

Local Interstellar Cloud Structure Imprinted in Antarctic Ice by Supernova ^{60}Fe

Dominik Koll^{1,2,3,*} Annabel Rolofs^{1,4} Florian Adolphi^{5,6} Sebastian Fichter¹ Maria Hoerhold⁵
 Johannes Lachner¹ Stefan Pavetich² Georg Rugel¹ Stephen Tims² Frank Wilhelms^{5,7}
 Sebastian Zwickel^{1,3} and Anton Wallner^{1,2,3}

¹Accelerator Mass Spectrometry and Isotope Research, *Helmholtz-Zentrum Dresden-Rossendorf*, Dresden, 01328, Germany

²Department of Nuclear Physics and Accelerator Applications, *The Australian National University*, Canberra, 2601, Australia

³Institute of Nuclear and Particle Physics, *TUD Dresden University of Technology*, Dresden, 01069, Germany

⁴Argelander-Institut für Astronomie, *University of Bonn*, Bonn, 53121, Germany

⁵Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, 27570, Germany

⁶Department of Geosciences, *University of Bremen*, Bremen, 28334, Germany

⁷Geoscience Centre, *University of Göttingen*, Göttingen, 37077, Germany



(Received 8 December 2025; revised 27 February 2026; accepted 13 March 2026; published 13 May 2026)

The solar system currently traverses the Local Interstellar Cloud (LIC), one of several warm cloudlets of the Complex of Local Interstellar Clouds (CLIC) in the solar neighborhood. The origin of these cloudlets is unknown and could be related to supernova shock wave dynamics. If supernovae are the source of these cloudlets or influence their properties, the CLIC may act as a cosmic archive for the supernova-produced radionuclide ^{60}Fe . We detected minuscule traces of interstellar ^{60}Fe in 295 kg of the European Project for Ice Coring in Antarctica Dronning Maud Land ice core, covering the time period 40–81 kyr ago. We find an $^{60}\text{Fe}/^{53}\text{Mn}$ ratio of $(8 \pm 5) \times 10^{-4}$, slightly above the expected cosmogenic production, corresponding to an interstellar deposition rate of $(0.22^{+0.14}_{-0.12})$ ^{60}Fe at/cm²/yr. This influx is significantly lower than that observed in recent Antarctic snow and marine sediment records during the last 40 kyr. These results suggest that the LIC is a cosmic archive for supernova-produced ^{60}Fe . The imprinted ^{60}Fe time profile is evidence for a changing local interstellar environment over the last 80 kyr.

DOI: 10.1103/nxjq-jwgp

The solar system crosses diverse regions of the dynamic galactic interstellar medium (ISM). The local ISM within 15 pc of the solar system is a collection of 15 warm and diffuse ($T = 5000\text{--}10\,000$ K, $n = 0.1\text{--}0.2$ cm⁻³) cloudlets [1–4], each distinguishable by their velocity vector [3,5] and commonly referred to as the Complex or Cluster of Local Interstellar Clouds (CLIC), see Ref. [6] for a recent review of the very local ISM. These cloudlets are embedded in the enveloping 100–200 pc wide, high temperature void ($T = 10^4\text{--}10^6$ K, $n = 0.005$ cm⁻³) known as the Local Bubble (LB) [7–11]. The formation of the LB itself was likely triggered by supernova-driven outflows from 14–20 supernovae in the Scorpius Centaurus Association starting around 10–15 Myr ago [12–16].

The cloudlets in the CLIC could have formed over the last 1 Myr [4] with the Local Interstellar Cloud (LIC), the cloudlet the solar system is currently traversing [17], believed to have formed just 130 kyr ago [4]. The mass

of the LIC alone is roughly $0.3M_{\odot}$ [18]. Estimates based on absorption line data and cloud density models constrain the solar system's entry into the LIC to roughly within the last 40 kyr, 64 kyr, or 124 kyr [6,17,19,20]. Depending on the clumpiness of the CLIC, the solar system was traversing a LB-like ISM before entering the LIC or an overlap region of the Aur cloud and the LIC [20]. The solar system will exit the almost perpendicularly moving LIC boundary within the next 2000–6000 yr, possibly transitioning to the adjacent G-cloud [6,19,20]. Recently, a mixing of the LIC and the G-cloud at the current location of the solar system was brought forward to better explain the velocity of interstellar neutral helium [21].

The origin of the CLIC is unclear: an interaction zone between the LB and the Loop I superbubble [22,23], fragmentation of the Loop I superbubble leading to cloud formation [24], supernova shocks interacting with existing Strömgren sphere gas leading to compression [10], a maverick magnetic flux-tube springing back from the LB wall [25], as well as supernova shocks expanding into a preevacuated cavity of the LB [4] are discussed as potential origins. Any influence of supernovae on the formation or the properties of the CLIC [4,26] could manifest itself as correlated supernova-produced radionuclide depositions over the last 100–200 kyr in Earth's geological record.

*Contact author: d.koll@hzdr.de, dominik.koll@anu.edu.au

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](#). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

Two influx peaks, 2–3 Myr and 7 Myr ago, of the long-lived supernova-produced radionuclide ^{60}Fe ($t_{1/2} = 2.6$ Myr [27,28]) were discovered in hydrogenetic ferromanganese crusts [29–33] and deep-sea sediments [30,34] on Earth as well as in lunar regolith [35], providing evidence of near-Earth supernova activity within the last 10 Myr. Interstellar dust, formed through condensation after the supernova and thereby trapping ejected ^{60}Fe , was brought forward as a carrier of ^{60}Fe to Earth [36,37]. These million year old supernova signals, however, were deposited into geological archives before the suggested formation of the CLIC [4]. Their long durations, and consequently the distances the solar system was crossing, are significantly larger than the spatial extension of the CLIC.

