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Lithium and beryllium in Population I dwarf stars

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Abstract. In the last few years a variety of lithium and beryllium surveys have been carried out among Pop. I stars in the field and open clusters, with the goal to trace the dependence of these element abundances on stellar mass, age, metallicity, and to understand the physical processes that lead to their depletion. I summarize here the most recent results, focusing on stars with temperatures similar to the Sun. In particular, I will discuss Li measurements in solar-type members of old open clusters, which definitively show that the low solar lithium is not the standard for a star of that age and mass.

Keywords. Stars: abundances, interiors – open clusters and associations: general

1. Introduction

Several papers in this conference have addressed the question whether metal poor Pop. II stars deplete some lithium (Li) during their lifetime and the issue is indeed still open and highly debated. On the contrary, a large number of observational evidences indicate that more metal rich Pop. I stars do deplete their initial Li content; this is indeed expected on theoretical grounds, due their thicker convective envelopes. However, understanding when and how Li depletion occurs in Pop. I stars of different masses is still a major challenge and several unsolved problems exist.

Among the most puzzling ones, I mention the so-called "Lithium-dip", a sharp decrease of Li abundance in a very narrow temperature range around 6500 K, first discovered in the Hyades (Boesgaard & Tripicco 1986) and then found in several other clusters older than a few hundred Myr; the dispersion in Li seen among stars cooler than $\sim$ 5000 K in the Pleiades and other young clusters (e.g., Jeffries 2006 and references therein); the main sequence (MS) Li depletion observed in the Sun and similar stars. In this paper I shall focus on the latter issue.

Li and Be are depleted from the stellar atmosphere when a mechanism exist which is able to transport surface material down in the stellar interior, where the temperature is high enough for Li/Be reactions. Standard models of stellar evolution (those including convection only as mixing mechanism) predict that solar-type stars should undergo a considerable amount of Li depletion during the pre-main sequence phases; on the contrary, these stars are not predicted to destroy any Li during the MS, since the base of the convective zone does not reach the layer where the temperature is high enough for Li burning to occur. Also, the amount of Li depletion should tightly depend on mass, age, and metallicity.

It is now well established on observational grounds that the Li pattern in solar-type stars contradicts standard model predictions. The Sun has undergone a factor of about 160 Li depletion with respect to its initial abundance witnessed by meteorites, and it is now well ascertained that solar depletion occurs during the MS, rather than in the

PMS phase. Indeed early observations of solar analogs in the Pleiades (100 Myr) and Hyades (600 Myr) clusters already suggested almost forty years ago that solar-analogs undergo less PMS depletion than predicted by models and that Li depletion must take place during the MS (Zappalà 1972).

Furthermore, as first found by Spite *et al.* (1987) and confirmed by several other studies (García López *et al.* 1988; Pasquini *et al.* 1997; Jones *et al.* 1999), otherwise similar members of the solar-age, solar-metallicity M 67 cluster are characterized by different Li abundances: part of them are similar to the Sun, while another fraction have a factor of ~ 10 larger Li, suggesting that the amount of MS depletion is not necessarily the same for stars with the same mass, metallicity, and age. Similar results were achieved for field stars: different studies reported both a dispersion in Li and relatively high Li abundances in old (as indicated by chromospheric activity or rotation) solar analogs (Duncan 1981; Spite & Spite 1982; Pallavicini *et al.* 1987; Pasquini *et al.* 1994).

All these findings support the idea that Li depletion in solar-type stars is not driven by age and mass only, but that some additional parameter likely plays a role. Several models including non standard physics (rotation, magnetic fields, gravity waves, termohaline instability) have indeed been developed, but so far no consensus has been reached neither on the extra-mixing mechanism, nor on the additional parameter(s).

In the last decade several new and more modern measurements of Li in solar-type stars have been performed both in the field and in clusters, allowing us to draw more solid conclusions on the Li depletion pattern in solar-type stars. I will summarize those results by addressing a few specific questions; Namely, **i.** Is the solar Li content typical for a star of that age and mass? **ii.** Is the dispersion seen among solar analogs in M 67 also observed in other open clusters? **iii.** What are the timescales of Li depletion for solar-type stars? **iv.** Does depletion depend on metallicity? **v.** Do solar analogs deplete Be along with Li?

I finally mention that, whereas I will follow here an empirical approach and I will not attempt any direct comparison between theoretical predictions and observed patterns, I encourage theoreticians to use the latter to put constraints on the different extra-mixing models and/or to discern among them.

