Recent near-Earth supernovae probed by global deposition of interstellar radioactive $^{60}$Fe

A. Wallner1, J. Feige2, N. Kinoshita3, M. Paul4, L. K. Fifield1, R. Golser2, M. Honda5, U. Linnemann6, H. Matsuzaki7, S. Merchel8, G. Ruge1, S. G. Tims1, P. Steier2, T. Yamagata9 & S. R. Winkler2

The rate of supernovae in our local Galactic neighbourhood within a distance of about 100 parsecs is estimated to be one every 2–4 million years, based on the total rate in the Milky Way (2.0 ± 0.7 per century)1,2. Recent massive-star and supernova activity in Earth’s vicinity may be traced by radionuclides with half-lives of up to 100 million years3–6, if trapped in interstellar dust grains that penetrate the Solar System. One such radionuclide is $^{60}$Fe (with a half-life of 2.6 million years)7,8, which is ejected in supernova explosions and winds from massive stars9,10. Here we report that the $^{60}$Fe signal observed previously in deep-sea crusts10,11 is global, extended in time and of interstellar origin from multiple events. We analysed deep-sea archives from all major oceans for $^{60}$Fe deposition via the accretion of interstellar dust particles. Our results reveal $^{60}$Fe interstellar influxes onto Earth at 1.5–3.2 million years ago and at 6.5–8.7 million years ago. The signal measured implies that a few per cent of fresh $^{60}$Fe was captured in dust and deposited on Earth. Our findings indicate multiple supernova and massive-star events during the last ten million years at distances of up to 100 parsecs.

The density and temperature distribution of the interstellar medium (ISM) is highly variable, with typical substructures of about 50–150 pc (superbubbles) having lifetimes of some ten million years (Myr). Several supernova explosions over the last 14 Myr or so shaped the present structure of the local superbubble (the Local Bubble)12–14. The Solar System, now embedded in the Local Bubble, is expected to have faced fronts of supernova ejecta and accumulated material from massive stars. To enter the Solar System, any material from the ISM must be condensed into larger dust grains to avoid being deflected away by the solar wind and interplanetary magnetic field15,16. ISM dust particles were indeed identified at Earth orbit17 and may accumulate on Earth in archives such as deep-sea sediments and ferromanganese (FeMn) crusts and nodules, which retain time information over millions of years. $^{60}$Fe as well as $^{26}$Al (half-life $t_{1/2} = 0.71$ Myr) have been observed13–15 in the ISM as a result of many supernovae and emission from massive stars. Direct detection of ‘live’ radionuclides15,18 on Earth would provide insight into recent and nearby nucleosynthesis in massive stars16,17,18, dust formation and transport into the Solar System. Extraterrestrial $^{60}$Fe has in fact already been observed in FeMn crusts in pioneering studies at TU Munich10,11; and is interpreted as being of supernova10,11,18 or (micro)meteoritic origin19,20.

Here, we determined the $^{60}$Fe contents of three different deep-sea archives (four sediment cores, two FeMn crusts and two FeMn nodules) recovered from the Indian, Pacific and Atlantic oceans respectively (Supplementary Fig. 1). All were dated via their $^{10}$Be (half-life $t_{1/2} = 1.39$ Myr) content, complemented by $^{26}$Al for the sediments31. All radionuclides ($^{60}$Fe, $^{26}$Al and $^{10}$Be) were counted using accelerator mass spectrometry (AMS) (Supplementary Information). The sediment cores provided a record from 1.7–3.2 Myr ago with a time resolution of <30,000 years (30 kyr), bracketed by recent and ~5–7-Myr-old samples. The Pacific ‘Crust-1’ extends from the present to 10.9 Myr ago with ~2.2-Myr time resolution and ‘Crust-2’ extends

