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^{7}Li evolution in the thin and thick discs of the Milky Way

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ABSTRACT

Recent detection of the isotope ^{7}Be (which decays into ^{7}Li) in the outbursts of classical novae confirms the suggestion made in the 1970s that novae could make ^{7}Li. We reconsidered the role of novae as producers of ^{7}Li by means of a detailed model of the chemical evolution of the Milky Way. We showed that novae could be *the* Galactic ^{7}Li source accounting for the observed increase of Li abundances in the thin disc with stellar metallicity. The best agreement with the upper envelope of the observed Li abundances is obtained for a delay time of ≈1 Gyr for nova production and an effective ^{7}Li yield of $1.8(\pm\,0.6)\times10^{-5}$ M$_\odot$ over the whole nova lifetime. Lithium in halo stars is depleted by ≈0.35 dex, assuming the pristine abundance from standard big-bang nucleosynthesis. We elaborate a model that matches the pristine stellar abundances, assuming that all stars are depleted by 0.35 dex. In this case, the delay remains the same, but the Li yields are doubled compared with the previous case. This model also has the merit of matching the Li abundance in meteorites and young T Tauri stars. A thick disc model, adopting the parameters derived for the thin disc, can also explain the absence of an increase of Li abundance in its stars. The thick disc is old, but formed and evolved in a time shorter than that required by novae to contribute significantly to ^{7}Li. Therefore, no ^{7}Li enhancement is expected in thick disc stars. We show that the almost constant Li abundance in the thick disc results from the compensation of stellar astration by spallation processes.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: individual: V5668 Sgr – novae, cataclysmic variables – Galaxy: evolution.

1 INTRODUCTION

^{7}Li nuclei are the heaviest nuclei produced in significant amounts during the big bang. Primordial ^{7}Li production is a sensitive function of the baryon-to-photon ratio and can be estimated in the framework of standard primordial nucleosynthesis once the baryon density is taken from either the primordial deuterium abundance or the fluctuations of the cosmic microwave background (CMB). The expected primordial value is A(Li) = 2.6, which is a factor of 3–4 higher than measured in halo dwarf stars (Spite & Spite 1982). This discrepancy is normally referred to as the *cosmological lithium problem*. The problem became clear by the time *Wilkinson Microwave Anisotropy Probe* (*WMAP*) measurement of universal baryon density was used to infer the primordial Li abundance within standard primordial nucleosynthesis (Cyburt, Fields & Olive 2003), although there were already earlier hints (Cayrel 1998). More recently, the baryon density measured by either the *Planck* mission (Planck Collaboration XIII 2016) or deuterium in quasar spectra confirmed the disagreement with the lithium abundance measured in halo stars (Tanabashi et al. 2018). The origin of this discrepancy still has to be identified with confidence, but a possible stellar fix has recently been proposed by Fu et al. (2015). Since the present Li abundance as measured in meteorites (Krankowsky & Müller 1964) or in young T Tauri stars is A(Li) ≈3.3, a Galactic source is required to account for the increase from the initial value of 2.6. The identification of such sources is generally referred to as the *Galactic lithium problem*. A large variety of nucleosynthesis processes and sources has been suggested so far. An established source is the spallation of atoms in the interstellar medium by energetic cosmic rays. The same processes also make ^{6}Li, ^{9}Be and $^{10,\,11}$B. Thus, from the abundance of these isotopes, in particular ^{9}Be, and by means of the relative cross-sections, it is possible to estimate the fraction of ^{7}Li produced by spallation. Spallation processes integrated over the Galactic lifetime can account for at most 30 per cent of the presently measured ^{7}Li and require other source(s) to enrich the Galaxy to its present values. Other proposed sources are spallation processes in the flares of low-mass active stars, red giants (RGs), asymptotic giant branch (AGB) stars, novae and neutrino-induced nucleosynthesis in supernovae explosions. ^{7}Li has been observed to be greatly enhanced in some AGB stars (Smith & Lambert 1989, 1990) and the case of Li in red giants was reviewed nicely in Casey et al. (2016).

Different sources have different time-scales for the production and therefore the time-scale of lithium increase in our Galaxy can

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point out the role of the different sources. However, possible ^{7}Li destruction inside a star complicates the picture. For instance, the Sun shows A(Li) $= 1.04$, which is more than two orders of magnitudes lower than the protosolar nebula, due to internal and poorly understood destruction. During stellar evolution off the main sequence, surface layers with lithium are mixed with more internal ones, producing a Li dilution that can be observed clearly in globular clusters, such as NGC 6397 (e.g. Lind et al. 2009).

Observations of metal-poor stars show that ^{7}Li remains constant at A(Li) ≈ 2.3 from the lowest metallicities up to approximately [Fe/H] ≈ -1, when the abundance starts to rise, reaching the meteoritic value of A(Li) $= 3.3$ at solar metallicities. After Rebolo, Beckman & Molaro (1988), it became common to assume that the upper envelope of the distribution of ^{7}Li abundances traces ^{7}Li abundance evolution. Galactic chemical evolution (GCE) models of ^{7}Li were pioneered by D'Antona & Matteucci (1991) and Romano et al. (1999), where the different contributions and time-scales were discussed. In these models, a shared feature is that AGB or SNe do not contribute much to ^{7}Li production and novae are potentially an important source. This outcome was confirmed by Izzo et al. (2015), using the lithium yields inferred by the observations of the nova V1369 Cen. Matteucci, D'Antona & Timmes (1995) also studied the possible contribution of the ν process during SN II explosions. The interplay of different sources was studied in the context of the GCE model of lithium by Travaglio et al. (2001), whereas Alibés, Labay & Canal (2002) analysed, in particular, the role of spallation for lithium, beryllium and boron. Prantzos (2012) concluded that 30 per cent of the lithium content of our Galaxy, at most, can be produced by galactic cosmic rays and a stellar origin is needed for the remaining fraction. Romano et al. (2001) and Prantzos et al. (2017) identified low-mass giant stars as the best candidates for reproducing the late rise off the lithium-metallicity plateau.

In fact, about 1–2 per cent of red giants show Li higher than A(Li) $\approx$1.5, which is the expected value predicted by standard stellar evolution theory, due to evolution along the first giant branch (Casey et al. 2016; Smiljanic et al. 2018; Lyubimkov 2016). The most Li-rich giant, recently discovered by Yan et al. (2018), reaches a value of A(Li) $= 4.51 \pm 0.09$. However, only about 30 other red giants show A(Li) greater than the meteoritic value, i.e. only about 0.1 per cent of red giants studied. The most promising explanation for this Li enrichment is similar to the Cameron–Fowler mechanism (Cameron & Fowler 1971) proposed to explain the Li in AGB stars. However, in RG stars the introduction of the extra mixing mechanism is required to bring fresh lithium to the surface (Sackmann & Boothroyd 1999; Lattanzio et al. 2015). Another possible explanation is that the lithium comes from external pollution, for example in the case of an engulfment of planets or planetesimals during evolution to the red giant branch (Siess & Livio 1999). Whatever the origin, high A(Li) cannot be maintained for a long time, due to convection activity in these stars, as also shown by the low percentage of RGs that are Li-rich (Yan et al. 2018). Therefore, their contribution to the Li enrichment of the interstellar medium remains quite uncertain.

The significant increase in measurements provided by recent surveys revealed a different behaviour in ^{7}Li evolution between the thin and thick disc of the Milky Way. At the lower metallicity end, thick and thin disc stars show the same Li abundance (Molaro, Bonifacio & Pasquini 1997). At higher metallicities, the increase in Li was steeper in thin than in thick discs (Guiglion et al. 2016; Fu et al. 2018). The precise behaviour of ^{7}Li abundance in the thick disc as a function of metallicity is still a matter of debate. It was found to be constant and at approximately the same value as the most metal-poor stars by Ramírez et al. (2012), while Delgado Mena et al. (2015) and Bensby & Lind (2018) found it to be decreasing and Fu et al. (2018) found it to be slightly increasing. The separation between thin and thick stars is not always straightforward and the presence of some contamination could explain the slightly different results for the thick disc. In any case, all these analyses show that thick disc abundances are equal to or lower than thin disc ones of similar metallicities. An additional feature for thin disc stars emerged recently: Li abundances of stars above solar metallicity show lower values than those at solar metallicity, suggesting a puzzling decrease of lithium. Guiglion et al. (2016) and Prantzos et al. (2017) tried to explain these features in terms of stellar migration, as has been done for the similar [O/Fe] versus [Fe/H] behaviour, but without achieving a robust conclusion.

