Search for Supernova-Produced ^{60}Fe in a Marine Sediment

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An ^{60}Fe peak in a deep-sea FeMn crust has been interpreted as due to the signature left by the ejecta of a supernova explosion close to the solar system 2.8 ± 0.4 Myr ago [Knie *et al.*, Phys. Rev. Lett. **93**, 171103 (2004)]. In an attempt to confirm this interpretation with better time resolution and obtain a more direct flux estimate, we measured ^{60}Fe concentrations along a dated marine sediment. We find no ^{60}Fe peak at the expected level from 1.7 to 3.2 Myr ago. Possible causes for the discrepancy are discussed.

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Some recent studies suggest that one or more supernova (SN) could have exploded near the solar system in the past 10 Myr [1,2]. Ellis, Fields, and Schramm [3] discussed possible isotopes that might be used to look for traces of such a nearby SN in geological reservoirs. An excess of ^{60}Fe ($t_{1/2} = 1.49$ Myr) has been observed in a FeMn crust [4,5]. This excess was interpreted as the signature left by a nearby SN explosion 2.8 ± 0.4 Myr ago. In this Letter, we present results of a concerted effort to confirm the ^{60}Fe result of [5], including a different chemical treatment of the same FeMn crust as well as using a different geological reservoir: marine sediment. The faster accumulation rate of sediments potentially allows a refinement of the time resolution as well as a more direct estimate of the flux.

The dating of the crust is a critical parameter in this study since it defines the time span over which ^{60}Fe measurements should be done along the sediment core. The dating of the crust reported in [5] was taken from ^{10}Be measurements [6] in material from a drill hole separated by a distance of at least 20 cm from that used for the ^{60}Fe measurements. For this reason, the ^{10}Be dating has been repeated in another drill hole right next to that one where the ^{60}Fe signal was found. Twelve layers of 1 mm were milled off and dissolved in aqua regia after adding about 2 mg of a stable Be carrier. Sample preparation has been described in [7]. The ^{10}Be/^{9}Be ratios have been measured by accelerator mass spectrometry (AMS) at the VERA lab in Vienna [8].

The results are depicted in Fig. 1. Except for the samples near the surface, one can see that the ^{10}Be concentration can be fitted to an exponential in the depth interval of 2–10 mm, which indicates a constant growth rate. Near the surface, the ^{10}Be data could suggest rapid diffusion or a much higher growth rate. The latter explanation was deduced in [6] from ^{230}Th measurements. Furthermore, the constant ^{10}Be data between 0 and 2 mm could not be identified in [6] since those measurements had a 2 mm depth resolution. To determine the age T_d at a depth $d \geq 2$ mm, we use the relation $T_d = t_{1/2}(^{10}\mathrm{Be}) \times [\ln(C_0/C_d)]/0.693$, with C_d the ^{10}Be concentration at depth d, C_0 that at $d = 2$ mm, and $t_{1/2}(^{10}\mathrm{Be})$ the ^{10}Be half-life. C_d is defined by the experimental data, while C_0 was calculated by extrapolation of the exponential fit.

When we began this work, the accepted value for $t_{1/2}(^{10}\mathrm{Be})$ was 1.51 Myr. Recently, a value of 1.36 ± 0.07 Myr has been suggested [9]. Using $t_{1/2}(^{10}\mathrm{Be}) = 1.36$ Myr and fitting the range from 2 to 10 mm to a single exponential gives a growth rate of 2.37 mm/Myr, and the depth interval of the ^{60}Fe signal (6–8 mm) corresponds to a time span of 1.69–2.53 Myr. The data from [6], if scaled vertically (which does not influence the chronology) by a factor of 1.15, overlap those from the present work (Fig. 1). The age for the 6–8 mm interval found above compares with 2.4–3.2 Myr cited in [5] based on the dating of [6],

