Mem. S.A.It. Vol. 79, 516
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Light element abundances in solar-type members of open clusters

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Abstract. Lithium and beryllium are widely recognized as key elements for investigating the physics of stellar interiors. For this reason, in the last 10-15 years several Li and, to some extent, Be surveys of open clusters of different age and metal content have been performed, with the aim to empirically trace the evolution of these light elements. Focusing on stars similar to the Sun, I will review the main results obtained from these studies. In particular, I will discuss how empirical patterns challenge evolutionary models that include non-standard mixing processes.

Key words. Stars: abundances – Stars: atmospheres – Stars: interiors – Stars: Population I – Galaxy: open clusters – Galaxy: abundances

1. Introduction

In spite of their low absolute abundances (lower than $\sim 2 \times 10^{-9}$ in number), measurements of lithium (Li), beryllium (Be), and boron (B) in stars provide key constraints on the physics of stellar interiors. In fact, due to their relatively low burning temperatures (2.5, 3.5, and 5 MK), each element survives to different depth and the initial abundance decreases if stellar surface material is circulated down inside the star to its individual temperature. Hence, LiBeB are ideal tracers of mixing processes at work inside stars. Whereas for evolved stars, that have already undergone chemical processing, other mixing tracers exist (e.g. Carretta 2008), LiBeB are unique tracers of mixing for unevolved stars. Understanding mixing processes is in turn very important to address several issues related to stellar and Galactic evolution, as well as to Big Bang Nucleosynthesis (see Randich & Pasquini 2006).

Due to their low abundances, measurements of these elements must rely on resonant lines; these are located in the optical (Li I, $\lambda = 6707.8$ Å), near-UV (Be II, $\lambda\lambda = 3130.420, 3131.064$), and UV (B I, $\lambda = 2496.77$ Å) spectral regions. Hence, the capability of observing these lines and measuring abundances decreases from Li to B. For this reason, several studies of Li among members of open clusters (OCs) down to the substellar regime have been carried out since the early 70's; much fewer surveys of Be have been performed, mostly focusing on F and G-type stars is the closest OCs; finally, B has been measured only in bright field stars.

We focus here on Li and Be measurements in solar-type members of Galactic OCs. For surveys of higher/lower mass stars and for a

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discussion of boron we refer to Boesgaard (2005 and references therein) and Jeffries (2006 and references therein).

2. Mixing on the main sequence phases

Solar models, along with results from helioseismology (e.g. Guzik 2008), show that the convective zone of the Sun (and of its analogs) does not reach deep enough in the solar/stellar interior to meet the zone of Li destruction; therefore, standard models including convection only predict that solar-type stars should not undergo any Li depletion on the MS.

In a seminal paper Zappalà (1972) first noticed that the difference in Li abundance between the ~ 100 Myr old Pleiades and the older Hyades (~ 600 Myr) must imply that, at variance with the predictions of standard models, solar-type stars undergo Li depletion during the main sequence (MS) phases. He also pointed out that determinations of Li abundances in OC stars older than the Hyades would be critical in order to put constraints on MS Li depletion and its timescales. Now, 35 years later, numerous high quality observations of Li in OCs of different ages have been collected, allowing us to gather a more solid empirical scenario. The early evidence of depletion during the MS is confirmed, implying that the Sun has depleted its Li (a factor of ~ 100 below the initial, meteoritic content) during the MS, rather than in the pre-main sequence phases, as it was initially suggested. Even more surprising is the finding that similar stars (i.e., stars with the same age, temperature, and metallicity) can be affected by different amounts of Li depletion, as shown by the factor of ~ 10 dispersion in Li observed in the solar-age, solar metallicity cluster M 67 (Jones et al. 1999 and references therein). About 40% of cluster members have a Li abundance comparable to the solar content, while the remaining stars (the upper envelope) have a factor of about 10 higher Li. This spread strongly suggests that Li depletion must be affected by an additional parameter besides mass, age, and chemical composition.

