Discovery Prospects for a Biogenic Supernova Signature

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Abstract

Within the universe, the astrophysical sites responsible for the production of radioactive ^{60}Fe, of half life 2.62 Myr, are primarily confined to two: Type 1a supernovae and massive stars that end their lives as Type II supernovae. Approximately 2.8 Myr before the present, our planet was subjected to the debris of a supernova explosion. The terrestrial proxy for this event was the discovery of *live* atoms of ^{60}Fe in a deep sea ferromanganese crust, from which the terrestrial flux of supernova ^{60}Fe was deduced. The signature for this supernova event should also be contained in microfossils produced by magnetotactic bacteria extant at the time of the Earth-supernova interaction. Using estimates for the terrestrial supernova ^{60}Fe flux, combined with our empirically derived microfossil concentrations of a deep sea drill core, we deduce a conservative estimate of the ^{60}Fe fraction as $^{60}\mathrm{Fe/Fe} \approx 3.6 \times 10^{-15}$; this value sits comfortably within the sensitivity limit of present accelerator mass spectrometry capabilities. The implication is that a biogenic signature of this cosmic event resides, and is detectable, in the Earth's fossil record.

Keywords: Earth; Geophysics; Geological processes; Minerology

1. Introduction

Within our Universe supernovae (SN) have been largely responsible for elemental synthesis beyond those few nuclear species (H, He, Li, Be) produced during the first few minutes after the Big Bang. Radioactive ^{60}Fe, with a newly revised half-life of 2.62 Myr [1], has a β-decay scheme [1] that gives rise to two gamma-rays, from the decay of excited states in ^{60}Ni, with energies, $E_{\gamma_1} = 1173$ keV and $E_{\gamma_2} = 1332$ keV. It is an important radionuclide for tracing active nucleosynthesis within our galaxy because its half-life is much shorter than stellar lifetimes, yet also long as compared to the expansion time scales of SN ejecta thereby allowing sufficient amounts of it to survive the opaque ejecta phase and be susceptible to observation with gamma-ray astronomy. Recent gamma-ray astronomy studies have detected these gamma-rays within the inner radiant portion of the galactic plane [2], known to be a site of massive stars. This is consistent with the present understanding that the main cosmic site for ^{60}Fe production is massive stars which produce ^{60}Fe during their helium- and carbon-shell burning phases [3, 4], and also from the shock heating of the helium and carbon shells during the core collapse stage of their evolution [3–5]. Carbon deflagration SN are another site for ^{60}Fe production [6, 7]. These are capable of producing of sizable amounts of ^{60}Fe and are the result of a thermonuclear deflagration within the core of a carbon-oxygen white dwarf (WD). In such a scenario, accretion of matter from a binary companion star onto the white dwarf's surface forces the mass of the white dwarf toward the Chandrasekhar limit of $\approx 1.4\ M_{\odot}$. The carbon and oxygen within the composition of the WD ignite under degenerate conditions, driving the material to nuclear statistical equilibrium (NSE). Electron capture on nuclei with low electron capture thresholds "neutronizes" the material. These two effects drive NSE mixture to the neutron-rich side of the iron peak nuclei. The nuclear energy liberated exceeds the gravitational binding energy of the WD, thus resulting in a disruption of the star known as

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a Type 1a supernova. Both supernova 1a and II are capable of producing up to $\sim 10^{-4}$ solar masses of ^{60}Fe per event.

Thus, ^{60}Fe is a definitive proxy for SN activity its detection in terrestrial geological reservoirs would be direct evidence for an Earth-supernova interaction.

Using the accelerator mass spectrometry (AMS) facility [8, 9] of the Maier-Leibnitz-Laboratory, operated by the Munich universities, *live* ^{60}Fe atoms were discovered in a deep sea ferromanganese crust extracted from the central Pacific Ocean and is reported in the works of Knie et al. [10, 11]. Shown in Fig. 1 is the ^{60}Fe/Fe atom-ratio within the crust versus epoch as determined with respect to the surface of the crust. A clear concentration "spike" in ^{60}Fe occurs centred around 2.8 Myr before the present, with a width in time of $\approx$ 500 kyr. Each datum point in the ^{60}Fe spike is comprised of ≈ 17 counts and the measured atom concentration is $^{60}\text{Fe/Fe} \approx 2 \times 10^{-15}$ [11].

