EPJ Web of Conferences **232**, 02001 (2020) https://doi.org/10.1051/epjconf/202023202001
HIAS 2019

Origin of Recent Interstellar ^{60}Fe on Earth

Dominik Koll[1,2,*], *Thomas* Faestermann[2,3], *Gunther* Korschinek[2,3], and *Anton* Wallner[1]

[1]Department of Nuclear Physics, Research School of Physics, The Australian National University, Canberra, ACT 2601, Australia.
[2]Physik-Department, Technische Universität München, 85748 Garching, Germany
[3]Excellence Cluster Universe, 85748 Garching, Germany

Abstract. Over the last 20 years, evidence for a 2 Myr old supernova ^{60}Fe influx onto Earth was provided by several authors. For the first time, independent investigations of samples from two different geological archives yielded conclusive data for a further, much younger ^{60}Fe influx onto Earth. The origin of this influx is currently unclear because of the limited data available, the lack of consistent astrophysical models and a gap in the data between 50 kyr and 1 Myr. Possible astrophysical scenarios will be discussed with respect to the different influx patterns from different sources and a measurement to close the gap will be proposed.

1 Introduction

Structure formation in the universe is governed by the life cycle of stars. They synthesize heavier elements in their interior which are then subsequently ejected by the winds of massive stars and by supernovae at the end of the stars' life. One interesting isotope for astrophysical studies is the long-lived radionuclide ^{60}Fe ($t_{1/2} = 2.6$ Myr [1, 2]), which is synthesized by double neutron capture on ^{58}Fe in the stellar s-process and by explosive nucleosynthesis. Other possible production sites of ^{60}Fe relevant for the detection on Earth comprise cosmic-ray irradiated interplanetary dust and meteorites and nuclear activities on Earth. In-situ production on Earth by cosmic rays and spontaneous fission is insignificant and all primordial ^{60}Fe has decayed (more than 1500 half-lives since the formation of Earth).

Evidence for ^{60}Fe on Earth was presented for the first time in 1999 by the Munich Accelerator Mass Spectrometry (AMS) group [3]. An indication for a nearby supernova activity was found in a ferromanganese crust which was confirmed in 2004 [4]. Subsequent investigations of deep-sea sediments, ferromanganese crusts and nodules further validated the initial finding [5, 6], complemented by lunar surface and cosmic-ray data [7, 8]. Previous investigations showed an ^{60}Fe activity around 2 Myr ago with some indication for an older influx around 6 Myr [5, 9]. None of the previous investigations targeted the very recent past and present of Earth's history for ^{60}Fe and therefore, no indication of recent ^{60}Fe was reported so far.

A recent supernova dust influx onto Earth would have implications for astrophysical models including structure formation by stellar explosions, dust dynamics in the local interstellar medium as well as in supernova ejecta, and transport mechanisms of interstellar dust into the Solar System.

*e-mail: dominik.koll@anu.edu.au

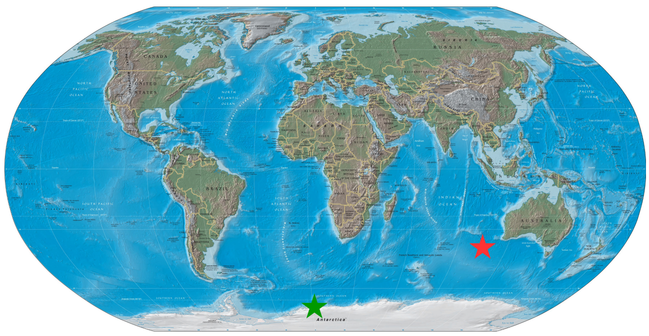

Figure 1: Sampling location of the ocean sediment (ANU) and the Antarctic snow (TUM) represented by a red and green star, respectively. Figure modified from [10].

2 Recent ^{60}Fe on Earth

In 2019, the AMS groups of The Australian National University (ANU) and Technical University of Munich (TUM) analyzed independently two different geological archives (Fig. 1) for a recent ^{60}Fe deposition with their dedicated gas-filled magnet detection systems [5, 11]. Only these two groups with their facilities achieved the required sensitivity to detect interstellar ^{60}Fe with background-free conditions so far.