As mentioned, MS Li depletion in solar-type stars cannot be due to convective mixing alone. In order to understand it, a number of models and extra-mixing (or non-standard) processes were proposed, which include diffusion (Michaud 1986, Michaud et al. 2004; Chaboyer et al. 2005), meridional circulation (Charbonnel & Talon 1999 and references therein), angular momentum loss and rotationally driven mixing (Eddington 1925; Zahn 1974, 1992; Pinsonneault et al. 1992; Deliyannis & Pinsonneault 1997), gravity waves (García López & Spruit 1991; Montalbàn & Schatzmann 2000), tachocline (Spergel & Zahn 1992; Brun et al. 1999; Piau et al. 2003), and combinations of waves and rotation (Charbonnel & Talon 2005). Each of these models makes specific predictions on the timescales of Li depletion, on the development of a spread, on Be depletion, and on Be vs. Li behavior. The goal here is to compare these predictions with the most recent results on Li and Be patterns in solar-type stars in OCs.

3. Model predictions

In this section I will schematically summarize the main predictions of various non-standard models. For the details and the physics of the models I instead refer to the studies mentioned in the previous section (see also Michaud 2008; Talon 2008).

- *Diffusion.* Ample evidence exists from helioseismology that diffusion has reduced the solar surface He abundance; also, diffusion plus turbulence might explain Li abundance pattern in globular clusters (Korn 2008). The question then arises whether diffusion can also account for MS Li depletion in solar-like members of OCs. According to Michaud et al. (2004), **i)** both Li and Be should undergo surface abundance variations $<$ 0.1 dex during the MS; **ii)** No dispersion in Li abundance is expected; **iii)** after post-MS dilution starts, Be is depleted together with Li and n(Be)$\propto$n(Li)$^\alpha$, with α depending on the particular model and evolutionary phase;
- *Rotational mixing –models of Deliyannis & Pinsonneault (1997).* Rotational mixing due to angular momentum loss and transfer is most likely the cause of Li depletion

of F-type stars in the Li dip (Deliyannis et al. 1998; Boesgaard et al. 2004). Again, the question is whether this mechanism also works for less massive late-F and G-type stars. In models including rotational mixing, the amount of depletion depends on rotational history and initial rotational velocity. Since young clusters are characterized by a dispersion in rotational properties, **i)** a dispersion in Li is expected at old ages, with original slow rotators having undergone less depletion. Also, **ii)** for a star with a temperature of 5800 K and low initial rotation (vsin i = 10 km/s), factors of ~ 8 and 2 depletion are expected between 0.1 and 2 Gyr and 2 and 4 Gyr, respectively; for higher values of the initial rotational velocity (vsin i = 30 km/s), factors of ~ 10 and 3 depletion are predicted in the two age intervals. In both cases therefore Li depletion continues up to at least 4 Gyr. No predictions are available for ages older than 4 Gyr. Finally, **iii)** this slow mixing process reaches deep enough in the stellar interior to cause Be depletion; hence, simultaneous Li and Be depletion is expected;

- *Gravity waves –Models of Montalbán & Schatzmann (2000).* These models predict that: **i)** Li abundance continuously decreases with age. A factor of ~ 100 depletion is expected for stars with 1 solar mass at 4.5 Gyr; **ii)** no dispersion is expected for similar stars, unless rotation is introduced in the models (see below); **iii)** Very little (if any) Be depletion is expected;
- *Gravity waves + rotation –models of Charbonnel & Talon (2005).* Similarly to models including only gravity waves, these models predict that: **i)** depletion should not stop at old ages (see Fig. 2 in Charbonnel & Talon); **ii)** As in models including rotational mixing due to angular momentum transport, the amount of depletion depends on initial rotation and thus a dispersion in Li is expected; **iii)** No predictions on Be are made.
- *Tacochline –Models of Piau et al. (2003).* This process is induced by a time dependent rotation and by differential rotation with latitude and it has been successfully introduced in solar modeling by Brun et al. (1999). The predictions for stellar models of solar analogs are: **i)** the quantitative amount of Li depletion depends on the Brunt-Väisälä frequency and the tachocline thickness, which, in turn, are partly constrained by helioseismology; **ii)** Depletion does not stop at old ages; **iii)** no dispersion is expected, unless stars with the same mass have different tachocline thickness, which is unlikely, or unless a dispersion in [Fe/H] and/or CNO abundances is present within the same cluster; **iv)** no Be depletion is expected.

4. Observational evidences

4.1. Lithium

In the last 10-15 years several surveys of Li in OCs have been carried out. In particular, thanks to the advent of multiobject spectrographs on 8m-class telescopes, it is now possible to precisely measure Li abundances in very large samples of stars in distant old OCs. A compilation and re-analysis of modern Li data for OCs has been provided by Sestito & Randich (2005 –see their Table 1). To this sample one must add 10 OCs that have been recently observed by our group in the context of two VLT/FLAMES projects (Randich et al. 2005; Pallavicini et al. 2006); nine of these clusters have ages larger than 800 Myr. The whole sample allows investigating with statistical significance both the timescales of Li depletion and the occurrence of a scatter in Li.