The discovery of a low present-day influx of $(1.2^{+0.6}_{-0.5})$ ^{60}Fe at/cm²/yr in recent (< 20 yr) Antarctic snow [38] was the first evidence for the presence of ^{60}Fe during the time period the solar system is within the LIC. The subsequent analysis of deep-sea sediments from the Indian Ocean [39] confirmed a recent influx and extended the time period from present to the last 33 kyr at a slightly higher deposition rate of $(3.5^{+1.1}_{-0.9})$ ^{60}Fe at/cm²/yr. These findings would be compatible with ^{60}Fe being present in the LIC, with the LIC acting as a cosmic archive for supernova-produced radionuclides. Besides the LIC, a fade-out of the supernova influx 2–3 Myr ago as well as a reflection of the ^{60}Fe flux on an astrophysical boundary have been suggested as reasons for a sustained influx of ^{60}Fe at recent times [39–41].

If the LIC is such a cosmic archive, the transition from a low-density LB-like ISM, a different cloud or a cloud-cloud interaction zone [21] into the LIC should have led to a changing influx of interstellar ^{60}Fe [40]. Depending on the actual density of the CLIC, the individual clouds could be separated in space or form a tightly packed region of the local ISM within 4 pc [20], which might be identifiable as characteristic ^{60}Fe depositions. Observations show that at larger distances space is only partially filled [20,42]. Furthermore, density variations within a cloud could also lead to variable ^{60}Fe depositions if the ^{60}Fe abundance scales with the ISM density. A highly time-resolved geological archive is required to account for these potentially short time periods of variations in ^{60}Fe deposition. Geological archives have, therefore, the potential to record the structure of the CLIC as well as to deduce the origin of the cloudlets in the local ISM.

In this work, we analyzed 295 kg of the EPICA Dronning Maud Land (EDML) Antarctic ice core from the European Project for Ice Coring in Antarctica (EPICA) [43], representing the narrow time interval of 40–81 kyr ago [44], for its interstellar ^{60}Fe abundance. The time interval was chosen to cover the potential time of entry of the solar system into the LIC and to trace back the ^{60}Fe deposition beyond the already investigated time periods.

Both, the recent Antarctic snow [38] and the EDML ice core of this work, were retrieved from the same location, i.e., the German Kohnen Station (75° 00' S, 0° 04' E at 2892 m asl), which alleviates the influence of atmospheric and geological processes that could lead to an inhomogeneous deposition of interstellar radionuclides [37,45]. The mass-weighted mean accumulation rate of the sample, based on the AICC23 chronology and $\delta^{18}\text{O}$ data [46,47], is calculated as (44.4 ± 0.7) mm w.e. yr⁻¹, accounting for a strong ice thinning with depth with a mean thinning factor of 0.35. The EDML ice core was melted for continuous flow analysis (CFA) and the meltwater originating from the outer fraction of the ice core [48], which is not used for CFA, was stored and refrozen in plastic containers at the Alfred Wegener Institute for Polar Research in Bremerhaven, Germany. For this study, this meltwater represents a valuable sample as it is available in large quantities of several hundred kilograms which are required to detect traces of ^{60}Fe . Interstellar radionuclides in the meltwater should be largely preserved, as was shown for cosmogenic radionuclides [49], which makes a repurposing of this large sample possible. After remelting and acidification to pH 2 with HNO_3 , the sample was homogenized, evaporated, and chemically processed after a waiting time of two months according to an established procedure for large ice samples [50]. Stable elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Helmholtz-Zentrum Dresden-Rossendorf, in particular to determine the stable Be, Al, Ca, Mn, and Fe content. Radionuclide abundances were determined using the single-atom counting technique of accelerator mass spectrometry (AMS) [51]. Uncertainties are displayed as $1\text{-}\sigma$ intervals and were calculated based on the prescription of Feldman and Cousins [52] in the case of low counting statistics.

Cosmogenic radionuclides ^{10}Be and ^{26}Al were measured at the DRESDEN AMS (DREAMS) facility [53,54], serving as tracers for archive integrity considering that losses of radionuclides during storage and melting of the sample need to be excluded. Both radionuclides are produced by cosmic-ray spallation in the upper atmosphere [55] and should follow similar atmospheric transport pathways as well as losses during storage and processing as interstellar radionuclides. The resulting $^{26}\text{Al}/^{10}\text{Be}$ atomic ratio of $(1.69 \pm 0.13) \times 10^{-3}$ (decay corrected to time of deposition: $(1.74 \pm 0.13) \times 10^{-3}$) is in perfect agreement with values from native EDML firn $(1.70 \pm 0.24) \times 10^{-3}$ and Antarctic air filters $(1.84 \pm 0.05) \times 10^{-3}$ [56]. The individual ^{10}Be and ^{26}Al concentrations and deposition rates [44] are also in agreement with previous investigations [56,57] from different Antarctic sites, however, show a higher concentration compared to other EDML measurements [56,58]. This is indicative that the evaporation method of this work, resulting in a concentrated nitric acid leaching, is recovering more cosmogenic radionuclides than

only using ion exchange columns as a concentration step. We conclude that no major radionuclide losses occurred during storage and processing and that CFA meltwater is a viable repurposed geological archive for the search of cosmogenic as well as interstellar radionuclides.

Cosmogenically produced ^{60}Fe , potentially present through the influx of interplanetary dust, micrometeorites, or meteorite fragments [59,60], could superimpose over any traces of interstellar ^{60}Fe . Large cosmogenic inputs through meteorite fragments were excluded in the Antarctic ice core sample by the nonpresence of cosmogenic ^{41}Ca [44], determined using the DREAMS facility [61].

The dyadic radionuclide system $^{60}\text{Fe}/^{53}\text{Mn}$ is a sensitive measure to distinguish between supernova-derived ^{60}Fe and cosmogenic ^{60}Fe [29,62,63]. Both, ^{60}Fe and ^{53}Mn , are produced in interplanetary dust and meteoroids by cosmic ray interactions on stable target elements Ni and Fe, respectively. A surplus of ^{60}Fe over the cosmogenic production ratio of $^{60}\text{Fe}/^{53}\text{Mn} = (1.77 \pm 0.07) \times 10^{-3} \times \text{Ni}/\text{Fe}$, which scales with the stable target element ratio Ni/Fe, indicates the presence of interstellar ^{60}Fe . Given typical solar system values of $\text{Ni}/\text{Fe} = 0.059$ (wt%/wt%) for chondrites [64] and $\text{Ni}/\text{Fe} = 0.1$ for iron meteorites [59], the expected cosmogenic $^{60}\text{Fe}/^{53}\text{Mn}$ ratio is on the order of 10^{-4} .