2. Lithium in solar analogs in the field

New measurements of Li in field stars similar to the Sun were recently carried out by Lambert & Reddy (2009) and Meléndez *et al.* (2009), who reached discrepant conclusions.

The first authors compared the Sun and stars with mass around one solar mass and found that none of their sample stars was as Li-poor as the Sun; actually all of them showed a factor of $\sim$10 larger abundance. Based on this, Lambert & Reddy concluded that the solar Li might not represent the standard. On the other hand, Meléndez *et al.* measured Li in a very small sample of solar twins (defined as stars with mass within 3% and [Fe/H] within ± 0.1 dex solar). Stars in their sample showed a decline of Li with age and, in particular, all the old solar twins were characterized by a low Li abundance. This led them to the conclusion that the solar Li is not abnormal and to the claim that previous results (i.e., the finding of Li-rich old solar-type stars) were due to biases in the samples and to considering young stars and/or stars that are not strict solar-twins.

Most obviously, ages of field stars are highly uncertain. A definitive answer to the question whether the solar Li is normal can only come from Li measurements in stars in old open clusters whose age is much better constrained.

3. Open clusters

Since the early study of Zappalá (1972), a huge amount of observational effort has been dedicated to Li measurements in open cluster stars. Sestito & Randich (2005) reanalyzed in a homogeneous fashion modern observations, putting together a sample of 22 open clusters from the literature, in order to derive the timescales of Li evolution in stars in different temperature intervals. They confirmed that solar-type stars deplete lithium during the MS phases; however, they evidenced that Li depletion slows down after the Hyades age and eventually stops for most of the stars after ∼ 1 Gyr. Noticeably, solar-type members of the very old (6 Gyr) cluster NGC 188 showed a less than a factor of 2 lower abundance than similar stars in the ten times younger Hyades (see also Randich *et al.* 2003). At that time M 67 was the only known old cluster characterized by a dispersion and showing the presence of severely depleted stars. However, the sample of old clusters was small and only a few stars (typically less than 10) per clusters had Li measurements available.

Taking advantage of available multiplex facilities on 8m class telescopes, in the last five years new, high quality Li measurements in open clusters were obtained. Some of them focused on low- or very-low mass stars (e.g., Manzi *et al.* 2008; Jeffries *et al.* 2009) or on F-type stars (Anthony-Twarog *et al.* 2009), while others concentrated on solar-type stars (Prisinzano & Randich 2007; Pasquini *et al.* 2008; Randich *et al.* 2009; Pace *et al.* 2010, these Proceedings). In the following, the latter ones will be discussed in more detail.

3.1. *A new analysis of M 67*

Pasquini *et al.* (2008) carried out VLT/FLAMES observations of a large sample of MS stars in M 67 in order to identify true solar analogs. At variance with previous studies, effective temperature were derived by spectroscopic means, rather than from photometry. The Li vs. $T_{\rm eff}$ distribution based on these observations still show a dispersion, which however is more evident for stars in the temperature range $5850\ {\rm K} \leqslant T_{\rm eff} \leqslant 6000$ K, rather than for members within ±50 K from the solar temperature. Most of these stars appear indeed Li-poor and only one of them has a high Li content. This apparently supports the claim of Meléndez *et al.* (2009) that the solar Li abundance is normal. However, we note that the sample of Pasquini et. al. includes only one of the high-lithium solar-type cluster members analyzed by Jones *et al.* (1999); hence, the inferred Li distribution for solar analogs is based on an incomplete sample and Li-rich stars might be missing. Indeed Randich *et al.* (2006) spectroscopically confirmed the solar-like temperature of star S969 ($T_{\rm eff} = 5800$ K); this star has a high Li ($\log n({\rm Li}) = 2.06$) and is not included in the sample of Pasquini *et al.* (2008).

3.2. *The VLT/FLAMES survey*

We have very recently carried out a VLT/FLAMES spectroscopic survey of a large sample of Galactic open clusters (Randich *et al.* 2005; Pallavicini *et al.* 2006). UVES fibers were allocated to evolved cluster members in order to obtain their chemical composition and investigate the issue of the radial metallicity gradient. The Giraffe spectrograph was instead used to obtain high resolution spectra ($R\sim 20,000$) of unevolved cluster candidates; our primary goals were membership determination and Li measurements among confirmed members. A total of 11 clusters were observed, nine of which are close enough to allow us to obtain good quality spectra of their solar-type members. In Table 1 I list the seven sample clusters whose Li analysis has been completed. Analysis for the remaining two clusters (NGC 2324 and To 2) is in progress. As the table shows, the clusters cover the age interval between ∼0.7 and 8 Gyr and the metallicity range $[{\rm Fe/H}] = -0.38 - +0.35$. After excluding radial velocity non members, each cluster sample typically consists of

Table 1. The sample clusters. I list ages, metallicities, and number of members for which we derived Li abundances.