4.1.1. Timescales: the plateau at old ages

In Fig. 1 we show the evolution of the average Li abundance as a function of age for stars in the temperature range 5750-6050 K. As already evidenced by Sestito & Randich (2005), Li depletion continuously occurs from the Zero Age Main Sequence (ZAMS) up to ~ 1 Gyr, with a typical timescale of ~ 1.4 Gyr. At older ages depletion becomes bimodal: a fraction of stars continue depleting Li at a faster rate; the Sun is part of this group, as well as

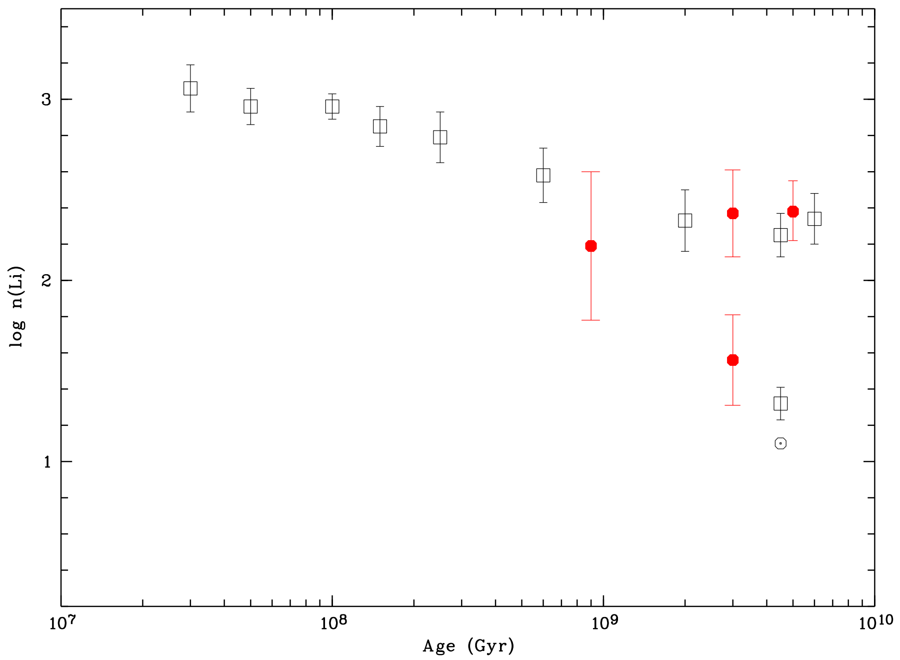

Fig. 1. Average Li abundance as a function of age. Open squares are OCs from Sestito & Randich (2005), while filled circles represent three clusters from the FLAMES sample: in age order, they are NGC 3960 (Prisinzano & Randich 2007); NGC 6253 (Randich et al. in prep.); Be 32 (Randich et al. 2007b). For M 67 and NGC 6253, characterized by a dispersion, the average values of the upper and lower envelopes are plotted. The Sun is also shown in the figure.

stars in the lower envelope of M 67 and of the other OCs showing a dispersion (see below). On the contrary, depletion completely stops for the majority of stars and all cluster average abundances converge to a plateau value that is quantitatively -and surprisingly- close to the famous "Spite plateau" of Pop. ii stars (Spite & Spite 1982). We stress that the evidence for the plateau of old OCs is confirmed by the results obtained for the old, slightly metal poor cluster Berkeley 32 (age ~ 5 Gyr, [Fe/H]=−0.3), whose average Li abundance is derived based on more than 60 members (Randich et al. 2007b).

