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Lithium abundances and metallicities: trends from metal-poor and AGB/RGB stars

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Abstract. Recent determinations of Li abundances in the Galaxy resulted in two important conclusions: first, there is a significant discrepancy between the predicted values by Standard Big Bang Nucleosynthesis (SBBN) and the observed values, reaching about 0.6 dex for the oldest, most metal-poor stars; second, for these stars there seems to exist an almost linear relationship between the Li abundances relative to H and the metallicity as given by the Fe abundances relative to the Sun. Concerning higher metallicity objects, present results show that a larger dispersion of Li abundances is observed for a given metallicity up to about [Fe/H] $\simeq$ 0.5. In the case of RGB and AGB stars, most of the objects analyzed have probably destroyed most of the pristine lithium. However, there is a number of galactic AGB and RGB stars, which show clear signs of Li enhancements, in particular those for which ϵ(Li) $\geq$ 1.5, which are known as Li-rich giants. Since the metallicities of the Li-rich giants are generally known, it is interesting to investigate whether or not the trend presented by the metal-poor stars can also be observed in their metal-rich counterparts. This will provide a better understanding of the chemical evolution of lithium during the galactic lifetime, as well as place constraints on the Li production in AGB stars. In this work, we consider a large sample of AGB and RGB stars for which accurate Li abundances are available, and investigate the existence of any trends between the Li abundances and the metallicities. Our preliminary results suggest that, in average, Li-rich AGB stars maintain the same average increase of Li abundances at higher metallicities, so that a similar slope is obtained both for metal-poor and metal-rich stars. This has possibly some consequences on the mechanisms of Li production in AGB stars.

Key words. Stars: abundances – Stars: atmospheres – Stars: metallicities

1. Introduction

Recent determinations of Li abundances in the Galaxy resulted in two important conclusions: first, there is a significant discrepancy between the predicted values by Standard Big Bang Nucleosynthesis (SBBN) and the observational values, which amounts to about 0.35 dex, reaching 0.6 dex for the oldest, more metal-poor stars; second, there seems to exist an almost linear relationship between the Li abundances relative to H, ϵ(Li) = log (Li/H) + 12 and the metallicity as given by the Fe abundances relative to the Sun, [Fe/H] (see for example Steigman 2010).

The first conclusion may have profound implications on the standard model, while the

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Send offprint requests to: W. J. Maciel second affects the chemical evolution of the light elements, since it is generally believed that there is a Li plateau at metallicities below solar, as originally proposed by Spite & Spite (1982). Several possibilities to solve this puzzle are being discussed in the literature (see for example Prantzos 2010).

Concerning higher metallicity objects, namely those for which [Fe/H] > -1, present results show that a higher dispersion of Li abundances is observed for a given metallicity up to about [Fe/H] $\simeq 0.5$. In the case of giant stars on the RGB or AGB branches, most of the objects analyzed so far have destroyed most of the Li initially available. In fact, the largest samples of well studied giants show that most are Li-poor, so that destruction or dilution of pre-existing Li has occurred [see for example Smith (2010), Brown at al. (1989)]. Low Li abundances are expected in these stars compared to main sequence stars, as their convection envelope mixes the Li-poor material from the inner parts of the star with the observable gas in the photosphere. In fact, the depletion shown by these stars is frequently in excess of the predictions by theoretical evolution models. However, there is a number of galactic AGB and RGB stars, which show clear signs of Li enhancements, in particular those for which $\epsilon(\mathrm{Li}) > 1.5$, which are generally known as Li-rich giants. This limit approximately coincides with the maximum abundance expected after the first dredge up process in red giants (see for example Palmerini et al. 2011). Some luminous AGB stars in the Magellanic Clouds also display high Li abundances, as shown for example by the survey of Smith et al. (1995). Part of the Li observed in these objects may have been produced by Hot Bottom Burning (HBB), or else in these objects Li has been diluted only, and not destroyed. HBB occurs in many AGB stars with masses larger than about 4 solar masses, and results in the synthesis of ^{7}Li by a mechanism initially suggested by Cameron & Fowler (1971). In some cases, Li-rich giants are also observed in globular clusters as shown for example by Smith et al. (1999) and Kraft et al. (1999). In these cases, the HBB mechanism is probably not efficient, since the stellar masses are generally lower than about 4 solar masses, so that a different mechanism of Li enhancement is needed.