Measurements of ^{53}Mn and ^{60}Fe were performed using AMS at the Heavy Ion Accelerator Facility (HIAF) at the Australian National University in Canberra, Australia [65]. The measured $^{60}\text{Fe}/^{53}\text{Mn}$ ratio of $(8 \pm 5) \times 10^{-4}$ is 1.4σ above the chondritic ratio $(1.04 \pm 0.04) \times 10^{-4}$, see Fig. 1. This indication for the presence of interstellar ^{60}Fe , based on seven detector events compared to none in the corresponding background measurement, would vanish for cosmic Ni/Fe ratios of 0.2, which are only common for rare Ni-rich iron meteorites. The resulting interstellar ^{60}Fe deposition of $(0.22^{+0.14}_{-0.12})$ at/cm²/yr is significantly lower than into recent Antarctic snow [38] from the same geological site or Indian Ocean deep-sea sediments [39]. The time profile of ^{60}Fe deposition (Fig. 2 and Table I) is in agreement with the expectation of the LIC being a cosmic archive for supernova-produced ^{60}Fe , and either intercloud density variations if the solar system was within the LIC over the last 80 kyr, or an entry into the LIC from the low density LB-like ISM less than 80 kyr ago. Considering that the LIC is part of the larger CLIC, other clouds of the CLIC would also host supernova-produced ^{60}Fe .

Other recently investigated sources for ^{60}Fe on Earth, such as anthropogenic ^{60}Fe from nuclear activities [38] or ^{60}Fe nuclei in the cosmic ray spectrum near Earth [45,66], have been shown to be at most minor contributors to the environmental ^{60}Fe abundance. Such a contribution would further reduce the evaluated dust-bound interstellar ^{60}Fe abundance in this work's Antarctic ice core during the time period 40–81 kyr ago.

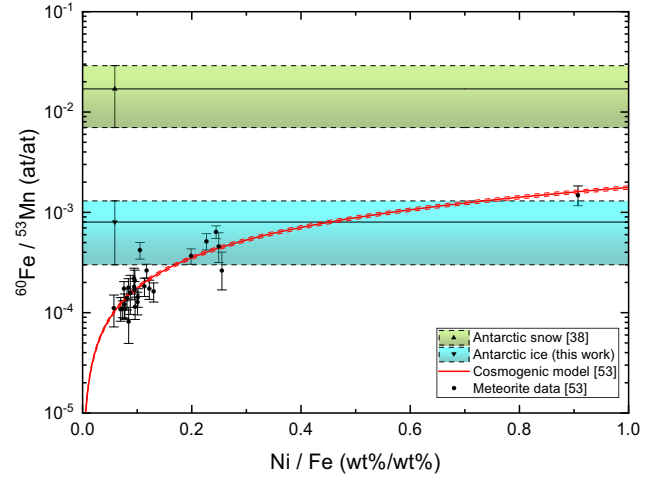


FIG. 1. Measured atomic $^{60}\text{Fe}/^{53}\text{Mn}$ ratios for Antarctic ice (this work), Antarctic snow [38], and meteorites [59]. The measured ratio of $(8 \pm 5) \times 10^{-4}$ of this work is significantly lower than in Antarctic surface snow [38] and 1.4σ above the cosmogenic expectation from meteorites and a nuclear cascade model [59], assuming the most likely chondritic Ni/Fe ratio of 0.059 (wt%/wt%) [64]. The colored bands represent the measured $^{60}\text{Fe}/^{53}\text{Mn}$ ratios of geological samples over any typical cosmic Ni/Fe ratio.

Which astrophysical scenarios would be compatible with a variable ^{60}Fe deposition over the last 80 kyr? A conspicuous explanation would be a correlation to the 2–3 Myr old ^{60}Fe influx to Earth. The solar system traverses

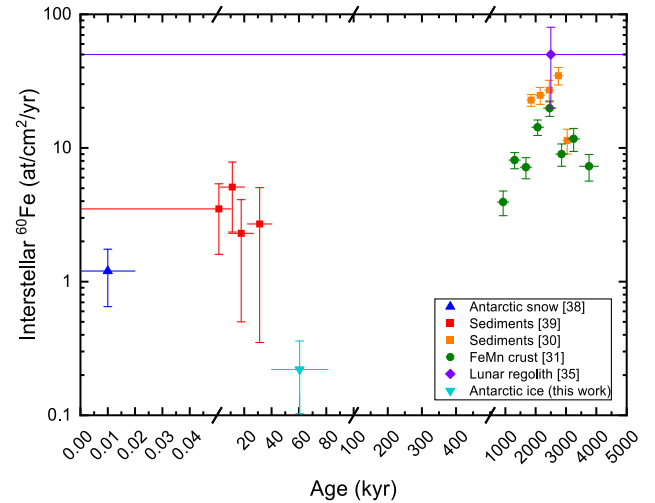


FIG. 2. Compilation of supernova-produced ^{60}Fe depositions into geological archives. Measurement uncertainties are given as $1\text{-}\sigma$ intervals and individual time resolutions are displayed as horizontal lines. An interstellar ^{60}Fe deposition rate of $(0.22^{+0.14}_{-0.12})$ at/cm²/yr for Antarctic ice is lower than in Antarctic surface snow [38] and deep-sea sediments [39]. The significant variation of ^{60}Fe deposition over the last 80 kyr is in agreement with the LIC being a cosmic archive for supernova-produced ^{60}Fe .

TABLE I. Summary of ^{60}Fe influx to Earth over the last 80 kyr. Deep-sea sediments and Antarctic snow cover the time period the solar system was inside the LIC, while the solar system was either partially outside the LIC or inside a cloud-cloud overlap region for the Antarctic ice core data of this work. The variable ^{60}Fe deposition profile over the last 80 kyr is compatible with the LIC being a cosmic archive for supernova-produced radionuclides.

