

# The galactic lithium evolution revisited<sup>\*</sup>

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**Abstract.** The evolution of the  ${}^7\text{Li}$  abundance in the Galaxy has been computed by means of the two-infall model of Galactic chemical evolution. We took into account several stellar  ${}^7\text{Li}$  sources: novae, massive AGB stars, C-stars and Type II SNe. In particular, we adopted new theoretical yields for novae. We also took into account the  ${}^7\text{Li}$  production from GCRs. In particular, the absolute yields of  ${}^7\text{Li}$ , as suggested by a recent reevaluation of the contribution of GCR spallation to the  ${}^7\text{Li}$  abundance, have been adopted.

We compared our theoretical predictions for the evolution of  ${}^7\text{Li}$  abundance in the solar neighborhood with a new compilation of data, where we identified the population membership of the stars on a kinematical basis. A critical analysis of extant observations revealed a possible extension of the Li plateau towards higher metallicities (up to  $[\text{Fe}/\text{H}] \sim -0.5$  or even  $-0.3$ ) with a steep rise afterwards.

We conclude that 1) the  ${}^7\text{Li}$  contribution from novae is required in order to reproduce the shape of the growth of  $A(\text{Li})$  versus  $[\text{Fe}/\text{H}]$ , 2) the contribution from Type II SNe should be lowered by at least a factor of two, and 3) the  ${}^7\text{Li}$  production from GCRs is probably more important than previously estimated, in particular at high metallicities: by taking into account GCR nucleosynthesis we noticeably improved the predictions on the  ${}^7\text{Li}$  abundance in the presolar nebula and at the present time as inferred from measures in meteorites and T Tauri stars, respectively. We also predicted a lower limit for the present time  ${}^7\text{Li}$  abundance expected in the bulge, a prediction which might be tested by future observations.

**Key words:** Galaxy: abundances – Galaxy: evolution – Galaxy: solar neighbourhood

## 1. Introduction

Since Spite & Spite (1982) discovered that the oldest, warm halo dwarfs in the Galaxy all show almost the same  ${}^7\text{Li}$  abundance, several papers have appeared in the literature supporting their

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<sup>\*</sup> Tables 3 and 4 are only available in electronic form at the CDS via anonymous ftp to: cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/Abstract.html>

initial interpretation that this is the primordial abundance of  ${}^7\text{Li}$  (Spite et al. 1984; Spite & Spite 1986; Rebolo et al. 1988, hereafter RMB; but see also Thorburn 1994).

The substantial flatness of the plateau and the absence of intrinsic scatter (Spite et al. 1996; Bonifacio & Molaro 1997), coupled with the detection of the fragile isotope  ${}^6\text{Li}$  in the metal-poor stars HD 84937 (Smith et al. 1993; Hobbs & Thorburn 1997; Cayrel et al. 1999) and perhaps BD+42 2667 (Cayrel et al. 1999), are the arguments for claiming that no significant depletion mechanisms should have acted in these stars to modify the pristine  ${}^7\text{Li}$  abundance (but see also Ryan et al. 1999).

We also note a competing theory, which claims that the highest  ${}^7\text{Li}$  abundance - measured in the most Li-rich Population I objects - is the primordial one (Boesgaard et al. 1998). In this case some depletion mechanisms able to deplete Li in all the halo stars by the same amount acting on a Galactic lifetime timescale are required. Possible mechanisms include diffusion (Vauclair 1988), rotational mixing (Pinsonneault et al. 1992) and stellar winds (Vauclair & Charbonnel 1995).

Recently, Fields & Olive (1999), using a standard model of Galactic cosmic ray (GCR) nucleosynthesis, found that only little  ${}^6\text{Li}$  (and  ${}^7\text{Li}$ ) depletion is allowed in halo stars. So that the observed Spite plateau should be indicative of the primordial Li abundance.

Younger stars span a wide range of lithium abundances. The highest values, measured in Orion T Tauri stars reach  $A(\text{Li})^1 \sim 3.83$  dex ( $\sim 3.5$  dex when corrected for NLTE effects, Duncan & Rebull 1996). Therefore, some mechanisms of  ${}^7\text{Li}$  production are required to increase the Li abundance from the plateau value to the present one. Nuclear reactions in stellar interiors and spallation processes on interstellar medium (ISM) particles involving either high or low energy GCRs have both been proposed as possible mechanisms able to synthesize  ${}^7\text{Li}$  and restore it back to the ISM, where it enters into the chemical composition of the new-formed stars.

Lithium evolution has already been studied in detail by several authors. D'Antona & Matteucci (1991), by means of a complete model of chemical evolution, have shown that both the Solar System lithium abundance and the rise from the Spite plateau could be explained assuming Li-production in classical

<sup>1</sup>  $A(\text{Li}) = \log_{10} (N_{\text{Li}}/N_{\text{H}}) + 12$ .

novae and AGB stars. Later, novae were ruled out as lithium producers at a Galactic level (Boffin et al. 1993). Matteucci et al. (1995) suggested a combination of  $\nu$ -process nucleosynthesis from Type II SNe and hot bottom burning in intermediate mass AGB stars to match the observations. Recently, Matteucci et al. (1999) used the same nucleosynthesis prescriptions to calculate the expected  ${}^7\text{Li}$  content in the Galactic bulge. Lithium production by low mass AGB stars (C-stars) and standard GCR nucleosynthesis were the key ingredients of the model of Abia et al. (1995), which was able to match also the behaviour of the lithium isotopic ratio. In any case, they had to require a percentage of Li-rich C-stars much higher (6–8%) than observed (2–3%). However, we note that C-stars at low metallicities are found much more numerous ( $\sim 10\%$ , Beers et al. 1992; Norris et al. 1997).

In this paper we deal with Galactic lithium evolution taking into account the lithium production both in stars and from GCRs. The aim of the paper is to reproduce the observed upper envelope of the diagram  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$ , assuming that the Population II  ${}^7\text{Li}$  is the primordial one.

In Sect. 2 we present the data-set we have used to constrain the model results, in Sect. 3 we review the main candidates as stellar lithium producers, in Sect. 4 we present the basic assumptions of the chemical evolution model and the lithium synthesis prescriptions, in Sect. 5 we illustrate our main results and in Sect. 6 we draw some conclusions.

## 2. Observational data

The observed evolution of the  ${}^7\text{Li}$  abundance with metallicity, when abundance determinations in disk and halo dwarfs are restricted to stars with effective temperature  $T_{\text{eff}} \geq 5700$  K, suggests that there is a general trend towards a larger ISM  ${}^7\text{Li}$  content with increasing metallicity. In previous papers (e.g. Matteucci et al. 1995, 1999) the abundances used to constrain Galactic chemical evolution models were pointing to a smooth increase from the Spite plateau to the Solar System value. In this paper we show the results of an analysis performed on a large selection of data taken from the literature. Li detections for those stars which are tracing the upper envelope of the observational  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  diagram have been critically analysed and a rise off the plateau steeper than previously assumed has been found. This result, coupled with a Spite plateau which extends towards larger metallicities, suggests a revision of the various contributions to the  ${}^7\text{Li}$  production from different sources. In particular,  ${}^7\text{Li}$  producers restoring their lithium to the ISM on long timescales should be preferred.

${}^7\text{Li}$  measurements in stellar atmospheres have been selected from the literature in the metallicity range  $-1.5 \leq [\text{Fe}/\text{H}] \leq -0.5$  dex<sup>2</sup>. This region is particularly interesting because it is the metallicity range where the observed lithium abundance is expected to start growing due to  ${}^7\text{Li}$  injection from the first Li factories.

<sup>2</sup> Sources in the literature: Deliyannis et al. 1990; Lambert et al. 1991; Pilachowski et al. 1993; Pasquini et al. 1994; Spite et al. 1996.

From the point of view of stellar nucleosynthesis, it is important to determine the metallicity at which the Li abundance starts rising off the Spite plateau. For instance, the constancy of the Spite plateau at  $[\text{Fe}/\text{H}] \leq -1.5$  translates into the requirement that Type II SNe coming from the first stellar generations should contribute only an amount of lithium smaller than the primordial one.