Thermonuclear production of ^{7}Be (which decays into ^{7}Li) during nova explosions was proposed by Arnould & Norgaard (1975) and Starrfield et al. (1978). At temperatures of 150 million K, ^{7}Be is formed from the reaction ^{3}He $(\alpha, \gamma)^7$Be (Hernanz et al. 1996). To avoid destruction ^{7}Be needs to be carried to cooler regions by convection on a short time-scale, as in the Cameron–Fowler mechanism (Cameron & Fowler 1971). When these cooler regions are subsequently ejected, ^{7}Be could be observed in absorption in the nova outburst (José & Hernanz 1998). Predicted in the mid-1970s, observational evidence of Li in a nova outburst has been found only recently by Izzo et al. (2015), who reported the possible detection of the ^{7}Li I $\lambda\lambda$6708 line in the spectra of Nova Centauri 2013 (V1369 Cen). This has been followed by the detection of the mother nuclei ^{7}Be in the post-outburst spectra of classical novae by Tajitsu et al. (2015, 2016), Molaro et al. (2016), Izzo et al. (2018) and Selvelli, Izzo & Molaro (2018). The observed ^{7}Be decays into ^{7}Li with a mean life of 53 days and all ^{7}Be observed ends up as ^{7}Li. The relative abundance of ^{7}Be/H has been measured in four classical novae, with overproduction factors that range between 4 and 5 orders of magnitude over the meteoritic abundance. In this article, we revise ^{7}Li evolution by considering this new evidence and see if we can reproduce the ^{7}Li behaviour. We also explore whether Li synthesis by classical novae could also explain the different ^{7}Li behaviour observed in the thick disc of the Galaxy.

2 ^{7}LI GALACTIC CHEMICAL EVOLUTION OF THE THIN DISC

2.1 Observational data for the thin disc

Abundances for Galactic thin disc stars are taken from the Archéologie avec Matisse Basée sur les aRchives de l'ESO (AMBRE) project (Guiglion et al. 2016) and from data by Bensby & Lind (2018). In the AMBRE project (Guiglion et al. 2016), lithium abundances for 7272 stars were derived. However, we use only their working sample of 3009 stars, which comprises only dwarf stars. Bensby & Lind (2018) measured Li abundances for 420 dwarf stars and provided upper limits on the Li abundance for a further 121. We integrate the results of this data set with previous results (Bensby, Feltzing & Oey 2014) for stellar ages, temperature and stellar kinematics, as defined by the calculated probability functions. As shown in Bensby & Lind (2018), some stars are not correctly classified as thick or thin disc by chemical selection only, although it is successful in most cases. In fact, depending on alpha elements, the quality of the chemical selection changes significantly. Tiny differences in chemical selection can change the outcome quite dramatically and selection becomes increasingly difficult toward solar metallicity. We therefore consider kinematical selection as the best option and

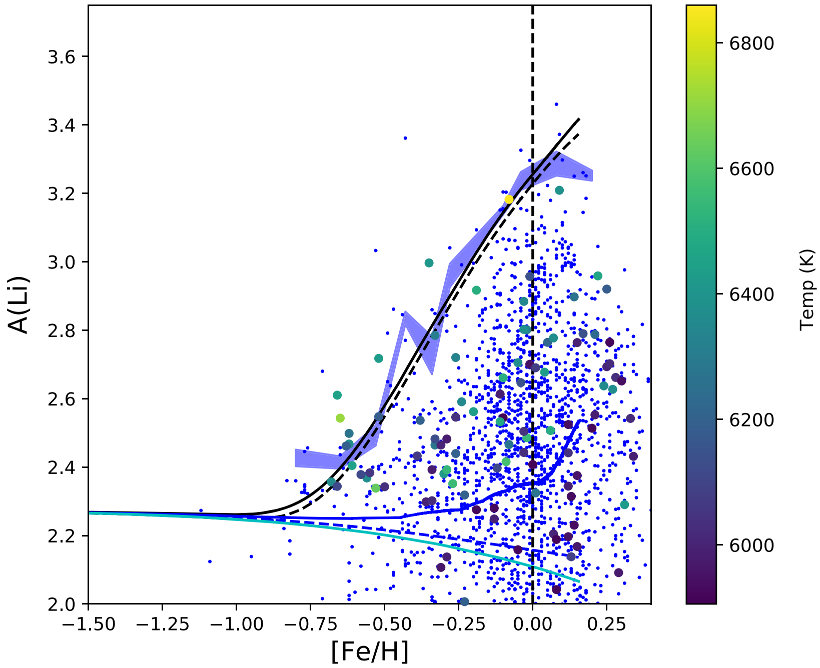

Figure 1. ^{7}Li abundances versus [Fe/H] for the Galactic thin disc. The blue dots are the ^{7}Li abundances of thin disc stars from the AMBRE project. The larger symbols are measurements of ^{7}Li abundances for thin disc stars from Bensby & Lind (2018), colour-coded according to their stellar temperature. The shaded area highlights the upper envelope of the AMBRE project data, defined in Section 2.1. The impact of the different ^{7}Li factories is shown. Solid cyan shows only astration with no ^{7}Li production; dashed blue is the production by AGB stars, solid blue the production by spallation; the dashed black line the production by novae. The sum of all three factories is shown as a black solid line.

use chemical selection only when kinematical information is not present. Kinematical parameters are not available in the AMBRE data and therefore we use their chemical selection with 2671 thin disc stars. For the AMBRE data, we compute an upper envelope obtained by computing the mean over the five data points with the highest ^{7}Li over 10 bins of 0.1 dex in [Fe/H] and after clipping for outliers. The envelope is shown in Fig. 1, with the shadowed area covering one standard deviation from the mean value. For Bensby & Lind (2018) data, we do not compute the envelope, due to the small number of stars, and show only stars with effective temperature higher than 5900 K, to partially exclude those main-sequence stars where internal stellar depletion is occurring. This temperature threshold is derived from fig. 8 of Bensby & Lind (2018) and fig. 11 of Lind et al. (2009). With this temperature cut-off, the sample is reduced to 116. We note that, in general, for stars with lower Li abundances, it is unclear whether ^{7}Li was partially depleted by convection or similar mechanisms or reflects a truly lower initial abundance.

2.2 Observational constraints on nova ^{7}Li yields

Normally, ^{7}Li I is not detected in the spectra of nova outbursts and the first, and so far unique, Li I detection by Izzo et al. (2015) implies that physical conditions in the ejecta of post-outburst novae only rarely permit the survival of neutral ^{7}Li I. However, the recent detection of the mother nuclei ^{7}Be in post-outburst spectra of all novae where it was possible to study the presence of ^{7}Be so far shows that thermonuclear production of ^{7}Be is effectively taking place and is probably a common feature of classical novae.

For three novae, the abundance of ^{7}Be is estimated relative to the Ca II for unsaturated and resolved lines, which are assumed to represent the abundances in all of the material ejected. The ^{7}Be/H by number is derived from the observations and corrected for ^{7}Be decay, assuming all ^{7}Be was made around nova maximum. In Nova Herculis 1990, the abundance was also derived from the emission, which takes into account the whole envelope, and a value of $\approx 2 \times 10^{-5}$ was found, consistent with the abundance derived from absorption lines (Selvelli et al. 2018). We note that the observed yields are significantly larger than the maximum theoretical yields predicted by the models of José & Hernanz (1998). In the long term, ^{7}Be $= ^7$Li and the derived fractions correspond to ^{7}Li logarithmic overabundances of 4–5 dex with respect to the meteoritic value of 1.3×10^{-9} (Lodders, Palme & Gail 2009).

These overproduction factors imply a production factor of 1–10 $\times 10^{-9}$ M$_\odot$ per nova event, assuming an ejected mass of $\approx 10^{-5}$ M$_\odot$, and a total production of 1–10 $\times 10^{-9}$ M$_\odot$ of Li during the whole nova lifetime, assuming a typical number of bursts of 10^4. A rate of 20 yr^{-1} of nova events in a Galaxy lifetime of $\approx 10^{10}$ yr producing $M_{\rm Li} \approx 3 \times 10^{-9}$ M$_\odot$ is enough to produce $M_{\rm Li} \approx 600$ M$_\odot$, which is comparable with that estimated to be present in the Milky Way. This simple estimation shows that novae could indeed be one of the main factories of ^{7}Li in the Galaxy.