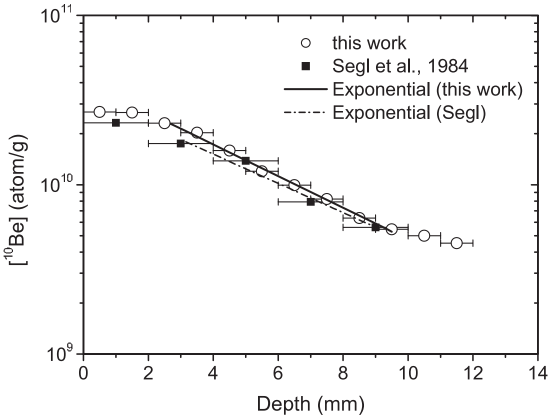

FIG. 1. [^{10}Be] (atom/g crust) versus the depth of the layer. The line is an exponential fit (2–10 mm) whose slope corresponds to a growth rate of 2.37 mm/Myr [with $t_{1/2}(^{10}\mathrm{Be}) = 1.36$ Myr].

where the exponential was fitted from 0 to 16 mm, using $t_{1/2}(^{10}\mathrm{Be}) = 1.5$ Myr. The growth rate adopted in [5] was an average between those deduced from ^{10}Be concentrations and $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratios given in [6]. To cover all possibilities, we investigated our sediment core over the time interval 1.68–3.2 Myr. The value of 1.69 Myr is a lower limit as (i) the growth rate of the 2 first millimeters cannot be infinite (based on a ^{230}Th profile, Segl *et al.* [6] calculated an age of 0.46 Myr at a 1.4 mm depth. Considering that, the time span of interest for the signal becomes 2.15–2.99 Myr) and (ii) we used ^{10}Be concentrations to calculate the growth rate of the crust, whereas growth rates from $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratios are expected to be lower [6], leading to calculate older ages. In fact, a lower ^{9}Be concentration was found in [6] near the surface, which may explain why our ^{10}Be concentration in the surface is lower than expected based on the fit from 2 to 10 mm.

The sediment was sampled from an Ocean Drilling Program (ODP) core, Leg 162, site 985 (66°56.5′ N, 6°27.0′ W) in the North Atlantic [10]. The average sedimentation rate is 3 cm/kyr, *in situ* density ∼1.6 $\mathrm{g/cm^3}$, and average [Fe] in the authigenic phase ∼0.5 wt%. A continuous sequence of 30 cm long samples was taken, corresponding to time intervals of 10 to 15 kyr each. Details of the dating of the sediment core, using paleomagnetic and stratigraphic information, are given elsewhere [11].

The deep-sea sediment chosen in this study is characterized by an accumulation rate about 3 orders of magnitude higher than that of FeMn crusts and therefore allows a much better time resolution. Where FeMn crusts are authigenic objects, that is, composed of species precipitated and adsorbed from the soluble phase of the ocean, sediments are composed of a larger variety of geochemical phases, particularly the aluminosilicate phase which contains most of the stable Fe of the sediment. Since the iron in this aluminosilicate phase is not equilibrated with the soluble ^{60}Fe in the ocean, its inclusion would lower the $^{60}\mathrm{Fe}/\mathrm{Fe}$ ratio compared to the authigenic phase. Therefore, we used a chemical procedure to isolate the authigenic fraction. The chemistry has been detailed elsewhere [11,12]. The AMS measurements were done at the facility of Munich [13]. In order to economize accelerator time, some samples were combined in groups of two or four.

To verify that our chemistry was indeed dissolving the phase containing the ^{60}Fe seen in the crust, we tested it on samples from a drill hole of the same crust used in [5]. Although our statistics are more limited, we observed an $^{60}\mathrm{Fe}/\mathrm{Fe}$ peak consistent with that found in [5] (Fig. 2). While our results suggest a slightly shallower depth than found in [5], this may be due to a small difference in the peak position at the two locations and/or in the sampling intervals themselves.

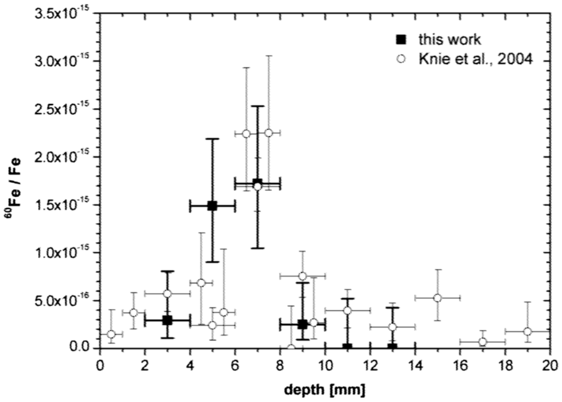

FIG. 2. Confirmation of the ^{60}Fe signal of Knie *et al.* [5] in the same FeMn crust using the chemical leaching procedure developed for the analysis of the sediment.