Selection criteria have been applied in order to remove from the sample all those stars which are likely to have passed through phases during which they either destroyed or diluted their initial lithium content. To this purpose, we selected only stars not suffering any  ${}^7\text{Li}$  convective depletion, i.e.  $T_{\text{eff}} \geq 5700$  K, according to standard models. Stars with  $T_{\text{eff}} < 5700$  K are cool enough to be threatened by Li burning in deep convective envelopes already during the pre-main sequence (see also Ryan & Deliyannis 1998). Moreover, we retained only stars included in the HIPPARCOS catalogue which provides accurate information on kinematics and luminosities. Objects recognized as giants or subgiants are likely to show Li surface abundances affected by dilution and have been rejected.

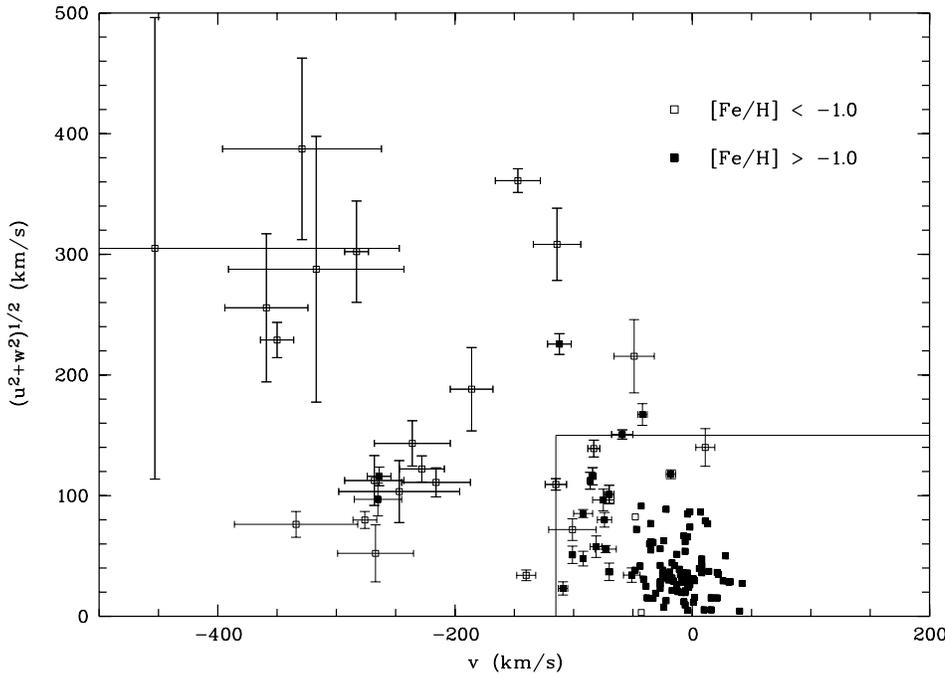
The program stars are listed in Table 3. For each star we give the HD, DM, G and HIP numbers and the U, V, W heliocentric space-velocity components with the associated errors. The membership to a specific Galactic population (halo or disk, either thin or thick) as derived from the kinematics and the evolutionary status are also provided.

### 2.1. Evolutionary status

In order to determine the evolutionary status of each star in our sample, we used the theoretical isochrones by Bertelli et al. (1994). We divided the program stars in three metallicity bins ( $[\text{Fe}/\text{H}] \geq -0.75$ ;  $-1.25 \leq [\text{Fe}/\text{H}] \leq -0.75$ ; and  $[\text{Fe}/\text{H}] \leq -1.25$ ). For each bin the data were compared with theoretical isochrones appropriately chosen for different ages at different metallicities. In the bin  $[\text{Fe}/\text{H}] \geq -0.75$  we used the isochrones of 2–9 Gyr; in the bin  $-1.25 \leq [\text{Fe}/\text{H}] \leq -0.75$  the 6–19 Gyr isochrones, and in the bin  $[\text{Fe}/\text{H}] \leq -1.25$  those of 8–20 Gyr. The absolute magnitudes for the stars in our data-base were obtained from the HIPPARCOS parallaxes. The effective temperatures were calculated using the  $(B - V) - T_{\text{eff}}$  calibration of Alonso et al. (1996). Within each metallicity bin and by using the appropriate isochrone we distinguished among turn-off, giant and subgiant stars following the criteria outlined by Beers et al. (1990). We found that most of the stars are turn-off stars; only few among them (HIP 36430, HIP 37723, HIP 86694, HIP 103987, HIP 115167, HIP 116082) are subgiants and are, therefore, not considered in the analysis.

### 2.2. Kinematics

The heliocentric Galactic space-velocity components, U, V and W, calculated from the star's proper motion, parallax and radial velocity following the Johnson & Soderblom (1987) analysis, are listed in Columns 5, 6, 7 of Table 3. The uncertainties  $\sigma_U$ ,  $\sigma_V$  and  $\sigma_W$  are also given in Columns 8, 9, 10. A left-handed



**Fig. 1.**  $V$  versus  $(U^2 + W^2)^{1/2}$  diagram for the sample stars. The stars have been divided into two metallicity bins, on the grounds of the metallicity values given in Table 4. In the case of multiple metallicity determinations we have adopted the average value.  $V > -115 \text{ Km s}^{-1}$  and  $(U^2 + W^2)^{1/2} < 150 \text{ Km s}^{-1}$  are the two selection criteria which have to be satisfied in order to ascribe the star to the Galactic disk (either thin or thick). For the sake of clarity, no error bars are drawn in the most dense region of the plot. In any case, stars lying in that region have quite small errors associated to the determinations of their velocity components. The stars HIP 106749 (the empty square in the upper left corner of the box) and HIP 74079 (the empty square in the lower left corner of the box) have been offset by  $+20 \text{ Km s}^{-1}$  in  $(U^2 + W^2)^{1/2}$  and by  $-40 \text{ Km s}^{-1}$  in  $V$ , respectively, to make them clearly visible.

coordinate system for  $U$ ,  $V$ ,  $W$ , so that they are positive in the directions of the Galactic anticenter, the Galactic rotation and the North Galactic Pole, respectively, is adopted. The radial velocities used to complement HIPPARCOS data are from the SIMBAD data-base or from the literature. For 12 objects lacking of radial velocity  $U$ ,  $V$ ,  $W$  are not provided. Stars for which the relative error on the parallax is greater or equal to 100% ( $\sigma_\pi/\pi \geq 1$ ) have also no kinematics determination.

With these data at hand we distinguished between a *disk population* and a *non-disk population*. Adopting a selection criterion based on the studies by Sandage & Fouts (1987) and Beers & Sommer-Larsen (1995), in order to belong to the disk population we required a star to have  $V > -115 \text{ Km s}^{-1}$  and  $(U^2 + W^2)^{1/2} < 150 \text{ Km s}^{-1}$ .

In Fig. 1 we show the  $V$  vs  $(U^2 + W^2)^{1/2}$  diagram obtained for our data sample. Stars with metallicities below or above  $[\text{Fe}/\text{H}] = -1.0$  are shown with different symbols. In this plot the kinetic energy associated to the rotation around the Galactic center is compared to the kinetic energy associated to any other motion. As expected, stars with  $[\text{Fe}/\text{H}] > -1.0$  concentrate in the region  $V > -50 \text{ Km s}^{-1}$ ,  $(U^2 + W^2)^{1/2} < 100 \text{ Km s}^{-1}$  and dilute outside. These objects compose the bulk of the Galactic *disk*. The *thick-disk* should be envisaged in those stars which rotate more slowly and with larger random motions. For the sake of simplicity, we choose here to distinguish only between disk and non-disk stars.

