

## PROCEEDING

# Can We Draw Conclusions on Supernova Shock Wave Propagation Using Short-Lived Radioactive Isotopes?

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## ABSTRACT

We run a three-dimensional Galactic chemical evolution (GCE) model to follow the propagation of  $^{53}\text{Mn}$  (exclusively produced from type Ia supernovae, SNIa),  $^{60}\text{Fe}$  (exclusively produced from core-collapse supernovae, CCSNe),  $^{182}\text{Hf}$  (exclusively produced from intermediate mass stars, IMs), and  $^{244}\text{Pu}$  (exclusively produced from neutron star mergers, NSMs). By comparing the predictions from our three-dimensional GCE model to recent detections of  $^{53}\text{Mn}$ ,  $^{60}\text{Fe}$ , and  $^{244}\text{Pu}$  on the deep-sea floor, we draw conclusions about their propagation in the interstellar medium.

## 1 | Introduction

Introducing short-lived ( $\sim\text{Myr}$ ) radioactive isotopes (SLRs) in Galactic chemical evolution (e.g., Audouze and Tinsley 1976; Gibson et al. 2003; Kobayashi et al. 2020a; Matteucci and Greggio 1986; Nomoto et al. 2013; Prantzos et al. 2020) further constrains the timing of galactic nucleosynthesis processes: Any

given amount of SLRs decays following an exponential law. This means, if we know two of the three characteristic values ((i) produced amount in an astrophysical nucleosynthesis site, (ii) measured/observed amount, (iii) elapsed time between the production and the measurement/observation of the SLR), we can draw conclusions about the third one. This enabled, for example, determining the source, and production sites and conditions for

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various SLRs that influenced the stellar nursery out of which the Sun formed (e.g., Lugaro et al. (2018)). In order to obtain the measured/observed amount at time of the formation of the Solar system, the excess of the daughter isotope of the SLR compared to a reference isotope in meteorites is used.

On the other hand, today's interstellar inventory of certain SLRs can be measured by detecting the  $\gamma$ -rays emitted along their decay chain (e.g., Diehl 2022). This approach has been used to pinpoint star forming regions in the Galaxy (e.g., Kretschmer et al. 2013), as well as the gas dynamics in the Galaxy (e.g., Krause et al. 2021; Kretschmer et al. 2013).

Here, we make use of a third way to detect SLRs of extraterrestrial origin: Some deep-sea Earth crust samples contain some interstellar  $^{53}\text{Mn}$ ,  $^{60}\text{Fe}$ , and  $^{244}\text{Pu}$  isotopes (e.g., Korschinek et al. (2020); Wallner et al. (2015, 2016, 2021)). These SLRs of interstellar origin accumulated on the bottom of the ocean over several My. Taking probes from the Earth's crust, and analyzing slices of these probes permits to draw conclusions about the interstellar densities of these SLRs over the course of the last 12 My. (e.g., Korschinek et al. (2020); Wallner et al. (2015, 2016, 2021)). In this work, we use these derived densities in our cubic three-dimensional GCE model Wehmeyer et al. (2019); Wehmeyer et al. (2015) to draw conclusions about the CCSN explosion shock wave propagation properties. We further predict the presence of a fourth key SLR,  $^{182}\text{Hf}$ , in these samples, and show its predicted densities in the interstellar medium over the course of the same time span as covered by the deep-sea probes.

## 2 | Model

We used the three-dimensional GCE model described in Wehmeyer et al. (2019, 2015). The model simulates a periodic boundary condition, three-dimensional box with an edge length of 2 kpc. The box is divided into sub-cubes with an edge length of 50 pc. Starting from this model, we added a radioactive decay module, and follow the evolution of the four SLRs,  $^{53}\text{Mn}$ ,  $^{60}\text{Fe}$ ,  $^{182}\text{Hf}$ , and  $^{244}\text{Pu}$  (Wehmeyer et al. 2023). The time step size is 1 Myr, during which the chemical evolution calculations are performed. We provide an overview of the calculations below:

1. *Gas infall.* Gas with primordial composition is inserted into the simulation volume, following an analytic formula that permits an early rise, and a late exponential decrease of the insertion.
2. *Star formation.* A Schmidt law (exponent  $\alpha=1.5$ , Kennicutt (Kennicutt and Robert 1998); Larson (1991); Schmidt (1959)) is used to determine the number of stars created in the time step. From the number of newly born stars, a Salpeter initial mass function (Salpeter 1955) with a slope of  $-2.35$  is used to determine the mass of the newly born stars within the range  $0.1M_{\odot} \leq m \leq 50M_{\odot}$ . The Geneva group's (Charbonnel et al. 1993; Schaerer et al. 1993a, 1993b) equation

$$\log(t) = (3.79 + 0.24Z) - (3.10 + 0.35Z) \log(M) + (0.74 + 0.11Z) \log^2(M), \quad (1)$$

is used to calculate the life expectation for each newly born star. ( $t$  is the expected lifetime of the star in Myr,  $Z$  is the metallicity, and  $M$  the mass in Solar masses).

3. *Stellar deaths.* During every time step, there is a number of stars which have reached the end of their life expectancy. For these stars, their death will be treated as outlined in Sections 2.1 and 2.2 below.
4. *Double star systems.* The Galaxy hosts many double- or triple star systems (e.g., Duchêne and Kraus (2013)). Depending on their initial mass, these systems have a chance to later end up in a thermonuclear supernova explosion (SNIa, for intermediate mass stars), or a neutron star merger (NSM, in the case of massive stars). We take this into account by introducing two probability factors, representing the probability of such a system to later undergo such an event,  $P_{\text{SNIa}} = 6 \cdot 10^{-3}$  as the fraction of all newly born IMSs to later undergo SNIa,  $P_{\text{NSM}} = 0.04$  representing the fraction of all newly born HMSs to later end up in a NSM. From the number for NSMs ( $P_{\text{NSM}}$ ), we can find the cosmic gravitational wave emission rate (see Côté et al. (2017) for details)  $\approx 1800 \text{ Gpc}^{-3} \text{ yr}^{-1}$ , which is a bit larger than the LIGO/Virgo rate of  $(810 \text{ Gpc}^{-3} \text{ yr}^{-1})$  Abbott et al. (2021)). The nucleosynthesis ejecta of the two sites are discussed in Sections 2.3 and 2.4 below.
5. At every time step, the gas content and the SLR abundance in every cell are stored.

### 2.1 | Intermediate Mass Stars

IMSs do not significantly contribute to the nucleosynthesis of the ISM. Their main task is to lock up gas during their lifetime, and then re-eject parts of the gas, together with  $^{182}\text{Hf}$  (with yields from table S1 in the Supporting Information of Lugaro et al. 2014) at the end of their lifetime.

### 2.2 | Massive Stars

At the end of their life, HMSs die in a CCSN explosion under the ejection of elements as in Nomoto et al. (1997); Thielemann et al. (1996), together with  $^{60}\text{Fe}$  according to yields in Table 3 in Limongi and Chieffi (2006). To account for the effect of hypernovae (e.g., Nomoto et al. 2013, 2004) and the propagation of the ejecta post-supernova (Feige et al. 2017; Fry et al. 2018), we consider different models, as outlined in Section 2.5.

### 2.3 | Thermonuclear Supernovae

Once this longer-lived IMS in a double star system has reached the end of its lifetime, the system ends as SNIa. The system ejects nuclei according to the yields in table 3 in Iwamoto et al. (1999) (model CDD2), as well as  $10^{-4} M_{\odot}$  of  $^{53}\text{Mn}$ , in agreement with (Kobayashi et al. 2020b; Seitenzahl et al. 2013). The kinetic energy ejected in the event will sweep up  $5 \times 10^4 M_{\odot}$  of ISM.

## 2.4 | Neutron Star Mergers

Once the two NS were produced in two preceding CCSNe, they orbit each other under the emission of gravitational waves for a coalescence time ( $t_{\text{coal}} = 10^8$  years in our simulation), until they merge. Upon merging, the NSM ejects  $10^{-8} M_{\odot}$  of  $^{244}\text{Pu}$  (in agreement with Eichler et al. (2015)), assuming a total ejecta mass of  $10^{-2} M_{\odot}$  and a mass fraction of  $X_{244} = 10^{-6}$ . The ejecta will then sweep up the surrounding ISM and pollute it with  $^{244}\text{Pu}$ .