4.1.2. Dispersion

Until recently the age sampling of OCs with available Li measurements was incomplete and Li measurements of OCs with ages intermediate between the Hyades and M 67 were not available; hence the common thinking was that the scatter in Li seen in the M 67, but not in the younger Hyades, would develop after about 600 Myr. New observations of OCs in the age range 1–6 Gyr, such as IC 4651, NGC 752, and NGC 188, have instead indicated that old clusters are not necessarily characterized by a dispersion and that M 67 is more an exception than a rule. The sample of clusters observed with FLAMES, along with samples from the literature, allows us to further constrain the occurrence of the scatter, based on statistical significant samples of clusters and samples of stars per cluster. Out of 9 OCs older than the Hyades with available Li measurements, only three show a significant (i.e., larger than errors) dispersion: M67, NGC 6253 (3 Gyr, [Fe/H]= +0.35, Randich et al. in preparation), Cr261 (7

Gyr, [Fe/H] ~ solar, Spanò et al. 2005). The analysis of four clusters from the FLAMES sample has not yet been completed and it might provide additional insights on this issue; hence, no definitive conclusions can be drawn at this stage. However, the current result is that the occurrence of the dispersion does not seems to depend on age, nor on metallicity, nor on other global cluster parameters. It is worth stressing that that the scatter in M 67 is not due presence of binaries and/or non membership, nor to a dispersion in abundances of other elements (Randich et al. 2006).

4.2. Beryllium

As mentioned in the introduction, observations of both Li and Be in the same star allow putting more stringent constraints on models. In fact, observations of Be in F-type stars in the field and close-by clusters (Hyades, Coma, Ursa Major) have shown that for these stars a tight Be vs. Li correlation does hold (Boesgaard 2005 and references therein). The availability of state-of-the art high resolution spectrographs with high near-UV efficiency has made it possible to observe not only bright stars in close-by clusters, but also fainter, solar-type members of more distant, old clusters (Randich et al. 2002, 2007a). In Fig. 2 we show Li vs. Be abundance for members of different clusters in two temperature regimes. The figure evidences distinct behaviors for stars in the two subsamples. Namely, stars warmer than 6150 K in both young and old clusters deplete Be and a correlation between Li and Be abundances is present, in agreement with the results of Boesgaard and collaborators. On the other hand, virtually all the stars in the range 5700 $\leq T_{\rm eff} \leq$ 6150 K show, within the errors, the same relative Be abundance. As a consequence, they do not follow any Be vs. Li correlation: indeed these stars span two orders of magnitude in Li abundances, they have different ages and metallicities, but they share the same Be content. This in turn implies that the mixing mechanism responsible for MS Li depletion in this temperature range does not extend deep enough to cause also Be depletion.

5. Models vs. observations

In Table 1 we summarize the results on the comparison between the main observational features and model predictions. The table clearly shows that *none* of those models makes the correct predictions for all the observables. In particular, whereas some of the models have the right timescales between the ZAMS (when depletion starts) and ~ 1 Gyr, none of them does predict the plateau in Li abundance at old ages. As an example, we show again in Fig. 3 the empirical evolution of the average Li abundance as a function of time and compare it with the predictions of Charbonnel & Talon (2005): the figure shows that models including only rotation predict in general a much faster depletion than observed. On the other hand, models including waves and rotation rather well reproduce the observed distribution up to 1 Gyr; also, the models with initial rotational velocity 50–80 km/s are in good agreement with the datapoints corresponding to the lower envelopes of NGC 6253 and M 67. However, even the model with the lowest initial rotation is not able to fit the plateau in Li. As to beryllium, the lack of depletion for stars cooler than 6150 K evidenced by the observations rules out a number of models.

To our opinion, the lack of agreement between observational evidences and model predictions does not necessarily mean that the proposed mechanisms themselves do not work; instead, it might just imply that the input physics, assumptions, and parameters entering the models might need some revision.

6. Conclusions

The large high-quality dataset for Li and Be in OCs acquired in the last years has enabled us to gather a secure picture of the empirical behaviour and evolution of Li and Be in solar analogs. The comparison of observational patterns with model predictions indicates that none of the currently available models that include different extra–mixing processes satisfies all empirical constraints. In particular, all models predict that Li depletion on the MS should continue at old ages, at variance with the obser-