Contrary to common assumption that all halo stars are also metal-poor we found three stars G 170-156 ( $[\text{Fe}/\text{H}] = -0.8$ , HIP 86321), G 17-21 ( $[\text{Fe}/\text{H}] = -0.6$ , HIP 80837) and G 182-19 ( $[\text{Fe}/\text{H}] = -0.7$ , HIP 86431) with metallicities larger than  $[\text{Fe}/\text{H}] > -1.0$  which do not show disk-like motion. One more star

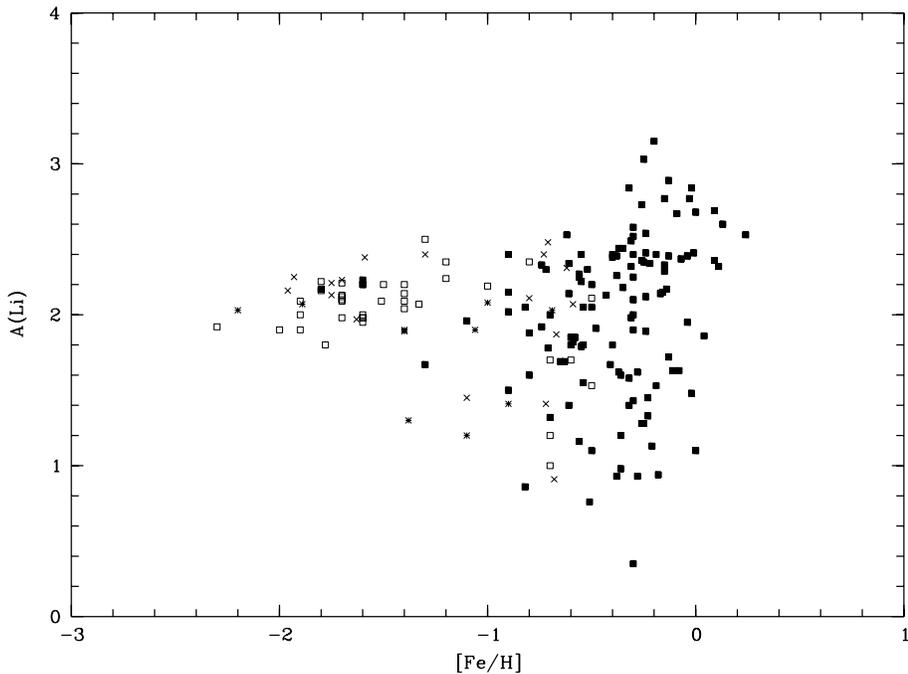
BD+01 3421 ( $[\text{Fe}/\text{H}] = -0.5$ , HIP 84905) is possibly belonging to the thick-disk.

On the other hand we found three stars HD 166913 ( $[\text{Fe}/\text{H}] = -1.8$ , HIP 89554), HD 205650 ( $[\text{Fe}/\text{H}] = -1.3$ , HIP 106749) and HD 134169 ( $[\text{Fe}/\text{H}] = -1.6$ , HIP 74079) with metallicity below  $-1.0$  which possess a disk-like motion. These three stars are members of the metal-weak tail of the Galactic disk. Other two stars with these properties have been found by Bonifacio et al. (1999).

Five stars (HIP 104659, HIP 37789, HIP 11952, HIP 37853 and HIP 55022) are lying just on the boundary which separates the halo from the disk stars.

In order to ascertain a possible correlation between the kinematics of the stars and the  ${}^7\text{Li}$  abundance, we drew in Fig. 2 the graph  $A(\text{Li}) - [\text{Fe}/\text{H}]$  indicating with different symbols disk stars, non-disk stars and objects without a precise kinematical membership. From Fig. 2 we note that the star HD 160693 (HIP 86431), with halo-like motion and a metallicity of  $-0.7$ , has  $A(\text{Li}) < 1.2$  falling well below the Li plateau. On the other hand the metal-poor stars with disk motions show a Li abundance at the plateau level. Thus lithium depletion is likely related only to metallicity and independent from the kinematics.

These findings allow us to assume that the upper envelope of the observational diagram traces those stars which have suffered only a minor lithium depletion during their life. This interpretation is also supported by the analysis of the stars with Be data, whose Be abundances imply Li abundances larger than actually observed (Molaro et al. 1997). Therefore, the upper envelope results from the various lithium enrichment processes occurred during the overall Galactic lifetime.



**Fig. 2.** The observational  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  diagram. Filled squares: disk stars; empty squares: non-disk stars; asterisks: objects with  $V_{\text{rad}}$  determination for which we were not able to provide an estimate on the kinematical membership; crosses: objects with no  $V_{\text{rad}}$  determination. All the entries of Table 4 have been plotted.

Our revised compilation of the data from the literature shows a plateau which may extend at metallicities larger than previously assumed and points to a very steep rise off the plateau starting at  $[\text{Fe}/\text{H}] \sim -0.5, -0.3$ . Details of the star by star critical Li analysis are provided in appendix.

### 3. Stellar sites for ${}^7\text{Li}$ production

#### 3.1. Novae as lithium factories

Both theoretical and observational evidence suggests that classical novae may be responsible for a non-negligible contribution to the ISM pollution in several nuclides ( ${}^7\text{Li}$ ,  ${}^{13}\text{C}$ ,  ${}^{15}\text{N}$ ,  ${}^{17}\text{O}$ ) and radioactive isotopes ( ${}^{22}\text{Na}$ ,  ${}^{26}\text{Al}$ ) (see Gehrz et al. 1998 for a review on this subject). The nova explosion results from thermonuclear runaway on the surface of a CO or ONeMg white dwarf (WD) accreting hydrogen-rich matter from a main sequence companion which fills its Roche lobe in a close binary system; so the material ejected into the ISM shows a composition enriched in elements synthesized by explosive hydrogen-burning.

The pre-explosion  ${}^3\text{He}$  concentration in the accreted envelope plays a key role in determining how much  ${}^7\text{Li}$  will be produced in the outburst. Starrfield et al. (1978) found that the  ${}^7\text{Li}$  yield does scale linearly with the initial  ${}^3\text{He}$  content. Their result was used by D’Antona & Matteucci (1991) who successfully reproduced the upper envelope of the observed  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  diagram for the solar neighborhood. These authors adopted  $A(\text{Li}) = 2.10$  dex as the primordial lithium abundance and explained the observed increasing trend in lithium abundance with time as due to Galactic enrichment coming from lithium production by stellar sources, identified in both novae and AGB stars.

Later, novae nucleosynthesis was discussed by Boffin et al. (1993), who reinvestigated  ${}^7\text{Li}$  production in explosive hydrogen-burning with the inclusion of the  ${}^8\text{B}(p,\gamma){}^9\text{C}$  reaction and ruled out novae as lithium producers at a Galactic level. In particular, they ruled out the linear dependence of Li production on the  ${}^3\text{He}$  abundance in the exploding envelope, which was a key ingredient in the D’Antona & Matteucci model. Boffin et al. used a parameterized one-zone explosive nucleosynthesis model and detailed numerical network calculations to demonstrate how the high peak densities prevailing at the base of the hydrogen-burning shell during the nova outburst prevent the build-up of  ${}^7\text{Li}$  amounts sufficient for ISM enrichment. However, they also stressed the need for testing their results by detailed hydrodynamic nova models.

This check was effectively carried out a few years later: Hernanz et al. (1996), using a hydrodynamic code able to treat both the accretion and the explosion stages, have obtained large overproduction factors relative to the solar abundance for  ${}^7\text{Be}$  - and hence  ${}^7\text{Li}$ . Therefore, although the final masses injected in the ISM are small, significant production of  ${}^7\text{Li}$  by novae seems possible. In their models, these authors have assumed a solar composition of the infalling material and the existence of processes able to mix it with the inner layers of the underlying white dwarf. This assumption allows one to obtain the enhanced CNO or ONeMg abundances required in order to give rise to a nova outburst and to explain some observations (see Livio 1994 for a recent review).

More recently, José & Hernanz (1998) computed an enlarged grid of hydrodynamical nova models for both CO and ONeMg WDs, spanning a total range of white dwarf masses of  $0.8 - 1.35 M_{\odot}$ . In these models different mixing levels - ranging from 25 to 75% - between the accreted envelope and the underlying WD core were assumed. These models predict ejected

quantities of  ${}^7\text{Li}$  able to affect the evolutionary history of this nuclide on a Galactic scale.

At this point, it is worth emphasizing the strong dependence of these results on the chemical composition at the onset of the explosion: the predicted  ${}^7\text{Li}$  overproduction factors will be correct only if the evolution of  ${}^3\text{He}$  during the accretion phase has been followed in the right manner. Moreover, we note that if the underlying WD is a CO one, the predicted  ${}^7\text{Li}$  abundances are  $\sim 1$  order of magnitude larger than in the case of an underlying ONeMg WD (see e.g. Table 1 of Hernanz et al. 1996).

### 3.2. Lithium production in massive AGB stars

${}^7\text{Li}$  production in AGB stars is the only Li stellar production mechanism supported by observations.