Since the metallicities of the Li-rich giants are generally known, it is interesting to investigate whether or not the trend presented by the metal-poor stars can also be observed in their metal-rich counterparts. This will provide a better understanding of the chemical evolution of lithium during the galactic lifetime, as well as place constraints on the Li production in AGB stars, as recently proposed and discussed in the literature (Prantzos 2010).

In this work, we consider a large sample of AGB and RGB stars for which accurate Li abundancs are available, and investigate the existence of any trends between the Li abundances and the metallicities. As we will see in section 3, our preliminary results suggest that, in average, Li-rich AGB stars maintain the same average increase of Li abundances at higher metallicities, so that a similar slope is obtained both for metal-poor and metal-rich stars.

2. The data

The data used in this investigation come basically from recent determinations in the literature, generally based on NLTE analyses of the λ6708 Å or 6104 Å Li lines. For the metal-poor stars we have used data from Boesgard, Stephens & Deliyannis (2005), Asplund et al. (2006), Aoki et al. (2009), which includes data by Bonifacio et al. (2007), Lind et al. (2009) and Meléndez et al. (2010). The objects in these samples are mostly halo dwarfs and subgiants or globular cluster stars, as in the the case of the data by Lind et al. (2009) for NGC 6397. We have considered only "plateau" stars, that have not undergone the dilution resulting in the lower Li abundances observed in most stars. In view of the observed distribution of the Li abundances with the stellar temperature, the adopted sample stars have $T_{eff} > 5700$ K. In this case, we exclude cooler stars, for which an increased dilution due to the deepening of the convective layer is observed. Typical uncertainties of the Li abundances are $\Delta(\mathrm{Li}) \simeq 0.07$ dex, with similar values for the metallicity [Fe/H].

For the metal-rich stars, which comprise basically AGB and RGB stars, the sources of the data include: (i) the extensive survey of Brown at al. (1989), containing 644 G and K giants. In many cases only upper limits to the Li abundances are obtained, especially for ϵ(Li) < 0.5, in which case the Li I 6708 Å doublet was not detected. In this work, a small fraction of the stars (about 1–2%) are considered as Li-rich, that is, they have ϵ(Li) > 1.5, which is the upper limit expected for most giants following predictions of theoretical models (cf. discussion by Brown at al. 1989). In this case, uncertainties in the Li abundances are higher than for metal-poor stars, reaching about 0.2–0.3 dex on the basis of the uncertainties in the determination of the effective temperatures, gravity, microturbulence velocity, continuum definition, and iron abundance, the latter being about 0.3 dex. The evolutionary status of these stars is not entirely clear, although they show evidences of fully convective envelopes and are located near or at the He-burning clump region on the HR diagram; (ii) Mallik (1999) analyzed a sample of 65 supergiant/giant/subgiant stars with spectral types in the range F3–M3 for which they have presented Li abundances and metallicities apart from the usual stellar parameters. 14 of these stars have ϵ(Li) > 1.5 based on equivalent widths of the Li I doublet at 6708 Å. As in the previous case, the main uncertainty source is the temperature sensitivity, and average uncertainties of 0.20–0.25 dex are obtained; (iii) Garcia-Hernandez et al. (2008) have recently determined Li abundances by high-resolution spectroscopy in massive O-rich galactic AGB stars, and identified several stars with ϵ(Li) > 1.5. These authors find evidences that several of these objects are massive AGB stars, with masses in the 3-4 $M_\odot$ range, which experience HBB. Again, the Li abundance uncertainties are typically Δ(Li) = 0.3 dex. From their galactic distribution and position on the IRAS two-colour diagram, these stars represent populations of AGB stars with different masses. The Li excess observed in some of these stars is interpreted in terms of HBB processes in massive AGB stars, for which $M > 4\ M_\odot$, which is reinforced by considerations on the variability period and OH expansion velocities. In this case, we have assumed solar metallicities for all stars, [Fe/H] = 0; (iv) Gonzalez et al. (2009) presented Li abundances and metallicities for a sample of K giants in the galactic bulge derived from spectral synthesis. Among the 13 stars with a detectablel Li line, 6 stars can be considered as Li-rich according to the criteria adopted here; (v) Monaco et al. (2011) recently collected a large database of stellar spectra of thick disk stars, in search for Li-rich giants. As a result, 5 new objects were found with Li abundances higher than ϵ(Li) = 1.5, most of which are probably thick disk red giants evolved past the RGB-bump. The total sample includes 814 stars, 67 of which are metal-poor [Fe/H] < −1) and 747 are more metal-rich ([Fe/H] > −1).

