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Chemical evolution of radioactive elements in the Milky Way

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Abstract. In this paper we show how to study the chemical evolution of radioactive isotopes with a numerical model that was never used for this type of nuclei until now. In particular, we focus on the evolution of ^{26}Al and ^{60}Fe throughout the Milky Way, from the inner bulge to the outer boundary (0-22 kpc). Our main goal is testing several yield models for these two isotopes and compare the results with the observations provided by two γ-ray surveys, COMPTEL and INTEGRAL, so as to highlight which set of yields best reproduces the observed values. For ^{26}Al we performed a comparison with observations (both COMPTEL and INTEGRAL provided a value for ^{26}Al mass) whereas for ^{60}Fe we provided an estimate to be used as future constraints (not COMPTEL neither INTEGRAL were able to observe the mass of ^{60}Fe). We assumed yield models for the main producers of ^{26}Al and ^{60}Fe which, accordingly to the latest nucleosynthesis precriptions, are massive stars (for both ^{26}Al and ^{60}Fe) and nova systems (just for ^{26}Al) and we also included minor contributions from low and intermediate mass stars and from Type Ia Supernovae. Our best model predicts 2.12 $M_\odot$ of ^{26}Al within 5 kpc from the Galactic centre (the scale radius of the observations), in agreement with observations, whereas for ^{60}Fe we predict $\sim$ 1.05 $M_\odot$ within a 5 kpc of Galactocentric distance. We also concluded that an extremely important role in ^{26}Al is played by the contribution of nova system. In fact, although they are not the main source of ^{26}Al their contribution is necessary to reproduce the observations.

Key words. Galaxy: abundances – Galaxy: disc – Galaxy: bulge

1. Introduction

^{26}Al and ^{60}Fe are two short-lived radioactive nuclei with decay time of τ_{26Al}=1.05 Myr and τ_{60Fe}=3.75 Myr, respectively. Their main producers are massive stars with short lifetime, therefore these nuclei are abundant in those regions which have suffered a recent event of star formation.

Since 1991, the γ-survey COMPTEL collected evidences of the flux coming from the decay of ^{26}Al and observed ~2 $M_\odot$ of ^{26}Al within 5 kpc from the Galactic centre (Diehl et al. , 1995). Later, from 2002 the γ-survey INTEGRAL performed the same measurements and confirmed the earlier COMPTEL results, having observed a mass of ^{26}Al in the range 1.8-3.6 $M_\odot$ within 5 kpc from the Galactic centre (Diehl , 2013). In addition it observed the flux ratio ^{60}Fe/^{26}Al, which is ~15% ± 5%.

Chemical evolution models are useful tools to offer theoretical constraints on observational data, and in case of unavailable data, they can perform predictions. The majority of the models used until now to study radioactive isotopes are analytical models (Clayton , 1984, 1988), where restrictive hypothesis such as a single burst of star formation and instantaneous recycling approximation are assumed.

In this study we used a numerical chemical evolution code already tested (as done by Timmes et al. , 1995) to study the evolution of ^{26}Al and ^{60}Fe in the Milky Way, comparing several sets of yields for massive stars and for nova systems (only for ^{26}Al).

2. The model

Our model describes the Galaxy as composed of concentric rings 2 kpc wide, homogeneously mixed without exchange of matter among them. The innermost region (R<2 kpc) represents the bulge. The formation of the disc is described by a double infall law (Chiappini et al. , 1997, 2001), where the first infall formed the thick disc and the second formed the thin disc on a longer timescale. We assumed a (Kennicutt , 1998) SFR and a (Kroupa et al. , 1993) IMF. For the bulge (Matteucci et al. , 2019) we assumed a single infall on a short timescale, a (Kennicutt , 1998) SFR and a Salpeter (1955) IMF. The model consider production by SNII, SNIb, SNIc, SNIa and nova systems (Matteucci & Greggio , 1986; Matteucci & Recchi , 2001; D'Antona & Matteucci , 1991). The fundamental chemical evolution equation studies how the composition of the ISM changes considering the effects of star formation, injection of elements from dying stars, infall and radioactive decay. With these prescription, our model can reproduce the main features of the Galaxy, such as the surface density of gas, the total mass, the fraction of stars and the infall rate. Moreover also the present rates of SNII, SNIa and novae are well reproduce as shown in Fig. 1.

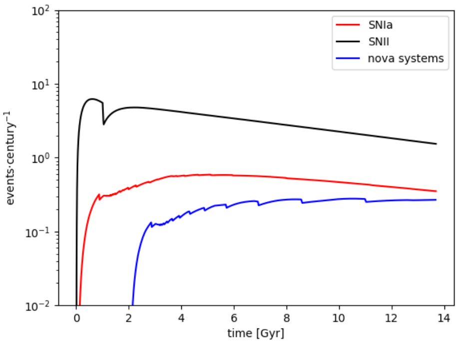

Fig. 1. Rates of supernovae and novae per century estimated using the model described above. Supernovae Type Ia are shown in red, Supernovae Type II in black and the rate of formation of nova systems is shown in blue. The nova rate plotted here can not be directly compared to the observations for two reasons. First of all, here this rate is shown per century whereas the observations provide it per year. Secondly, this is the rate of formation of nova systems whereas the observed one is the rate of nova explosion, which differ for the number of times that each nova explodes, which is estimated to be around 10^4. To compare the rate plotted to the one observed these two factors have to be taken into account.