Smith & Lambert (1990) analysed high-resolution spectra for 27 red giants in the Magellanic Clouds, spanning a range in bolometric absolute magnitudes  $M_{bol} \sim -5$  to  $-9$ . They found that Li-rich stars were confined to those with  $M_{bol} \sim -6$  to  $-7$ , while lower ( $M_{bol} \sim -5$  to  $-5.5$ ) and higher ( $M_{bol} \sim -7$  to  $-9$ ) luminosity red giants showed no Li features. In addition, all their Li-strong stars presented  $C/O < 1$  and bore evidence of strengthened s-process atomic lines. These facts were interpreted as a signature of the dredge-up and subsequent envelope burning mechanism, occurring in the massive AGB stars ( $M \sim 4-8 M_{\odot}$ ). Since every luminous AGB star observed showed the Li I doublet, it seemed to be very likely that the  ${}^7\text{Li}$  produced in the outer envelope was not destroyed quickly, but it was surviving in the stellar atmosphere and injected into the ISM by stellar winds. Smith & Lambert derived a maximum abundance of  ${}^7\text{Li}$  as large as  $A(\text{Li}) \sim 4.0$  for the luminous AGB stars and indicated them as a major source of  ${}^7\text{Li}$  in a galaxy.

These observational findings were confirmed by theoretical calculations in which a time-dependent “convective diffusion” algorithm for the hot bottom envelopes of AGB stars was coupled with a fully self-consistent evolutionary sequence (Sackmann & Boothroyd 1992). It was shown that values of  $A(\text{Li})$  lying between 4 and 4.5 could be obtained for stars in the luminosity range  $M_{bol} \sim -6$  to  $-7$ , in excellent agreement with observations of the most lithium-rich giants in external galaxies (Smith & Lambert 1990; Smith et al. 1995) but in poorer agreement with observations in our Galaxy (Abia et al. 1991). According to Sackmann & Boothroyd, super-rich lithium giants would occur in the mass range  $M \sim 4-6 M_{\odot}$ , when the temperature at the base of the convective envelope exceeds  $50 \times 10^6$  K and the Cameron-Fowler mechanism<sup>3</sup> works (in these models, stars with  $M \geq 7 M_{\odot}$  ignite carbon in the center before they become AGB stars and never experience hot bottom burning).

Later, Plez et al. (1993) enlarged the Smith & Lambert sample of giants in the Small Magellanic Cloud (SMC) and pointed out that several of these metal-poor giants have atmospheric abundances of  ${}^7\text{Li}$  too low to provide a significant contribution to Galactic enrichment. On the other hand, Sackmann &

Boothroyd had shown that a decrease in the metallicity causes the hot bottom burning to start at smaller masses, resulting in a larger  ${}^7\text{Li}$  production! This seems to lead to a discrepancy with Plez et al.’s observations, but it should be recalled that low metallicity giants lose their envelope mass at a smaller rate than more metal-rich giants, thus allowing Li-burning to occur before the planetary nebula (PN) ejection and thus preventing significant ISM pollution and explaining Plez et al.’s findings.

Recent studies (Mazzitelli et al. 1999) confirm that  ${}^7\text{Li}$  abundances as large as  $A(\text{Li}) \sim 4.0$  dex at maximum can be found in the atmospheres of massive AGB stars.

The  ${}^7\text{Li}$  production by C-stars (coming from progenitors in the mass range  $2-5 M_{\odot}$ ) can be regarded as negligible on a Galactic scale, on the ground of the very small number of Li-rich C-stars detected with respect to their total number (see Wallerstein & Conti 1969; Abia et al. 1993a, 1993b; but see also Beers et al. 1992). Such a low number of Li-rich C-stars can be easily explained if it is assumed that these stars represent a short-lived phase with respect to the overall stellar lifetime on the AGB. On the contrary, one should assume that for stars with progenitor masses in the range  $5-8 M_{\odot}$  the envelope ejection in the PN stage shortly follows the lithium production in the envelope itself. We want to recall briefly that lithium production in these stars is thought to be due either to hot bottom burning, occurring during thermal pulses (TPs) at the base of the common envelope, or to a mechanism such as that described by Iben (1973), involving only the region of the outer convective envelope lying near the hydrogen burning shell, during the long timescale of the interpulse phases.

### 3.3. ${}^7\text{Li}$ synthesis in Type II supernova explosions

${}^7\text{Li}$  synthesis in massive stars ( $M > 10 M_{\odot}$ ) is theoretically explained as being due to a particular mechanism, the neutrino process. The first realistic exploration of the so-called neutrino process ( $\nu$ -process), acting during SNeII explosion, was undertaken by Woosley et al. (1990). Such a process occurs in the shells overlying the collapsing core of a contracting massive star. In these conditions, the flux of neutrinos is so large that, despite the small cross section, evaporation of neutrons or protons from heavy elements and helium is expected. The back reaction of these nucleons on other species alters the outcome of traditional nucleosynthesis calculations, resulting in a large production of a great number of rare isotopes.  ${}^7\text{Li}$  is one of these; it is thought to be made mainly in the helium and in the silicon shells from  $\mu$ - and  $\tau$ -neutrinos interacting with helium. In their work, Woosley et al. strongly supported the idea that this lithium production by  $\nu$ -process in massive stars could be large enough to explain the full  ${}^7\text{Li}$  Solar System abundance.

This point was later revised when Timmes et al. (1995), using the output from a grid of 60 Type II supernova models of varying mass and metallicity (Woosley & Weaver 1995), computed the chemical evolution of several stable isotopes, taking into account also the nucleosynthesis from Type Ia supernovae and from single stars with  $M \leq 8 M_{\odot}$ . They found that massive stars are producing lithium prior to  $[\text{Fe}/\text{H}] \sim -1.0$  dex, but until

<sup>3</sup> See Cameron & Fowler (1971) for a detailed description of this mechanism.

this metallicity value the contributions are small compared to the infall values, thus preserving the flat shape of the diagram  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  inferred from the observations. Finally, they concluded that Type II supernovae contribute about one-half the solar  ${}^7\text{Li}$  abundance<sup>4</sup>, pointing to a lower  ${}^7\text{Li}$  production rate by the  $\nu$ -mechanism than Woosley et al. (1990). Such an outcome was confirmed also by Matteucci et al.'s (1995) analysis, where C-stars plus massive AGB stars on the one hand and Type II SNe on the other hand were found to contribute each one-half the Solar System  ${}^7\text{Li}$  abundance, although the authors did not conclusively rule out a fraction between 1/4 and 3/4 from both sources, because of the uncertainties in the input nucleosynthesis.

## 4. The model

### 4.1. Basic assumptions

The adopted model of chemical evolution is that of Chiappini et al. (1997), in which we included the  ${}^7\text{Li}$  evolution, taking into account Li production from all the stellar sources identified above and from GCR spallation. This model assumes that the halo and thick-disk formed quickly (on a timescale of  $\sim 2$  Gyr) during a first infall episode and the thin-disk formed on a much larger timescale ( $\sim 8$  Gyr) during a second independent infall episode.

The nova system nucleosynthesis has been included in the model in a detailed way under simple hypotheses. We first computed the nova systems formation rate at the time  $t$  as a fraction of the formation rate of white dwarfs at a previous time  $t - \Delta t$  as in D'Antona & Matteucci (1991):

$$R_{\text{novae}}(t) = \alpha \int_{0.8}^8 \psi(t - \tau_m - \Delta t) \phi(m) dm.$$

Here  $\Delta t$  is a delay time whose value has to be fixed to guarantee the cooling of the WD at a level that ensures a strong enough nova outburst. We chose  $\Delta t = 1$  Gyr as a suitable average value (D'Antona 1998) and assumed that all stars with initial masses in the range  $0.8 - 8 M_{\odot}$  end their lives as WDs.

$\psi(t)$  is the star formation rate (SFR),  $\tau_m$  is the lifetime of the star of mass  $m$  and  $\phi(m)$  is the initial mass function (IMF). More about SFR and IMF parameterization can be found in Chiappini et al. (1997) concerning the disk of the Galaxy and in Matteucci et al. (1999) concerning the Galactic bulge.

The rate of nova eruptions is related to the WD formation rate:

$$R_{\text{outbursts}} = \alpha R_{\text{WDs}} n,$$

where  $\alpha R_{\text{WDs}}$  is the formation rate of WDs in binary systems which will give rise to nova eruptions, and  $n = 10^4$  is the average number of nova outbursts for a typical nova system (Bath & Shaviv 1978; see also Shara et al. 1986).