Therefore, we decide to reconsider the role of novae as the main producers of ^{7}Li in the Milky Way. To investigate this role, we implement the lithium production from novae in a detailed GCE model of the Milky Way thin disc (see the next section). We do not assume the observational yields in the modelling directly, given the spread in observed abundances. Instead, we estimate the best set of parameters for lithium production by novae – described in the next section – by comparing the chemical evolution model results with the abundance measured in thin disc stars. Only at the end of this procedure do we verify whether or not these theoretically computed yields are compatible with the observational constraints obtained from nova outbursts.

2.3 Thin disc chemical evolution model

Our model for the thin disc adopts prescriptions similar to those used in Romano et al. (2010) and Grisoni et al. (2017). Grisoni et al. (2017) modified the original two infall frameworks (Chiappini, Matteucci & Gratton 1997) and set the parameters to reproduce the α elements and the metallicity distribution function determined in the AMBRE project at best. The initial mass function (IMF) is from Kroupa (2001), whereas the stellar lifetimes are from Meynet & Maeder (2002). SNe Ia follow the single degenerate scheme as in Matteucci & Greggio (1986), with a fraction of successful binary systems of 0.05 and iron yields from the W7 model by Iwamoto et al. (1999). Iron nucleosynthesis for massive stars is from Kobayashi, Karakas & Umeda (2011). The main characteristic of the model is a prolonged exponential infall following the relation

$$G_{\rm inf}(t) = A\, {\rm e}^{(t/\tau_{\rm D})}, \tag{1}$$

with a time-scale $\tau_{\rm D} = 4$ Gyr and a total evolution that lasts for 10 Gyr.

Star formation follows the equation

$$\psi(r,t) = \nu \left(\frac{\Sigma(r,t)}{\Sigma(r_\odot,t)}\right)^{2(k-1)} \left(\frac{\Sigma(r,t_{\rm Gal})}{\Sigma(r,t)}\right)^{k-1} G^k_{\rm gas}(r,t), \tag{2}$$

with a mild efficiency ($\nu_{\rm SFR} = 0.5$).

2.3.1 *Lithium nucleosynthesis*

In this article we assume that the principal producers of ^{7}Li are nova systems. Given the relatively large spread in lithium produced by novae, we study the space of parameters that describes this production and compare the results obtained by means of a detailed chemical evolution model with observational data for thin disc stars. The main assumptions are the following.

(i) Only binary systems formed by stars in the mass range 0.8 M$_\odot$ < M < 8 M$_\odot$ can develop nova systems that produce ^{7}Li and the main parameter is the fraction $N_{\rm lithium}$ of these systems that actually develop nova systems and produce ^{7}Li. The probability of forming a binary system of a certain mass is weighted on the IMF, as it is made of a single star with that same mass. Given our imperfect knowledge of the coupling between IMF and binaries, this method is a reasonable approximation and is similar to that developed in Matteucci & Greggio (1986) for the progenitors of SNe Ia. The maximum total mass of the binary is therefore 16 M$_\odot$. On the other hand, the minimum mass ($M_{\rm low}$) of the binary would be 1.6 M$_\odot$; however, once we explored this parameter we obtained better results using $M_{\rm low} = 3$ M$_\odot$. A model with $M_{\rm low} = 1.6$ M$_\odot$ is presented to show the different outcome. The probabilities of configurations of primary and secondary stars are considered following the equation

$$f(\mu) = 2^{1+\gamma}(1+\gamma)\mu^\gamma, \tag{3}$$

where μ is the mass of the secondary divided by the total mass of the binary system and $\gamma = 2$ (Greggio & Renzini 1983). In this way, in contrast to most of the previous chemical evolution models considering lithium production from novae, we find a probability distribution of the mass of the secondary star.

(ii) ^{7}Li production takes place after the time required by the primary to evolve into a white dwarf plus a delay time $\tau_{\rm nova}$, which is the time the white dwarf needs to accumulate material to ignite the first nova outburst. Binaries with components of the same mass never develop a nova and, therefore, we consider ^{7}Li producers as only binaries with sufficient difference between the lifetimes of primary and secondary, namely $\tau(M_{\rm sec}) - \tau(M_{\rm prim}) \geq \tau_{\rm nova}$.

(iii) Nova systems encounter several bursts over their whole lifetime: a typical number is 10^4 bursts (Bath & Shaviv 1978; Shara et al. 1986). In previous chemical evolution models, for mathematical and technical simplification, a single lithium production event was considered to make all the lithium for an entire lifetime. In our work, we improve this treatment and consider multiple ejections, instead of ejecting all the ^{7}Li produced as a single event, as previously done. We find significant differences after considering more than a single burst. Ideally, we should take into account 10^4 bursts, but, assuming an increasing number of ejections (up to 100), we note that these differences become negligible with more that five enrichments and to spare computational time we use five ejection events for each nova.

(iv) For the sake of simplicity, we assume that during their life all novae produce the same amount of ^{7}Li in all events, regardless of the masses of the original binary systems or the $\tau_{\rm nova}$ considered. We define this quantity as $^{\rm Li}Y_{\rm Nova}$ and, as we will show in the next section, the best value we find is $^{\rm Li}M_{\rm Nova} = 1.8 \times 10^{-5}$ M$_\odot$. This simplified assumption is contradicted by current observations, which show one order of magnitude difference in the novae where ^{7}Be, i.e. ^{7}Li, has been measured. On the other hand, we prefer to keep the model as simple as possible. Moreover, this value is compatible with observations and can be taken as a typical averaged amount.

In summary, in our model the nova nucleosynthesis of ^{7}Li is fully described by three parameters: the delay time between the end of life of the primary star and the first nova outburst ($\tau_{\rm nova}$), the number of binary systems that develop a nova ($N_{\rm lithium}$) and the total ^{7}Li produced by a nova in its lifetime $^{\rm Li}Y_{\rm Nova}$.

By comparison with observations, we explore the space of these three parameters. For the parameter $\tau_{\rm nova}$, we investigate time-scales of 0, 1, 2 and 5 Gyr. The nova bursts probably will explode with different time-scales, depending on the mass loss of the secondary star, but a quantitative lower limit, i.e. the shortest time-scale allowed, can be derived from the upper envelope of the data in [Li/H] versus [Fe/H] or [Li/H] versus time.

The other two parameters, the nova yields $^{\rm Li}Y_{\rm Nova}$ and the nova rate $N_{\rm lithium}$, are degenerate in terms of ^{7}Li production in the model, since the total ^{7}Li produced by a stellar generation is proportional to their product. Thus, in our modelling we keep the rate $N_{\rm lithium}$ fixed and vary only $^{\rm Li}Y_{\rm Nova}$. Comparison with the data is an effective constraint on their combined production. An estimation of uncertainties is obtained by applying a change of production of 33 per cent to the standard value of $^{\rm Li}Y_{\rm Nova} = 1.8 \times 10^{-5}$ M$_\odot$. We will also present a model with more extreme enhancement $^{\rm Li}Y_{\rm Nova} = 4.14 \times 10^{-5}$ M$_\odot$, which is able to recover the lithium abundance measured in meteorites.

The parameter $N_{\rm lithium}$ varies the number of nova systems in the model results and also the number of bursts expected nowadays, assuming that each nova system produces 10^4 bursts. We take a value of $N_{\rm lithium} = 0.03$, which provides a rate of nova bursts compatible with the 20–30 yr $^{-1}$ observed in the Galaxy at the present time (Shafter 1997).

Lithium is normally destroyed inside stars at temperatures of a few million degrees and therefore the surface abundance is decreased by stellar mixing. This process, i.e. astration, is taken into account in our model by assuming that ^{7}Li is destroyed completely in stars of all masses.

A known ^{7}Li contribution comes from spallation of cosmic rays with nuclei in the interstellar medium. This production has a rather small impact that is not sufficient to account for all the observed lithium in our Galaxy. In our model, we consider this contribution starting from observations of the stable isotope ^{9}Be (Molaro et al. 1997; Smiljanic et al. 2009). ^{9}Be is produced only by cosmic rays and therefore, by scaling this production, it is possible also to evaluate lithium production by cosmic rays. We obtain this relation for ^{7}Li: log (Li/H) = −9.50 + 1.24[Fe/H], starting from the relation derived for ^{9}Be by Smiljanic et al. (2009) and assuming as scaling ratio ^{7}Li / ^{9}Be ∼ 7.6 (Molaro et al. 1997). Their results are obtained by means of a linear fit applied to 73 stars, belonging mostly to the halo (39) and the thick disc (27); only six stars belong to the thin disc and a star has equal chances of belonging to the halo or the thick disc. Possibly, it would be more accurate for our task to have more data for the thin disc. However, to our knowledge these are the best results available and they will have a limited impact – as we will see – on the final results for the thin disc. In Smiljanic et al. (2009), a linear fit is also computed for the thick disc. This could be used specifically for our thick disc model but, given the almost negligible difference, we keep the same prescription in both models.