The ^{60}Fe signal in the FeMn crust was observed in [5] over a depth interval corresponding to about 800 kyr. However, the estimated deposition time of a SN ejecta on Earth is likely to be of order ∼10 kyr [14], and the residence time of Fe in the ocean is much smaller than this value. Because it can be sampled at a much higher time resolution, we expected the $^{60}\mathrm{Fe}/\mathrm{Fe}$ signal in the sediment to be much higher than in the crust. While iron can be reduced and become mobile in some sedimentary systems, this effect is generally limited to a few tens of centimeters below the sediment surface. Even if such an effect were present, we would not expect it to significantly distort the signal since our samples were 30 cm in length. On the basis of the measured $^{60}\mathrm{Fe}/\mathrm{Fe}$ in the crust and an estimated uptake factor, Knie *et al.* [5] inferred a ^{60}Fe fluence of 2×10^{9} $\mathrm{at/cm^2}$ in the interstellar medium. The latter corresponds to a ^{60}Fe fluence on Earth of 1.4×10^{8} $\mathrm{at/cm^2}$ when corrected for radioactive decay. Because the input of stable Fe to the ocean is not uniform, the expected $^{60}\mathrm{Fe}/\mathrm{Fe}$ in our sediment cannot be directly inferred from that observed in a crust from a different location. To estimate this, we assume that the ^{60}Fe fluence in the sediment will be the same as that deposited on the surface water above it (i.e., 1.4×10^{8} $\mathrm{at/cm^2}$), an assumption that seems reasonable taking into account the short oceanic residence time of Fe. Using the parameters of the sediment given earlier, we calculate the flux of stable authigenic iron as $0.5\ \mathrm{wt\%} \times 3\ \mathrm{cm/kyr} \times 1.6\ \mathrm{g/cm^3} = 2.6 \times 10^{20}\ \mathrm{at/cm^2\,kyr}$. Assuming a deposition time of 10 kyr for the ^{60}Fe, we can thus calculate that the expected $^{60}\mathrm{Fe}/\mathrm{Fe}$ ratio in the authigenic phase of the sediment is 5×10^{-14} (Fig. 3). If the sampling or the effective measuring interval is >10 kyr, then the expected signal will be proportionally reduced. This is the case for the time intervals corresponding to samples which were grouped by two or four for the AMS measurements, as mentioned above.

As seen in Fig. 3, the measured $^{60}\mathrm{Fe}/\mathrm{Fe}$ ratio along the sediment core from 1.68 to 3.2 Myr is much lower than the expected value. Around $t \sim 2.25$ Myr, samples were measured for longer times, because we initially had a spurious indication of a peak in this region. However, upper limits for these measurements are comparable to those in the

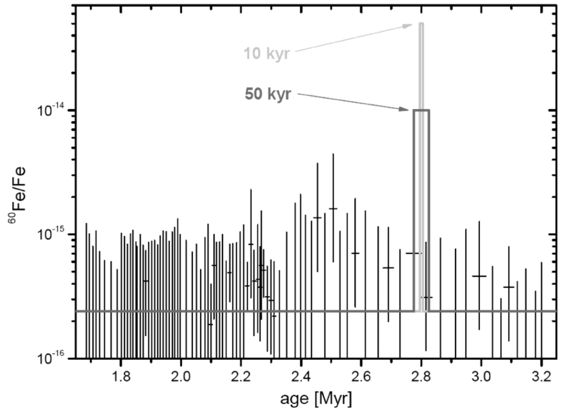

FIG. 3. Measured ^{60}Fe/Fe (note log scale) in the sediment core. Vertical error bars (68.3% confidence level) were calculated using counting statistics appropriate for small numbers [21]. Horizontal error bars on the experimental data represent the time span covered by the measurement where samples were measured individually or combined by 2 or 4 (see text). The expected SN signal (shown at 2.8 Myr) was calculated assuming samples were measured individually or combined by 4. The horizontal line at 2.4×10^{-16} is the background level given in [5].

other time range. We thus have no evidence for a ^{60}Fe signal at the levels expected based on the local interstellar ^{60}Fe fluence given in [5] and the assumptions described above. There are at least four possible explanations: (i) The deposition time of ^{60}Fe is much longer than the simple expectation for a SN. (ii) The interstellar fluence derived in [5] is overestimated due to an error in the uptake efficiency. (iii) Our sediment core has not recorded the expected global signal. (iv) The excess of ^{60}Fe observed in the FeMn crust is from another source which we have not identified.