2.1 Antarctic Snow

The TUM group chose for the first time ever Antarctic surface snow for the analysis. Antarctic snow is intrinsically pure and readily available. Due to the high accumulation rate for Antarctic snow of mm/yr compared to mm/kyr or mm/Myr for sediments and crusts, high initial sample masses are needed to detect single atoms from an interstellar dust influx. Five hundred kilograms of snow from the Kohnen Station (75° S, 0° E at an elevation of 2892 m) with a measured recent accumulation rate of 80 mm / yr water equivalent were collected and chemically processed [12]. The AMS analysis yielded in total 10 atoms of ^{60}Fe which correspond to an ^{60}Fe deposition rate of $1.2^{+0.6}_{-0.5}$ at / cm^2 / yr considering the sampled mass and accumulation rate [13].

2.2 Deep-Sea Sediments

The ANU group focused on surface sediment samples which were a subset of already available sediments from [5]. The sediment cores were taken from the Indian Ocean (38°S, 104° E, at - 4200 m). Five samples were analyzed with a total of 15 g of sediment covering up to 33 kyr with a sedimentation rate of about 4 mm / kyr [14]. In total, 19 atoms of ^{60}Fe were detected corresponding to an average deposition rate of $3.5^{+1.1}_{-0.9}$ at / cm^2 / yr over 33 kyr [14]. For the average it was assumed that the influx did not change significantly over 33 kyr considering this very small timescale in the astrophysical context, which is supported by the data.

2.3 Further Data

In addition to the discussed recent ^{60}Fe influx targeting measurements, data are available from other projects. The same sediment core gave already an upper limit for a recent influx of < 2.2 at / cm^2 / yr with material younger than 200 kyr in 2016 [5]. Furthermore, the latest ^{60}Fe study analyzing a ferromanganese crust found a non-zero recent influx of ^{60}Fe with material younger than 370 kyr [9]. The measured value of 0.2 at / cm^2 / yr has to be corrected for the crust incorporation efficiency of 17% yielding 1.2 ± 0.4 at / cm^2 / yr, in remarkable agreement with the snow data. Other published data on ocean sediments, ocean crusts and lunar regolith integrate over longer time steps, where no information about the recent component could be deduced. We combine the three available values for a recent ^{60}Fe influx from crust, sediments and snow to obtain an arithmetic mean of 2.0 ± 0.8 at / cm^2 / yr. The arithmetic mean was chosen because of the very different timescales covered by these samples, the different origin of the samples and the low counting statistics responsible for the uncertainties. Anisotropies in the absolute ^{60}Fe deposition for different archives and latitudes could be explained by a non-uniform distribution over Earths surface through atmospheric processes [15] and by differences in uptake, remobilization and bioperturbation. Lunar samples should retain the source characteristic influx pattern, unfortunately without time-resolution [7].

3 Astrophysical Scenarios

The previous ^{60}Fe signal around 2 Myr ago was interpreted as transient supernova ejecta coming from the Scorpius-Centaurus Association or the Tuc-Hor group [16–20]. Astrophysical modelling already indicated that a recent influx of ^{60}Fe could be induced by preceding supernovae [18]. We discuss three different influx scenarios, based on the assumption that there is a correlation between the old ^{60}Fe signal and the recent influx of ^{60}Fe, similar but extended to the discussion in [14].

First, the source responsible for the recent influx could be identical to that of the previous signal, whereby the ^{60}Fe deposition is much lower due to a gradual fade out of the signal. This would mean that there is a continuous influx from 2 Myr up to the present which monotonically decreases. Considering a supernova remnant radius of 50 - 100 pc, which is needed for candidates in Sco-Cen or Tuc-Hor to reach the Solar System, the expansion time becomes on the order of Myr [15, 21]. Considering the width of previously obtained signals of at least a Myr, one order of magnitude less ^{60}Fe deposition at recent times compared to the 2 Myr signal is in reach.

Second, the origin of the recent influx is identical to any of the previous signals, but the influx is not monotonic. For example, the 2 Myr signal could decrease at first to a minimum and then increases to the recent value. This could be realized by a magnetic reflection of the supernova ejecta on astrophysical structures, such as a contact discontinuity between the supernova shock front and the shocked interstellar medium besides others, which could lead to a bounce back of the ejecta towards the Solar System [22]. The influx direction would therefore be different, maybe even fully inverse to the previous signals, which could be monitored on other planets or satellites without an atmosphere.