Cluster	age (Gyr)	[Fe/H]	$N_{\rm stars}$
NGC 3960	0.7	0.02±0.04	36
NGC 2477	1.0	0.07±0.04	73
NGC 2506	2.2	-0.20 ± 0.02	71
NGC 6253	3.0	0.36±0.07	54
Melotte 66	4.0	-0.33 ± 0.03	53
Be 32	6.0	-0.29 ± 0.04	57
Cr 261	8.0	0.13±0.05	135

~40-140 stars. The analysis of the data was homogeneously carried out as following Sestito & Randich (2005) and Randich *et al.* (2009). Briefly, effective temperatures ($T_{\rm eff}$) were derived employing the $T_{\rm eff}$ vs. B–V calibration of Soderblom *et al.* (1993a) for solar metallicity stars or that of Alonso *et al.* (1996) for stars with non-solar [Fe/H] content. Li abundances were then derived from equivalent widths and using curves of growths. For more details on the Li analysis (in particular on the estimate of the contribution of the Fe I 670.74 nm line to the Li I 670.8 nm feature) I refer to Randich *et al.* (2009).

I mention that Pace *et al.* (2010, these Proceedings) warn that effective temperatures estimated from colors might be in error, due to uncertain knowledge of reddening. However, I note that for all the FLAMES clusters reddening is known relatively well (in several cases has been estimated from spectroscopy). Also, whereas one cannot exclude that $T_{\rm eff}$ values of individual stars might be somewhat in error, we can exclude that the overall temperature distribution within a given cluster is shifted towards lower/higher temperatures. If this was indeed the case, there would be an inconsistency with cluster ages derived from turn-off stars. In conclusion, use of photometric temperatures, should not greatly affect our results and conclusions.

3.2.1. *Li vs. temperature distribution*

In Fig. 1, I compare the log n(Li) vs. $T_{\rm eff}$ distributions of M 67 and NGC 188 with those of four FLAMES clusters (Be 32 –6 Gyr, $[{\rm Fe/H}]=-0.29$; Collinder 261 –6 Gyr, $[{\rm Fe/H}]=0.13$; Melotte 66 –4 Gyr, $[{\rm Fe/H}]=-0.31$, and NGC 6253 –3 Gyr, $[{\rm Fe/H}]=+0.36$). The comparison of the four panels in the figure clearly shows that the upper envelope of the Li vs. $T_{\rm eff}$ distribution is very similar for the six clusters; however, each of them behaves in a different way as far as the dispersion and the fraction of Li-poor and Li-rich stars around the solar temperature is concerned. The distribution of the metal poor Be 32 is similar to that of NGC 188: at variance with M 67, it is characterized by virtually no dispersion and all stars have a Li abundance more than a factor of 10 larger than the Sun. Cr 261 shows a larger amount of dispersion, but none of its members is as Li depleted as the Sun or the lower envelope of M 67. Viceversa, most members of Mel 66 are heavily Li depleted and only five stars (out of 53) have log n(Li)>2. Finally, the very metal rich NGC 6253 exhibits an intermediate behaviour, more similar to the pattern of M 67: a fraction of stars shares the same low Li as the Sun, while another fraction has a much higher Li. As to the other three (younger) FLAMES clusters (NGC 3960, NGC 2477 and NGC 2506), all of them show almost no dispersion and all their members are Li-rich (log n(Li)$\sim 2.2-2.4$). Note that all these would hold true even if considering a very narrow (±50 K) temperature interval around the solar value.

I believe that these results confirm on solid and statistically significant grounds that old stars with temperatures close to the Sun are not necessarily as Li poor as the Sun.