Table 1 | Averaged $^{60}$Fe/Fe atom ratios from AMS measurements at ANU of the sediment samples

| Sediment cores | Sediment samples | Time period (Myr) | $^{60}$Fe counts detected | Background- and decay-corrected $^{60}$Fe/Fe (10$^{-15}$ atoms per atom) | Background- and decay-corrected Fe concentration (10$^{-7}$ grams per gram) | $^{60}$Fe concentration (10$^{-10}$ atoms per gram) | $^{60}$Fe deposition rates (atoms cm$^{-2}$ yr$^{-1}$) | $^{60}$Fe deposition (10$^{-15}$ atoms cm$^{-2}$ per layer) |
|---------------|-----------------|------------------|--------------------------|-------------------------------------------------|-------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------|
| 45–21/50–02   | 5               | <0.2             | 2                        | 0.06 ± 0.04                                      | 0.02 ± 0.02                                      | 0.30 ± 0.10                                      | <0.2                                          | <0.2                                            |
| 49–53/45–21   | 14              | 1.71–2.0         | 123                      | 1.67 ± 0.15                                      | 2.52 ± 0.23                                      | 0.23 ± 0.01                                      | 6.0 ± 0.6                                      | 22.8 ± 2.3                                      |
| 49–53/45–21/50–02 | 11 | 2.0–2.3         | 51                       | 1.51 ± 0.21                                      | 2.48 ± 0.35                                      | 0.24 ± 0.01                                      | 6.7 ± 1.0                                      | 24.8 ± 3.6                                      |
| 49–53/45–21/50–02 | 7 | 2.3–2.6         | 33                       | 1.96 ± 0.34                                      | 3.50 ± 0.61                                      | 0.17 ± 0.01                                      | 6.5 ± 1.2                                      | 27.1 ± 5.0                                      |
| 49–53/45–15   | 2               | 2.6–2.9         | 54                       | 3.40 ± 0.46                                      | 6.61 ± 0.90                                      | 0.16 ± 0.01                                      | 10.3 ± 1.5                                    | 34.8 ± 5.2                                      |
| 49–53/45–15   | 6               | 2.9–3.9         | 27                       | 1.18 ± 0.23                                      | 2.41 ± 0.47                                      | 0.03 ± 0.01                                      | 3.4 ± 0.7                                      | 11.4 ± 2.4                                      |
| 45–16          | 2               | ~4–7            | 1                        | 0.11 ± 0.11                                      | 0.20 ± 0.30                                      | 0.2 ± 0.01                                       | <0.4                                          | <1                                              |
| Commercial iron | 99              | Background | 7                       | 0.042 ± 0.015                                    | NA                                              | NA                                             | NA                                             | NA                                              |

52 sediment samples from four sediment cores (Eltanin) from the Indian Ocean were analysed (individual data are listed in the Supplementary Information) as well as a series of blank samples (commercial iron). For the measured $^{60}$Fe/Fe ratios, the uncertainties from $^{52}$Fe denote statistical uncertainties only (1σ; using Poisson statistics). For background- and decay-corrected $^{60}$Fe/Fe data, surface and old layers are compatible with the measurement background obtained from chemistry blank samples. The age is based on the $^{26}$Al and $^{10}$Be data and tie-points of magnetic reversals. The stable iron content of the leached material was measured via inductively coupled plasma mass spectrometry (ICP-MS) (averaged values). The average leachable Fe content for the four cores was measured to 0.18% (core Eltanin 49–53, 0.25%; 45–16, 0.3%; 45–21 and 0.45% (50–02). The mean dry density of the sediments was 1.16 g cm$^{-2}$. For sediments with 100% incorporation efficiency, the Fe deposition equals the terrestrial fluence.

*Uncertain by ~1 Myr.

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from 1.2–7 Myr ago (~100-kyr resolution). Two nodules covered a time period from the present to 5.4 Myr ago (~2-Myr resolution).

In the sediment, 288 Fe-events were registered for the time period 1.71–3.18 Myr ago (45 individual samples) with a mean isotopic ratio of $^{60}$Fe/Fe = (1.79 ± 0.10) × 10^−15, a factor of ~40 above the measurement background of (0.042 ± 0.015) × 10^−15 (Table 1). None of the recent or old sediment samples show evidence for $^{60}$Fe above background (three 60Fe-events). The first two layers in Crust-1 gave $^{60}$Fe-signals $\sigma$ and $\Delta$ $\sigma$ above background; layers 3 and 5 are close to the measurement background, but layer 4, which spans the period 6.5–8.7 Myr ago, has a higher ratio (~$\sigma$ above background, Table 2). For Crust-2 a clear $^{60}$Fe-signal was also found at <3.5 Myr. The nodules support this finding (Table 3, Supplementary Tables 3–5).