Third, the influx is not identical but related to the previous signals. The Solar System entered the so called Local Interstellar Cloud up to 40 kyr ago, which is one of several cloudlets in the Complex of Local Interstellar Clouds around the Solar System [23–26]. These clouds were formed by the interaction of superbubbles in supernova regions. It is reasonable to assume that these structures contain fragments of supernova synthesized material, possibly including ^{60}Fe. The penetration of our Solar System into these clouds could lead to an influx of ^{60}Fe [13].

These three scenarios are exemplarily illustrated in Fig. 2 by the black trendlines, which have no deeper meaning than visualization. The peak around 2 Myr could either monotonically decrease which would indicate the first scenario or drastically fall off to a minimum before increasing again. This would be indicative that either the second or the third explanation might be true. The increase in influx would happen at a specific time for the cloud hypothesis, namely when the Solar System entered the cloud, whereas the increase would happen at an arbitrary time, possibly closer to the peak around 2 Myr for the second scenario.

In contrast to a correlated influx pattern, the ^{60}Fe influx at recent times could also be constant and unrelated to nearby supernova activities. The currently available data only covers a single time range or integrates over much longer time scales. Therefore, a constancy could not be ruled out by current data and we have shown that they agree within the errors. This would then imply that the detected ^{60}Fe is a product of cosmic ray interactions with interplanetary and interstellar dust. The radionuclide ^{53}Mn, which is dominantly produced by cosmic rays, was mea-