	Sample	Origin	Acc. rate (mm/yr)	Age (kyr)	^{60}Fe flux (at/cm ² /yr)
Koll <i>et al.</i> (2019) [38]	Surface snow	Antarctica	80	< 0.02	$1.2^{+0.6}_{-0.5}$
Wallner <i>et al.</i> (2020) [39]	Sediments	Indian Ocean	4×10^{-3}	0–33	$3.5^{+1.1}_{-0.9}$
This work	Ice core	Antarctica	44.4	40–81	$0.22^{+0.14}_{-0.12}$

distances within the LB on the order of one hundred parsecs over several million years [39]. Considering a fading of the 2–3 Myr ^{60}Fe influx as the reason for a sustained ^{60}Fe influx over the last 80 kyr, the LB would need to be filled with ^{60}Fe over the solar system’s trajectory and over most of its volume with only about a one order of magnitude difference in ^{60}Fe density (Fig. 2). Such a fading would then be unrelated to the presence of the CLIC, because the velocity vectors of the CLIC and the solar system are distinctly different [6] and the density of the CLIC is significantly larger than the ambient LB ISM. The interpretation of the measured variable ^{60}Fe profile over the last 80 kyr as a consequence of just a fading of the 2–3 Myr influx [31,32] in an ^{60}Fe -filled LB would require a complex ISM structure in the LB. An alternative interpretation of the 2–3 Myr influx is that it was caused by a directly impinging supernova blast wave. The predicted ^{60}Fe influx duration for such a scenario is on the order of a few hundred kyr [37,41,67], hence in tension with the measured time interval of the 2–3 Myr influx. A “pinball” behavior [68] of interstellar dust inside a supernova remnant through magnetic reflections could explain the width of the recorded ^{60}Fe peak 2–3 Myr ago. The model, however, does not address the variations in ^{60}Fe deposition over the considerably shorter time period of the last 80 kyr.

Reflections of supernova-produced ^{60}Fe on the LB outer shell [14,69] would be viable candidates to induce a reinstated influx at recent times after the termination of the 2–3 Myr peak [15]. One could expect a chaotic ^{60}Fe influx profile over the last 10 Myr if reflections on the LB shell are non-negligible, given the large number of supernovae occurring within the last 10–15 Myr in the LB [69] at distances of 100–300 pc to the solar system and from the neighboring Loop I superbubble [14] at distances of 200–400 pc. Consequently, a multitude of ^{60}Fe peaks were predicted by reflections from the LB shell [15,69]. The isolated single but broad peaks of ^{60}Fe influxes 2–3 Myr and 7 Myr ago without a significant ^{60}Fe influx during the time period 4–6 Myr ago [30–32] do not indicate such a multitude of peaks. Deep-ocean sediments at higher time resolution capable of resolving short but pronounced individual supernova peaks similarly show an isolated but broad peak 2–3 Myr ago [30].

The solar system’s trajectory through the CLIC would naturally explain the experimentally obtained time profile of recent ^{60}Fe deposition. It was proposed that the CLIC was formed through mass clumping at the surface of a supernova remnant shell [4]. Since supernovae are well-known to produce significant amounts of ^{60}Fe [70], a presence of ^{60}Fe in the CLIC could be expected. Given that the deposition rate of ^{60}Fe on Earth during the traversal of the LIC is about a factor of 10 lower than during the 2–3 Myr influx, it would be astonishing if the CLIC were essentially a pure fragment from a supernova within the last 1–2 Myr [4]. If the LIC is such a fragment, the ^{60}Fe abundance should align with the nucleosynthesis predictions for ^{60}Fe from core-collapse supernovae. A LIC dust density of 2×10^{-24} kg/m³ [71] over ≈ 2 pc, a typical ^{60}Fe mass fraction relative to the total supernova ejecta of about 10^{-7} – 10^{-6} [70,72] fully condensed into dust [36,67], and a relative dust yield of a supernova of 1% [73–75] yields a predicted column density of ^{60}Fe in the LIC on the order of 10^9 – 10^{10} at/cm². The measured deposition rate of about 1 at/cm²/yr on Earth over the transit period of about 100 kyr leads to a measured column density of ^{60}Fe in the LIC on the order of 10^5 at/cm² which needs to be scaled by the solar system penetration efficiency of ^{60}Fe -bearing dust. A penetration efficiency of 10^{-5} – 10^{-4} is required to align the measured deposition of ^{60}Fe with the assumption of the LIC being a pure supernova remnant fragment. Dust models indicate that the fraction of ^{60}Fe from supernovae that reaches Earth as dust is on the order of 10^{-2} [36,67] with complete condensation into dust and full dust survival. A reduced influx of ^{60}Fe by more than 2 orders of magnitude compared to the expectation, and significantly lower than the influx peak 2–3 Myr ago, does not favor the CLIC representing a pure supernova fragment. A possible explanation is that a significant fraction of the dust in the LIC did not form in a recent supernova but was old interstellar dust swept up by the supernova ejecta forming the CLIC. Another explanation would be that the CLIC was already present and thereby consisting of old ISM dust and was subsequently seeded by a recent supernova with freshly synthesized ^{60}Fe . It is unclear whether clouds with densities and sizes such as the LIC are capable

of stopping and confining dust grains from supernovae [41]. If it can be demonstrated that the LIC represents a pure supernova remnant fragment, a different scenario with a significantly higher ^{60}Fe density in the ISM surrounding the solar system or different ISM dynamics is required to explain the influx of ^{60}Fe 2–3 Myr ago. Importantly, the data of this and previous studies [38,39] covering the last 80 kyr indicate that a deposition of ^{60}Fe from the ISM is possible without the need for a supernova blast wave penetrating the solar system.

While the origin of the LIC is still not settled, our data suggest that the LIC is a cosmic archive for supernova-produced ^{60}Fe and that the imprinted deposition pattern of ^{60}Fe allows us to investigate the structure of the LIC. The significantly lower influx of ^{60}Fe deposited 40–81 kyr ago compared to more recent times suggests that the solar system was either mostly outside the LIC during that time period, compatible with a CLIC density of 0.2 cm^{-3} and individual clouds separated by a thin LB-like ISM [20], or that the solar system was within clouds at all times over the last 80 kyr, compatible with a CLIC density of 0.1 cm^{-3} [20], however with significant variations of ^{60}Fe -bearing dust densities within the LIC. If the clouds are well mixed, then the density variations seen in ^{60}Fe dust would translate to cloud density variations. Future work on ^{60}Fe deposition profiles on Earth covering time periods beyond 100 kyr at high time resolution might be able to track the solar system's journey through the entire CLIC as well as its first entry into the CLIC. Highly time-resolved ^{60}Fe data from samples covering the last few millennia might be able to time the potential occurrence of a transition from the LIC to an interaction zone of the LIC and the G-cloud [21].