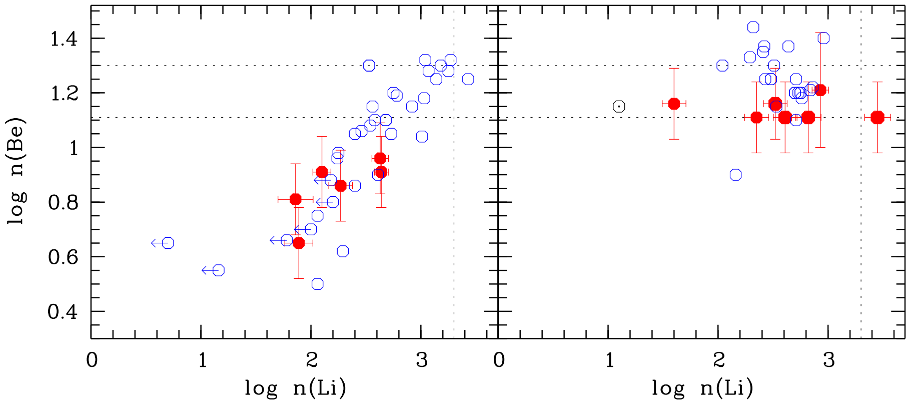

Fig. 2. Be vs. Li abundances for stars with $T_{\rm eff}>$ 6150 K (left-hand panel) and for stars with 5700 $\leq T_{\rm eff} \leq$ 6150 K (right-hand panel). Open circles are Hyades and Coma stars from Boesgaard et al. (2003, 2004), while filled circles denote M 67, IC 4651, IC 2391 and NGC 2516 members from Randich et al. (2007a). The horizontal lines bound the range of initial Be abundances in the different scales, while the vertical line indicates the initial Li abundance.

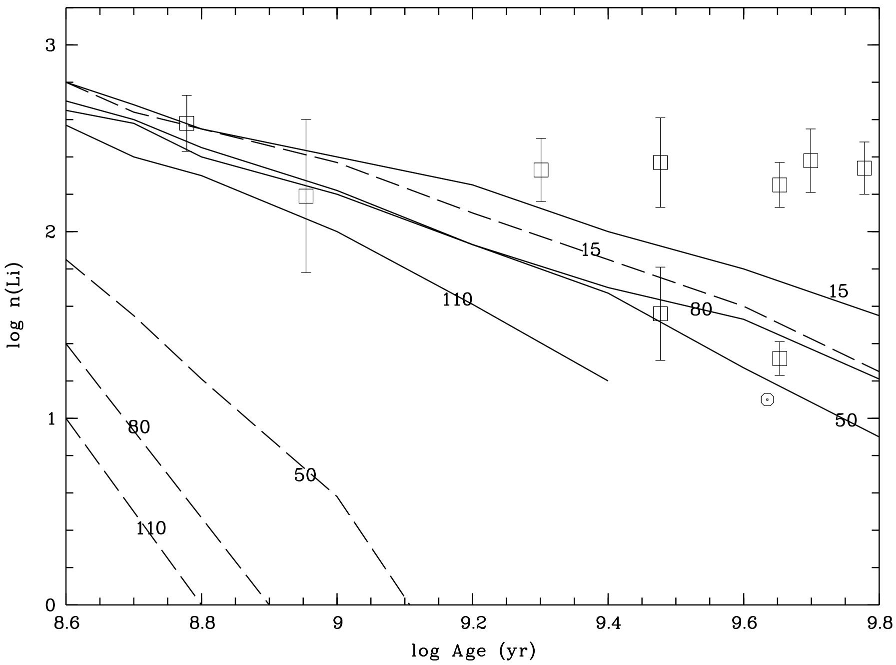

Fig. 3. Average Li abundance as a function of age (see Fig. 1) and predictions of models of Charbonnel & Talon (2005). The latter have been reconstructed starting from Fig. 2 in that paper. Different curves are for different initial rotational velocities (in km/s) as labeled. Solid curves correspond to model including waves + rotation, while dashed lines denote models including only rotation.

Table 1. Summary of comparison between model predictions and observations.

MODEL	Timescales (ZAMS–1 Gyr)	Convergence	Dispersion	Beryllium
Diffusion	NO	N/A	NO	NO
Rot. mixing	YES	NO	YES	NO
Gravity Waves	YES	NO	NO	YES
Rot.+ Waves	YES	NO	YES	–
Tacochline	YES	NO	NO?	YES

vational evidence of the convergence toward a plateau in Li for the majority of cluster stars.

We believe that at this stage the major open observational issues have been settled based on solid and secure grounds, both as far as statistics and data quality are concerned. On the other hand, the capability of simultaneously reproducing all empirical features remains a major challenge on the theoretical side. As a final note, we stress that the convergence in Li abundance at old ages and the similarity with the Pop. II plateau is very intriguing; it is tempting to interpret it as the evidence that, whatever the initial Li abundance and whatever the mixing mechanism, the final Li abundance is the same for metal-poor Pop II stars and more metal rich ones, with exception of those stars, like the Sun, that instead deplete a much larger amount of Li.

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