Be with the depth of the layer [20], assuming a constant ^{10}Be flux in the past. For further considerations we will use a growth rate of 2.5 mm Myr^{-1}, which is the average between 2.3 and 2.7 mm Myr^{-1}, deduced from the ^{10}Be/^{9}Be ratio and the ^{10}Be concentration in the crust, respectively.

In order to get a clear and time-resolved signal, 28 layers, between 1 and 2 mm thick, were removed, corresponding to a total time span from 0 to 13 Myr. From each layer, iron was extracted with diisopropyl ether, purified by ion exchange chromatography with AG1 × 8 resin and precipitated with NH_3. The concentrations of ^{60}Fe relative to stable iron were determined with AMS at the Munich MP-Tandem accelerator [16]. Since these concentrations were extremely low, the layers have been measured repeatedly in different measurement series (in total up to 30 h per layer) to reduce statistical and systematic errors. To exclude contaminations during sample preparation, different AMS samples have been independently prepared from each layer.

Figure 1 shows the results of the AMS measurements of the respective layers. The layers from 7 until 13 Myr (20–46 mm) are considered as background caused by the AMS apparatus and/or by impurities in the samples. This is the most reliable background determination, because the samples are chemically nearly identical, but almost no signal is expected for samples older than 7 Myr since practically all ^{60}Fe nuclei have decayed already. In these samples an average ^{60}Fe/Fe ratio of 2.4×10^{-16} has been measured, which is considered by us as background and demonstrates the extremely high sensitivity of our measurements [16]. Most of the younger samples have concentrations that are compatible with this background within 2σ. However, the layers 6–8 mm (2.4–3.2 Myr), 6–7 mm, and 7–8 mm show a clear signal (see Fig. 1). In total, 69 ^{60}Fe events have been detected in those three layers, corresponding to an ^{60}Fe/Fe ratio of 1.9×10^{-15}. Corrected for background and radioactive decay, the ^{60}Fe fluence can be calculated to $\Phi_{60,\mathrm{crust}} = (2.9 \pm 1.0) \times 10^6$ atoms cm^{-2}. The error constitutes from the statistical error of the AMS measurement, the error of the half-life (18%), the error of the ^{10}Be dating (assumed to be 10%), and the 5% error for the crust's density and its iron content, respectively. Although it has a comparable ^{60}Fe anomaly, the ^{60}Fe profile of another crust measured before [15] does not show such a clearly resolved ^{60}Fe pulse. This is due to that crust's nonuniform surface, its relatively high porosity, and the much larger sampling area compared to 237KD. Therefore, the two results are fully compatible.

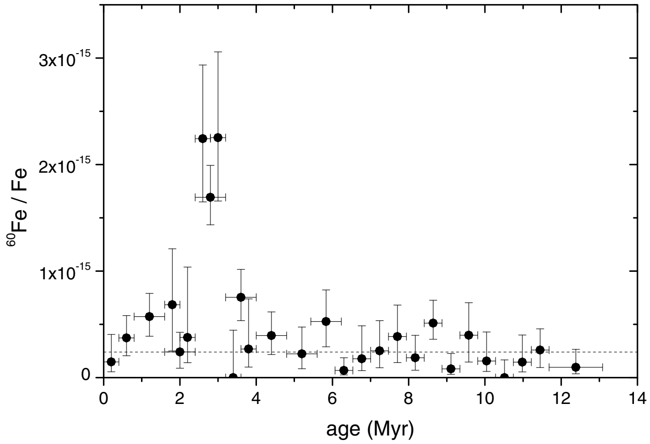

FIG. 1. ^{60}Fe/Fe ratios versus the age of the layer. The data are not corrected for radioactive decay, background, and uptake of iron into the crust. The vertical error bars correspond to a confidence level of 68.3%; the horizontal error bars indicate the time interval covered by the layer. The background level of 2.4×10^{-16} is indicated by the dashed line.