We first examine the assumed deposition time of 10 kyr. The ^{60}Fe signal observed in [5] corresponded to a time interval of ~800 kyr. However, we assumed that this was due to the inherent time resolution associated with the growth and sampling of the FeMn crust. It is interesting to examine our results compared to predicted ones for a signal ≫ 10 kyr. To do this, we show in Fig. 4 the running means calculated by combining our data in intervals of ~400 and 800 kyr, respectively. If we neglect the structure in the curves and assume all of the events are background, we get an average value of $^{60}\mathrm{Fe/Fe} = 2.3 \pm 0.3 \times 10^{-16}$, as shown by the horizontal dotted lines in Fig. 4(a). Within 2σ, this is consistent with all of the data in Fig. 4(a) and is almost exactly equal to the background signal found in [5], with the same AMS setup, in the crust beyond the peak region. Alternatively, we can note that the lowest observed signal ($1.0 \pm 0.4 \times 10^{-16}$) in Fig. 4(b), at ~1.9 Myr, is significantly less than the expected background. If we consider this as the real background for our measurements, we find signals of marginal significance in the 400 kyr running mean of $2.6 \pm 0.8 \times 10^{-16}$ centered at ~2.4 Myr and $2.9 \pm 1.7 \times 10^{-16}$ at 2.65 Myr. Even for such long deposition times, there is a discrepancy with the predicted signal. This might be accommodated by the uncertainty in the uptake factor of [5] or by our assumption that the ^{60}Fe fluence at the location of our sediment is quantitatively representative of the average global value. While statistically valid, we hesitate this latter interpretation because it requires that the background level was rigorously constant for all of our measurements (done over several months). However, the sources of background are not fully identified and only speculations are possible.

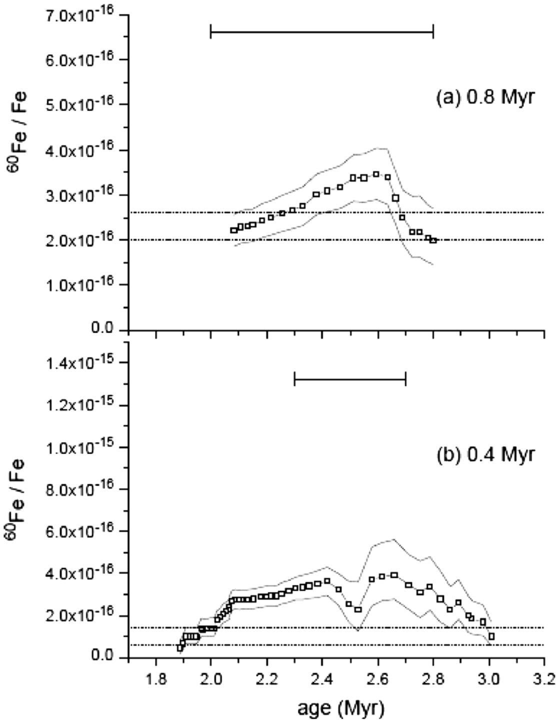

FIG. 4. Data in Fig. 3 plotted as (a) 800 and (b) 400 kyr running means and standard deviation (SD). Scale bars represent the expected ratio in our sediment calculated from the fluence given in [5]. Horizontal dotted lines in (a) correspond to ±1 SD limits of the whole data set and in (b) to the lowest significant signal measured during these experiments (see text).

What would be the implications of a ^{60}Fe signal lasting ≫ 10 kyr? It is unlikely that such a signal could originate from a fast (i.e., pressure sufficient to overcome the solar wind) SN shock wave traversing the solar system. One might imagine, however, such a signal coming from the encounter of the solar system with a locally enhanced concentration of SN ejecta from a shock wave that had slowed down, or even stopped, relative to the local interstellar reference frame (LSR). If we assume a velocity of ~15 km/s for the solar system relative to the LSR, then the size of a feature traversed in 400 kyr is ~6 pc. This is roughly the size of the local interstellar cloud in which the solar system is currently embedded [15]. It is believed that there are many such warm clouds within the Local Bubble (LB), a region of hot, low density gas in which the solar system has been traveling for several million years. While there is still considerable discussion on the exact formation mechanism of the LB (e.g., [16] and references within), most of these involve SN explosions in one way or another.