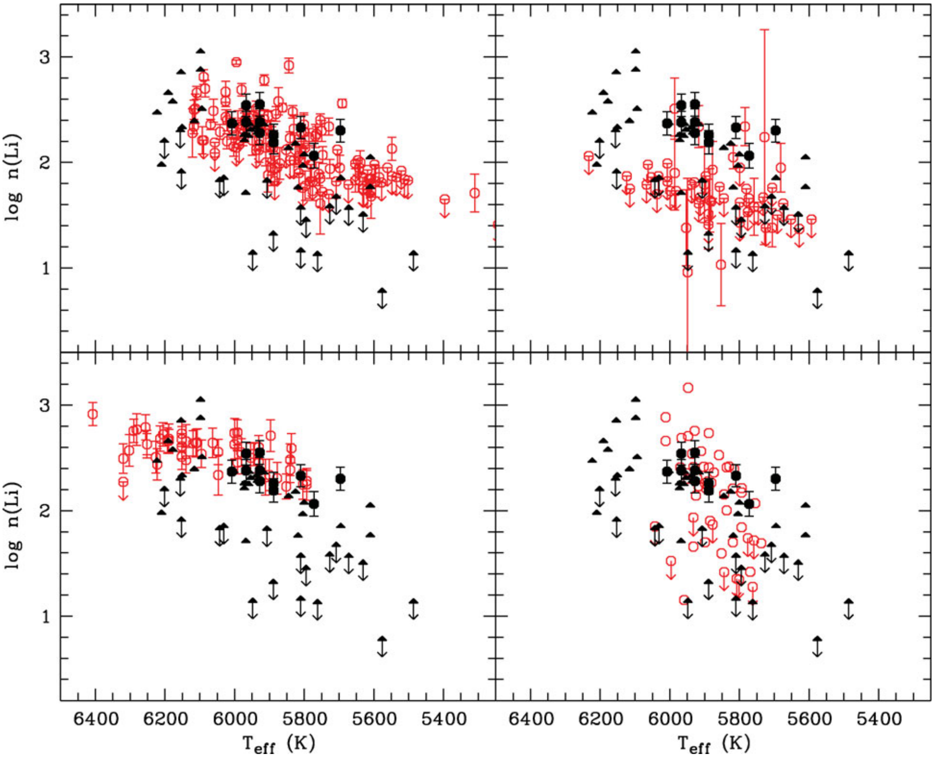

Figure 1. Li abundances (log n(Li) –in the usual logarithmic scale where log n(H) = 12) vs. effective temperature distributions of different FLAMES clusters (red open circles) are compared to M 67 (black filled triangles) and to NGC 188 (black filled circles). Namely, in the top panels the distributions of Collinder 261 (left-hand) and Melotte 66 (right-hand) are plotted, while in the bottom panels Berkeley 32 (left-hand) and NGC 6253 (right-hand) are shown. Li abundances for NGC 188 and M 67 have been retrieved from Sestito & Randich (2005) and had been derived in the same fashion as for the FLAMES sample clusters.

Old open cluster members show a variety of Li patterns and there is not a 'standard'. In a few clusters Li-rich and Li-poor stars are both present, while in others only the Li rich population exist. This provides strong support to the idea that the solar Li is not representative of the Li content of solar-type stars at the solar age and that other parameters, besides age and mass, drive Li depletion during the MS. Also note that the Li pattern of the clusters shown in Fig. 1 does not apparently depend on the cluster metallicity, since clusters with similar age and [Fe/H] (e.g., Be 32 and Mel 66) are characterized by completely different distributions, while clusters with significantly different metallicity (e.g. Be 32 and NGC 188) have similar Li patterns.

Our conclusion is that some initial cluster condition or property might have affected the following evolution of Li. Unfortunately, at the old ages of the clusters memory of that is lost, but Li might represent an important fossil record.

3.2.2. *Evolution of Li with age*

In Fig. 2 I show the evolution of Li with age as inferred from available open clusters measurements. For each cluster I consider stars in the temperature interval 5750 K $\leqslant$ T_{eff} $\leqslant$ 6050 K, i.e. solar-type stars and slightly warmer ones. Note that the 300 K temperature interval was chosen as to have relatively large samples of stars. Fig. 1 however