Finally, the contribution by AGB is also considered. The theoretical yields computed by Ventura et al. (2013) are included in the chemical evolution model for stars in the mass range 1 $M_\odot$ < M < 6 $M_\odot$.

In the context of this article, we made the assumption that the initial gas composition has a ^{7}Li abundance of A(Li) = 2.25. This assumption is not critical, as long as the reason that produces disagreement with the *Planck* ^{7}Li value does not depend on metallicity and affects all stellar populations in the same way. To explore a possible solution for this disagreement, we also run a model with an initial A(Li) = 2.6, which is compatible with the abundance of ^{7}Li derived by measurements of the CMB of *Planck*.

2.4 Results for the thin disc

In this section, we analyse the results obtained with our chemical evolution model for the thin disc.

In Fig. 1 we show the thin disc chemical evolution with different ^{7}Li factories: AGB stars, spallation of cosmic rays and novae, taken separately or all together. For illustrative purposes, in the figure we also show the extreme case where only astration is taken into account, namely when there is no ^{7}Li production.

As displayed in Fig. 1, the AGB contribution to ^{7}Li increases the ^{7}Li by ∼0.05 dex. Therefore, we confirm that the enrichment due to AGB stars does not influence the overall chemical evolution of ^{7}Li. This was also a result of Romano et al. (1999, 2001). We note that, in the stellar evolution model considered (Ventura et al. 2013), lithium production can be activated efficiently only in intermediate-mass stars (≥3 $M_\odot$) and the possible contribution from extra mixing processes in low-mass red giant branch or AGB stars is not included.

The spallation of cosmic rays starts to play a role from a metallicity of [Fe/H] ∼ −0.5, increasing the primordial level assumed here by a factor of 2 (0.3 dex), and a factor of 3 (0.5 dex) compared with the lithium destroyed by astration. Thus, the total amount of ^{7}Li is still dominated by a contribution from a different source. This was the result by Prantzos (2012).

Likely, the dominant source for ^{7}Li is the nova contribution. In fact, the nova contribution assumed here with $^{\rm Li}Y_{\rm Nova}$ = 1.8 × 10^{-5} $M_\odot$ and $\tau_{\rm nova}$ = 1 Gyr can reproduce the observed values and the general behaviour of the Galactic growth very well.

In Fig. 2, we show the ^{7}Li evolution results considering four different delay times for the start of ^{7}Li enrichment, i.e. $\tau_{\rm nova}$: 0, 1, 2 and 5 Gyr, keeping $^{\rm Li}Y_{\rm Nova}$ fixed at 1.8 × 10^{-5} $M_\odot$ per nova. For negligible delay time (0 Gyr), the ^{7}Li abundances start to rise almost immediately, due to a very short time-scale for ^{7}Li enrichment. In this case, the earliest effects are as short as 30 Myr, the lifetime of a 8-$M_\odot$ star. There are some sparse data points close to this line and also above; nevertheless, they are a negligible fraction and probably do not reflect the general behaviour. Concordance with the bulk of the data requires a longer characteristic time-scale. A time-scale of 1 Gyr provides the best match to the upper envelope, whereas 2 Gyr is slightly too long for $\tau_{\rm nova}$. We could actually search for the precise time-scale to match the upper envelope, but, given the uncertainties considered, we prefer to keep 1 Gyr as the best value for $\tau_{\rm nova}$. It is interesting to note that a delay of 5 Gyr largely misses the upper envelope of the data, but still intercepts stars with slightly lower ^{7}Li. We can actually consider a more complex situation for the lithum chemical evolution, in which stars with a lower initial value show their real initial lithium rather than a depleted value. In this case, longer time-scales for $\tau_{\rm nova}$ could account for the observed spread below the envelope.

We also studied the impact of changing the lower limit for the mass of the binary system from 3 $M_\odot$ to 1.6 $M_\odot$ and this model is shown in Fig. 2 with a dashed line. The effects of a change at the lower end of the mass range appear evident on long time-scales and, indeed, the trend of lithium above solar metallicity is steeper for the model with $M_{\rm low}$ = 1.6 $M_\odot$. Since the data appear not to have such a steep trend, we use $M_{\rm low}$ = 3 $M_\odot$. We note that if we increase $M_{\rm low}$ further, this will also impact the trend at intermediate metallicity (−1 < [Fe/H]<0) and will worsen the fit to the data. A possible solution would be to have mass-dependent yields, but – as mentioned before – we prefer to keep modelling as simple as possible.

In Fig. 3, we use the ages derived for stars in Bensby et al. (2014), instead of the usual proxy for the ages: [Fe/H]. In this case, we cannot compute an upper envelope because of the low number of stars, but the time-scale $\tau_{\rm nova}$ of 1 Gyr is also a suitable value in the space A(Li) versus Age. The model $\tau_{\rm nova}$ = 2 Gyr appears to be the best in this plot, but we suspect that this could be due to the low number of stars available with ages. Still, this is the first time that chemical evolution model results for lithium have been shown against the ages of stars and the results are extremely good.

In Fig. 4, we explore the change in evolution obtained by changing the ^{7}Li yields. A new curve (blue line) is obtained by multiplying the $^{\rm Li}Y_{\rm Nova}$ standard value by a factor of 2.3. We intend to study the impact of variation of this parameter and we selected this extreme value to reproduce the solar Li abundance of 3.3 measured in meteorites formed at the time of solar system formation, 4.56 Gyr ago (cf. Fig. 5). We note that this model overestimates the lithium abundance in all thin disc stars, apart from a few extreme cases of the AMBRE sample. The other two curves are instead obtained by a milder variation of 33 per cent from the standard value of $^{\rm Li}Y_{\rm Nova}$. The motivation for these new curves is to evaluate the variation needed to encompass the upper envelope of the AMBRE set of data, as shown in Fig. 4. In Fig. 4, we also note that the mild decrease of the yields mimics an increase in $\tau_{\rm nova}$, but the curves are not identical and they can be distinguished in future by an increased number of good-quality observations of stars.

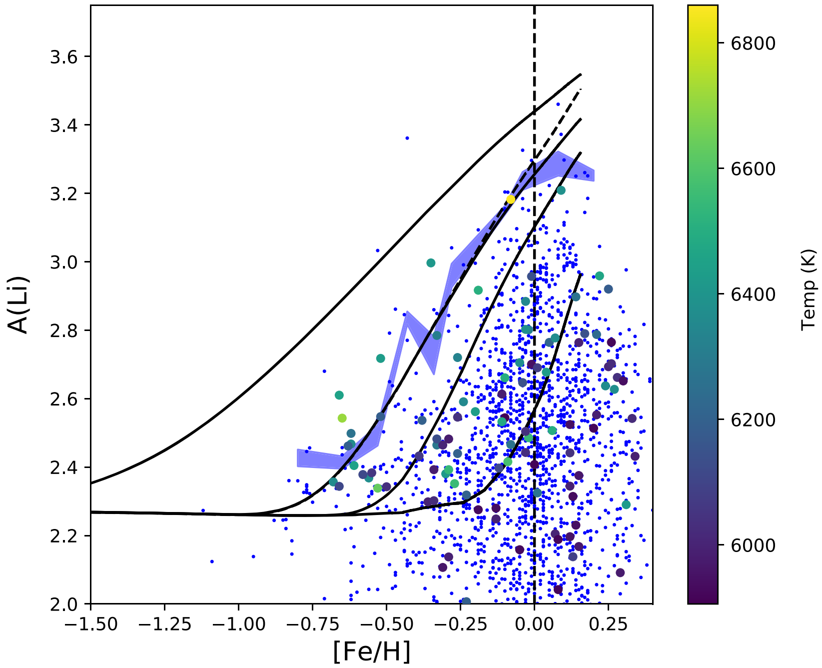

Figure 2. ^{7}Li abundances versus [Fe/H] for the Galactic thin disc. The observational data are the same as in Fig. 1. Models with five different characteristic times ($\tau_{\rm nova}$) of ^{7}Li enrichment are shown, from left to right: $\tau_{\rm nova} = 0$, 1, 2 and 5 Gyr. The dashed line shows the effect of changing the lower limit to $M_{\rm low} = 1.6$ M$_\odot$ from $M_{\rm low} = 3$ M$_\odot$, applied only to the model with $\tau_{\rm nova} = 1$ Gyr for simplicity.

