The Galactic Lithium Evolution Revisited

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Abstract. We study the temporal evolution of the $^7$Li abundance in the gaseous medium for all the components (halo, disk and bulge) of our Galaxy. We adopt nucleosynthesis prescriptions on stellar lithium production based upon recent observational results and up-to-date theoretical considerations in the framework of a fully consistent chemical evolution model. $^7$Li production by AGB stars and SNeII is discussed and the contribution by novae is reintroduced. To gain some insight into the stellar factories which should be taken into account to reproduce the upper envelope of the observational A(Li) vs [Fe/H] diagram for the solar neighborhood, we critically analyse Li data from several authors. The contribution from nova outbursts seems to be fundamental in order to reproduce the high $^7$Li abundances observed in the most metal-rich dwarfs. Finally, we make predictions on the $^7$Li content that should be expected in the most metal-rich stars of the Galactic bulge. To test similar predictions, $^7$Li observations in a statistical significant sample of high metallicity bulge stars are absolutely necessary; the advent of microlensing should help us in reaching this goal.

1. Introduction

$^7$Li is a key element in quite a lot of astrophysical and cosmological problems:

- it is one of the few elements synthetized during the Big Bang, so its primordial abundance (tied to the parameter $\eta$) can in principle be used to constrain primordial nucleosynthesis models;

- there is both theoretical and observational evidence that $^7$Li can be produced and/or destroyed in stars, the production and depletion mechanisms being so complex and so far from being understood that one may thinks there is a cosmic conspiracy that keeps us from drawing any firm picture of the $^7$Li abundance evolution in the Galaxy!

A key point generally accepted is that the $^7$Li abundance in warm halo dwarfs is nearly constant and representative of the pristine $^7$Li abundance (Spite & Spite 1982; Rebolo et al. 1988; Bonifacio & Molaro 1997). Keeping this as a starting point...
point, chemical evolution models have been constructed which explain the rise off the so-called Spite plateau by means of stellar $^7$Li production (D’Antona & Matteucci 1991; Matteucci et al. 1995). We will present new chemical evolution results on the temporal variation of the $^7$Li abundance in the ISM for both the solar neighborhood and the Galactic bulge.

We will start by illustrating the data-sample we have used to constrain the chemical evolution model ($\S$2); then we will present the chemical evolution model itself, focusing mainly on the nucleosynthesis prescriptions used to account for $^7$Li production from different stellar sources ($\S$3); finally, we will show the predicted trends of A(Li) versus [Fe/H] for both the solar neighborhood and the Galactic bulge and draw some conclusions ($\S$4).

2. Observational data

We selected from the literature a great number of $^7$Li measurements in stellar atmospheres, with the aim of exploring in particular the A(Li) versus [Fe/H] behaviour in the metallicity range $-1.5 \leq [\text{Fe/H}] \leq -0.5$ dex. Our main fonts are:

- Deliyannis et al. (1990)
- Lambert et al. (1991)
- Pilachowski et al. (1993)
- Pasquini et al. (1994)
- Spite et al. (1996)

We considered only stars with HIPPARCOS parallax and proper motion, in order to give a homogeneous and accurate estimate of their membership to the different Galactic kinematical components. To do that, we evaluated $u$, $v$ and $w$ (the usual Galactic space-velocity components with respect to the Local Standard of Rest, in a left-handed coordinate system) by means of the Johnson & Soderblom (1987) matrices. With further selection criteria we also identified all those stars that we know to have already suffered Li depletion (objects with $T_{\text{eff}} < 5700$ K, see Ryan & Deliyannis 1998) or dilution (evolved stars, identified by using theoretical isochrones from Bertelli et al. 1994). Disk stars in our sample, selected on the basis of their space-velocity components (see Fig.1 caption for the selection criteria) have mostly metallicities greater than -1.0 dex and show a large scatter in their lithium abundances (Fig.1); all the others show Li depletion starting from very low metallicities; moreover, they show no evidence of a rise off the plateau values. For stars with multiple $^7$Li detections lying on the upper envelope, we take an averaged value for both A(Li) and [Fe/H] (see Romano et al. 1999); we do not take into account the upper limits, because they are not significant in order to constrain chemical evolution models.

Plotting the target stars in a diagram with rotational velocities around the Galactic center as abscissae and non-rotational velocities as ordinates (Fig.2), we can see how, in general, stars with metallicities greater than -1.0 show disk-like features (although there are some exceptions). From Fig.1 and Fig.2 we conclude
Figure 1. $A(\text{Li})$ vs $[\text{Fe/H}]$ diagram for the solar neighborhood. Theoretical trends obtained under different nucleosynthesis assumptions are superimposed to the observational points. Disk stars (defined as those with $v > -115$ km s$^{-1}$, $(u^2 + w^2)^{1/2} < 150$ km s$^{-1}$) are shown as filled symbols; non disk stars (defined as objects that do not satisfy simultaneously the conditions on $u$, $v$, $w$ given above) are shown as empty symbols. Asterisks: halo stars from Spite et al. 1996; filled squares: Pasquini et al. 1994; empty squares: halo stars from Bonifacio & Molaro 1997; circles: Pilachowski et al. 1993; triangles: Lambert et al. 1991; lozenges: Deliyannis et al. 1990. Crosses are stars for which we do not have $u$, $v$, $w$ determinations; clovers are averaged values for stars on the upper envelope for which we have found multiple $^7\text{Li}$ detections in the literature. (Details on data analysis can be found in Romano et al. 1999.) $^7\text{Li}$ abundances in the Sun (Anders & Grevesse 1989) and in T-Tauri stars are also shown with different symbols.
Figure 2. The \((u^2 + w^2)^{1/2}\) vs \(v\) diagram for our target stars. Two different ranges in metallicity have been considered. The box in the low right corner tentatively puts limits on the minimum rotational velocity around the Galactic center and on the maximum kinetic energy associated to non-rotative motions for a star to be ascribed to the disk (either thin or thick).

that the stellar Li content is likely to be independent of the star kinematics, although more data are needed to draw firm conclusions.