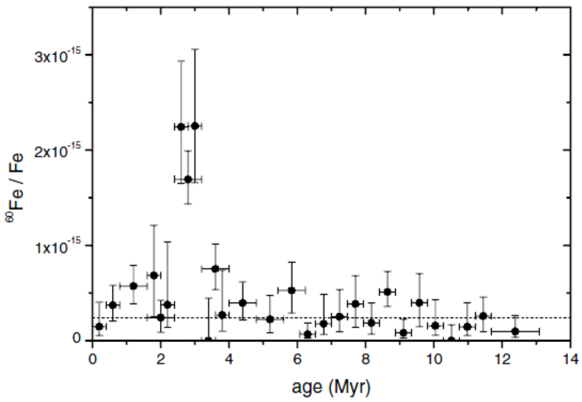

Figure 1: Ratio of ^{60}Fe/Fe, as a function of age before the present, as measured in a central Pacific deep sea ferromanganese crust via AMS measurements [11].

From these data, it has been concluded that our planet was exposed to the debris of a supernova $\approx$ 2.8 Myr before the present. Furthermore, theoretical efforts [12] suggest that the best candidate for the SN source, based on distance estimators, is the the Scorpius-Centaurus OB association. This association is already known to have been a site of active supernova explosions going back as far as 10 Myr, and these explosions are, thus, most likely responsible for the low density region of the local interstellar medium – the Local Bubble – in which the solar system presently resides [13].

We propose here another terrestrial reservoir in which a biogenic signature of this supernova should be contained; namely, microfossils comprised of single-domain crystals of magnetite (Fe_3O_4), produced by Magnetotactic bacteria extant with this SN event. We have obtained a deep ocean drill core from the Ocean Drilling Program (ODP) and have performed magnetic remanence measurements on that portion of it contemporaneous with the SN event so as to characterize its microfossil content. From our measurements, we conclude that these fossils should contain ^{60}Fe/Fe concentrations safely within the sensitivity limits of AMS and, moreover, that there is sufficient quantity of microfossils in our drill core to perform the AMS measurements.

2. Microfossil Reservoir

Magnetotactic bacteria are single cell eukaryotes that are ubiquitous in both freshwater and marine environs [14–23] in both the northern and southern hemispheres. These bacteria have found their ecological niche living in the so-called oxic-anoxic transition zone (OATZ) [24, 25], where the vertical oxygen gradient sharply drops, resulting in a well defined boundary between oxic and strongly anaerobic regimes. This boundary tends to occur at, or just below, the sediment-water interface, and as such it is here where magnetotactic bacteria achieve their highest population density.

These organisms are unique in that they produce intracellular crystals of chemically pure, single-domain (SD) magnetite (Fe_3O_4) [26], which, depending on the specific species, are then assembled into a linear chain, or bundle, of magnetite crystals called the *magnetosome* [25]. Arrangement of the magnetosome in a linear chain increases the total magnetic anisotropy, giving the chain an enhanced magnetic stability [27]. Transmission electron micrograph images [26, 28] reveal these crystals to be of crystallographic perfection and, depending on the specific species, the crystals come in a variety of shapes [25]. The purpose of the magnetosome, and why it was ultimately selected for in the course of the evolutionary history of these organisms, is still a matter of research; one possible explanation is that the magnetosome acts as a passive compass to align the bacteria along the Earth's magnetic field lines. This magnetic alignment makes magnetotactic bacteria move along straight lines (magnetotaxis), in contrast to the biased random walk displacement common for chemotaxis. A combination of chemo- and magnetotaxis (originally referred to as magneto-aerotaxis) is thus believed to be a more efficient means, than that of chemotaxis alone, for finding the correct living conditions in a chemically stratified environment [29].