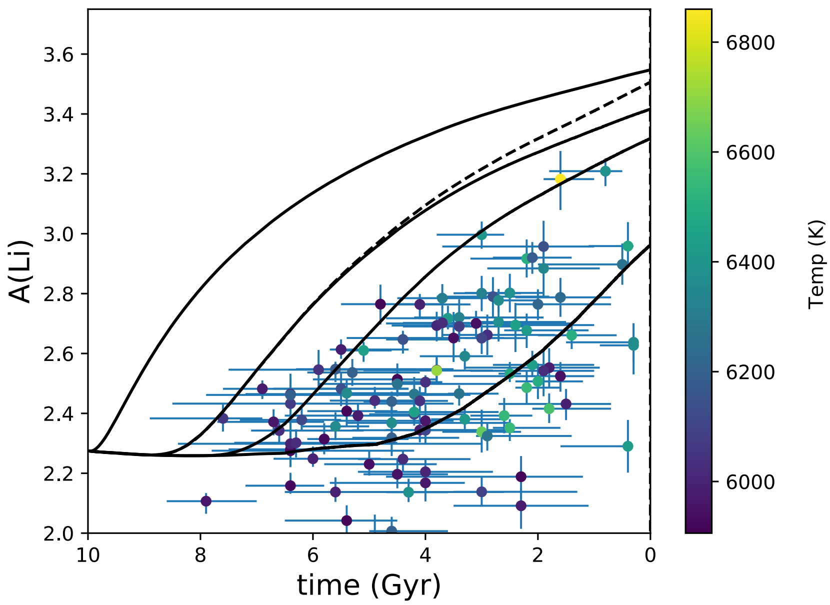

Figure 3. ^{7}Li abundances versus time for the Galactic thin disc. The circles show the ^{7}Li abundances from Bensby & Lind (2018) with ages from Bensby et al. (2014). Models with five different characteristic times of ^{7}Li enrichment are shown, from left to right: $\tau_{\rm nova} = 0$, 1, 2 and 5 Gyr. The dashed line presents the results of assuming a lower limit for the binary system $M_{\rm low} = 1.6$ M$_\odot$ as in Fig. 2.

In Fig. 5, we show the same model results, but comparing A(Li) with age. The model with mildly decreased yields can intercept all the stars in the Bensby & Lind (2018) sample with very high ^{7}Li abundance at the given ages. This could be also obtained with a slightly longer $\tau_{\rm nova}$, basically confirming the results in Fig. 4 using ages instead of [Fe/H].

In Fig. 5, the model with $^{\rm Li}Y_{\rm Nova}$ increased by a factor of 2.3 predicts a lithium abundance too high when compared with the entire Bensby & Lind (2018) sample and matches only the solar system abundance measured in meteorites (by construction). We present a possible explanation for this problem, the solar lithium problem, in Section 2.4.1.

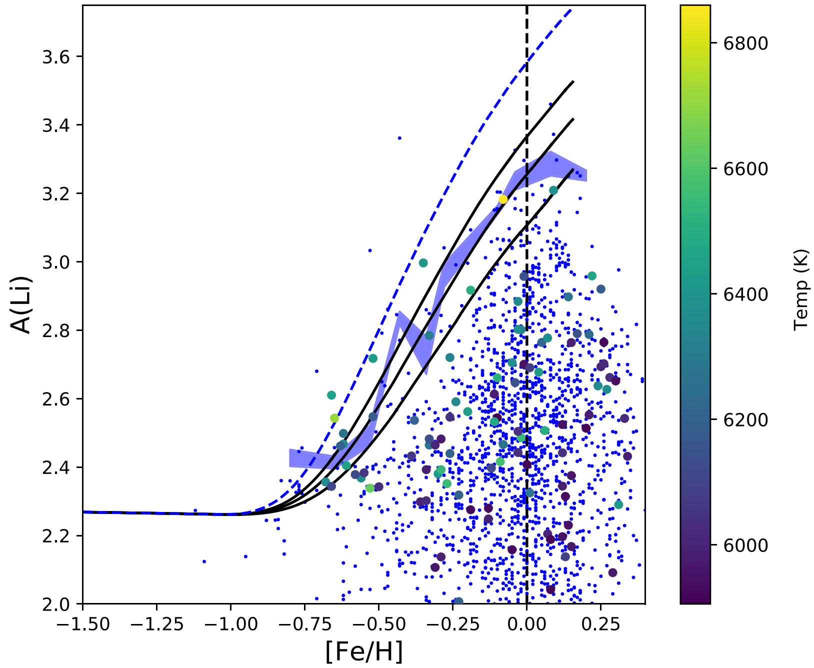

Figure 4. Same as Fig. 2. Effects of changing the parameter ${}^{\rm Li}Y_{\rm Nova}$. The central black line is the model with the standard value of ${}^{\rm Li}Y_{\rm Nova}$, while the upper (lower) black line is obtained by increasing (decreasing) ${}^{\rm Li}Y_{\rm Nova}$ by 33 per cent. The dashed blue line shows the model obtained increasing the parameter ${}^{\rm Li}Y_{\rm Nova}$ by a factor of 2.3.

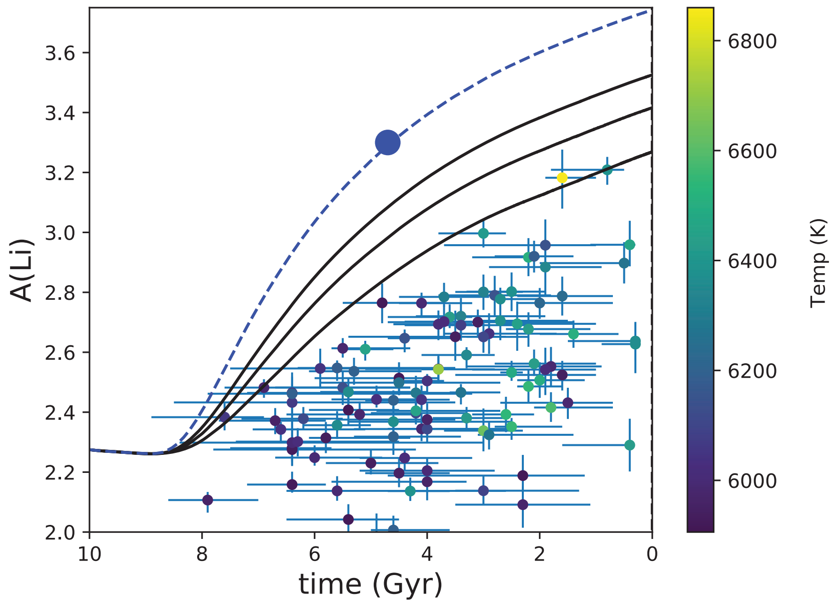

Figure 5. Same as Fig. 4. Effects of changing ${}^{\rm Li}Y_{\rm Nova}$. The central black line is the model with the standard value of ${}^{\rm Li}Y_{\rm Nova}$, while the upper (lower) black line is obtained by increasing (decreasing) ${}^{\rm Li}Y_{\rm Nova}$ by 33 per cent. The dashed blue line shows the model obtained increasing the parameter ${}^{\rm Li}Y_{\rm Nova}$ by a factor of 2.3.

In summary, the model for the thin disc provides a $\tau_{\rm nova}$ of 1 ± 0.5 Gyr and an effective nova yield ${}^{\rm Li}Y_{\rm Nova}$ of $1.8 \pm 0.6 \times 10^{-5}$ M$_{\odot}$, showing that, apart from a relatively small contribution from cosmic rays and an even smaller contribution from AGB stars, the bulk of Galactic ^{7}Li can be made consistently by novae, which are able to provide not only the amount of ^{7}Li at the end of the evolution but also the rate of increase of this element in the thin disc during its chemical evolution.