3. Nucleosynthesis prescriptions and yields

We tested stellar yields for massive stars by Woosley & Weaver (1995) metallicity dependent and at solar metallicity, Limongi & Chieffi (2006) at solar metallicity and Limongi &

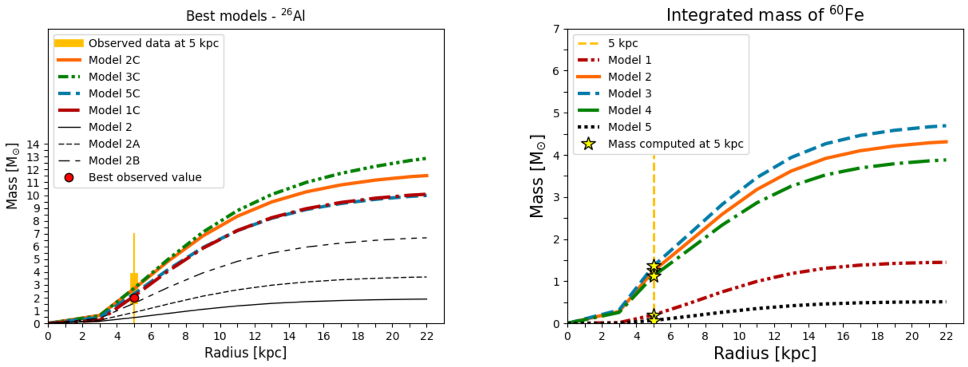

Fig. 2. *Left panel*: mass of ^{26}Al as a function of Galactocentric radius. The four colored models (green, orange, red and blue) are those compatible with the observations (yellow thick line). The three black lines are examples of non-compatible models. The best observational value is represented by the red dot. We consider as best model the red one, which assumes yields by Woosley & Weaver (1995) for massive stars and high contribution from novae. *Right panel*: mass of ^{60}Fe as a function of Galactocentric radius. The lines represent the five different models tested and the stars show the value each model predicts at 5 kpc from the Galactic centre.

Chieffi (2018) metallicity and rotation dependent. We also tested, only for ^{26}Al, three sets of nova system yields, one by Jose & Hernanz (1998) and two by Jose & Hernanz (2007), and the case of no contribution from novae. For ^{26}Al, we combined the four models of massive star yields with the four models for nova systems, for a total of sixteen models tested. For ^{60}Fe we have only the five models for massive stars Limongi & Chieffi (2006) offer two sets for ^{60}Fe, one assuming Schwarzschild convection criterion, one assuming Ledoux convection criterion.

4. Results

For both isotopes we computed the mass as a function of Galactocentric radius (0–22 kpc) and the present time injection rate (the present time rate at which ^{26}Al and ^{60}Fe are injected in the ISM at the stellar death). We compared the masses with observations by INTEGRAL and the injection rates with the previous theoretical result by Timmes et al. (1995).

For ^{26}Al mass, among the sixteen models tested, only four were compatible with the observed range 1.8-3.6 M$_\odot$ within 5 kpc from the Galactic centre. The left panel of Fig. 2 shows the four compatible models (the colored ones) which overlap with the observed range (yellow thick band) together with some examples of non compatible ones (black models). The best model assumes yields by Woosley & Weaver (1995) metallicity dependent and produces 2.12 M$_\odot$ within 5 kpc. We selected this one since is the closest to the best observational value, ~2 M$_\odot$ (red dot). It is noteworthy that all the compatible models have a high contribution coming from novae, therefore without nova systems it is not possible to reproduce the observations.

For ^{60}Fe mass we compared our results to estimates obtained from flux observation (it is important to stress that they are uncertain), which state that ^{60}Fe should lie in the range 0.9-1.8 M$_\odot$. We have only one model compatible, which assumes yields by Limongi & Chieffi (2006) with Schwarzschild convection criterion and predicts ~1 M$_\odot$ within 5 kpc from the Galactic centre, and is shown in the right panel in Fig. 2.

5. Conclusions and future perspectives

We studied the chemical evolution of ^{26}Al and ^{60}Fe in the Galaxy by means of a numerical model whose prescriptions reproduce the present features of the Milky Way. We estimated $\sim$2.12 M$_\odot$ ^{26}Al within 5 kpc from the Galactic centre with a high contribution coming from nova systems. We stress that without nova production the data can not be reproduced. Regarding ^{60}Fe we estimate its mass to be $\sim$1 M$_\odot$ within 5 kpc from the Galactic centre. We also computed the present time injection rates for both elements. With respect of the previous results by Timmes et al. (1995) our injection rates are larger and peaked in the region 5-7 kpc as we expected considering the present time star formation.

Regarding the future perspectives of this topic it will be interesting to investigate the abundances of ^{26}Al and ^{60}Fe also in nearby galaxies such as the Large Magellanic Cloud in view of a new γ-ray instrument, COSI (The COmpton Spectrometer and Imager), whose launched is scheduled for 2025/2026. It will be sensitive enough to explore radioactive elements (^{26}Al, ^{60}Fe and ^{44}Ti) also in the LMC and it will provide the first measurement of the ^{60}Fe mass in the Milky Way. Moreover, an important aspect to focus on is the role played by the inhomogeneities in the Milky Way (as well as those in the LMC). We know that these two elements decays quickly so we should question the approximation of instantaneous mixing that we assume in our model. We plan to investigate this aspect in a future paper where we will keep trace of the specific location of production of the elements using a inhomogeneous model, performing more precise estimates and possibly some considerations on the 2D distribution map of ^{26}Al and ^{60}Fe.

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