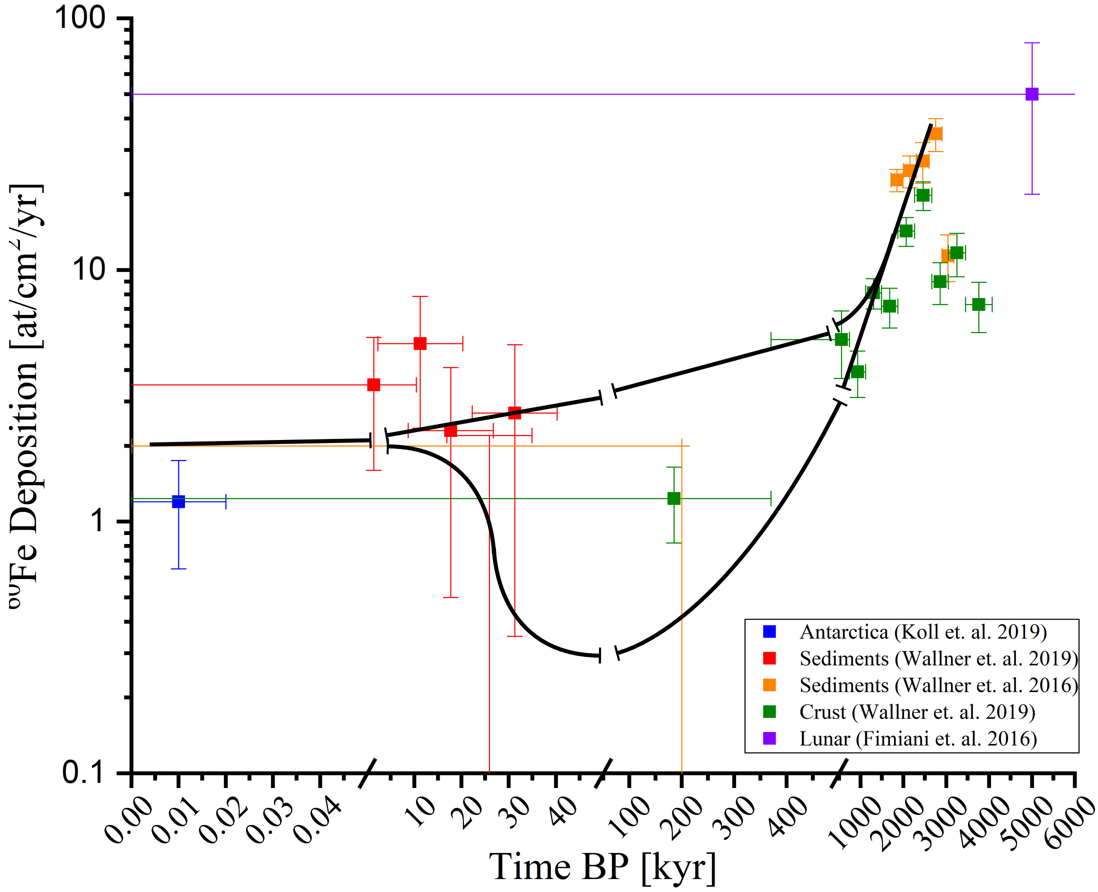

Figure 2: Compilation of ^{60}Fe investigations over four different timescales with focus on the recent component of their data. The lunar data only gives an integral value over several Myr, the top layers of the crust and the previous sediments over several 100 kyr. The crust data fits remarkably well with the Antarctic snow data. The top layer of the sediment from [5] only gave an upper limit consistent with most of the recent data within the errors. The black lines indicate possible influx patterns which could be assumed for different origins of the recent ^{60}Fe.

sured in Antarctic snow to a much smaller extent than anticipated for a purely cosmogenic origin of the ^{60}Fe. The Ni content was measured in the sediments and compared to the expected amount of cosmogenic Ni which is needed to account for all the measured ^{60}Fe. Furthermore, the dust accretion onto Earth was used to estimate the total influx of cosmogenic ^{60}Fe onto Earth. Both estimations fall short of explaining the detected ^{60}Fe. If the recent influx is interpreted as cosmogenic ^{60}Fe, then this would challenge our understanding of dust accretion on Earth as well as models on production rates of ^{60}Fe in cosmic dust. Therefore, this possibility is regarded as unlikely. Recently, it was proposed that the present day influx into Antarctic snow could be a one-time event in 2005 [27], which is is no longer supported by the sediment data.

It was indicated that the cloud hypothesis could be tested by older material from Antarctic ice cores [13]. Here, we extend this suggestion to different samples, such as deep-sea sediments, fast growing ferromanganese crusts as well as Antarctic and Arctic ice with focus on the time period between 50 kyr and 300 kyr. No time resolved data is available that is exclusively focusing and covering this time period. Targeted investigations could close the gap and reveal the influx pattern over several ten to hundred kyr which could then be used to deduce the origin of the recent ^{60}Fe influx. For sediment samples, around 50 g in total are needed for several data points at different time steps with good statistics, for crusts even less material is needed because of higher growth rates and the higher abundance of Fe compared to sediments. For Antarctic ice cores in the mentioned time period, the growth rate changes significantly [28]. However, the growth rate is significantly lower than for surface snow, for instance around 100 kyr ago the growth rate is below 20 mm / yr. Assuming a conservative growth rate of 20 mm / yr and taking into account the detection efficiency of the AMS facility at ANU, which is higher by a factor 2.5 compared to TUM, the 500 kg of surface snow from TUM would turn into 100 kg of ice core material over several hundred meters of ice for more than 20 counts of ^{60}Fe, if the first scenario would be true. For Arctic ice cores, where growth rates are considerably higher [29], the measurement would require more sample material. We note, that the requirements for ice cores are also met by ice core chips, which are generally easier available than full ice cores. If the second or third scenario would be true one could either deduce the location of the astrophysical boundary where the supernova remnant is reflected by the transition time from the incident wave to the reflected wave or one could reveal the time when the Solar System entered either the Local Interstellar Cloud or the Complex of Local Interstellar Clouds.

With the proposed measurements of terrestrial material, the mechanics of the ^{60}Fe influx could be pinned down to a specific astrophysical scenario. The most promising geological archives in the 100 kyr time range are deep-sea sediments and Antarctic ice cores because of their good time resolution and reasonable sample masses. After the gap is closed we will have a 10 Myr history of nearby supernova activity depositing ^{60}Fe on Earth in the year, ten kiloyear, hundred kiloyear and Myr timescale. The influx of supernova dust could therefore be monitored on different timescales which is needed to understand the dynamics of supernova ejecta in the interstellar medium.