3. Results

The main results are shown in figures 1-3. Fig. 1 includes the whole sample, namely metal-poor and metal-rich objects. The former show a clear correlation, which can be approximated by

$$\epsilon(\mathrm{Li}) = \log(\mathrm{Li/H}) + 12 = a + b\,[\mathrm{Fe/H}] \qquad (1)$$

where $a = 2.410$ and $b = 0.094$, the correlation coefficient is $r = 0.67$, and the relation is valid in the range $-3.5 < [\mathrm{Fe/H}] < -1$, approximately. In agreement with the discussion in Section 1, the metal-rich objects show a higher dispersion, with no apparent trend. However, as discussed elsewhere (Smith 2010), Li-rich giants show clear evidences of Li-enhancements, reaching values considerably higher than the limit ϵ(Li) = 1.5. In fact, an "upper envelope" of Li abundances in AGB stars produced by HBB was predicted in the models by Sackmann & Boothroyd (1992), in analogy with the upper envelope observed in metal-poor halo and disk stars shown for example by Steigman (2010), as can be seen in the left part of Figure 1. From now on we will consider only these objects, and Figure 2a shows only the metal-rich giant having ϵ(Li) > 1.5, while Figure 3a is still more restrictive, showing the stars for which ϵ(Li) ≥ 2.0.

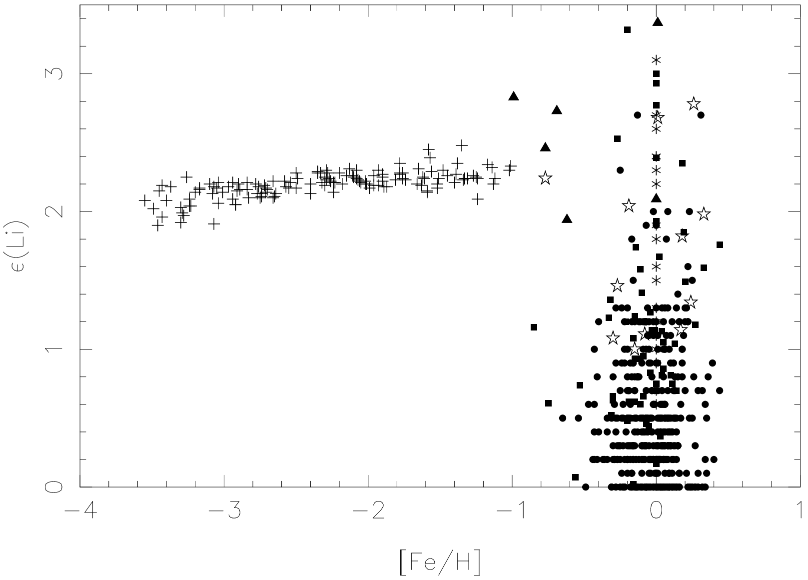

Fig. 1. Li abundances and metallicities: Metal-poor stars and metal-rich RGB/AGB stars. The sources for the metal-rich star data are: Brown at al. (1989), filled circles; Mallik (1999), filled squares; Garcia-Hernandez et al. (2008), asterisks; Gonzalez et al. (2009), stars; Monaco et al. (2011), filled triangles.