In contrast to ^{60}Fe , other supernova-produced radionuclides such as ^{26}Al or ^{53}Mn suffer from overwhelming cosmogenic background on Earth and might not be applicable to study the history of the solar system's traversal through the CLIC. However, variations in the heliosphere through its interaction with the variable ISM during the solar system's traversal of the CLIC [6] could lead to a changing galactic cosmic ray intensity near Earth. Cosmogenic radionuclide abundances on Earth, such as ^{10}Be or ^{14}C , could reflect such changes. Known anomalies such as Miyake events [76–78] induced by solar activity variations [78,79] on the annual scale or the recently discovered Late Miocene anomaly [80] provide insights into geological and cosmic processes. Dedicated searches for radionuclide anomalies over the timescale of the solar system's passage of the CLIC coupled with heliospheric models accounting for ISM-induced modulations might complement supernova-produced ^{60}Fe records.

Acknowledgments—The authors acknowledge the facilities, and the scientific and technical assistance provided by Heavy Ion Accelerators (HIA). HIA is supported by the

Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS) program. This research was partially carried out at the Ion Beam Center (IBC) at the Helmholtz-Zentrum Dresden-Rossendorf e.V., a member of the Helmholtz Association, Project No. 23003438-ST. This work is a contribution to the European Project for Ice Coring in Antarctica (EPICA). The main logistic support for the work in Dronning Maud Land (DML) was provided by the Alfred Wegener Institute. This is EPICA publication No. 327. F. A. was supported through the Helmholtz Association (VH-NG 1501). A. R. wants to thank the Sponsors' Association of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) e.V. for supporting her. The authors thank Sabrina Beutner for ICP-MS measurements, Johannes Freitag and Hubertus Fischer for their ice core storage efforts, Jenny Feige for discussions about the local interstellar medium, and Gunther Korschinek for initiating the search for ^{60}Fe in Antarctica.

Data availability—The data that support the findings of this article are openly available [44].

-
- [1] P. C. Frisch, The galactic environment of the Sun, *J. Geophys. Res.* **105**, 10279 (2000).
 - [2] J. D. Slavin, The origins and physical properties of the Complex of Local Interstellar Clouds, *Space Sci. Rev.* **143**, 311 (2009).
 - [3] S. Redfield and J. L. Linsky, The structure of the local interstellar medium. IV. Dynamics, morphology, physical properties, and implications of cloud-cloud interactions, *Astrophys. J.* **673**, 283 (2008).
 - [4] C. Zucker, S. Redfield, S. Starcheski, R. Konietzka, and J. L. Linsky, The origin of the Complex of Local Interstellar Clouds, *Astrophys. J.* **986**, 58 (2025).
 - [5] S. Redfield and J. L. Linsky, Evaluating the morphology of the local interstellar medium: Using new data to distinguish between multiple discrete clouds and a continuous medium, *Astrophys. J.* **812**, 125 (2015).
 - [6] J. Linsky, S. Redfield, D. Ryder, and E. Moebius, Inhomogeneity in the local ISM and its relation to the heliosphere, *Space Sci. Rev.* **218**, 16 (2022).
 - [7] D. Breitschwerdt and M. de Avillez, The history and future of the Local and Loop I bubbles, *Astron. Astrophys.* **452**, L1 (2006).
 - [8] R. K. Smith and D. P. Cox, Multiple supernova remnant models of the Local Bubble and the soft x-ray background, *Astrophys. J. Suppl. Ser.* **134**, 283 (2001).
 - [9] M. A. de Avillez and M.-M. Mac Low, Mixing timescales in a supernova-driven interstellar medium, *Astrophys. J.* **581**, 1047 (2002).
 - [10] J. L. Linsky and S. Redfield, Could the local cavity be an irregularly shaped Strömgren sphere?, *Astrophys. J.* **920**, 75 (2021).
 - [11] T. J. O'Neill, C. Zucker, A. A. Goodman, and G. Edenhofer, The Local Bubble is a local chimney: A new model from 3D dust mapping, *Astrophys. J.* **973**, 136 (2024).