The parameter  $\alpha$ , set equal to a constant value along the overall evolutionary history of the Galaxy, can be fixed by the

<sup>4</sup> This result is achieved for  $\mu$ - and  $\tau$ -neutrino temperatures in the range 6–8 MeV, which is the range suggested by SN 1987 A.

rate of nova outbursts in our galaxy at the present time. Estimates of this quantity in the current literature range from as few as 11 to as many as 260 nova outbursts  $\text{yr}^{-1}$ . In particular, predictions based on scalings from extragalactic nova surveys suggest low values (11–46  $\text{yr}^{-1}$ , Ciardullo et al. 1990; 15–50  $\text{yr}^{-1}$  - with the lowest values, between 15 and 25  $\text{yr}^{-1}$ , strongly favored – Della Valle & Livio 1994), whereas estimates based on extrapolations of Galactic nova observations give the highest rates ( $73 \pm 24 \text{ yr}^{-1}$ , Liller & Mayer 1987; 260  $\text{yr}^{-1}$ , Sharov 1972; 50  $\text{yr}^{-1}$ , Kopylov 1955; 100  $\text{yr}^{-1}$ , Allen 1954)<sup>5</sup>. We chose for the present time rate of nova outbursts in the Galaxy  $R_{\text{outbursts}}(t_{\text{Gal}}) \sim 25 \text{ yr}^{-1}$  for the following reasons: (1) observation of novae in nearby galaxies would avoid, or at least minimize, most of the problems encountered by Galactic observations; (2) a recent study of Shafter (1997) shows that the nova rate based on Galactic observations can be made consistent with the rate predicted from the extragalactic data, particularly if the Galaxy has a strong bar oriented in the direction of the Sun (in this latter, most favourable case, the suggested value is near  $\sim 20 \text{ yr}^{-1}$ , otherwise, if the bar is weak or misaligned, the global rate can be reduced only to  $\sim 30 \text{ yr}^{-1}$ ).

### 4.2. Nucleosynthesis prescriptions

We assumed a homogeneous Big Bang  ${}^7\text{Li}$  abundance of 2.2 dex (Bonifacio & Molaro 1997) as the primordial one and considered all the contributions from the various classes of stellar  ${}^7\text{Li}$  factories seen in Sect. 3 in the Galactic chemical evolution model.

In this study we adopted the updated lithium yields from theoretical nova outbursts provided by José & Hernanz (1998). We took the mean mass ejected as  ${}^7\text{Li}$  averaged on 7 evolutionary sequences for CO WDs and the mean mass ejected as  ${}^7\text{Li}$  averaged on so many evolutionary sequences for ONeMg WDs. ONeMg WDs are believed to originate from stars with initial masses in the range  $7 M_{\odot} - M_{\text{up}}$ <sup>6</sup> (but there is still debate on this point). Since the lifetime of a  $7 M_{\odot}$  star is  $\sim 0.045$  Gyr, we assumed that for  $t \leq 0.045$  Gyr only ONeMg WDs can contribute to nova systems; for times larger than 0.045 Gyr, about 30% of novae occur in systems containing ONeMg WDs, while the remaining take place in systems accreting hydrogen-rich envelopes onto CO WDs.

In particular, the prescriptions for  ${}^7\text{Li}$  yields from novae we used in our model are as follows:

for  $t < 0.045$  Gyr we assumed

$$M_{\text{ej}} = 1.95 \times 10^{-1} M_{\odot}$$

<sup>5</sup> Hatano et al. 1997 reanalyzed Liller & Mayer's data and argued that the correct rate should be  $\sim 41 \text{ yr}^{-1}$  rather than  $73 \pm 24 \text{ yr}^{-1}$ .

<sup>6</sup> Here we assume  $M_{\text{up}}$ , the limiting mass for the formation of a degenerate CO core, equal to  $8 M_{\odot}$ , although some authors suggest 5–6  $M_{\odot}$  as a more suitable value, when overshooting is taken into account (Chiosi et al. 1992; Marigo et al. 1996).

**Table 1.** Nucleosynthesis prescriptions.

Model	C-stars	M-AGB	SNeII	novae
A	A(Li) = 3.85	A(Li) = 4.15	WW95	no
B	A(Li) = 3.85	A(Li) = 4.15	WW95	yes
C	no	A(Li) = 3.50	WW95/2	yes

(mean mass ejected by a single nova system during its overall evolution) and

$$X_{7\text{Li}} = 9.24 \times 10^{-7}$$

(mean  $^7\text{Li}$  abundance - in mass fraction - in the ejected material). For  $t > 0.045$  Gyr we assumed

$$M_{\text{ej}} = 2.63 \times 10^{-1} M_{\odot}$$

with

$$X_{7\text{Li}} = 2.85 \times 10^{-6}$$

as the mean lithium abundance in the ejected envelope.

As far as AGB stars are concerned, we included here a metallicity dependence of the lithium yields from massive AGB stars as in Matteucci et al. (1995), which accounts for the lower  $^7\text{Li}$  abundances observed in the low metallicity SMC AGB stars relative to the higher ones exhibited by their more metal-rich Galactic counterparts. We assumed no production of lithium by AGB stars until a metallicity of  $Z = 10^{-3}$ , then allowing lithium production only in the mass range  $5 M_{\odot} - M_{\text{up}}$ , where  $M_{\text{up}}$  increases from 5 to  $8 M_{\odot}$  as  $Z$  reaches the solar value. The  $^7\text{Li}$  abundance in the ejected material is assumed to be either  $A(\text{Li}) = 4.15$  or  $A(\text{Li}) = 3.50$  dex (see Table 1 for different model prescriptions). Since only a small number of Li-rich C-stars (coming from progenitors with masses in the range  $2 - 5 M_{\odot}$ ) are known out of hundreds of C-stars observed in the Galaxy and in the Magellanic Clouds, we assumed their contribution to the lithium enrichment to be almost negligible and followed the D'Antona & Matteucci (1991) prescriptions. In one model (model C) we also completely suppressed this class of lithium factory.

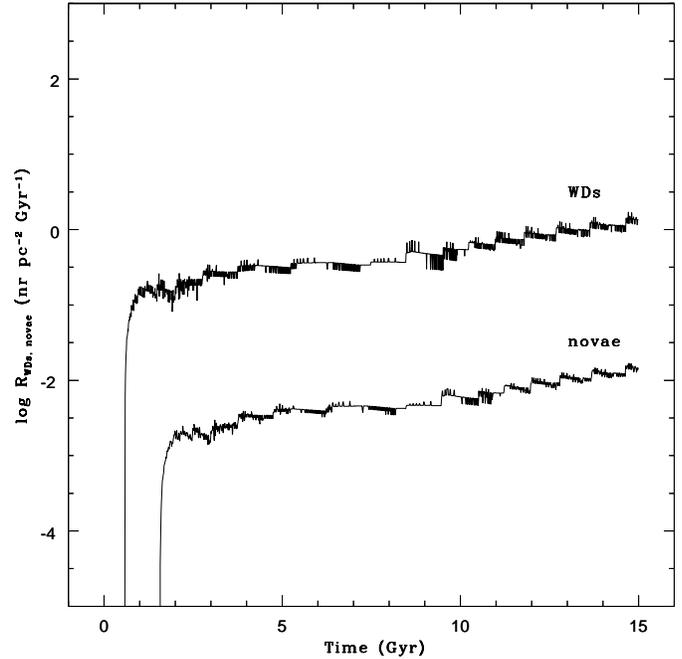
To account for lithium production in Type II supernovae, we considered the metallicity dependent  $^7\text{Li}$  yields given by Woosley & Weaver (1995). We included in our computation both the full yields (model A and B) and those reduced to a half (model C).

$^7\text{Li}$  astration in stars of all masses has also been taken into account.

The contribution of GCR spallation has been taken into account by incorporating the absolute yields from Lemoine et al. (1998) into the chemical evolution model. We took the yields from the lower-bound spectrum in their Table 1.