2.4.1 The solar lithium problem

As mentioned in the previous section, our model tuned for stellar observations fails to match the solar value. Only by increasing the effective yields by a factor of 2.3 does the model reach the solar abundance measured in meteorites. However, the meteorite value and the stellar determination may differ, since they are obtained with different techniques and at two different moments of the stellar lifetime and may not be directly comparable. In particular,

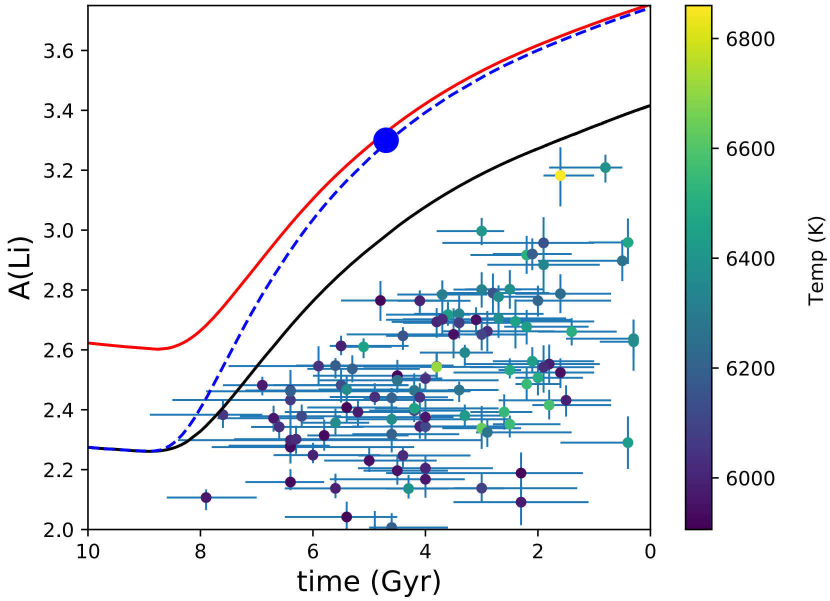

Figure 6. Same as Fig. 4. Effects of assuming a depletion during the pre-main-sequence phase. The solid line is the model with the standard value of ${}^{\rm Li}Y_{\rm Nova}$. The dashed blue line shows the model obtained assuming ${}^{\rm Li}Y_{\rm Nova} = 4.14 \times 10^{-5}$ M$_{\odot}$. The red line is the model with an increased ${}^{\rm Li}Y_{\rm Nova} = 4.14 \times 10^{-5}$ M$_{\odot}$, but here we also assume an initial A(Li) = 2.6.

the meteoritic value is not affected by pre-main-sequence depletion, in contrast to stellar measurements (Molaro et al. 2012; Fu et al. 2015; Thévenin et al. 2017). In Fig. 6, we present a possible solution. The model pre-main-sequence depletion (red line) is obtained by increasing the yields from novae again by 2.3 times, so that ${}^{\rm Li}Y_{\rm Nova} = 4.14 \times 10^{-5}$ M$_{\odot}$, but starting from a primordial A(Li) = 2.6 taken from big-bang nucleosynthesis. Interestingly, the meteorite value is matched and the model is also able to reach the lithium abundance in T Tauri stars, extremely young objects.

Therefore, if we consider a simplified assumption that all stars suffer a depletion of approximately 0.35 dex during the pre-main-sequence, the model falls back to the standard case (black line). If this is the case, the real effective yields from novae should be approximately two times larger than the ${}^{\rm Li}Y_{\rm Nova}$ obtained from stellar constraints and – according to our computation – ${}^{\rm Li}Y_{\rm Nova} = 4.14 \times 10^{-5}$ M$_{\odot}$. We note that this value is still within the uncertainties of the lithium production from nova bursts.

3 ^{7}LI GALACTIC CHEMICAL EVOLUTION OF THE THICK DISC

3.1 The Galactic thick disc

The Milky Way, like almost two-thirds of disc galaxies, has two major disc components, the thin and the thick one, with different histories and formation (Gilmore & Reid 1983). In the solar vicinity, the thick disc dominates the stellar population at distances between 1 and 5 kpc above the Galactic plane and it is generally accepted to be the oldest part of the disc, i.e. older than ≈8–9 Gyr. The mechanism of formation of the thick disc is still debated. The proposed scenario includes vertical heating from infalling satellites (Quinn, Hernquist & Fullagar 1993; Villalobos & Helmi 2008), a turbulent gas-rich disc phase at high redshift (Bournaud, Elmegreen & Martig 2009; Forbes, Krumholz & Burkert 2012) and massive gas-rich satellites (Brook et al. 2005). Formation of thick discs by radial migration was also proposed as a mechanism by Schönrich & Binney (2009). This idea was challenged by Minchev et al. (2012), demonstrating that migrators in N-body models do not have any significant effect on disc thickening. Several groups have now supported these findings in more recent works (Martig, Minchev & Flynn 2014; Grand et al. 2016), establishing this as a generic result of disc dynamics. In the most recently proposed model for the formation of thick discs by Minchev et al. (2015, 2017), it is shown that, in galactic discs formed inside-out, mono-age populations (groups of coeval stars) are fitted well by single exponentials and always flare (the disc thickness increases with radius). In contrast, when the total stellar density is considered, a sum of two exponentials is required for a good fit, resulting in thin and thick discs that do not flare. Such a scenario explains why chemically or age-defined thick discs are centrally concentrated (Bensby et al. 2011; Bovy et al. 2012), but geometrically thick populations in both observations of external edge-on galaxies (Comerón et al. 2012) and the Milky Way (Robin et al. 1996; Jurić et al. 2008) extend beyond the thinner component. From this scenario, thick disc stars in the solar vicinity are the oldest mono-age populations.

3.2 ^{7}Li in thick disc stars

The first attempt to measure Li in thick disc stars was made by Molaro et al. (1997), who measured Li in seven metal-poor thick disc stars and found an abundance of Li consistent with that of halo stars. Romano et al. (1999) used the kinematical properties to separate thin disc from thick disc stars. In their sample, there is also a thick disc star BD + 01 3421 with [Fe/H]=−0.5, but with a lithium abundance of A(Li) = 2.11, which is much lower than the Li abundance of thin disc stars of similar metallicity. The lack of increase of Li abundance among thick disc stars was established by Ramírez et al. (2012) for a larger data sample, showing that the maximum thick disc lithium abundances remain close to the Spite plateau, regardless of their metallicity. Delgado Mena et al. (2015) and Bensby & Lind (2018) even suggested that thick disc lithium abundances decrease with increasing metallicity. Guiglion et al.

(2016) used the AMBRE catalogue, composed of 363 stars, and found that the highest lithium abundances seem to increase slightly with [Fe/H], from about Li = 2.0–2.4 dex at [Fe/H] = −0.3. In the AMBRE sample, the distribution of Li abundances in thick disc clusters is ∼2.2 and ∼1.2 dex, respectively. The higher value seems to correspond to an extension of the Spite plateau, while the lower values are likely due to lithium destruction in stellar interiors. Fu et al. (2018) investigated Li enrichment in the sample of 1399 stars of the CES iDR4 sample. By means of the chemical division proposed by Adibekyan et al. (2012), they identified 73 stars belonging to the thick disc. However, these generally have a relatively higher abundance of *A*(Li) ≈2.4 and possibly a modest rise at the highest metallicity.

3.3 ^{7}Li evolution model for the thick disc

In this section, we probe the hypothesis that novae are also the main Li source in the thick disc by using the parameters that reproduce best the lithium evolution in thin disc. We use the standard model and do not test the pre-main-sequence depletion model. In fact, given the available constraints, we prefer to adopt the model able to reproduce stellar observations. In our model, the thick and thin discs evolve independently from each other, without any exchange of gas or stars. Our approach is similar to that followed by Grisoni et al. (2017) for the α–elements. Instantaneous recycling is relaxed and the stellar lifetimes are taken into account, as for our thin disc model.

The thick disc is characterized by a more intense star formation history than the thin disc. There is quicker evolution, with a stronger efficiency (ν = 3) and shorter time-scale of 0.1 Gyr for infall. The chemical evolution lasts for 2 Gyr, but with only residual star formation after approximately 1.2 Gyr. These parameters are well suited to account for the oldest mono-age populations, following the scenario presented in Minchev et al. (2017). For the rest, the model is identical to that of the thin disc.

3.4 Results for the thick disc

Our model with $\tau_{\rm nova}$ of 1 Gyr and with the same Li yields derived for thin disc stars predicts no increase in the ^{7}Li abundance for thick disc stars up to [Fe/H] = −0.2. This is because the time of evolution of the thick disc is shorter than the characteristic time at which novae start to contribute with Li. At variance with thin disc evolution, our model for the thick disc predicts no Li increase, in excellent agreement with the observational result. Actually, if we consider only nova production, ^{7}Li should decrease and is kept about constant under the action of spallation processes, which are the only active nucleosynthetic processes in the thick disc. Bensby & Lind (2018) for the first time provide an age estimation for thick disc stars. These ages are compatible with an old thick disc, as we have assumed in our model. We note, however, that some stars have relatively lower ages (and fewer a higher one). We cannot explain the ages of this younger population. They could be due to a false thick disc identification or a problem in measuring the ages. Our model produces a thick disc over a relatively short time-scale of 2 Gyr. Thus, assuming that the formation of the thick disc started 12 Gyr ago, its star formation was over about 10 Gyr ago. Following Bensby & Lind (2018), we consider *bona fide* thick disc stars as those with an age greater than 8 Gyr. The result of our model for the thick disc in *A*(Li) versus age space is shown in Fig. 7. Given the uncertainties in the age determination, there is substantial agreement with the model.