Supernova iron arriving in the Earth's atmosphere in atomic/molecular form, or in the form of nanometer-sized oxides, is expected to rapidly react in aqueous environments via dissolution, binding to organic ligands, and re-precipitation in the form of poorly crystalline ferrous hydroxides (FHO) [30]; ^{60}Fe is thus rendered to the oceans in dissolved form (bound to organic ligands) or as FHO. In this form, Fe has a very short residence time of < 100 yr [31] in the global ocean system and finally becomes incorporated into the sediment by settling, or through chemical reactions involving the dissolved form such as with ferromanganese crusts. Organic complexes, FHO, and iron oxide nanoparticles incorporated into the sediment are easily dissolved and reprecipitated through sedimentary redox reactions. Specialized classes of bacteria actively drive the iron redox cycle by reducing available Fe(III) to Fe(II), which is then incorporated into new minerals such as magnetite (Fe_3O_4) and greigite (Fe_3S_4). Among these, dissimilatory metal reducing bacteria (DMRB), which extracellularly induce the precipitation of secondary iron minerals such as siderite (Fe_3CO_3) and magnetite [32]; while magnetotactic bacteria intracellularly grow their precisely controlled chains of magnetite or greigite crystals [33]. Additionally, from the point of view of surface to volume ratios and chemical reactivity, these bacteria would preferentially utilize these fine-grained iron oxides and ferrous hydroxides as their iron source over the bulk secondary minerals in the sediment [34]. It is therefore plausible, if not inevitable, that magnetotactic bacteria extant during the exposure of Earth to the SN-ejecta took up ^{60}Fe and incorporated it into their magnetosomes, thus recording the signature of this event in the biological record of our planet.

3. Discovery Potential of Supernova ^{60}Fe in Fossil Magnetosomes

Because AMS makes a measurement of an atom ratio, the discovery potential of ^{60}Fe in fossil magnetosomes hinges on not only the incident flux of ^{60}Fe arriving on Earth, but also on the degree to which the ^{60}Fe is diluted in sedimentary marine reservoirs by influxes of stable Fe from the terrestrial iron-cycle. We have seen that ^{60}Fe can be incorporated into secondary minerals produced by DMRB or abiogenically during sediment diagenesis. In like manner, terrestrial Fe is rendered to the sediment by these same mechanisms and, additionally, by way of minerals sufficiently large and chemically resistant to remain unaltered and, thus, survive diagenesis. Iron in primary minerals is exclusively of terrestrial origin, while all secondary minerals, whose formation was coeval with the SN event, will contain both ^{60}Fe and terrestrial Fe. Thus, those sediments having had conditions conducive for the support of magnetotactic bacteria and the Fe redox cycle, while having minimal detrital inputs, are best suited for detecting a SN event.

As a demonstrative example, and evidence in support of these ideas, we discuss the case of an Ocean Drilling Project sediment core (ODP core 848, Leg 138), from the Eastern Equatorial Pacific ($2°59.6'$ S, $110°29'$ W, 3.87 km water depth), focusing on the 2.4 – 3.3 Myr age interval corresponding to the SN event reported in Knie et al. [11]. The sediment is a pelagic carbonate (60 – 80% $CaCO_3$, 20 – 30% SiO_2) with a total iron content of 1.5 – 3.5 wt% [35]. The core-depth age correlation was established by comparison of the Earth's magnetic field direction, as recorded by magnetic minerals in the sediment, with a reference polarity time scale [36]. The mean sedimentation rate of core 848 for the 2.4 – 3.3 Myr age interval is 0.54 cm/kyr [37]. The location of this core, being far removed from continental landmasses, should minimize detrital Fe inputs from coastal runoff.

The concentration of fossil magnetosomes (magnetofossils) in this sediment core can be estimated by measuring two types of remanent magnetizations acquired in the laboratory: a so-called isothermal remanent magnetization (IRM), acquired in a 0.1 T field; and an anhysteretic remanent magnetization (ARM), acquired in a slowly decaying alternating field with an initial amplitude of 0.1 T superimposed on a 0.1 mT field of constant bias. The magnetic moments imparted by both magnetizations to ≈ 5 g samples of powdered sediment were measured in a 2G superconducting rock magnetometer. The IRM measurements are shown in panel (a) of Fig. 2 as a function of sediment age. While an IRM records the remanent magnetization of all ferrimagnetic minerals in the sample, regardless of their domain state, ARM is predominantly acquired by single-domain (SD) ferrimagnetic grains, or linear chains of such grains, that are well dispersed in a non-magnetic matrix [38]; therefore, the ratio between ARM susceptibility χ_{ARM} (ARM normalized by the bias field) to IRM, $\chi_{\mathrm{ARM}}/\mathrm{IRM}$, is a sensitive domain state indicator that can be used to discriminate between primary and secondary ferrimagnetic minerals based on the large difference in typical grain sizes between the two types. Panel (b) of Fig. 2 shows our measured $\chi_{\mathrm{ARM}}/\mathrm{IRM}$ values as a function of sediment age. Well dispersed SD particles are characterized