## 5. Results

In Fig. 3 we show the predicted  $\log(R_{\text{WDs}})$ ,  $\log(R_{\text{novae}})$  trends vs time in the solar neighborhood for models with  $\alpha = 0.0125$ . By assuming a Galactic scale height of 300 pc for WDs - and



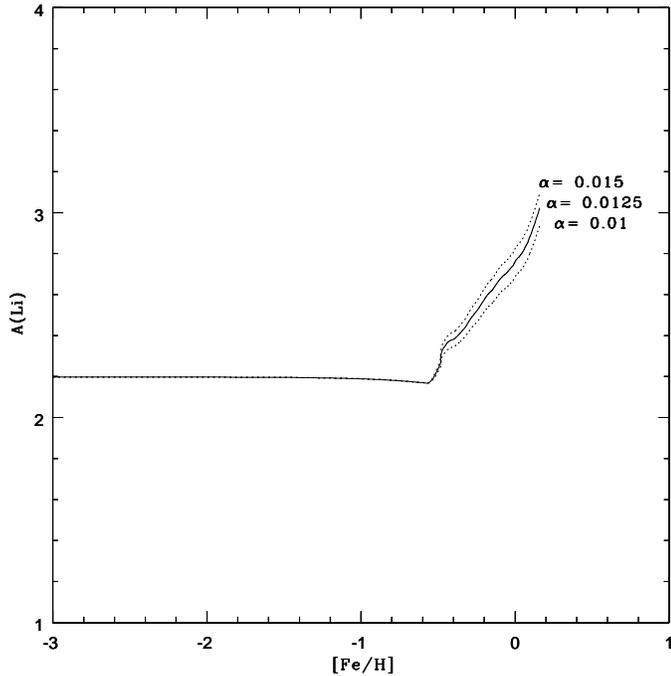
**Fig. 3.** Birthrates of white dwarfs and nova systems as functions of time, predicted with the two-infall Galactic chemical evolution model that considers a threshold in the surface gas density below which star formation is suppressed (see text for details). The nova systems formation rate is assumed to be a fraction  $\alpha = 0.0125$  of the WDs formation rate.

hence novae - and a Galactic volume of  $10^{11} \text{ pc}^3$  we obtain  $R_{\text{outbursts}}(t_{\text{Gal}}) = 24.5 \text{ yr}^{-1}$ , in good agreement with observations (see Sect. 4.1).

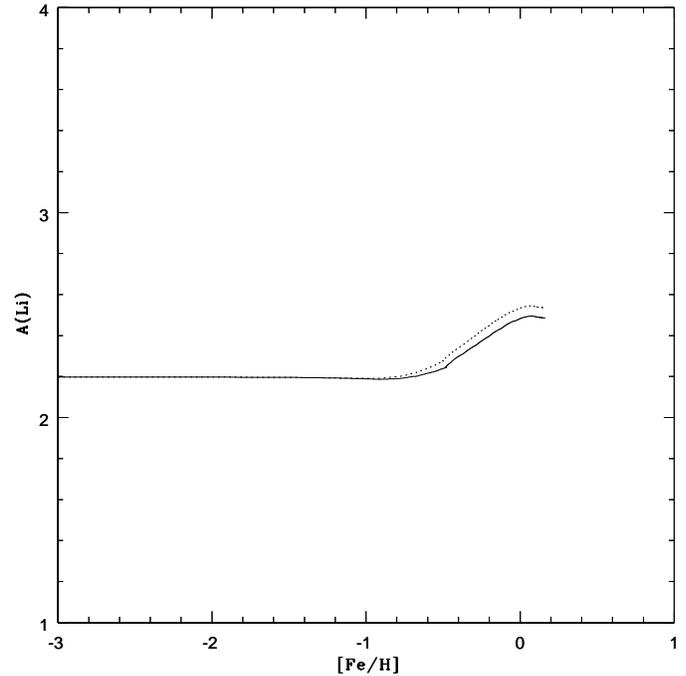
We predict also that the current WD birthrate in the Galaxy should be  $R_{\text{WDs}}(t_{\text{Gal}}) = 2.27 \times 10^{-12} \text{ WDs pc}^{-3} \text{ yr}^{-1}$ , to be compared with observational estimates which give  $R_{\text{WDs}}(t_{\text{Gal}}) = 1 \times 10^{-12} \text{ WDs pc}^{-3} \text{ yr}^{-1}$  (Yuan 1989) and  $D_{\text{WDs}}$  (spatial density)  $\sim 1 \times 10^{-2} \text{ pc}^{-3}$  (Weidemann 1967). This slight discrepancy, however, can be explained by recent dynamical calculations (Chamcham 1998) suggesting that about 40% of the white dwarfs originally formed in the thick-disk have moved from their birthplaces so that they should be observed at a higher scale height at the present time.

Note that the oscillations in the theoretical curves in Fig. 3 are caused by the introduction of a threshold in the surface gas density ( $7 M_{\odot} \text{ pc}^{-2}$ ) below which star formation stops, owing to gas instability against density condensations in these conditions (see Chiappini et al. 1997). The presence of such a threshold leads also to a delay in the WD formation, which starts only after  $\sim 0.6$  Gyr (compare Fig. 3 here with Fig. 2 in D'Antona & Matteucci 1991, whose model does not include such a threshold in the gas density).

We ran several models considering separately all the  $^7\text{Li}$  stellar sources discussed above. The Galactic lithium enrichment in the solar neighborhood due only to novae is sketched in Fig. 4: novae start injecting material into the ISM with a time delay of  $\sim 2$  Gyr, when the ISM has already achieved a metallicity  $[\text{Fe}/\text{H}] \sim -0.5$  dex. This long time-lag in the occurrence



**Fig. 4.**  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  theoretical trends predicted for the solar neighborhood by three models taking into account lithium production in nova outbursts under slightly different assumptions on the percentage of newly formed WDs that enters in the building-up of nova systems.



**Fig. 5.** Accounting for lithium production by both C-stars and massive AGB stars (dotted line) one obtains a slightly higher  ${}^7\text{Li}$  abundance at the present time than in the case in which only massive AGB stars are considered (continuous line).

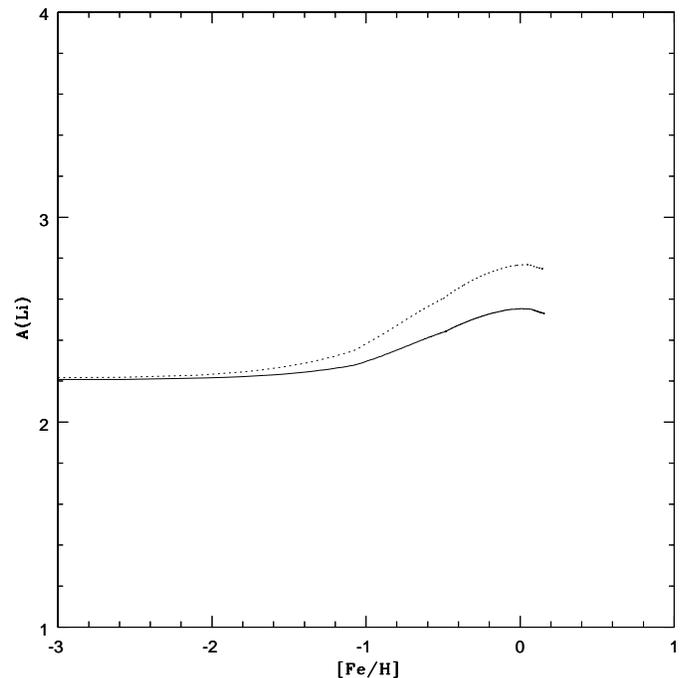
of an ISM pollution by novae is the direct consequence of two elements characterizing the evolution of such systems, both acting in the same direction: 1) the time-lag required to form the WD and 2) the time necessary for the WD to cool enough to allow strong nova outbursts.

The effects produced by changing  $\alpha$  from 0.0125 to smaller or greater values on the predicted  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  trend are also shown in Fig. 4. We analysed two possible different choices,  $\alpha = 0.01$  and  $\alpha = 0.015$ . The first choice leads to  $R_{\text{outbursts}}(t_{\text{Gal}}) = 19.6 \text{ yr}^{-1}$ , the second one to  $R_{\text{outbursts}}(t_{\text{Gal}}) = 29.4 \text{ yr}^{-1}$ . These estimates reproduce very well the lower and upper limits of the permitted values inferred from the analysis of Shafter (1997). We have chosen  $\alpha = 0.0125$  as the most suitable value and used it in all the calculations.