Already in Figures 2a and 3a, it can be seen that most objects have Li abundances in the range 3.0 > ϵ(Li) > 1.5, which gives average values of ϵ(Li) $\simeq$ 2.26 and ϵ(Li) $\simeq$ 2.55, not very different from the maximum value obtained by the metal-poor stars, for which we have [Fe/H] $\simeq -1$. In view of the limited sample presently available, we show in Figures 2b and 3b the averages of the Li abundances for the objects in Figures 2a and 3a. A more meaningful result can be obtained by dividing the metal-rich region in metallicity bins of 0.2 dex width, and plotting the average Li abundances for each bin. This is done in Figures 2c and 3c, again for the same samples of Li-rich stars of figures 2a and 3a. These figure also show that the trend defined by the metal-poor stars are approximately followed by the metal-rich giants, as can be seen from the dashed line extension of the metal-poor stars trend. The Li-rich red giants reported by Adamów, Niedzielski & Wolszczan (2012) as well as the RGB stars by Lebzelter et al. (2012) andUttenthaler et al. (2012), also show a good agreement with the data of Figures 2 and 3.

4. Implications for AGB stars as Li sources

From the results shown in Figures 1 to 3, it can be concluded that, in average, Li-rich AGB stars maintain the same average increase of Li abundances at higher metallicities, so that a similar slope is obtained both for metal-poor and metal-rich stars.

Apart from RGB/AGB stars, other Li sources are known in the Galaxy, such as novae, supernovae, and the spallation process occurring in the interstellar medium. Chemical evolution models usually attempt to reproduce the global Li production, including all possible sources (cf. Matteucci 2010). Therefore, a steeper slope is obtained for metallicities around solar or higher, which reflect the upper envelope of the measured Li abundances at higher metallicities. The Li production in AGB/RGB stars probably depends on the stellar mass, metallicity, duration of the Li production phase and, especially, on the adopted mass loss rate. Here we are interested in the *average* contribution by the RGB/AGB stars. In fact,

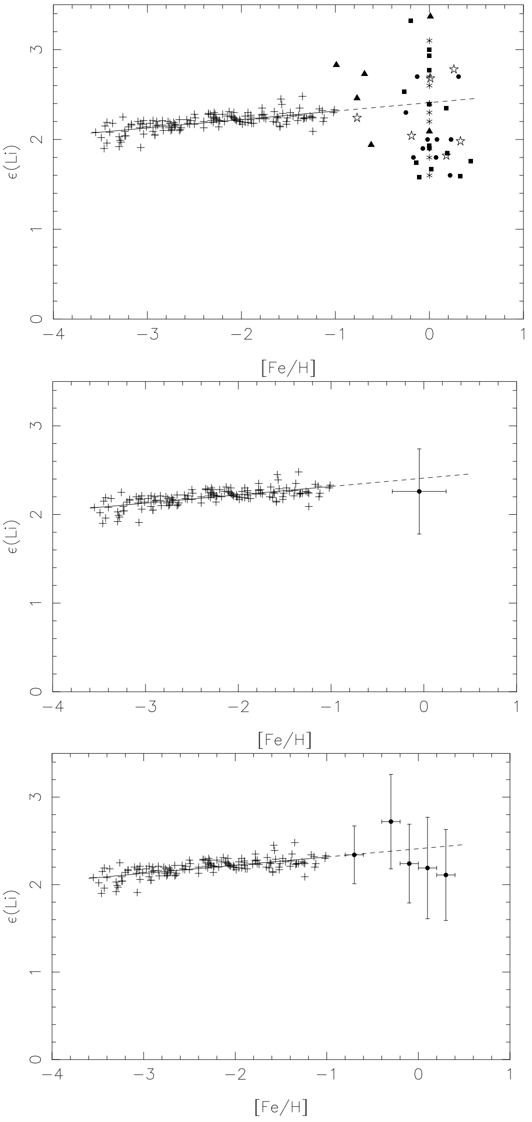

Fig. 2. Li abundances and metallicities: Metal-poor stars and metal-rich RGB/AGB stars. For the latter: (a) Stars are shown for which ϵ(Li) > 1.5; (b) Average with error bars; (c) Averages in 0.2 dex metallicity bins. The dashed line is an approximate linear fit to the metal-poor star data.

from models by D'Antona & Matteucci (1991) (see also Matteucci 2010), the steep rise in the Li abundances for [Fe/H] > −1 is essentially due to the Li production in novae.