- [12] J. Maiz-Apellaniz, The origin of the Local Bubble, *Astrophys. J. Lett.* **560**, L83 (2001).
- [13] B. Fuchs, D. Breitschwerdt, M. A. De Avillez, C. Dettbarn, and C. Flynn, The search for the origin of the Local Bubble redivivus, *Mon. Not. R. Astron. Soc.* **373**, 993 (2006).
- [14] M. M. Schulreich, D. Breitschwerdt, J. Feige, and C. Dettbarn, Numerical studies on the link between radioisotopic signatures on Earth and the formation of the Local Bubble—I. ^{60}Fe transport to the solar system by turbulent mixing of ejecta from nearby supernovae into a locally homogeneous interstellar medium, *Astron. Astrophys.* **604**, A81 (2017).
- [15] M. M. Schulreich, J. Feige, and D. Breitschwerdt, Numerical studies on the link between radioisotopic signatures on Earth and the formation of the Local Bubble—II. Advanced modelling of interstellar ^{26}Al , ^{53}Mn , ^{60}Fe , and ^{244}Pu influxes as traces of past supernova activity in the solar neighbourhood, *Astron. Astrophys.* **680**, A39 (2023).
- [16] C. Zucker, A. A. Goodman, J. Alves, S. Bialy, M. Foley, J. S. Speagle, J. Grossschedl, D. P. Finkbeiner, A. Burkert, D. Khimey, and C. Swiggum, Star formation near the Sun is driven by expansion of the Local Bubble, *Nature (London)* **601**, 334 (2022).
- [17] P. C. Frisch and J. D. Slavin, Short-term Variations in the Galactic environment of the Sun, in *Solar Journey: The Significance of Our Galactic Environment for the Heliosphere and Earth* (Springer, New York, 2006), pp. 133–193.
- [18] P. C. Frisch, S. Redfield, and J. D. Slavin, The interstellar medium surrounding the Sun, *Annu. Rev. Astron. Astrophys.* **49**, 237 (2011).
- [19] H.-R. Müller, P. C. Frisch, V. Florinski, and G. P. Zank, Heliospheric response to different possible interstellar environments, *Astrophys. J.* **647**, 1491 (2006).
- [20] H. Vannier, S. Redfield, B. E. Wood, H.-R. Müller, J. L. Linsky, and P. C. Frisch, Mapping our path through the local interstellar medium: High-resolution ultraviolet absorption spectroscopy of sight lines along the Sun’s historical trajectory, *Astrophys. J.* **981**, 102 (2025).
- [21] P. Swaczyna, N. A. Schwadron, E. Möbius, M. Bzowski, P. C. Frisch, J. L. Linsky, D. J. McComas, F. Rahmanifard, S. Redfield, R. M. Winslow, B. E. Wood, and G. P. Zank, Mixing interstellar clouds surrounding the Sun, *Astrophys. J. Lett.* **937**, L32 (2022).
- [22] D. Breitschwerdt, M. Freyberg, and R. Egger, Origin of HI clouds in the local bubble. I. A hydromagnetic Rayleigh-Taylor instability caused by the interaction between the Loop I and the local bubble, *Astron. Astrophys.* **361**, 303 (2000), <https://articles.adsabs.harvard.edu/pdf/2000A%26A...361..303B>.
- [23] H. Kimura, I. Mann, and E. K. Jessberger, Elemental abundances and mass densities of dust and gas in the Local Interstellar Cloud, *Astrophys. J.* **582**, 846 (2003).
- [24] P. C. Frisch, J. M. Dorschner, J. Geiss, J. M. Greenberg, E. Grün, M. Landgraf, P. Hoppe, A. P. Jones, W. Krätschmer, T. J. Linde, G. E. Morfill, W. Reach, J. D. Slavin, J. Svestka, A. N. Witt, and G. P. Zank, Dust in the local interstellar wind, *Astrophys. J.* **525**, 492 (1999).
- [25] D. P. Cox and L. Helenius, Flux-tube dynamics and a model for the origin of the Local Fluff, *Astrophys. J.* **583**, 205 (2003).
- [26] J. D. Slavin, Interstellar dust and gas in the heliosphere, *J. Phys. Conf. Ser.* **1620**, 012019 (2020).
- [27] G. Rugel, T. Faestermann, K. Knie, G. Korschinek, M. Poutivtsev, D. Schumann, N. Kivel, I. Günther-Leopold, R. Weinreich, and M. Wohlmuther, New measurement of the ^{60}Fe half-life, *Phys. Rev. Lett.* **103**, 072502 (2009).
- [28] A. Wallner, M. Bichler, K. Buczak, R. Dressler, L. K. Fifield, D. Schumann, J. H. Sterba, S. G. Tims, G. Wallner, and W. Kutschera, Settling the half-life of ^{60}Fe : Fundamental for a versatile astrophysical chronometer, *Phys. Rev. Lett.* **114**, 041101 (2015).
- [29] K. Knie, G. Korschinek, T. Faestermann, E. A. Dorfi, G. Rugel, and A. Wallner, ^{60}Fe anomaly in a deep-sea manganese crust and implications for a nearby supernova source, *Phys. Rev. Lett.* **93**, 171103 (2004).
- [30] A. Wallner, J. Feige, N. Kinoshita, M. Paul, L. Fifield, R. Golser, M. Honda, U. Linnemann, H. Matsuzaki, S. Merchel, R. Rugel, S. Tims, P. Steier, T. Yamagata, and S. Winkler, Recent near-Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe , *Nature (London)* **532**, 69 (2016).
- [31] A. Wallner, M. B. Froehlich, M. A. C. Hotchkis, N. Kinoshita, M. Paul, M. Martschini, S. Pavetich, S. G. Tims, N. Kivel, D. Schumann, M. Honda, H. Matsuzaki, and T. Yamagata, ^{60}Fe and ^{244}Pu deposited on Earth constrain the r-process yields of recent nearby supernovae, *Science* **372**, 742 (2021).
- [32] D. Koll, A 10-million year time profile of interstellar influx to Earth mapped through supernova ^{60}Fe and r-process ^{244}Pu , Ph.D. thesis, The Australian National University and TUD Dresden University of Technology, 2023, [10.25911/5NJB-YC98](https://nbn-resolving.org/urn:nbn:de:bsz:5njb-yc98).
- [33] D. Koll, S. Fichter, M. A. C. Hotchkis, S. T. Battison, S. Beutner, L. K. Fifield, M. B. Froehlich, J. Lachner, S. Pavetich, G. Rugel, Z. Slavkovska, S. G. Tims, and A. Wallner, The timing of the last r-process event near Earth from interstellar ^{60}Fe , ^{244}Pu and ^{247}Cm , *Nat. Astron.* **10**, 1038/s41550-026-02841-6 (2026).
- [34] P. Ludwig, S. Bishop, R. Egli, V. Chernenko, B. Deneva, T. Faestermann, N. Famulok, L. Fimiani, J. M. Gómez-Guzmán, K. Hain, G. Korschinek, M. Hanzlik, S. Merchel, and G. Rugel, Time-resolved 2-million-year-old supernova activity discovered in Earth’s microfossil record, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 9232 (2016).
- [35] L. Fimiani, D. L. Cook, T. Faestermann, J. M. Gómez-Guzmán, K. Hain, G. Herzog, K. Knie, G. Korschinek, P. Ludwig, J. Park, R. C. Reedy, and G. Rugel, Interstellar ^{60}Fe on the surface of the Moon, *Phys. Rev. Lett.* **116**, 151104 (2016).
- [36] T. Athanassiadou and B. Fields, Penetration of nearby supernova dust in the inner solar system, *New Astron.* **16**, 229 (2011).
- [37] B. J. Fry, B. D. Fields, and J. R. Ellis, Radioactive iron rain: Transporting ^{60}Fe in supernova dust to the ocean floor, *Astrophys. J.* **827**, 48 (2016).
- [38] D. Koll, G. Korschinek, T. Faestermann, J. M. Gómez-Guzmán, S. Kipfstuhl, S. Merchel, and J. M. Welch, Interstellar ^{60}Fe in Antarctica, *Phys. Rev. Lett.* **123**, 072701 (2019).
- [39] A. Wallner, J. Feige, L. K. Fifield, M. B. Froehlich, R. Golser, M. A. C. Hotchkis, D. Koll, G. Leckenby, M.