## 2.5 | Supernova Ejecta Dynamics

To account for the effect of hypernovae (e.g., Nomoto et al. 2013, 2004), and the effect of a varied CCSN bubble remnant geometry due to, e.g., magnetic fields, or hydrodynamical effects (e.g., Feige et al. 2017; Fry et al. 2018), we set up four different scenarios (Table 1) to study the implications assuming different CCSN ejecta dynamics with the ISM:

1. *Standard case.* All CCSNe explode with a kinetic energy of  $10^{51}$  erg, and which corresponds to  $5 \cdot 10^4 M_{\odot}$  of swept-up ISM. All ejected elements and SLRs are deposited the blast wave shell.
2. *Increased explosion energy case (hypernova model, HN).* To estimate the contribution of hypernovae, we increase the explosion energy of all CCSNe to sweep up  $2 \cdot 10^5 M_{\odot}$  of ISM. As in the standard case, the remnant geometry is the same as in the standard case, all ejected elements and SLRs are deposited the blast wave shell.
3. *Modified geometry case (PINBALL).* To estimate the impact of magnetic field effects, we use a “pinball model”-style remnant geometry (Fry et al. 2018). Here, the magnetic field inside the remnant reflects the SLRs backwards, so they behave like a pinball inside of the remnant, which results in a much more well-distributed remnant bubble. As in the standard case, all CCSNe explode with an energy of  $10^{51}$  erg, but 1% of the swept-up SLRs stay within the explosion bubble.
4. *Combination of increased explosion energy and modified geometry (HN PINBALL).* The combination of models HN and PINBALL. All CCSNe pollute  $2 \cdot 10^5 M_{\odot}$  of ISM, as in the HN model, and 1% of the swept-up ISM stay inside the explosion bubble as in the PINBALL model.

In the model, we deliberately chose a time step size of 1 Myr because this allows us to simplify all thermo- and hydrodynamic processes (as considered in, e.g., Feige et al. 2017) into one single value, the swept-up mass. This choice further enables us to

**TABLE 1** | Overview over the different models.

Model name	ISM polluted	Remnant geometry
Standard	$5 \cdot 10^4 M_{\odot}$	Standard
HN	$2 \cdot 10^5 M_{\odot}$	Standard
PINBALL	$5 \cdot 10^4 M_{\odot}$	PINBALL model
HN PINBALL	$2 \cdot 10^5 M_{\odot}$	PINBALL model

omit all the microphysics regarding star formation processes, as we can simply use the statistical Schmidt law.

## 3 | Results

Figure 1 shows a zoom-in of the evolution of the abundances of the four SLRs, close to current day, for the different models described in Section 2.5. Also, we added the (time-shifted) deep-sea detections from Wallner et al. (2016), Korschinek et al. (2020) and Wallner et al. (2021) to the Figure. Since the statistical evolution of the SLR in all cells (gray scales/black) does not tell us much about their correspondence to the deep-sea detections, we also added the evolution of the single, best fitting sub-cell of the entire simulation volume to the Figure (green line).

To better be able to draw better conclusions, we introduced a time-shift factor  $\Delta t$ , as well as a vertical shift factor  $\lambda$  for all isotope detections, since it is more interesting to fit the shape of the detection curves, rather than the actual values. The values for these factors for each model are listed in Table 2.

In the top left panel of Figure 1, we can see the radioactive decay of all four isotopes around 13335 Myr.