In summary, two clear $^{60}$Fe signals with a total of 538 $^{60}$Fe events were observed. In the sediments, the signal covers the time period 1.7–3.2 Myr. In the two crusts, 60Fe is found up to 3.5 Myr ago and up to about 4 Myr ago, respectively, with a second influx between 6.5–8.7 Myr ago. The nodules confirm the presence of $^{60}$Fe at <3.5 Myr ago. No $^{60}$Fe signal is found in recent (~<0.2 Myr old) or older (~≥5 Myr old) sediments and nodules, or in crust layers 4.4–6.5 Myr and 8.7–10.9 Myr old.

Between 1.7 Myr ago and 3.18 Myr ago, the $^{60}$Fe deposition rate into the sediments was ~11–35 $^{60}$Fe atoms·cm^−2·yr^−1 (300-kyr averages), whereas incorporation rates into crust material were much lower at 1–2 atoms·cm^−2·yr^−1 (Fig. 1; all data are decay-corrected). This suggests an incorporation efficiency into Crust-1 and Crust-2 of 17% and 7%, respectively. The deposition in the 1.5-Myr interval covered by the signal in the sediment is (35 ± 2) × 10^6 atoms·cm^−2. For the second $^{60}$Fe signal (6.5–8.7 Myr ago, Crust-1, 17% incorporation efficiency) it is (21 ± 6) × 10^6 atoms·cm^−2 (Tables 2 and 3).

Although the 1.5-Myr time spread of $^{60}$Fe influx measured in the present work exceeds the ~0.8 Myr previously reported for crust 237KD11,18, the two time profiles are not inconsistent given the lower counting statistics and signal-to-background ratio in ref. 11. Furthermore, the marginally positive result for the same time period for an Atlantic sediment18 is consistent with our data, considering their lower counting statistics and signal-to-background ratio. $^{60}$Fe has also been reported in lunar material, though without time information27, and recently in Pacific sediments25,31.

Clearly, our data are incompatible with a constant $^{60}$Fe production or deposition. A terrestrial origin can be ruled out, because there is no suitable target for cosmic-ray-induced production and anthropogenic input would be concentrated in the surface layer. Since $^{60}$Fe was found in each of the major oceans, it is reasonable to assume a uniform global distribution. A micro-meteoritic or meteoritic origin can be excluded, given that the measured cosmic-dust flux is 400 times lower than would be required (Supplementary Information and Supplementary Fig. 6). Similarly, a hypothetical break-up of a single object, comparable to the asteroid invoked in relation to the Cretaceous–Tertiary event 65 Myr ago, would have delivered 4,500 times less $^{60}$Fe.

We assume that the extraterrestrial $^{60}$Fe flux through Earth’s cross-section is homogenously distributed over Earth’s surface. Thus, the measured mean deposition of ~24.5 atoms·cm^−2·yr^−1 (1.7–3.2 Myr...
signal) corresponds to a $^{60}$Fe flux of 98 atoms cm$^{-2}$ yr$^{-1}$ into the inner Solar System or integrated over 1.5 Myr to an $^{60}$Fe flux of $(1.46 \pm 0.15) \times 10^{8}$ atoms cm$^{-2}$ at Earth orbit; the fluence for the older event is $(1.2 \pm 0.4) \times 10^{9}$ atoms cm$^{-2}$. Interstellar grains, filtered by the Solar System in size to an average of $\sim 0.5$ µm, were detected by space missions,$^{15}$ suggesting that (6 ± 3)% of the mass of ISM dust reaches the inner Solar System$^{5}$. These grains follow the flow velocity of the ISM.