Acknowledgements

The work at TUM was supported by the DFG Cluster of Excellence "Origin and Structure of the Universe". The work at ANU was supported by the Austrian Science Fund (FWF), project no. AI00428, through the European Science Foundation Collaborative Research Project CoDustMas, the Australian Research Council (ARC), project numbers DP140100136, DP180100495, DP180100496, the German Academic Exchange Service (DAAD), project no. 56266169, and The Group of Eight Australia–Germany Joint Research Cooperation Scheme. The support for the Heavy Ion Accelerator Facility at ANU by NCRIS is highly appreciated. The authors want to explicitly thank Silke Merchel for her advice and efforts in chemistry for both projects.

References

[1] G. Rugel, T. Faestermann, K. Knie *et al.*, Phys. Rev. Lett. **103**, 072502 (2009).

[2] A. Wallner, M. Bichler, K. Buczak *et al.*, Phys. Rev. Lett. **114**, 041101 (2015).

[3] K. Knie, G. Korschinek, T. Faestermann *et al.*, Phys. Rev. Lett. **83**, 18 (1999).

[4] K. Knie, G. Korschinek, T. Faestermann *et al.*, Phys. Rev. Lett. **93**, 171103 (2004).

[5] A. Wallner, J. Feige, N. Kinoshita *et al.*, Nature **532**, 69 (2016).

[6] P. Ludwig, S. Bishop, R. Egli *et al.*, P. Natl. Acad. Sci. USA **113**, 9232 (2016).

[7] L. Fimiani, D.L. Cook, T. Faestermann *et al.*, Phys. Rev. Lett. **116**, 151104 (2016).

[8] W. R. Binns, M. H. Israel, E. R. Christian *et al.*, Science **352**, 677(2016).

[9] A. Wallner, M. Froehlich, M. Hotchkis *et al.*, submitted (2019).

[10] World map (modified by DK, Public Domain), *https://commons.wikimedia.org/wiki/Maps_of_the_world*.

[11] D. Koll, C. Busser, T. Faestermann *et al.*, Nucl. Instrum. Methods B **438**, 180 (2019).

[12] S. Merchel, U. Herpers, Radiochim. Acta **84,** 215 (1999).

[13] D. Koll, G. Korschinek, T. Faestermann *et al.*, Phys. Rev. Lett. **123**, 072701 (2019).

[14] A. Wallner, J. Feige, L. K. Fifield *et al.*, submitted (2019).

[15] B. J. Fry, B. D. Fields, J. R. Ellis, Astrophys. J. **800**, 71 (2015).

[16] N. Benitez, J. Maiz-Apellaniz, M. Canelles, Phys. Rev. Lett. **88**, 081101 (2002).

[17] D. Breitschwerdt, J. Feige, M. M. Schulreich *et al.*, Nature **532**, 73 (2016).

[18] M. M. Schulreich, D. Breitschwerdt, J. Feige *et al.*, Astron. Astrophys. **604**, A81 (2017).

[19] E. E. Mamajek, Proceedings of the International Astronomical Union **10**, 21 (2015).

[20] B. J. Fry, B. D. Fields, J. R. Ellis, Astrophys. J. **827**, 48 (2016).

[21] D. A. Leahy, J. E. Williams, Astrophys. J. **153**, 239 (2017).

[22] B. J. Fry, B. D. Fields, J. R. Ellis, arXiv:1801.06859 (2018).

[23] D. P. Cox, R.J. Reynolds, Annu. Rev. Astron. Astr. **25**, 303 (1987).

[24] P. Frisch, J. Geophys. Res.-Space **105**, 10279 (2000).

[25] J. D. Slavin, Space Sci. Rev. **143**, 311 (2009).

[26] I. Mann, Annu. Rev. Astron. Astr. **48**, 173 (2010).

[27] J. L. Linsky, S. Redfield, D. Tilipman, Astrophys. J. **886**, 41 (2019).

[28] U. Ruth, J. M. Barnola, J. Beer *et al.*, Clim. Past **3**, 475 (2007).

[29] D. A. Meese, A. J. Gow, R. B. Alley *et al.*, J. Geophys. Res.-Oceans **102**, 26411 (1997).