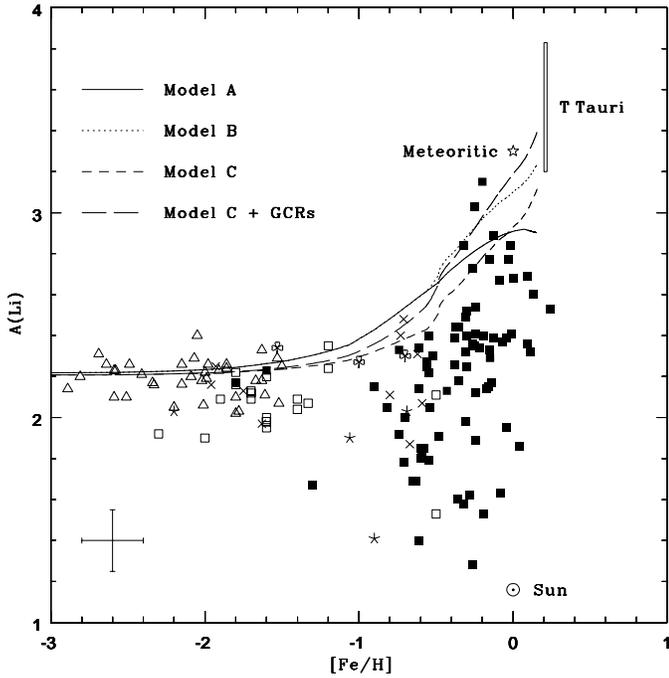
In Fig. 5 we show the evolution of the  ${}^7\text{Li}$  abundance in the solar neighborhood as predicted by two models both allowing lithium production to happen only in AGB stars (prescriptions on lithium production as in model A). If we assume  ${}^7\text{Li}$  production to take place in both C-stars and massive AGB stars (dotted line) we obtain a slightly higher  ${}^7\text{Li}$  abundance than assuming  ${}^7\text{Li}$  production only in massive AGB stars (continuous line).

In Fig. 6 we show the effect of  ${}^7\text{Li}$  production only by massive stars. We used either the full  ${}^7\text{Li} + {}^7\text{Be}$  yields (Woosley & Weaver 1995) or the same yields reduced to one half.

From Figs. 4, 5 and 6 we can immediately see how novae, giving rise to a strong Li-enrichment at high metallicities, can in principle account for the present  ${}^7\text{Li}$  abundance in the gas without any other stellar source. However, acting on evolutionary timescales as long as 1.5 Gyr at least, they cannot justify



**Fig. 6.** Theoretical predictions for the trend  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  from two models when only  ${}^7\text{Li}$  production from massive ( $M > 10 M_{\odot}$ ) stars is allowed. Dotted line: we used the Woosley & Weaver (1995)  ${}^7\text{Li} + {}^7\text{Be}$  yields; continuous line: we used the same yields but reduced to a half. Note that the metallicity dependence of such yields guarantees the flatness of the Spite plateau until  $[\text{Fe}/\text{H}] \sim -1.0$ .



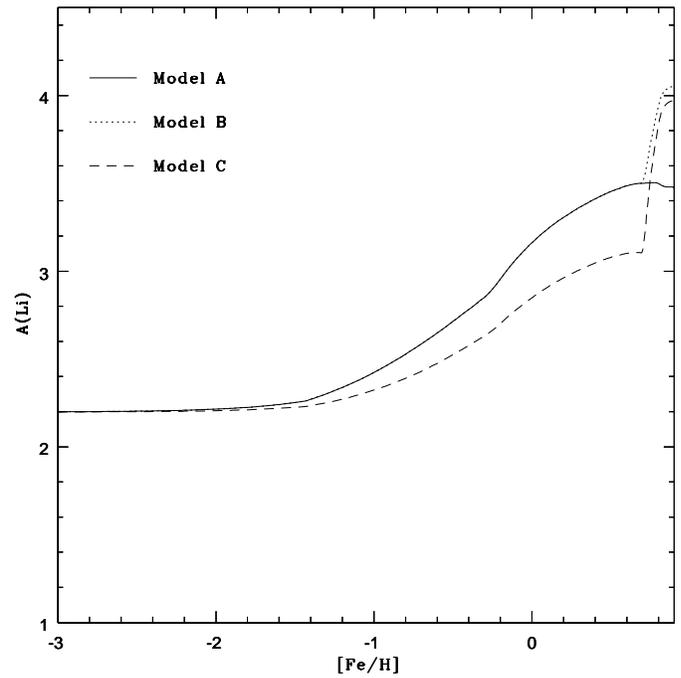
**Fig. 7.**  $A(\text{Li})$  versus  $[\text{Fe}/\text{H}]$  theoretical predictions for the solar neighborhood from models A, B, C, and C + GCRs (see text), compared with the observational diagram coming out from our data analysis. The upper limits have been removed from the sample. Filled symbols: disk stars; empty symbols: non-disk stars (triangles: halo stars from Bonifacio & Molaro 1997; squares: stars from our data-base). Crosses and asterisks identify stars without kinematical membership determination; clovers are objects with multiple  ${}^7\text{Li}$  determination in the literature for which we took the average value. Solar, meteoritic (Anders & Grevesse 1989) and T Tauri (see text for references)  ${}^7\text{Li}$  abundances are also shown.

at the same time the rise off the Spite plateau. On the other hand, Type II supernovae start restoring their  ${}^7\text{Li}$  into the ISM at earlier times, but they are not able to fully explain the present gas content of lithium, if they are not coupled to other stellar Li producers. The AGB stars present a quite similar behaviour, but restore their  ${}^7\text{Li}$  a bit later than SNeII, and in minor (if not almost equal) amounts (compare Figs. 5 and 6).

Therefore, one single stellar category of  ${}^7\text{Li}$  producers could never explain all the observed features of the diagram  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$ , under realistic prescriptions about  ${}^7\text{Li}$  synthesis!

Therefore we computed three different chemical evolution models for both the solar vicinity and the Galactic bulge, adding together the different stellar sources.

In Figs. 7 and 8 we sketch the  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  trends obtained in the case of the solar neighborhood evolution and in the case of the bulge evolution, respectively. Models A, B and C are referring to the different nucleosynthesis prescriptions outlined in Table 1. The observational points plotted in Fig. 7 are those given in Table 4 after the upper limits have been removed. An average value has been taken for the three objects with multiple  ${}^7\text{Li}$  detections which are tracing the upper envelope (see the appendix). From Fig. 7, we see that model A, using the nucleosynthesis prescriptions from the best model of Matteucci et al.



**Fig. 8.** Theoretical predictions on  ${}^7\text{Li}$  abundance evolution in the ISM in the Galactic bulge. Model A (best model in Matteucci et al. 1999), accounting for  ${}^7\text{Li}$  production by all stellar sources but novae, predicts the lowest present lithium abundance in the gas in the central region.

(1995), does not reproduce the highest values of  $A(\text{Li})$ , found in some of the most metal-rich stars, nor the observed upper envelope in the metallicity range  $-1.5 \leq [\text{Fe}/\text{H}] \leq -0.5$  dex. Model B, constructed by adding the contribution from nova outbursts to the previous one, produces a curve which becomes much steeper at the highest metallicities, hardly reaching the highest Li abundances exhibited by the most metal-rich stars in our sample. In model C, lithium production from C-stars is set to zero, and  ${}^7\text{Li}$  yields from both massive AGB stars and TypeII SNe are reduced. In particular, SNeII yields are assumed to be one half of the original ones. As one can see from Fig. 7, model C reproduces at best the observational data in the metallicity range  $-1.5 \leq [\text{Fe}/\text{H}] \leq -0.5$ , but fails in reproducing the meteoritic and the T Tauri  ${}^7\text{Li}$  abundances.  ${}^7\text{Li}$  production from GCR spallation could be helpful in reproducing the highest observed  ${}^7\text{Li}$  abundances.

Molaro et al. (1997), by studying a large sample of stars with  ${}^9\text{Be}$  determinations, found that  $A(\text{Be})^7$  correlates linearly with  $[\text{Fe}/\text{H}]$ , with a slope confirmed also by Duncan et al. (1997) and García-López et al. (1998).  ${}^9\text{Be}$  is produced only by GCR spallation. Using the Steigman & Walker (1992) formula,  ${}^7\text{Li}/{}^9\text{Be} = 7.6$  for PopII stars with  $T_{\text{eff}} < 6200$  K, one can see that the  ${}^7\text{Li}$  amount expected from GCR spallation alone is about 1% of the primordial  ${}^7\text{Li}$  abundance at  $[\text{Fe}/\text{H}] \sim -2.5$ , and that it becomes more important with increasing metallicity, being about 25% around  $[\text{Fe}/\text{H}] \sim -1.0$ . At larger metallicities one could expect an even larger contribution, although other au-

$${}^7 A(\text{Be}) = \log_{10}(N_{{}^9\text{Be}}/N_{\text{H}}) + 12.$$

**Table 2.**  ${}^7\text{Li}$  abundances at the epoch of Solar System formation and in the interstellar medium as predicted by our four models for the solar neighborhood.