Assuming that the $^{60}$Fe-loaded grains follow the same mass distribution as determined for ISM grains at Earth orbit, we deduce an interstellar $^{60}$Fe concentration in dust of $(2.8 \pm 1.4) \times 10^{-11}$ $^{60}$Fe atoms cm$^{-3}$ for 1.7–3.2 Myr and, integrated over the full period of 11 Myr, an average concentration of $(5.5 \pm 1.5) \times 10^{-12}$ $^{60}$Fe atoms cm$^{-3}$. Observations of $^{60}$Fe decay$^{18,19}$ and nucleosynthesis models$^{2}$ suggest an average Galaxy concentration of $(6 \pm 1) \times 10^{-12}$ $^{60}$Fe atoms cm$^{-3}$ (Supplementary Information), in agreement with the 11-Myr period of local data reported here.

$^{60}$Fe is produced in massive stars$^{22,24-27}$ in their late phases, predominantly just before supernova explosions, and then ejected into space. (Super)asymptotic-giant-branch stars also produce and eject $^{60}$Fe through their stellar winds for a period of about 50 kyr, leading to a time profile similar to supernovae; however, their contribution to the Galactic $^{60}$Fe inventory is small$^{28}$.

Models suggest a travel time of about 200 kyr with a time spread of approximately 100–400 kyr (ref. 5) for ejecta from a single supernova at a distance from Earth of about 100 pc. Our measured spread of about 1.5 Myr is inconsistent with the interpretation in terms of ejecta from a single supernova (or asymptotic-giant-branch star) moving across the Solar System (Supplementary Fig. 6). It suggests multiple supernova and massive-star events within the last ten million years or so in Earth’s vicinity and during two distinct periods 1.7–3.2 Myr ago and around 6.5–8.7 Myr ago. The recent time profile would be compatible with movement across the Solar System of ejecta in a series of supernova fronts in short succession within 1.5 Myr.

This would, however, require a high frequency of supernovae (around two to three supernovae per million years), since large fluctuations were not observed in the time profile. Alternatively, the ejecta containing the $^{60}$Fe-bearing grains could have come to rest in the ambient ISM and diffused into volumes or clouds that were then traversed by the Solar System$^{18}$.

The Solar System is currently embedded in a flow of ISM material with interstellar grains moving parallel to the flow of neutral interstellar gas in local ISM clouds, which suggests a common history or driver$^{29}$. Such clouds have been suggested as part of an expanding superbubble shell driven by supernovae and winds from massive stars$^{12,14,29}$.

Assuming the ejecta originate from a distance of 70–100 pc (the approximate limit of the Local Bubble) and that $^{60}$Fe is equally distributed into the outer shell of size 30 pc (a distance representing 1.5 Myr of travel), that is, a spherical shell of mean radius 70–100 pc with a thickness of 30 pc, we deduce a total $^{60}$Fe mass trapped in ISM dust of $(5–11) \times 10^{-17}$ solar masses ($M_\odot$) in the shell volume. This number represents a lower limit because it reflects the fraction of $^{60}$Fe condensed into dust without correction for radioactive decay and neglects the granularity of clumpy ejecta. Models predict core-collapse and electron-capture supernova nucleosynthesis yields for $^{60}$Fe to be $(0.5–14) \times 10^{-17} M_\odot$ for stars of mass $8 M_\odot–25 M_\odot$ depending on the progenitor mass, and with large uncertainties in the nuclear physics input$^{24,27}$ (Super)asymptotic-giant-branch stars produce $(0.003–1) \times 10^{-15} M_\odot$ $^{60}$Fe$^{28}$. Our observed signals therefore favour supernova events. The fraction of $^{60}$Fe in dust can be roughly estimated by a comparison of our measured $^{60}$Fe deposition with nucleosynthesis yields. Under these assumptions and assuming reasonable distances (20–100 pc) about 0.4% to 9% of $^{60}$Fe would have been trapped in ISM dust particles (Supplementary Information, Supplementary Figs 7 and 8).

Comparing our data with a similar work for ISM $^{244}$Pu in sediments and crust samples$^{6}$ yields a $^{244}$Pu/$^{60}$Fe atomic ratio of $<2–3 \times 10^{-5}$ (2σ) during periods of elevated $^{60}$Fe deposition over the past ten million years, which agrees with the recently reported low $^{244}$Pu supernova yields$^{6}$ (Supplementary Information).