At the high-metallicity end, [Fe/H] = −0.2, our model predicts a sharp increase in ^{7}Li abundance, reaching values up to *A*(Li)∼2.6. This is because novae start to contribute significantly. However, the very mild star formation rate (SFR) that characterizes this phase would effectively mark the end of stellar formation of the thick disc. Our threshold for stellar formation is conservatively set at 1 $M_\odot$ pc^{-2}, while, for comparison, it was set to 4 $M_\odot$ pc^{-2} in Chiappini et al. (1997) for the thick halo phase. It is not clear whether there is a real chance of finding stars of the thick disc in this area, but if they are, according to our model, they should show relatively higher Li abundances than average thick disc stars.

4 CONCLUSION

The idea that nova systems could produce lithium dates back to the mid-1970s and works by Arnould & Norgaard (1975) and Starrfield et al. (1978). They applied to novae the idea put forward by Cameron and Fowler (1971) to explain high ^{7}Li abundances in some luminous red giants. This possibility was then incorporated in Galactic chemical ^{7}Li evolution models by D'Antona & Matteucci (1991) and Romano et al. (1999), together with other possible Li sources, to explain the ^{7}Li behaviour. However, the non-detection of the ^{7}Li I line in nova outbursts led these authors to favour low-mass red giants as the most likely Li source (Romano et al. 2001; Prantzos et al. 2017). Observational evidence has been found only recently, with the systematic detection of the mother nuclei ^{7}Be in the post-outburst spectra of classical novae by Tajitsu et al. (2015, 2016), Molaro et al. (2016), Izzo et al. (2018) and Selvelli et al. (2018). The observed ^{7}Be decays into ^{7}Li with a mean life of 53 days and all observed ^{7}Be decays into ^{7}Li. Moreover, the ^{7}Be/H ratio has been measured with abundances that are higher than those of nova theoretical models and provide overproduction factors between 4 and 5 dex over the meteoritic abundance of ^{7}Li. The total amount of ^{7}Li produced by a nova is quite uncertain, since it depends on the ejected mass and on the number of outbursts a nova experiences in its whole lifetime.

In this article, we have revised ^{7}Li evolution by considering these most recent observations. By means of a detailed chemical evolution model for the thin disc, we have shown that nova systems start to enrich interstellar ^{7}Li with a delay of about 1 Gyr. In order to match the increase of Galactic ^{7}Li observed in the thin disc, an effective yield of $1.8(\pm 0.6) \times 10^{-5}$ $M_\odot$ of ^{7}Li per nova in a whole lifetime is required. It is quite remarkable that this value is consistent with that inferred in nova outbursts. Considering that there is an average ^{7}Li mass ejection of 10^{-9} $M_\odot$ in a nova event and that there are about 10^4 events per nova, we obtain a yield of $\approx 10^{-5}$ $M_\odot$ per nova, which is remarkably close to our model-derived yields, considering the uncertainties in all parameters. This model is tuned to reproduce Li observations in stars and fails to reproduce the meteoritic solar value 4.56 Gyr ago. However, it has been suggested that stellar abundances could have been affected by pre-main-sequence destruction (Molaro et al. 2012; Fu et al. 2015; Thévenin et al. 2017). In this context, we are able to reproduce the stellar trend by doubling the standard effective yields, starting from the primordial value inferred by big-bang nucleosynthesis and assuming a depletion of ∼0.35 dex during the pre-main-sequence. This pre-main-sequence depletion model matches the lithium abundance measured in meteorites and young T Tauri stars.

We have also applied the parameters derived from thin disc ^{7}Li evolution to a model for the thick disc. In this way, we have shown that, assuming classical novae as the main ^{7}Li factory, we can also explain the absence of any ^{7}Li enhancement observed in thick disc

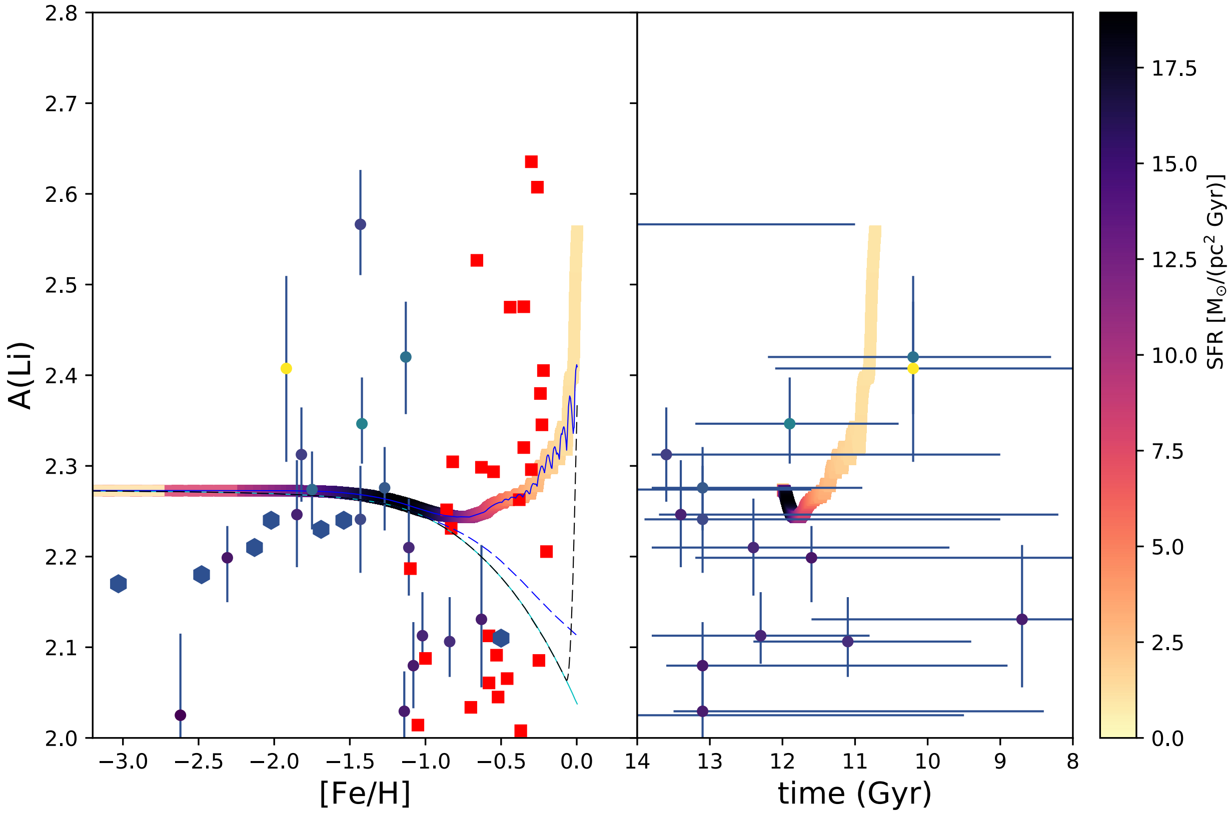

Figure 7. Results for the Galactic thick disc. Left panel: ^{7}Li abundances versus [Fe/H]. The red squares are stars from the AMBRE project; the circles are thick disc stars from Bensby & Lind (2018), colour-coded according to their stellar temperature (see colour bar in previous figures); blue hexagons are from Molaro et al. (1997). The thick line shows the model results and is colour-coded depending on the star formation rate. The thinner lines show the model results for no ^{7}Li production (cyan), only novae (black dashed), only AGB (blue dashed) and only spallation (blue). Right panel: ^{7}Li abundances versus time. The data are from Bensby & Lind (2018), while the thick line shows the model results and it is colour-coded depending on the star formation rate, as in the left panel.

stars. We have found that ^{7}Li does not decrease due to astration, thanks to spallation processes, which are the only active nucleosynthetic processes in the thick disc. Thus, the ^{7}Li abundance can be used as a test to confirm or reject that a star belongs to the thick disc population. This can be considered as a new criterion to be used in combination with the more popular α knee.