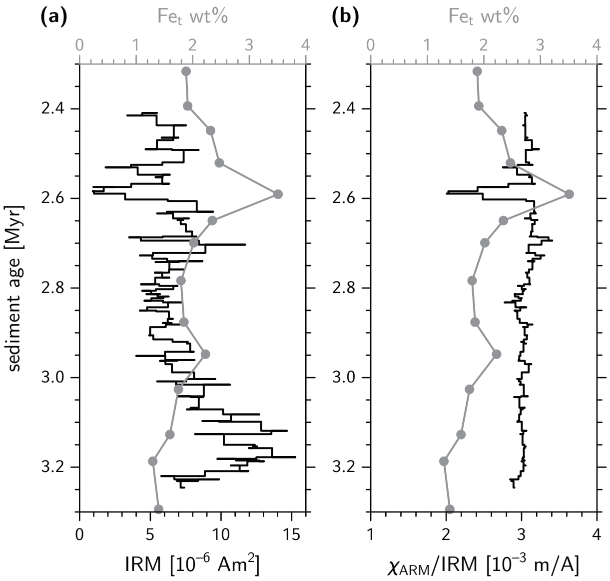

Figure 2: IRM and $\chi_{\mathrm{ARM}}/\mathrm{IRM}$ results as a function of sediment age in ODP drill core 848, Leg 138. Panel (a) shows our IRM results, while panel (b) shows our $\chi_{\mathrm{ARM}}/\mathrm{IRM}$ results. The grey data points display the known iron percentage and are to be read from the top horizontal axis.

by $\chi_{\mathrm{ARM}}/\mathrm{IRM} > 10^{-3}\,\mathrm{m/A}$, while for most primary minerals $\chi_{\mathrm{ARM}}/\mathrm{IRM} < 2\times10^{-4}\,\mathrm{m/A}$. Intact magnetosome chains are known to have the highest reported values of $3^{+2}_{-1}\times10^{-3}\,\mathrm{m/A}$ [17, 39]; our drill core sediment has values, shown in panel b) of Fig. 2, similar to what is expected for magnetosomes. We therefore conclude that the IRM of this core section is almost entirely carried by secondary SD minerals with a high proportion of magnetofossils; indeed, more detailed magnetic measurements on other freshwater and marine sediments have shown that magnetofossils can carry > 50% of the total IRM [17]. As revealed by our data in Fig. 2, the magnetic mineralogy of this core section is homogeneous, with the exception of an anomalous Fe input at ≈ 2.6 Myr, corresponding to a decrease of $\chi_{\mathrm{ARM}}/\mathrm{IRM}$; this is compatible with a large detrital input.

These IRM data in combination with the estimated supernova ^{60}Fe fluence determined in Knie et al. [11] permit an estimate of the ^{60}Fe/Fe ratio in this core section under the reasonable assumption that the measurements shown in Fig. 2 are representative of well dispersed SD magnetite. Since the switching fields of secondary ferrimagnetic minerals are smaller than the 0.1 T field employed to magnetize our sediment samples, the IRM corresponds to a saturation remanent magnetization, which, for non-interacting, uniaxial SD particles, corresponds to half the saturation magnetization.