3. Theoretical models

To reproduce the upper envelope of the observed diagram Li-metallicity, under the hypothesis that it is indicative of the ISM enrichment during the Galactic lifetime, we adopt the two-infall chemical evolution model of Chiappini et al. (1997). It assumes that the Galaxy formed out of two main infall episodes. During the first and faster episode, both the halo and the bulge formed; during the second, the Galactic disk slowly grew, in the framework of an inside-out scenario of formation (Matteucci & François 1989).

We assume the Li content observed in stars belonging to the Spite plateau as indicative of the primordial value \((A(\text{Li})_p \sim 2.2 \ \text{dex}; \ \text{Bonifacio} & \ \text{Molaro} \ 1997)\) and justify the rise off the plateau as due to Li injection into the ISM from several lithium factories (C-stars, massive AGB stars, Type II SNe, nova systems). The possible contribution to \(^7\text{Li}\) production by cosmic rays is not taken into account.
We ran three models:

- model A, accounting for $^7\text{Li}$ production from C-stars, massive AGB stars and Type II SNe (best model in Matteucci et al. 1995, 1999);
- model B, the same as model A with the addition of Li synthesis from thermonuclear runaway in nova outbursts (see Romano et al. 1999);
- model C, like model B but without any contribution from C-stars and with a lower Li production from both massive AGB stars and SNeII.

Model results are compared to the observational data in Fig. 1.

4. Model results and conclusions

Let us first point out how using a single category of stellar lithium producers, we can not explain all the features of the observed diagram: for example, nova systems, evolving on long timescales ($\geq 1$ Gyr), cannot account for a rise of the Spite plateau before a metallicity of about -0.5 dex, but they are able to explain the highest abundances measured in the most metal-rich stars (see Fig. 3). Opposite considerations hold for both AGB stars and Type II SNe, acting on shorter timescales but being able to explain only 1/2 of the observed present ISM $^7\text{Li}$ abundance.

So, we have tried to reproduce the upper envelope outlined by the experimental points by considering all the possible stellar sources together in the chemical evolution model (Fig. 1). Model A, accounting for all the sources but novae, fails to reproduce the highest values observed in the more metal-rich dwarfs. To succeed in doing this, we need to add nova systems (model B = model A + novae); in that case, also lowering the contribution by AGB stars and supernovae a satisfactory result can be found, the only difference with respect to the previous one being a slower rise off the plateau (model C). Models accounting for nucleosynthesis from novae predict an increase in the ISM $^7\text{Li}$ abundance from the epoch of the Solar System formation up to now. On the contrary, if we rule out novae as lithium producers, we find a flat trend. We suggest that the contribution to Li enrichment from neutrino-induced nucleosynthesis in Type II SN explosions is probably not so significant as assumed in previous chemical evolution models, although the paucity of data in the region $-1.5 \leq [\text{Fe/H}] \leq -0.5$ does not allow us to draw any firm conclusion. Our main conclusion is that a significant $^7\text{Li}$ production from nova systems seems to be strongly requested to gain the high lithium abundances observed in the most metal-rich stars of the sample.

Finally, let us have a look at the situation predicted for the Galactic bulge. This central region of the Galaxy is thought to be the result of a faster collapse with a more efficient star formation, so that metallicities higher than the present one in the solar neighborhood should be gained in a shorter timescale. Therefore, when novae start restoring their newly synthesized $^7\text{Li}$, a metallicity as large as $\sim 0.5$ dex is likely to have been already achieved in the gas in the bulge. A present Li abundance as high as 4 dex should be expected in the most metal-rich (and of course undepleted) bulge stars. If novae are suppressed, the present Li content
Figure 3. $A(\text{Li})$ vs $[\text{Fe/H}]$ theoretical trends for the solar neighborhood as predicted when only a single category of stellar lithium producers is allowed: a) nova systems (yields from José & Hernanz 1998); b) Type II SNe (yields from Woosley & Weaver 1995; straight line: total yields, dashed line: yields reduced to a half); c) AGB stars (prescriptions from Matteucci et al. 1995; straight line: massive AGB stars plus C-stars, dashed line: only massive AGB stars).
Figure 4. $A(\text{Li})$ vs $[\text{Fe/H}]$ theoretical diagram for the bulge. Model B and C, taking into account $^7\text{Li}$ production by novae, predict a steep rise at the highest metallicities. Similar trends are due to the interplay between the long timescales of Li production in novae and the short timescale of bulge formation.
in these stars should be 3.5 dex (see Fig.4). For testing similar predictions we need observations of the Li I feature in a statistical significant sample of very peculiar objects: metal-rich bulge stars which have never suffered lithium depletion. This is a hardly achievable goal, because we know that stars become more and more efficient in destroying their initial lithium content already in the pre-main sequence phase as long as their metallicity increases (e.g. Ventura et al. 1998). The recent detection of the Li I line in the bulge star 97 BLG 45 by Minniti et al. (1998) is at the moment the only one of this type, and unfortunately shows a star which is likely to have depleted its initial lithium content (Matteucci et al. 1999). So, observational efforts in this sense will be very welcome.

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