Extrapolating these results to the dwarf galaxy satellites of our Milky Way, we expect the ^{7}Li abundances in stars to show an enhancement in ^{7}Li only for those galaxies with a star formation history long enough to provide nova products to contribute to gas enrichment. Thus, no ^{7}Li abundance above $A(\mathrm{Li}) = 2.3$ is expected in very small objects, such as ultra-faint galaxies, which evolve on short time-scales relative to nova evolution. An important test will be the Galactic bulge, which is likely to fall into this category – at least its older and metal-poor population (Cescutti, Chiappini & Hirschi 2018). We intend also to extend our prediction to this structure of the Milky Way as soon as we have new ^{7}Li abundance determinations in stars belonging to this component.

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REFERENCES

Adibekyan V. Z., Sousa S. G., Santos N. C., Delgado Mena E., González Hernández J. I., Israelian G., Mayor M., Khachatryan G., 2012, A&A, 545, A32
Alibés A., Labay J., Canal R., 2002, ApJ, 571, 326
Arnould M., Norgaard H., 1975, A&A, 42, 55
Bath G. T., Shaviv G., 1978, MNRAS, 183, 515
Bensby T., Lind K., 2018, A&A, 615 , A151
Bensby T., Alves-Brito A., Oey M. S., Yong D., Meléndez J., 2011, ApJ, 735, L46
Bensby T., Feltzing S., Oey M. S., 2014, A&A, 562, A71
Bournaud F., Elmegreen B. G., Martig M., 2009, ApJ, 707, L1
Bovy J., Rix H.-W., Liu C., Hogg D. W., Beers T. C., Lee Y. S., 2012, ApJ, 753, 148
Brook C. B., Gibson B. K., Martel H., Kawata D., 2005, ApJ, 630, 298
Cameron A. G. W., Fowler W. A., 1971, ApJ, 164, 111
Casey A. R. et al., 2016, MNRAS, 461, 3336
Cayrel R., 1998, Space Sci. Rev., 84, 145
Cescutti G., Chiappini C., Hirschi R., 2018, in Chiappini C., Minchev I., Starkenburg E., Valentini M., eds, IAU Symp. Vol. 334, Rediscovering Our Galaxy. Cambridge Univ. Press, Cambridge, 94
Chiappini C., Matteucci F., Gratton R., 1997, ApJ, 477, 765
Comerón S. et al., 2012, ApJ, 759, 98
Cyburt R. H., Fields B. D., Olive K. A., 2003, Phys. Lett. B, 567, 227
D'Antona F., Matteucci F., 1991, A&A, 248, 62

Delgado Mena E. et al., 2015, A&A, 576, A69
Forbes J., Krumholz M., Burkert A., 2012, ApJ, 754, 48
Fu X. et al., 2018, A&A, 610, A38
Fu X., Bressan A., Molaro P., Marigo P., 2015, MNRAS, 452, 3256
Gilmore G., Reid N., 1983, MNRAS, 202, 1025
Grand R. J. J., Springel V., Gómez F. A., Marinacci F., Pakmor R., Campbell D. J. R., Jenkins A., 2016, MNRAS, 459, 199
Greggio L., Renzini A., 1983, A&A, 118, 217
Grisoni V., Spitoni E., Matteucci F., Recio-Blanco A., de Laverny P., Hayden M., Mikolaitis Ŝ., Worley C. C., 2017, MNRAS, 472, 3637
Guiglion G., de Laverny P., Recio-Blanco A., Worley C. C., De Pascale M., Masseron T., Prantzos N., Mikolaitis Š., 2016, A&A, 595, A18
Hernanz M., Jose J., Coc A., Isern J., 1996, ApJ, 465, L27
Iwamoto K., Brachwitz F., Nomoto K., Kishimoto N., Umeda H., Hix W. R., Thielemann F.-K., 1999, ApJS, 125, 439
Izzo L. et al., 2015, ApJ, 808, L14
Izzo L. et al., 2018, MNRAS, 478, 1601
José J., Hernanz M., 1998, ApJ, 494, 680
Jurić M. et al., 2008, ApJ, 673, 864
Kobayashi C., Karakas A. I., Umeda H., 2011, MNRAS, 414, 3231
Krankowsky D., Müller O., 1964, Geochim. Cosmochim. Acta, 28, 1625
Kroupa P., 2001, MNRAS, 322, 231
Lattanzio J. C., Siess L., Church R. P., Angelou G., Stancliffe R. J., Doherty C. L., Stephen T., Campbell S. W., 2015, MNRAS, 446, 2673
Lind K., Primas F., Charbonnel C., Grundahl F., Asplund M., 2009, A&A, 503, 545
Lodders K., Palme H., Gail H.-P., 2009, Landolt Börnstein, 712
Lyubimkov L. S., 2016, Astrophys., 59, 411
Martig M., Minchev I., Flynn C., 2014, MNRAS, 443, 2452
Matteucci F., Greggio L., 1986, A&A, 154, 279
Matteucci F., D'Antona F., Timmes F. X., 1995, A&A, 303, 460
Meynet G., Maeder A., 2002, A&A, 390, 561
Minchev I., Famaey B., Quillen A. C., Dehnen W., Martig M., Siebert A., 2012, A&A, 548, A127
Minchev I., Martig M., Streich D., Scannapieco C., de Jong R. S., Steinmetz M., 2015, ApJ, 804, L9
Minchev I., Steinmetz M., Chiappini C., Martig M., Anders F., Matijevic G., de Jong R. S., 2017, ApJ, 834, 27
Molaro P., Bonifacio P., Castelli F., Pasquini L., 1997, A&A, 319, 593
Molaro P., Bonifacio P., Pasquini L., 1997, MNRAS, 292, L1
Molaro P., Bressan A., Barbieri M., Marigo P., Zaggia S., 2012, Mem. Soc. Astron. Ital. Suppl., 22, 233
Molaro P., Izzo L., Mason E., Bonifacio P., Della Valle M., 2016, MNRAS, 463, L117
Planck Collaboration XIII, 2016, A&A, 594, A13
Prantzos N., 2012, A&A, 542, A67
Prantzos N., de Laverny P., Guiglion G., Recio-Blanco A., Worley C. C., 2017, A&A, 606, A132
Quinn P. J., Hernquist L., Fullagar D. P., 1993, ApJ, 403, 74
Ramírez I., Fish J. R., Lambert D. L., Allende Prieto C., 2012, ApJ, 756, 46
Rebolo R., Beckman J. E., Molaro P., 1988, A&A, 192, 192
Robin A. C., Haywood M., Creze M., Ojha D. K., Bienayme O., 1996, A&A, 305, 125
Romano D., Matteucci F., Molaro P., Bonifacio P., 1999, A&A, 352, 117
Romano D., Matteucci F., Ventura P., D'Antona F., 2001, A&A, 374, 646
Romano D., Karakas A. I., Tosi M., Matteucci F., 2010, A&A, 522, A32
Sackmann I.-J., Boothroyd A. I., 1999, ApJ, 510, 217
Schönrich R., Binney J., 2009, MNRAS, 396, 203
Selvelli P., Izzo L., Molaro P., 2018, MNRAS, 481, 2261
Shafter A. W., 1997, ApJ, 487, 226
Shara M. M., Livio M., Moffat A. F. J., Orio M., 1986, ApJ, 311, 163
Siess L., Livio M., 1999, MNRAS, 304, 925
Smiljanic R. et al., 2018, A&A, 617, A4
Smiljanic R., Pasquini L., Bonifacio P., Galli D., Gratton R. G., Randich S., Wolff B., 2009, A&A, 499, 103
Smith V. V., Lambert D. L., 1989, ApJ, 345, L75
Smith V. V., Lambert D. L., 1990, ApJS, 72, 387
Spite F., Spite M., 1982, A&A, 115, 357
Starrfield S., Truran J. W., Sparks W. M., Arnould M., 1978, ApJ, 222, 600
Tajitsu A., Sadakane K., Naito H., Arai A., Aoki W., 2015, Nature, 518, 381
Tajitsu A., Sadakane K., Naito H., Arai A., Kawakita H., Aoki W., 2016, ApJ, 818, 191
Tanabashi M. et al., 2018, Phys. Rev. D, 98, 030001
Thévenin F., Oreshina A. V., Baturin V. A., Gorshkov A. B., Morel P., Provost J., 2017, A&A, 598, A64
Travaglio C., Randich S., Galli D., Lattanzio J., Elliott L. M., Forestini M., Ferrini F., 2001, ApJ, 559, 909
Ventura P., Di Criscienzo M., Carini R., D'Antona F., 2013, MNRAS, 431, 3642
Villalobos Á., Helmi A., 2008, MNRAS, 391, 1806
Yan H.-L. et al., 2018, Nature Astron., 2, 790

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