This broad and global $^{60}$Fe influx on Earth demonstrates recent (within the past ten million years) and widespread massive-star ejections in our near Galactic neighbourhood (less than 100 pc from Earth), most probably from supernova explosions. Interestingly, the older event coincides with a strong increase in $^{7}$Be and temperature change at about 8 Myr ago$^{30}$, while the more recent activity starting about 3 Myr ago occurred at the same time as Earth’s temperature started to decrease during the Plio–Pleistocene transition.

### Table 3 | Summary of $^{60}$Fe deposition at various locations

| Deep-sea archive | Cores Location | Time period (Myr) | $^{60}$Fe concentration (10$^{4}$ atoms cm$^{-2}$ yr$^{-1}$) |
|------------------|---------------|------------------|--------------------------------------------------|
| Sediment         | 4 Indian Ocean | 1.71–3.18        | 288                                              |
|                  |               |                  | 35.4 ± 2.6                                      |
| FeMn Crust-1     | 2 Pacific Ocean | 0–2.35           | 97                                               |
|                  |               |                  | 5.9 ± 0.8                                       |
| FeMn Crust-1     | 1.2–3.1        | 26               | 3.5 ± 1.4                                       |
| FeMn Crust-2     | 1.8–3.3        | 13               | 0.6 ± 0.2                                       |
| Crust-2          | 0–3.3          | 20               | 1.4 ± 0.5                                       |
| FeMn nodules     | 2 Atlantic Ocean | 1.74–1.9        | 69                                               |
|                  |               |                  | 1.5 ± 0.4*                                      |
| FeMn Mona Phipol$^{10}$ | 1 Pacific Ocean | 0–5.9          | 21                                               |
|                  |               |                  | $-9.11±0.2$                                     |
| Lunar material$^{22}$ | 4 Moon Integral | $~10$            |                                                  |

Data were obtained in this work and as given in the literature$^{10,11,22}$ (no correction for incorporation efficiency). Uncertainties are 1σ. For Crust-1 and Crust-2 an incorporation efficiency of 7% and 9%, respectively, has to be taken into account to calculate the $^{60}$Fe fluence from the deposition values; similarly 2% and 4% for the nodules.

†Not listed in ref. 22.

‡Background-corrected, adjusted for revised $^{60}$Fe half-life and interpolation between the two layers.

### Figure 1 | Deposition rates for sediment (150-kyr averaged data) and incorporation rates for two crust samples. $^{60}$Fe concentrations ($^{60}$Fe per gram) for the sediment are given in the insert; they were on average $6.7 \pm 3.0 \times 10^{8}$ atoms per gram between 1.7 Myr and 3.2 Myr, but $260 \times 10^{8}$ atoms per gram of crust and $95 \times 10^{8}$ atoms per gram of nodule, reflecting the difference in growth rate and incorporation efficiency (see Supplementary Information). The error bars (1σ Poisson statistics) include all uncertainties and scale with decay correction, so that uncertainties and upper limits become larger for older samples. The absolute ages for the sediment samples have an uncertainty of 0.1 Myr, except for the 5.5-Myr-old sediments, which have an uncertainty of about 1 Myr. The age of Crust-1 has an uncertainty of 0.3 Myr and the age of Crust-2 has an uncertainty of 0.5 Myr.
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Supplementary Information is available in the online version of the paper.

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Author Contributions A.W. initiated the study and wrote the main paper together with J.F., M.P. and L.K.F.; all authors were involved in the project and commented on the paper. A.W., with J.F., L.K.F. and S.R.W., organized the Eltanin sediment samples. N.K. and M.P. organized the crust samples. S.M. and U.L. organized the nodules. J.F. and S.M. were primarily responsible for sample preparation of the sediment and nodules and N.K. was responsible for the crusts. A.W., L.K.F. and S.G.T. performed the AMS measurements for 60Fe at the ANU. K.P.S., S.R.W. and A.W. performed the 26Al and 10Be measurements at the ANU. P.S., S.R.W., J.F. and A.W. performed the 26Al and 10Be measurements at VERA. G.R., S.M. and J.F. performed 10Be measurements at HZDR. N.K., M.H., H.M. and T.Y. performed 60Fe measurements at MALT. J.F., A.W. and N.K. performed the data analysis.

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