The iron concentration $\mathcal{C}_{\mathrm{SDFe}}$ contained in SD magnetite from this core can be estimated by way of,

$$\mathcal{C}_{\mathrm{SDFe}} = \frac{2m_{\mathrm{rs}}}{w\mu_s}\frac{M_{\mathrm{Fe}}}{M_{\mathrm{Fe_3O_4}}} \tag{1}$$

where m_{rs} and μ_s are the IRM-determined magnetic moment and saturation magnetization, respectively, of the magnetic mineral, w is the IRM sample mass, and M is the atomic mass of iron or magnetite as implied by the corresponding subscript label. From panel (a) of Fig. 2, an average value of $m_{\mathrm{rs}} \approx 6\times10^{-6}\,\mathrm{Am^2}$ is taken over the entire age span. The saturation magnetization of magnetite is $\mu_s = 92\,\mathrm{Am^2/kg}$, and the mass of each measured core sample was $w \approx 5\,\mathrm{g}$. These numbers yield an estimated single domain iron mass concentration of $\mathcal{C}_{\mathrm{SDFe}} \approx 1.9\times10^{-5}\,\mathrm{g/g}$.

The corresponding flux of SD Fe in this core sample is determined by

$$\Phi_{\mathrm{Fe}} = \mathcal{C}_{\mathrm{SDFe}}\frac{N_A}{M_{\mathrm{Fe}}}\rho\frac{dh}{dt} \tag{2}$$

where N_A is Avogadro's constant, while ρ and dh/dt are, respectively, the estimated density and sedimentation rate of the core material. We take $\rho \approx 2.7\,\mathrm{g/cm^3}$, consistent with that of calcium carbonate, along with the known sedimentation rate [37] $dh/dt = 0.54$ cm/kyr. With these numbers, Eq. 2 yields $\Phi_{\mathrm{Fe}} \approx 2.9\times10^{17}\,\mathrm{atom/cm^2kyr}$ in SD magnetite.

From the work of Ref. Knie et al. [11], the estimated terrestrial fluence, ϕ_{60}, of ^{60}Fe is $\phi_{60} = 2.8 \times 10^8$ atom/cm^2, after correcting for the newly determined ^{60}Fe half-life [1]. Additionally, the width of the spike in the ^{60}Fe/Fe data of Fig. 1 suggests a characteristic exposure time, τ, of Earth to this fluence of $\tau \approx 500$ kyr, assuming that the residence time of iron in the ocean (< 100 yr) [31] is short compared to the exposure time. With these, the terrestrial flux of supernova ^{60}Fe is estimated using

$$\Phi_{60} = \frac{\phi_{60}}{\tau}. \quad (3)$$

Though we have adopted the width of the spike as the characteristic exposure time, it is possible that this value could be much shorter ($\tau \approx 10$ kyr) [40]. However, as Eq. 3 shows, a shorter exposure time can only serve to increase the value of our flux; we therefore use the more conservative value of $\tau \approx 500$ kyr for our prospect estimates.

Under the assumption stated in § 2 that the bacteria will preferentially utilize the fine-grained iron-oxides and ferrous hydroxides as their source of iron from which they construct their magnetosomes, the resulting ^{60}Fe/Fe ratios contained in the magnetosome fossils is obtained by taking the ratio of Eq. 3 with Eq. 2.

Table 1 shows the resulting estimated ^{60}Fe/Fe ratios for three values of exposure time τ (250, 500 and 750 kyr) and for two different terrestrial supernova ^{60}Fe fluences: $\phi_{60} = 2.8 \times 10^8$ atom/cm^2 as described above, and a more conservative case of $0.006 \times \phi_{\mathrm{Fe}}$. This conservative case is considered because the ^{60}Fe fluence determined in the work of Knie et al. [11] relied on knowing the uptake factor for iron of the ferromanganese crust, then determined to be 0.6%. This uptake factor is presently being reevaluated [41] and it may, in fact, be unity; we, therefore, also consider this case. Table 1 summarizes the resulting ^{60}Fe/Fe ratios for both candidate ^{60}Fe fluences. It can be seen that, in both cases, the resulting ^{60}Fe/Fe ratios are well within the capabilities of the Maier-Leibnitz AMS facility across all exposure times τ.