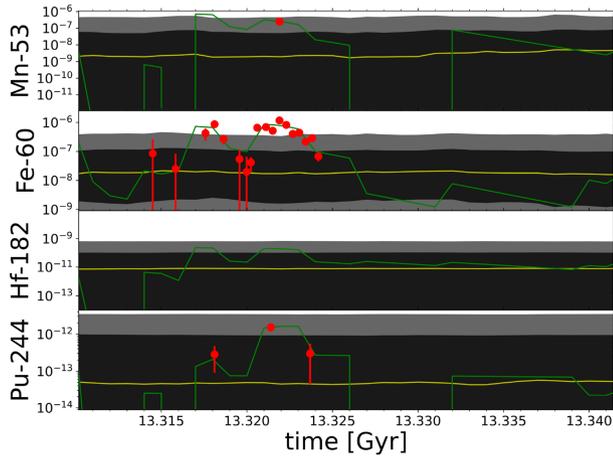
But, the more striking feature of that plot is the violent upward and downward movements that often coincides in more of the SLRs. This effect originates in the Sedov-Taylor-like expansion pattern of CCSN shock waves, as SLRs are pushed violently throughout the simulation volume. The sudden decreases in SLRs can be explained by CCSN shock waves traveling through and emptying the best-fitting sub-cell (green line). The sudden increases occur if such a CCSN shock wave is stopped right in the location of the best-fitting sub-cell (green line) and thus enhancing that sub-cell with all the swept-up material.

This effect can be observed in all four panels of Figure 1. The difference, though, is the intensity of this effect:

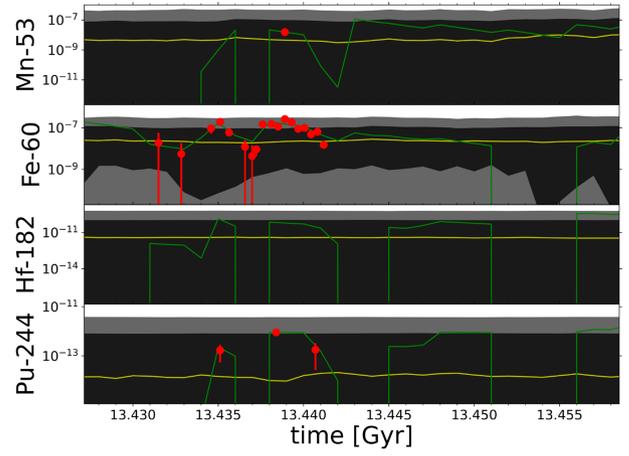
In the top right panel of Figure 1 (HN model), the fluctuations are much more prominent. This comes from the fact that the CCSN explosions are much more violent than in the standard model, and thus push around the ISM and SLRs much more violently, which leads to a more abrupt behavior of the SLRs in the best-fitting sub-cell (green line).

For the PINBALL model case (bottom left panel of Figure 1), we can see that the evolution of the best-fitting sub-cell (green line) is more variable than in the top left panel of Figure 1. This is because more cells are affected by every CCSN explosion shock wave, since more material is left behind, instead of depositing all the material (and SLRs) only on the shell. More cells affected by every CCSN means more sub-cells affected per time step, which in turn means that the abundance in the best-fitting sub-cell (green line) is affected more often in any given time interval.

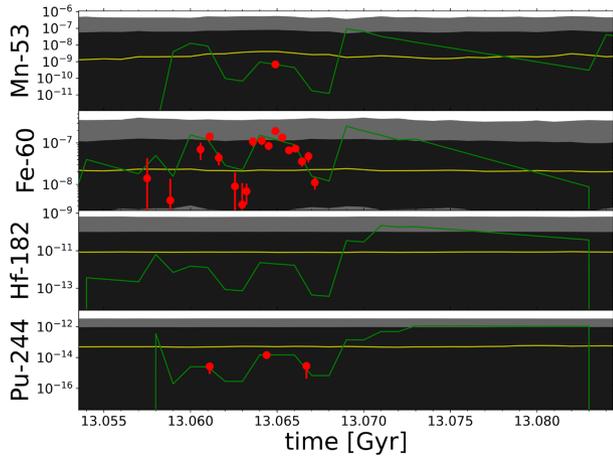
The evolution of the SLRs in the best-fitting sub-cell (green line) oscillates strongest of all models in the lower right panel of Figure 1 (HN PINBALL model). In this model, not only the radii of the CCSN explosion shock waves are highest (as high as in the