Model	$A(\text{Li})_{\text{SS}}$	$A(\text{Li})_{\text{ISM}}$
A	2.91	2.90
B	3.12	3.24
C	2.95	3.12
C + GCRs	3.21	3.39

thors suggest that GCRs can contribute to the present ISM  ${}^7\text{Li}$  abundance by no more than  $\sim 10\%$ , on the basis of the  ${}^7\text{Li}/{}^6\text{Li}$  ratio towards  $\zeta$  Oph (e.g. Lemoine et al. 1995). In order to include GCR nucleosynthesis in our chemical evolution model in a self-consistent way, we used the absolute yields provided by Lemoine et al. (1998) for various metallicities. As a result, we produced a smoother rise from the plateau, and we were finally able to match the meteoritic and T Tauri lithium abundances (see Table 2).

The lithium abundance in the Galactic bulge at the present time predicted by our model C is as high as  $\sim 4$  dex (Fig. 8); if novae are not included in the computation, a lower present Li abundance is expected in the bulge ( $\sim 3.5$  dex, see also Matteucci et al. 1999). However, this is only a lower limit, since  ${}^7\text{Li}$  production from GCRs was not included in the bulge model. In fact, giving the uncertainties in the relevant parameters (see Lemoine et al. 1998), it seems not so meaningful to translate the GCR nucleosynthesis results for the solar neighborhood to the central region of the Galaxy.

## 6. Conclusions

In this paper we have computed the evolution of the  ${}^7\text{Li}$  abundance in the ISM of the solar neighborhood and the bulge of our Galaxy.

We took into account several stellar  ${}^7\text{Li}$  factories (novae, massive AGB stars, C-stars and Type II SNe), together with the GCR contribution. In particular, we adopted new nucleosynthesis prescriptions for novae (José & Hernanz 1998) and the yields of  ${}^7\text{Li}$  of Lemoine et al. (1998) as far as GCR nucleosynthesis is concerned.

We compiled a new data sample for  ${}^7\text{Li}$  abundances in the solar neighborhood stars identifying the stars belonging to disk and halo Galactic components on the basis of their kinematics. The identification of metal-rich Li depleted halo stars provides evidence that Li depletion depends from metallicity only, thus supporting the use of the upper envelope in the Li data-set as the true indicator of Li Galactic evolution. The selection of the stars which have likely preserved their  ${}^7\text{Li}$  content reveals a possible extension of the Li plateau towards higher metallicities, up to  $[\text{Fe}/\text{H}] \sim -0.5$ ,  $-0.3$ , with a steeper rise afterwards.

Comparing theoretical predictions with the data we derived the following conclusions:

1 – In order to reproduce the upper envelope of the  $A(\text{Li})$  vs  $[\text{Fe}/\text{H}]$  diagram we need to take into account several stellar

Li sources: AGB stars, Type II SNe and novae. In particular, novae are required to reproduce the steep rise of  $A(\text{Li})$  between the formation of the Solar System and the present time, as is evident from the data we sampled. On the other hand,  ${}^7\text{Li}$  yields for SNeII should be lowered by at least a factor of two in order to reproduce the extension of the Spite plateau.

- 2 – We produced arguments suggesting that GCRs could be responsible for the production of a non-negligible amount of Li at metallicities larger than  $[\text{Fe}/\text{H}] \sim -1.0$  dex. In particular, we showed that without any GCR contribution it is impossible to reach the high values observed in meteorites and T Tauri stars: GCRs are responsible for  $\sim 45\%$  of the Solar System  ${}^7\text{Li}$  (prescriptions on stellar nucleosynthesis as in model C).
- 3 – By adopting the nucleosynthesis prescriptions of our model C for the Galactic bulge, we predicted a lower limit for the present time  ${}^7\text{Li}$  abundance in this central region of the Galaxy of the order of 4.0 dex, which is 0.5 dex higher than previously estimated in Matteucci et al. (1999) neglecting the novae contribution.

If new  ${}^7\text{Li}$  measurements in stars with  $[\text{Fe}/\text{H}]$  around  $-0.5$  dex will confirm the extension of the plateau towards such high metallicities, a revision of the contribution to the  ${}^7\text{Li}$  abundance from GCR spallation too could be needed.

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## Appendix

### Star by star analysis

In order to identify the stars which can be actually considered as tracers of the upper envelope at every metallicity, and discard the depleted ones, we analysed in detail the abundances of all the stars defining the upper envelope in the  $A(\text{Li}) - [\text{Fe}/\text{H}]$  diagram for metallicities larger than  $\sim -1.5$  dex. The stars are listed below in order of metallicity.

- 1 – HIP 42887: Deliyannis et al. (1990) give  $A(\text{Li}) \leq 2.50$  and  $[\text{Fe}/\text{H}] = -1.30$ ; Glaspey et al. (1994) reduce this upper limit to  $A(\text{Li}) < 1.20$  and assume  $[\text{Fe}/\text{H}] = -1.22$ . Since these are only upper limits for the Li abundance in this star, we do not take this object into account as a tracer of the upper envelope.
- 2 – HIP 99423: we assume  $A(\text{Li}) = 2.34$  and  $[\text{Fe}/\text{H}] = -1.53$  for this star (averaging on three measures, see Table 4).
- 3 – HIP 3026: only one Li detection ( $A(\text{Li}) = 2.35$ ,  $[\text{Fe}/\text{H}] = -1.20$ ).

- 4– HIP 86321: two A(Li) determinations in substantial agreement (from the compilation of Deliyannis et al. 1990). We took their average value:  $A(\text{Li}) = 2.27$ . For the metallicity we preferred the value  $-1.00$ , according with the estimate in Cayrel de Strobel et al. (1992).
- 5– HIP 108490: we listed three  ${}^7\text{Li}$  determinations for this star in Table 4. They differ by  $0.1 - 0.2$  dex, the mean value being  $2.30$ . This estimate agrees with the most recent determination of the atmospheric lithium abundance in this star by Stephens et al. (1997) ( $A(\text{Li}) = 2.39$ ).
- 6– HIP 79720 ( $A(\text{Li}) = 2.40$ ,  $[\text{Fe}/\text{H}] = -0.73$ ) and HIP 29001 ( $A(\text{Li}) = 2.48$ ,  $[\text{Fe}/\text{H}] = -0.71$ ). For these two crucial objects we found a Li detection only by Lambert et al. (1991), and an independent confirmation is desirable considering their importance in the economy of the discussion.
- 7– The Li I feature in the atmosphere of HIP 112935 is given as  $W(\text{Li}) = 47 \text{ m}\text{\AA}$  by Deliyannis et al. (1990), referring to the detection by Duncan (1981), whereas Balachandran (1990) gives less than  $1 \text{ m}\text{\AA}$  ( $A(\text{Li}) < 0.82$ ). Moreover, both the Lambert et al. (1991) and Boesgaard et al. (1998) estimates ( $A(\text{Li}) < 1.28$  and  $A(\text{Li}) \leq 0.90$ , respectively) agree with the Balachandran one. These upper limits and the detection by Duncan are not consistent; we choose the upper limit as the correct indicator of the  ${}^7\text{Li}$  content in HIP 112935.
- 8– HIP 14181 ( $A(\text{Li}) = 2.31$  and  $[\text{Fe}/\text{H}] = -0.62$ ) and HIP 21167 ( $A(\text{Li}) = 2.34$  and  $[\text{Fe}/\text{H}] = -0.61$ ), both single detections from Lambert et al. (1991).
- 9– At  $[\text{Fe}/\text{H}] \sim -0.5$  there are some stars lying around  $A(\text{Li}) \sim 2.40$ , then a steep rise occurs at  $[\text{Fe}/\text{H}] \sim -0.3$ : HIP 10306, HIP 11783 and HIP 46853 show that the ISM Li abundance rapidly increases to  $\sim 3.2 - 3.3$ .

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