Origins: From the Protosun to the First Steps of Life
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Short-lived radioisotopes in meteorites from Galactic-scale correlated star formation

Yusuke Fujimoto[1], **Mark R. Krumholz**[1] **and Shogo Tachibana**[2]

[1]Research School of Astronomy & Astrophysics, Australian National University, Canberra, Australian Capital Territory 2611, Australia
email: yusuke.fujimoto@anu.edu.au

[2]UTokyo Organization for Planetary and Space Science (UTOPS), The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan

Abstract. Meteoritic evidence shows that the Solar system at birth contained significant quantities of short-lived radioisotopes (SLRs) such as ^{60}Fe and ^{26}Al produced in supernova explosions and in the Wolf-Rayet winds. Explaining how they travelled from these origin sites to the primitive Solar system before decaying is an outstanding problem. In this paper, we present a chemo-hydrodynamical simulation of the entire Milky Way to measure for the distribution of ^{60}Fe/^{56}Fe and ^{26}Al/^{27}Al ratios over all stars in the Galaxy. We show that the Solar abundance ratios are well within the normal range. We find that SLRs are abundant in newborn stars because star formation is correlated on Galactic scales, so that ejecta preferentially enrich atomic gas that will subsequently be accreted onto existing GMCs or will form new ones. Thus new generations of stars preferentially form in patches of the Galaxy contaminated by previous generations of stellar feedback.

Keywords. hydrodynamics, methods: numerical, Galaxy: disk, ISM: kinematics and dynamics, meteors, meteoroids

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1. Introduction

Short-lived radioisotopes (SLRs) are radioactive elements with half-lives ranging from 0.1 Myr to more than 15 Myr that existed in the early Solar system. They were incorporated into meteorites' primitive components when the oldest solids formed in the Solar protoplanetary disc.

Most SLRs form in the late stages of massive stellar evolution, followed by injection into the ISM by stellar winds and SNe (e.g., Huss *et al.* 2009). Explaining how they travelled from these origin sites to the primitive Solar system before decaying is an outstanding problem (e.g., Adams 2010). Proposed mechanisms fall into three broad scenarios. The first scenario is a SN-triggered collapse: a nearby Type II SN injects SLRs and triggers the collapse of the early Solar nebula (e.g., Cameron & Truran 1977; Boss *et al.* 2010; Gritschneder *et al.* 2012). The second scenario is direct pollution: the Solar system's SLRs were injected directly into an already-formed protoplanetary disc by SN ejecta within the same star-forming region (e.g., Chevalier 2000; Ouellette *et al.* 2010). The third scenario is sequential star formation events and self enrichment in a giant molecular cloud (GMC, e.g., Gounelle & Meynet 2012; Young 2014; Kuffmeier *et al.* 2016).

Consensus has not reached yet, and no one has yet investigated galactic-scale SLR distributions. However, one should take account of Galactic-scale chemodynamics for chemical enrichment due to massive stars. Here, we study the Galactic-scale distributions of ^{26}Al and ^{60}Fe produced in stellar winds and supernovae, and propose a new contamination scenario: contamination due to Galactic-scale correlated star formation.