- Martschini, S. Merchel, S. Panjkov, S. Pavetich, G. Rugel, and S. G. Tims, ^{60}Fe deposition during the late Pleistocene and the Holocene echoes past supernova activity, *Proc. Natl. Acad. Sci. U.S.A.* **117**, 21873 (2020).
- [40] D. Koll, T. Faestermann, G. Korschinek, and A. Wallner, Origin of recent interstellar ^{60}Fe on Earth, *EPJ Web Conf.* **232**, 02001 (2020).
- [41] A. F. Ertel, B. J. Fry, B. D. Fields, and J. Ellis, Supernova dust evolution probed by deep-sea ^{60}Fe time history, *Astrophys. J.* **947**, 58 (2023).
- [42] J. L. Linsky, S. Redfield, D. Ryder, and A. Chasan-Taber, Inhomogeneity within Local Interstellar Clouds, *Astron. J.* **164**, 106 (2022).
- [43] EPICA Community Members, One-to-one coupling of glacial climate variability in Greenland and Antarctica, *Nature (London)* **444**, 195 (2006).
- [44] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/nxjq-jwgp> for stable nuclide, radionuclide and ice core data.
- [45] D. Koll, S. Fichter, M. Hotchkis, M. Martschini, S. Merchel, S. Pavetich, A. Rolofs, S. Tims, S. Zwickel, and A. Wallner, Recent progress on interstellar radionuclides on Earth and the Moon, *Eur. Phys. J. A* **61**, 101 (2025).
- [46] U. Ruth, J.-M. Barnola, J. Beer, M. Bigler, T. Blunier, E. Castellano, H. Fischer, F. Fundel, P. Huybrechts, P. Kaufmann, S. Kipfstuhl, A. Lambrecht, A. Morganti, H. Oerter, F. Parrenin, O. Rybak, M. Severi, R. Udisti, F. Wilhelms, and E. Wolff, “EDML1”: A chronology for the EPICA deep ice core from Dronning Maud Land, Antarctica, over the last 150 000 years, *Clim. Past* **3**, 475 (2007).
- [47] M. Bouchet, A. Landais, A. Grisart, F. Parrenin, F. Prié, R. Jacob, E. Fourré, E. Capron, D. Raynaud, V. Y. Lipenkov, M.-F. Loutre, T. Extier, A. M. Svensson, P. Martinerie, M. C. Leuenberger, W. Jiang, F. Ritterbusch, Z.-T. Lu, and G.-M. Yang, The Antarctic ice core chronology (AICC2023). PANGAEA. [10.1594/PANGAEA.961019](https://doi.org/10.1594/PANGAEA.961019) (2023).
- [48] G. Winckler and H. Fischer, 30,000 years of cosmic dust in Antarctic ice, *Science* **313**, 491 (2006).
- [49] C. I. Paleari, F. Mekhaldi, T. Erhardt, M. Zheng, M. Christl, F. Adolphi, M. Hörhold, and R. Muscheler, Evaluating the 11-year solar cycle and short-term ^{10}Be deposition events with novel excess water samples from the East Greenland Ice-core Project (EGRIP), *Clim. Past* **19**, 2409 (2023).
- [50] S. Fichter, D. Koll, A. Rolofs, and A. Wallner, Case studies of three geological archives for rare radionuclide measurements using accelerator mass spectrometry, *Front. Environ. Chem.* **5**, 1379862 (2024).
- [51] W. Kutschera, A. J. Timothy Jull, M. Paul, and A. Wallner, Atom counting with accelerator mass spectrometry, *Rev. Mod. Phys.* **95**, 035006 (2023).
- [52] G. J. Feldman and R. D. Cousins, Unified approach to the classical statistical analysis of small signals, *Phys. Rev. D* **57**, 3873 (1998).
- [53] G. Rugel, S. Pavetich, S. Akhmalaliev, S. M. Enamorado Baez, A. Scharf, R. Ziegenrucker, and S. Merchel, The first four years of the AMS-facility DREAMS: Status and developments for more accurate radionuclide data, *Nucl. Instrum. Methods Phys. Res., Sect. B* **370**, 94 (2016).
- [54] J. Lachner, G. Rugel, C. Vivo Vilches, D. Koll, K. Stübner, S. Winkler, and A. Wallner, Optimization of ^{10}Be measurements at the 6 MV AMS facility DREAMS, *Nucl. Instrum. Methods Phys. Res., Sect. B* **535**, 29 (2023).
- [55] U. Heikkilä, J. Beer, J. Abreu, and F. Steinhilber, On the atmospheric transport and deposition of the cosmogenic radionuclides (^{10}Be): A review, *Space Sci. Rev.* **176**, 321 (2013).
- [56] M. Auer, D. Wagenbach, E. M. Wild, A. Wallner, A. Priller, H. Miller, C. Schlosser, and W. Kutschera, Cosmogenic ^{26}Al in the atmosphere and the prospect of a $^{26}\text{Al}/^{10}\text{Be}$ chronometer to date old ice, *Earth Planet. Sci. Lett.* **287**, 453 (2009).
- [57] K. Horiuchi, H. Matsuzaki, A. Ohta, Y. Shibata, and H. Motoyama, Measurement of ^{26}Al in Antarctic ice with the MALT-AMS system at the University of Tokyo, *Nucl. Instrum. Methods Phys. Res., Sect. B* **259**, 625 (2007).
- [58] J. Beer, K. G. McCracken, F. Adolphi, M. Christl, H. Fischer, H. Miller, R. Muscheler, H. A. Synal, and F. Wilhelms, Heliomagnetic and geomagnetic activity cycles on millennial timescales, *Quaternary Science Reviews* **361**, 109364 (2025).
- [59] I. Leya, J.-C. David, T. Faestermann, M. Froehlich, N. Kivel, D. Koll, G. Korschinek, S. McIntyre, S. Merchel, S. Pavetich, G. Rugel, D. Schumann, T. Smith, and A. Wallner, ^{53}Mn and ^{60}Fe in iron meteorites—New data and model calculations, *Meteorit. Planet. Sci.* **55**, 818 (2020).
- [60] R. Trappitsch and I. Leya, Cosmogenic production rates and recoil loss effects in micrometeorites and interplanetary dust particles, *Meteorit. Planet. Sci.* **48**, 195 (2013).
- [61] C. Vivo-Vilches, G. Rugel, J. Lachner, D. Koll, K. Stübner, S. Fichter, S. Winkler, and A. Wallner, Pushing the limits of ^{41}Ca AMS with CaF_2 targets at DREAMS, *Nucl. Instrum. Methods Phys. Res., Sect. B* **540**, 188 (2023).
- [62] C. Fitoussi, G. M. Raisbeck, K. Knie, G. Korschinek, T. Faestermann, S. Goriely, D. Lunney, M. Poutivtsev, G. Rugel, C. Waelbroeck, and A. Wallner, Search for supernova-produced ^{60}Fe in a marine sediment, *Phys. Rev. Lett.* **101**, 121101 (2008).
- [63] D. Koll, T. Faestermann, G. Korschinek, I. Leya, S. Merchel, and A. Wallner, The dyadic radionuclide system $^{60}\text{Fe}/^{53}\text{Mn}$ to distinguish interstellar from interplanetary ^{60}Fe , *EPJ Web Conf.* **260**, 11022 (2022).
- [64] K. Lodders, *Solar Elemental Abundances* (Oxford University Press, New York, 2020).
- [65] A. Wallner, L. Fifield, M. Froehlich, D. Koll, G. Leckenby, M. Martschini, S. Pavetich, S. Tims, D. Schumann, and Z. Slavkovská, Accelerator mass spectrometry with ANU’s 14 million volt accelerator, *Nucl. Instrum. Methods Phys. Res., Sect. B* **534**, 48 (2023).
- [66] W. Binns, M. H. Israel, E. R. Christian, A. C. Cummings, G. A. de Nolfo, K. A. Lave, R. A. Leske, R. A. Mewaldt, E. C. Stone, T. T. von Rosenvinge, and M. E. Wiedenbeck, Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays, *Science* **352**, 677 (2016).
- [67] B. J. Fry, B. D. Fields, and J. R. Ellis, Astrophysical shrapnel: Discriminating among near-earth stellar explosion sources of live radioactive isotopes, *Astrophys. J.* **800**, 71 (2015).