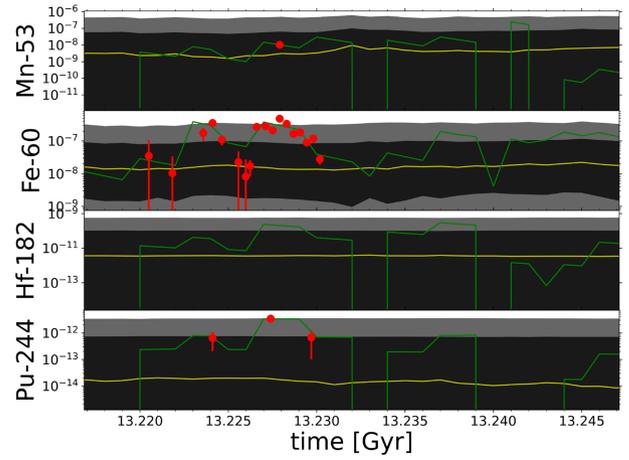
(a) Standard model



(b) HN model



(c) PINBALL model



(d) HN PINBALL model

**FIGURE 1** | Zoomed-in evolution of the four focus SLRs,  $\pm 15$  Myr around the respective  $\Delta t$ . Inferred ISM densities for  $^{53}\text{Mn}$ ,  $^{60}\text{Fe}$ , and  $^{244}\text{Pu}$ , are also shown as red symbols with error bars (shifted by factors  $\lambda$  and  $\Delta t$ ). The evolution of the best-fitting sub-cell is represented in a green line.

HN model) due to the higher explosion energies, but also the pinball remnant geometry leads to more sub-cells within the shock wave remnant to be polluted. The combination of these two factors leads to most sub-cells affected of all the four models per time step, which in turn means that the best-fitting sub-cell (green line) is most affected of all models during any given time interval. Overall, it is possible to find a best-fitting sub-cell (green line) that reasonably agrees with the deep-sea detections in all four models. To be able to judge how good the agreement is, we introduce a “goodness factor”  $S$ , the mean squared distance of the logarithm of the abundances to the actual deep-sea detections<sup>1</sup>, with  $S$  given by

$$S = \frac{1}{N} \sum \left( \frac{\ln R(t_i) - \ln Y_i}{\ln(Y_i + E_i) - \ln Y_i} \right)^2. \quad (2)$$

where  $R(t_i)$  is the abundance of the model at time  $t_i$ , and  $Y_i$  and  $E_i$  the deep-sea measurement and uncertainties at time  $t_i$ . For the standard model, the S-factor is 4.07, for the HN model, the

**TABLE 2** | Vertical ( $\lambda$ ) and time-shift ( $\Delta t$ ) factors for the ISM densities of the deep-sea detection of the three detected isotopes.

Model name	$\lambda_{^{53}\text{Mn}}$	$\lambda_{^{60}\text{Fe}}$	$\lambda_{^{244}\text{Pu}}$	$\Delta t$ (Myr)
Standard	0.211	134	16.5	174.63
HN	0.125	29.7	1.01	57.63
PINBALL	0.002	22.1	0.0439	431.63
HN PINBALL	0.476	55.2	0.669	268.63

S-factor is 4.15, for the PINBALL model, the S factor is 4.24, and the HN PINBALL model, it is 4.23. This means, that the standard model best fits the deep-sea detections.

#### 4 | Conclusions and Discussion

We have presented a three-dimensional model to follow the evolution of four focus SLRs,  $^{53}\text{Mn}$ ,  $^{60}\text{Fe}$ ,  $^{182}\text{Hf}$ , and  $^{244}\text{Pu}$ . We have

compared the evolution of these SLRs to their detections in different layers in the deep-sea deposits, corresponding to their infall on Earth at different times. We conclude that our standard model (all CCSNe explode with a kinetic energy of  $10^{51}$  erg, their ejecta distributed in a non-pinball-style pattern, that is, exclusively homogeneously distributed on the shock wave shell) statistically best reproduces the shape of the detections. Further investigations are necessary to draw firmer conclusions about the propagation mechanism of the SLRs.

Future detections of live radioisotopes of interstellar origin in the deep-sea floor (e.g., Wang et al. 2021a, 2021b) will further constrain the mechanism and properties of the associated nucleosynthesis sites. Further, real magnetic field calculations and their implications should be applied, as well as proper thermodynamic treatment (as done in, e.g., Feige et al. 2017).

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Endnotes

<sup>1</sup> Assuming the abundances follow a normal distribution with  $\sigma$  equal to the uncertainty.

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