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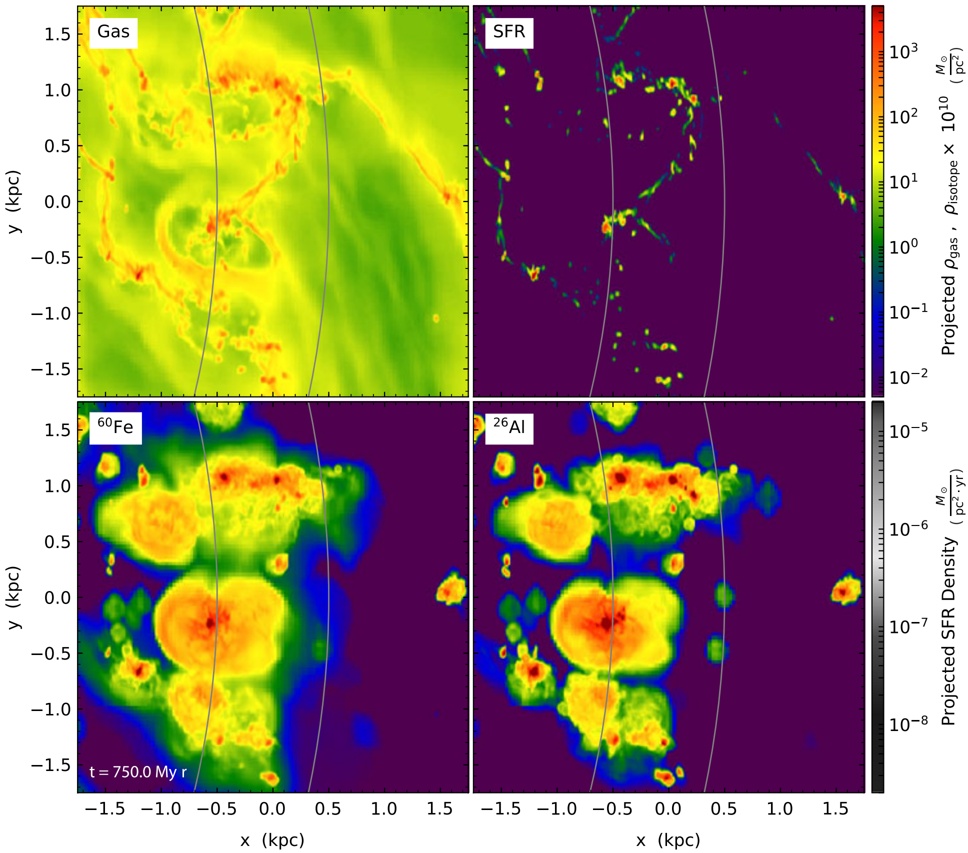

Figure 1. The face-on galactic disc zoomed in on a spot near the Solar Circle (Figure from Fujimoto *et al.* 2018). Panels show the gas (top-left), star formation rate (top-right), ^{60}Fe (bottom-left) and ^{26}Al (bottom-right) surface densities. The two arcs show Galactocentric radii of 7.5 and 8.5 kpc, bounding the Solar annulus.

2. Method

We study the abundances of ^{60}Fe and ^{26}Al in newly-formed stars by performing a high-resolution chemo-hydrodynamical simulation of the interstellar medium (ISM) of a Milky-Way like galaxy. The simulation includes hydrodynamics, self-gravity, radiative cooling, photoelectric heating, stellar feedback in the form of photoionisation, stellar winds and supernovae to represent dynamical evolution of the turbulent multi-phase ISM, and a fixed axisymmetric logarithmic potential to represent the gravity of old stars and dark matter, which causes the galactic-scale shear motion of the ISM in a flat rotation curve. In the simulation, when self-gravity causes the gas to collapse past our ability to resolve, we insert "star particles" that represent stochastically-generated stellar populations drawn star-by-star from the initial mass function (IMF). Each massive star in these populations evolves individually until it produces a mass-dependent yield of ^{60}Fe and ^{26}Al at the end of its life. We subsequently track the transport and decay of these isotopes, and their incorporation into new stars. Further details on our numerical method are given in Fujimoto *et al.* (2018).

3. Results

Fig. 1 shows the distributions of gas and isotopes in the Galactic disc zoomed in on a 3.5 kpc-region centred on the Solar Circle. The distributions of ^{60}Fe and ^{26}Al are

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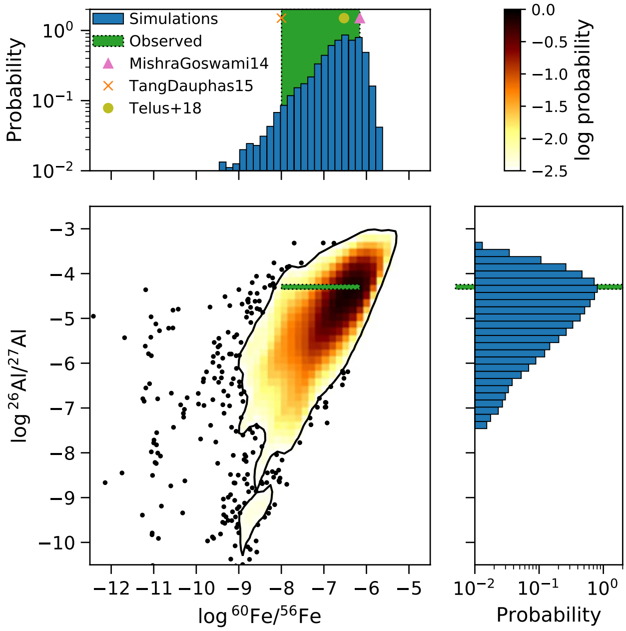