It has to be noted that only a fraction, $U_{\mathrm{Fe}} = \Phi_{60,\mathrm{crust}}/\Phi_{60,\mathrm{tot}}$, of the total ^{60}Fe amount introduced into the water column above the crust ($\Phi_{60,\mathrm{tot}}$) is actually incorporated into the crust. This uptake efficiency, U_{Fe}, cannot be determined directly. For this reason, the concentration of the long-lived radionuclide ^{53}Mn ($T_{1/2} = 3.7$ Myr, produced mainly by cosmic radiation in extraterrestrial dust and meteoroids) was measured, also by means of AMS, resulting in a flux into the crust $\phi_{53,\mathrm{crust}} = 1.7 \times 10^8$ atoms cm^{-2} Myr^{-1}. This value has to be compared with the determined fluxes $\phi_{53,\mathrm{ice}} = (6.1 \pm 1.4) \times 10^9$ atoms cm^{-2} Myr^{-1} in the Arctic ice [21] and $\phi_{53,\mathrm{sed}} = (2.0 \pm 0.9) \times 10^9$ atoms cm^{-2} Myr^{-1} in deep-sea sediments [22]. For these samples, $\phi_{53,\mathrm{ice}} \approx \phi_{53,\mathrm{sed}} \approx \phi_{53,\mathrm{tot}}$ can be assumed. For further estimations, we use an average of $\phi_{53,\mathrm{tot}} = 4 \times 10^9$ atoms cm^{-2} Myr^{-1}, thus $U_{\mathrm{Mn}} \approx 4\%$. Taking into account the different elemental concentrations in the ocean water and the crust, the uptake factor for ^{60}Fe can be estimated to $U_{\mathrm{Fe}} = U_{\mathrm{Mn}}(C_{\mathrm{Mn,water}}/C_{\mathrm{Fe,water}})(C_{\mathrm{Fe,crust}}/C_{\mathrm{Mn,crust}})$, with the concentrations $C_{i,\mathrm{water}}$ of the dissolved element i in the northern Pacific at a depth of 4800 m ($C_{\mathrm{Mn,water}} \approx 0.15$ nmol kg^{-1}, $C_{\mathrm{Fe,water}} \approx 0.6$ nmol kg^{-1} [23]) and the concentrations $C_{i,\mathrm{crust}}$ of element i in the manganese crust ($C_{\mathrm{Mn,crust}} = 26\%$, $C_{\mathrm{Fe,crust}} = 15\%$), resulting in $U_{\mathrm{Fe}} \approx 0.6\%$. Besides this correction, one has to take into account that the ^{60}Fe is spread over the Earth's surface, which has an area of 4 times its cross section, and therefore yields to a local interstellar fluence $\Phi_{60,\mathrm{LIS}} = 4/U_{\mathrm{Fe}} \times \Phi_{60,\mathrm{crust}} \approx 2 \times 10^9$ atoms cm^{-2}.

How does this signal compare to that of a possible nearby SN? A type II SN of solar metallicity typically ejects 2×10^{-5} solar masses of ^{60}Fe [13], corresponding to 4×10^{50} atoms. Distributed over a sphere with a radius $R \approx 40$ pc ($A = 2 \times 10^{41}$ cm^2), the surface density equals our observed value of $\phi_{60,\mathrm{LIS}}$. (Other calculations [14] yield higher ^{60}Fe masses and therefore a higher distance of the SN.) Following the discussion in [4], this result is very reasonable, because a much lower distance is very unlikely and should have left additional marks on Earth, whereas for a much higher distance the explosion front would not have reached the Earth. As a location of the SN either the B1 subgroup of the Pleiades [24] or the LCC subgroup of the Scorpius-Centaurus Association [5] have been proposed. Both stellar groups, which are expected to have SN rates of roughly one per Myr, have been traced back to solar distances of their centers of 100 pc and below.

In this context, it is still an open question whether such a close SN might have implications on Earth's biosphere. In several publications [4,5,25], it has been suggested that an effect could be due to enhanced solar ultraviolet radiation as a consequence of the ozone depletion by CRs. UV radiation can reduce phytoplankton and biomass, which are propagating to other species of zooplankton. Also, a "cosmic-ray winter" lasting for some thousands of years because of a large increase in the Earth's cloud cover has been considered [4]. However, all these considerations are based on the assumption of a substantial increase in the CR flux for only a relatively short period.