- [68] B. J. Fry, B. D. Fields, and J. R. Ellis, Magnetic imprisonment of dusty pinballs by a supernova remnant, *Astrophys. J.* **894**, 109 (2020).
- [69] D. Breitschwerdt, J. Feige, M. M. Schulreich, M. A. de Avillez, C. Dettbarn, and B. Fuchs, The locations of recent supernovae near the Sun from modelling ^{60}Fe transport, *Nature (London)* **532**, 73 (2016).
- [70] M. Limongi, L. Roberti, A. Falla, A. Chieffi, and K. Nomoto, The chemical yields of stars in the mass range $9\text{--}15M_{\odot}$, *Astrophys. J. Suppl. Ser.* **279**, 41 (2025).
- [71] H. Krüger, P. Strub, E. Grün, and V. J. Sterken, Sixteen years of Ulysses interstellar dust measurements in the solar system. I. mass distribution and gas-to-dust mass ratio, *Astrophys. J.* **812**, 139 (2015).
- [72] M. Limongi and A. Chieffi, The Nucleosynthesis of ^{26}Al and ^{60}Fe in solar metallicity stars extending in mass from 11 to $120M_{\odot}$: The hydrostatic and explosive contributions, *Astrophys. J.* **647**, 483 (2006).
- [73] P. Todini and A. Ferrara, Dust formation in primordial Type II supernovae, *Mon. Not. R. Astron. Soc.* **325**, 726 (2001).
- [74] A. Sarangi and I. Cherchneff, Condensation of dust in the ejecta of Type II-P supernovae, *Astron. Astrophys.* **575**, A95 (2015).
- [75] S. Bianchi and R. Schneider, Dust formation and survival in supernova ejecta, *Mon. Not. R. Astron. Soc.* **378**, 973 (2007).
- [76] F. Miyake, K. Nagaya, K. Masuda, and T. Nakamura, A signature of cosmic-ray increase in A.D. 774–775 from tree rings in Japan, *Nature (London)* **486**, 240 (2012).
- [77] F. Miyake, A. Suzuki, K. Masuda, K. Horiuchi, H. Motoyama, H. Matsuzaki, Y. Motizuki, K. Takahashi, and Y. Nakai, Cosmic ray event of A.D. 774–775 shown in quasi-annual ^{10}Be data from the Antarctic Dome Fuji ice core, *Geophys. Res. Lett.* **42**, 84 (2015).
- [78] F. Mekhaldi, R. Muscheler, F. Adolphi, A. Aldahan, J. Beer, J. R. McConnell, G. Possnert, M. Sigl, A. Svensson, H.-A. Synal, K. Welton, and T. Woodruff, Multiradionuclide evidence for the solar origin of the cosmic-ray events of AD 774/5 and 993/4, *Nat. Commun.* **6**, 8611 (2015).
- [79] I. G. Usoskin, A history of solar activity over millennia, *Living Rev. Solar Phys.* **20**, 2 (2023).
- [80] D. Koll, J. Lachner, S. Beutner, S. Fichter, S. Merchel, G. Rugel, Z. Slavkovská, C. Vivo-Vilches, S. Winkler, and A. Wallner, A cosmogenic ^{10}Be anomaly during the late Miocene as independent time marker for marine archives, *Nat. Commun.* **16**, 866 (2025).