Thus it seems quite plausible that some of the clouds in the Bubble contain relatively fresh SN ejecta and that the solar system encountered such a cloud ~2.5 Myr ago.

If the SN ejecta did not have sufficient pressure to overcome the solar wind, then the ^{60}Fe could not have entered the solar cavity in ionized form but would instead have to have been in the form of neutral atoms or condensed material with a relatively large size of >0.1 micron (smaller particles are believed to be excluded due to their charge [17]); see also the discussion in [4]. Since most of the Fe in the warm clouds is believed to be in the condensed form [16], this latter scenario is perhaps not unreasonable. A related question is how such Fe could have been incorporated into the FeMn crust. Either it would require that the particles containing the Fe were dissolved in the ocean and then incorporated in the authigenic phase or that they accumulated as solid particles in the crust but were dissolved during the extraction process, including that used in the present study. In either case, we would expect to find a corresponding signal in our sediment.

In fact, Basu *et al.* [18] have recently argued that the ^{60}Fe signal observed in [5] results from incorporation of "micrometeorites" in the crust (they do not make it clear whether they are referring to actual micrometeorites, i.e., objects which have been exposed in interplanetary space as small objects, or atmospheric ablation products of much larger "classical" iron meteorites). Such a source of ^{60}Fe was not considered in [5]. The ^{60}Fe is assumed to have come from the interaction of galactic cosmic rays with the Ni in these objects. Basu *et al.* [18] estimate the ^{60}Fe concentration from the saturation concentration found in iron meteorites, typically 8×10^8 atoms/g Ni [19]. This can be compared to the ^{60}Fe/Fe in the crust [5] (corresponding to $\sim 4 \times 10^7$ atoms/g Fe when corrected for decay). This would require that the crust have a ratio of extraterrestrial $\mathrm{Ni(Ni_{ex})/Fe} = 0.05$. Since the ratio of total Ni/Fe in the crust, including the layer containing the ^{60}Fe, is $\sim 0.5\%/15\% = 0.03$ [20], this hypothesis is clearly untenable. The argument for rare large particles accounting for the ^{60}Fe in the crust is also inconsistent with the fact that the signal was observed every time a sample was measured of the layers between 6 and 8 mm depth: on successive layers 6–7 and 7–8 mm, as well as on the 6–8 mm layer [5], and after drilling a new hole in this crust (this work, Fig. 2). This would be an extremely improbable accident. More specifically, Basu *et al.* claim that a single micrometeorite of 500 μm diameter of composition like that of the meteorite Dermbach, i.e., ~0.26 mg Ni containing 2.0×10^5 atoms of ^{60}Fe, can account for the ^{60}Fe measured in the crust [5]. Yet, in [5], the reported fluence of $\Phi_{60\mathrm{Fe,crust}} = (2.9 \pm 1.0) \times 10^6$ atoms/cm^2 (background and radioactive decay corrected), and this measurement was made in a sample from a drill hole that had a diameter of 13 mm. Therefore, the crust sample contained $(3.9 \pm 1.3) \times 10^6$ atoms ^{60}Fe which cannot be accounted for by a 500 μm particle of the type hypothesized in [18] by more than an order of magnitude.

In summary, our results appear to be inconsistent with the traversal of the solar system by a young SN shock wave having the ^{60}Fe fluence estimated in [5]. Our upper limits are also lower than the predicted value for longer duration signals such as those that might result from the interaction of the solar system with SN ejecta that has greatly slowed down or come to rest with respect to the LSR. The most optimistic interpretation of our results would allow one (or two) signals of ~400 kyr duration and a fluence ~5 times less that estimated in [5]. The discrepancy could possibly be due to the fact that our sediment has not quantitatively registered the average global signal. Additional experiments with other sediment cores would help to clarify this possibility. More probable, however, is an overestimate of the ^{60}Fe fluence in Ref. [5]. Some of the authors are involved in experiments to remeasure ^{53}Mn in Antarctic ice which might help to better constrain the ^{53}Mn uptake factor on which the ^{60}Fe fluence is based.

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