To evaluate this assumption, we have performed more detailed numerical calculations on the evolution of supernova remnants (SNRs) including particle acceleration. Although the direct observational evidence for acceleration of CRs up to energies of 10^{15} eV nuc^{-1} is only marginal as detected by the supernova remnant SN1006 [26], it is commonly accepted that a first order Fermi mechanism operating in shock waves is the most promising mechanism for the source of galactic CRs. For the numerical simulations [27] of a SNR evolution in spherical symmetry, we have assumed a standard SN energy of 10^{51} ergs. The time-dependent acceleration of CRs is included through a hydrodynamical formalism characterizing the cosmic rays where a mean diffusion coefficient κ_{CR} as well as the adiabatic coefficient $\gamma_{\mathrm{CR}} = 4/3$ have to be specified in accordance with the observed properties of CRs. We have adopted the standard value of $\kappa_{\mathrm{CR}} = 10^{27}\ \mathrm{cm}^2\,\mathrm{s}^{-1}$. The intensity and the duration of the CRs depend also on the gas density of the surrounding ISM where we have chosen values between 0.1 atoms cm^{-3} and 1 atom cm^{-3}. During the SNR evolution, the explosion energy is shared between the kinetic, the thermal, and the cosmic-ray energy. In particular, the SNR evolution at later stages is characterized by radiative losses of the thermal plasma. Clearly, the onset of this radiative phase depends on the particle density and occurs for the adopted values of the interstellar medium for radii larger than about 20 pc [28]. Hence, the amount of cosmic rays accelerated by the remnants shock wave can only be calculated if the radiative cooling effects are taken into account. A typical result for 0.5 atoms cm^{-3} is depicted in Fig. 2 where the grid surface shows the temporal variation of the CR energy density relative to the initial value for distances from 30–50 pc from the explosion center. After the shock wave has passed, the CR intensity decreases due to the adiabatic expansion of the remnant, and the further evolution is then characterized by a diffusive transport of the accelerated particles from the shock wave towards the interior. For a remnant of radius R, the diffusion time scale can be estimated according to $t \sim R^2/\kappa_{\mathrm{CR}}$, yielding values between 270 and 750 kyr for 30 pc $\leq R \leq$ 50 pc, respectively. In order to compute the CR intensity, the SNR simulations have to be carried throughout the radiative cooling phase and we find that a SN at a distance of 40 pc increases the CR intensity only by about 15%, however, for a period of some 100 kyr. Less ISM density yields an even lower CR intensity. In any case, the amplitude of the CR increase is not enough for a significant reduction of the ozone layer.

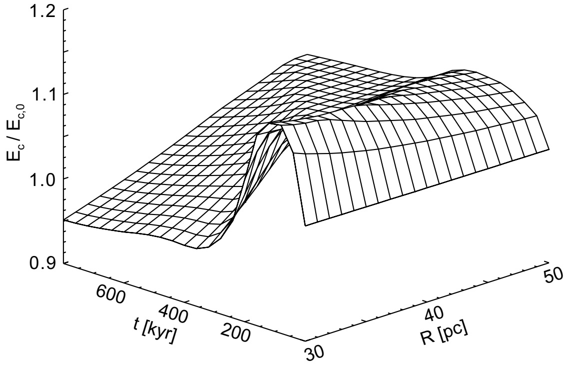

FIG. 2. Temporal variation of the cosmic-ray energy density E_c relative to the initial value $E_{c,0}$ for distances from 30–50 pc from the explosion center. The calculations have been performed for an ISM density of 0.5 atoms cm^{-3}.

On the other hand, a correlation between the cosmic-ray flux, the Earth's lower cloud cover, and thus the Earth's climate has been observed [29]. It has not yet been established that such an increase of the CR intensity could have had a significant influence on the Earth's climate. However, speculatively, we can say that the consequences are profound if the correlation can be confirmed. There is a coincidence between the onset ($\approx$3 Myr) and the duration ($\approx$300 kyr) of the enhanced cosmic-ray flux and a change in the African climate. The African climate shifted towards more arid conditions about 2.8 Myr ago, evidently resulting from remote forcing by cold North Atlantic Sea surface temperatures associated with the onset of Northern Hemisphere glacial cycles [30]. In this work, it is also suggested that this shift towards more arid and open conditions mediated Pliocene-Pleistocene speciation occurrences and that some of the major events in early hominid evolution appear to be coeval with the African climate changes.

In conclusion, we find that the measured ^{60}Fe anomaly at $t = 2.8$ Myr gives strong evidence for a nearby SN source. The CR flux enhancement due to an expanding SNR is estimated to be around 15% for a few 100 kyr (for an ISM density of 0.5 atoms cm^{-3}). The corresponding anomalies of cosmogenic radionuclides such as ^{10}Be might be experimentally detected. If an increase of the cosmic-ray flux is accompanied by a decrease in the mean Earth's temperature, then this SN could have triggered a climate change that possibly caused significant developments in hominid evolution.

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