The main process suggested to enhance the Li abundances as observed in the Li-rich AGB and RGB stars is the HBB process leading to ^{7}Li production by a mechanism proposed by Cameron & Fowler (1971). In this case, the bottom of the AGB star convective envelope reaches the inner, H-burning layers, which are hot enough for the reaction ^{3}He$(\alpha, \gamma)^7$Be to oc-

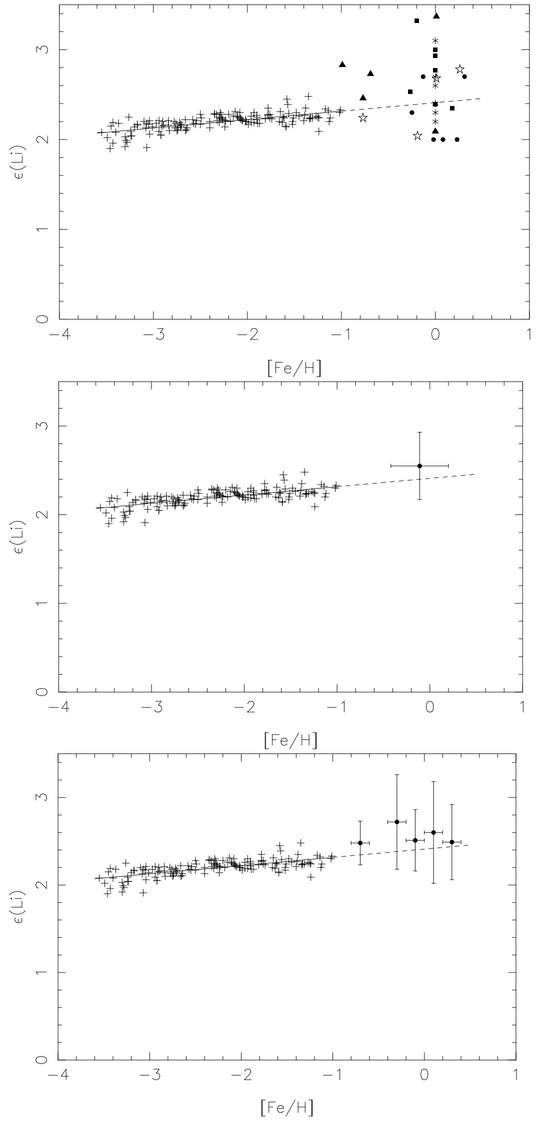

Fig. 3. The same as figure 2, including only metal-rich stars with ϵ(Li) > 2.0.

cur, followed by the reaction ^{7}Be(β^-, ν)^{7}Li involving the transported ^{7}Be, so that the outer convective layers are Li-enriched. Detailed discussions of this mechanism with appropriate references can be found in Smith (2010), D'Antona & Ventura (2010), and Lattanzio & Wood (2004). Li production by the so-called "cool-bottom-burning" has also been proposed, as well as the Li-production in nova envelopes or engulfing of planets or brown dwarfs (see for example D'Antona & Ventura 2010, Ventura & D'Antona 2010, and de la Reza 2000).

On the basis of recent theoretical models for AGB stars with masses up to 6 solar masses and super-AGB stars, with masses above 6 solar masses, D'Antona & Ventura (2010) suggested that the Li yield is expected to increase both with the stellar mass and metallicity. In particular, increasing the metallicity would increase the duration of the lithium production phase. A similar conclusion was reported on the basis of theoretical models by Lau et al. (2012) for SAGB stars, in the sense that higher metallicity stars produce more Li overall. The results shown in figures 2 and 3 seem to confirm these predictions, since the trend of increasing the Li abundances with the metallicity observed in the metal-poor halo stars apparently continues in the higher metallicity range, up to about [Fe/H] $\simeq 0.5$. In fact, it can be seen that near this limit the Li abundances seem to be closer to the predicted values of the SBBN, namely $\epsilon(\mathrm{Li}) \simeq 2.7$, as given by Steigman (2010) and Cyburt et al. (2009).

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