Remaining is the issue of the quantity of core material that would be required to achieve a meaningful result from an AMS measurement. Because an AMS measurement is the direct counting of the target atoms of interest, we should consider what total number of ^{60}Fe atoms exist per gram of drill core material, given our estimates in Table 1. We need only consider the most conservative case for ^{60}Fe/Fe to make the point. The number of ^{60}Fe atoms per gram of drill core material is given by,

$$N_{60} = \mathcal{C}_{\mathrm{SDFe}} \frac{N_A}{M_{\mathrm{Fe}}} \left(\frac{^{60}\mathrm{Fe}}{\mathrm{Fe}} \right) \quad (4)$$

where all symbols have been previously defined. Inspecting Table 1, let us take ^{60}Fe/Fe $\approx 3.6 \times 10^{-15}$ as our conservative estimate of this ratio. We then obtain $N_{60} \approx 760$ per gram of drill core material. The total efficiency ϵ of the AMS facility for ^{60}Fe, including the ion-source efficiency, the chosen charge state of Fe after passage through the Tandem thin carbon stripper foil, beam transport, and ionization detector efficiency is $\epsilon \approx 10^{-4}$. Thus, per gram of drill core material, the ^{60}Fe counting estimate should be something on the order of $\epsilon \cdot N_{60} \approx 7.6 \times 10^{-2}$ atoms. An unambiguous detection, then, of this supernova event in the magnetosome fossil record would only require a modest ≈ 200 g of sediment material, yielding ≈ 3.8 mg of single-domain iron. This amount of iron is also a sufficient quantity for an AMS measurement, which typically requires several milligrams of sample material.

Based on these estimates, we conclude there is a plausible prospect for detecting a biogenic signature of this supernova event in magnetofossils.

4. Conclusion

Radioactive ^{60}Fe is a definitive proxy for supernovae. Stellar evolution models and results from gamma-ray astronomy paint a clear picture that this nuclide is produced in both massive stars and in Type Ia supernovae, where a WD stellar remnant is blown apart by the runaway nuclear burning of the carbon and oxygen that comprise its structure. Those magnetofossils coeval with the supernova event of ≈ 2.8 Myr ago, being of secondary origin and because of their chemical stoichiometry, should contain supernova ^{60}Fe. Using the half-life corrected flux estimates determined by the ^{60}Fe AMS measurements of [11] along with the total mass concentration of magnetofossil iron from our magnetic remanence results from ODP drill core 848, we have estimated the ^{60}Fe/Fe ratio contained within the magnetofossils of this drill core. Our most pessimistic estimate of the ratio, ^{60}Fe/Fe $\approx 3.6 \times 10^{-15}$, sit comfortably within the

	^{60}Fe/Fe		
	$\tau = 250$ kyr	$\tau = 500$ kyr	$\tau = 750$ kyr
ϕ_{60}	1.8×10^{-12}	9.0×10^{-13}	6.0×10^{-13}
$0.006 \times \phi_{60}$	1.1×10^{-14}	5.4×10^{-15}	3.6×10^{-15}

Table 1: Estimated ^{60}Fe/Fe ratios in single domain magnetite in Site 848 drill core for different SN-ejecta exposure times and fluences.

sensitivity capability of the existing AMS facility at the Maier-Leibnitz laboratory. This estimate, and all others in Table 1, however, are based on the assumption that the Magnetotactic bacteria preferentially uptake iron from iron-bearing compounds of the smallest grain size; namely, the nano-sized iron oxides, and ferrous hydroxides formed when fine grain iron particles enter the aqueous environment. If, instead, the Magnetotactic bacteria uptake iron in equal measure from all iron bearing minerals, irrespective of their sizes or surface to volume ratios, then, based on the total iron content of drill core 848 ($\approx 2\%$ in Fig. 2) the ^{60}Fe/Fe ratio will be ≈ 3 orders smaller than the estimates presented in Table 1, placing it beyond the sensitivity limits of present AMS capabilities.

Detecting this biogenic supernova signature can only be achieved through a multidisciplinary approach utilizing the knowledge of theoretical and observational studies of supernovae; the microbiology of Magnetotactic bacteria; the experimental techniques of nuclear physics; and collaboration with geophysicists expert in drill core selection and geomagnetism. Techniques for dissolving and, hence, extracting the iron contained in single-domain magnetite are known within the geophysics community: one possibility is the known citrate-bicarbonate-dithionite (CBD) leaching technique [42]. It now remains to conduct an AMS measurement for ^{60}Fe on this drill core to determine the existence of a biogenic signature for this supernova event; efforts on this front are now underway.

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