Figure 2. The abundance ratios of short-lived isotopes in newly-formed stars (Figure from Fujimoto *et al.* 2018). The central panel shows the joint PDF of ^{60}Fe/^{56}Fe and ^{26}Al/^{27}Al from our simulations, with colours showing probability density and black points showing individual stars in sparse regions. The top and right panels show the PDFs of ^{60}Fe/^{56}Fe and ^{26}Al/^{27}Al individually, with simulations shown in blue. All simulation data are for stars formed from $740-750$ Myr, at Galactocentric radii from 7.5 - 8.5 kpc. Green bands show the uncertainty range of Solar System meteoritic abundances (Lee *et al.* 1976; Mishra & Goswami 2014; Tang & Dauphas 2012; Telus *et al.* 2018); for ^{60}Fe, due to the wide range of values reported in the literature, we also show three representative individual measurements as indicated in the legend.

strongly-correlated with the star-forming regions, which correspond to the highest-density regions (reddish colours) visible in the gas plot. This is as expected, since these isotopes are produced by massive stars, which, due to their short lives, do not have time to wander far from their birth sites.

However, there are important morphological differences between the distributions of ^{60}Fe, ^{26}Al, and star formation. The ^{60}Fe distribution is the most extended, with the typical region of ^{60}Fe enrichment exceeding 1 kpc in size, compared to ~ 100 pc or less for the density peaks that represent star-forming regions. The ^{26}Al distribution is intermediate, with enriched regions typically hundreds of pc in scale. The larger extent of ^{60}Fe compared to ^{26}Al is due to its larger lifetime (2.62 Myr versus 0.72 Myr for ^{26}Al) and its origin solely in fast-moving SN ejecta (as opposed to pre-SN winds, which contribute significantly to ^{26}Al).

To investigate abundance ratios of isotopes in newborn stars, whenever a star particle forms in our simulations, we record the abundances of ^{60}Fe and ^{26}Al in the gas from which it forms, since these should be inherited by the resulting stars. Fig. 2 shows the probability distribution functions (PDFs) for the abundance ratios ^{60}Fe/^{56}Fe and ^{26}Al/^{27}Al; we derive the masses of the stable isotopes ^{56}Fe and ^{27}Al from the observed abundances of those species in the Sun. The PDF of ^{60}Fe peaks near $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} \sim 3 \times 10^{-7}$, but is ~ 2 orders of magnitude wide, placing all the meteoritic estimates well within the ranges covered by the simulated PDF. The ^{26}Al abundance distribution is similarly broad, but the measured meteoritic value sits very close to its peak, as $^{26}\mathrm{Al}/^{27}\mathrm{Al} \sim 5 \times 10^{-5}$.

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Clearly, the abundance ratios measured in meteorites are fairly typical of what one would expect for stars born near the Solar Circle, and thus the Sun is not atypical.

4. Conclusion

Our results lead us to propose a new enrichment scenario: SLR enrichment via Galactic-scale correlated star formation. We find that GMCs are at most 100 pc in size and their star forming regions are much smaller, while regions of ^{60}Fe and ^{26}Al contamination due to supernovae are an order of magnitude larger (Fig. 1). The SLRs are not confined to the molecular clouds in which they are born. However, SLRs are nonetheless abundant in newborn stars (Fig. 2) because star formation is correlated on Galactic scales. Thus, although SLRs are not confined, they are in effect pre-enriching a halo of the atomic gas around existing GMCs that is very likely to be subsequently accreted or to form another GMC, so that new generations of stars preferentially form in patches of the Galaxy contaminated by previous generations of stellar winds and supernovae.

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Discussion

Kamp: Should I read from your diagram that given the lower value of ^{60}Fe, the probability of having an environment with Solar radio-nuclei composition is more like $\sim 1\%$, so in fact not so common in the galaxy as a whole?

Fujimoto: The PDF is distributed very wide, almost 4 orders of magnitude. Considering this wide distribution, the Solar abundance is well within a normal range.

Johnstone: Do you find a radial dependence of the ratios in the Galaxy?

Fujimoto: We don't find any radial dependence of the abundance ratios.

Kokubo: How does the radial migration of the sun affect the results?

Fujimoto: The radial migration might not affect our results because there is no radial dependence of the abundance.

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