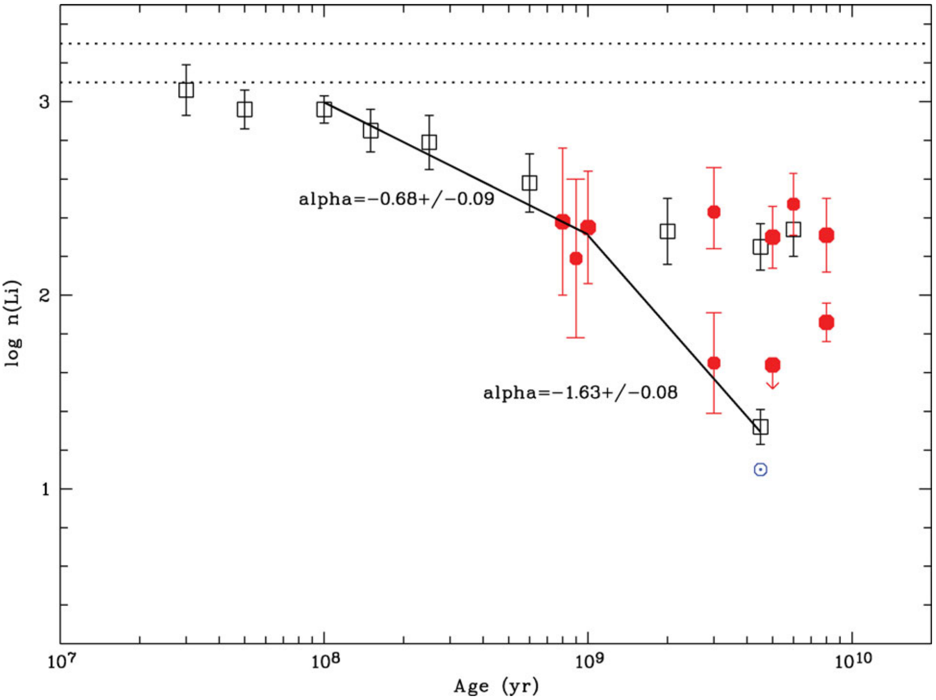

Figure 2. Average Li abundance as a function of age for solar-type stars (5750 K $\leqslant$ $T_{\rm eff}$ $\leqslant$ 6050 K). Open symbols indicate clusters from Sestito & Randich (2005), while filled circles denote the new FLAMES clusters. Error bars indicate the 1σ deviation from the average. Symbols at the same age indicate the average of the upper and lower envelopes of the Li vs. $T_{\rm eff}$ distribution of clusters characterized by a dispersion. The two dotted lines limit the range of initial Li abundances for Pop. I stars. The Sun is also plotted. The best fit exponential decays (log n(Li)$\propto t^{-\alpha}$) between 100 Myr and 1 Gyr, and between 1 and 4.5 Gyr are also shown.

indicates that the results would not change very much if considering a narrower temperature range around the solar value.

Fig. 2 confirms, based on a much larger sample of clusters, the results of Sestito & Randich: very little depletion (less than a factor of 2) occurs up to 100 Myr. Then, a phase of continuous depletion follows up to an age of about 1 Gyr; the decay of Li abundance is well fitted with an exponential law log n(Li)$\propto t^{-\alpha}$ with $\alpha = -0.68 \pm 0.09$. After 1 Gyr depletion becomes bimodal: part of the stars do not undergo any additional depletion and Li abundances converge towards a plateau value. I mention in passing that this plateau value is surprisingly similar to the Spite plateau of Pop. II stars. Another fraction of the stars, including the Sun, instead continue depleting Li at a very fast rate ($\alpha = -1.63 \pm 0.08$).

4. Beryllium

Be is destroyed at a higher temperature than Li (3.0 vs 2.5 MK) and thus simultaneous observations of Li and Be allow us to understand how deep in the stellar interior the mixing process extends and to put tighter constraints on models. Different models indeed predict different patterns of Be vs. Li depletion. Measurements of beryllium however rely on the resonant lines of Be II which are located in the near-UV spectral region at $\lambda\lambda = 3130.420, 3131.064$. Hence, the capability of observing these lines and measuring

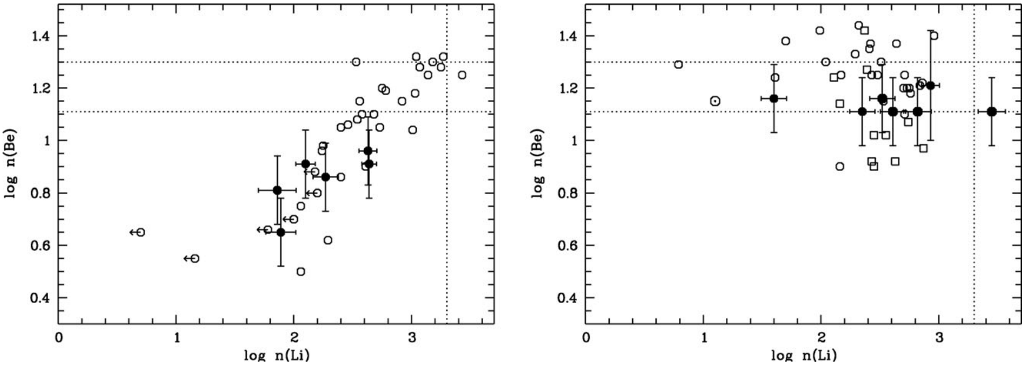

Figure 3. Be vs. Li abundances for stars with $T_{\rm eff} > 6000$ K (left-hand panel) and for stars with $5700 \leqslant T_{\rm eff} \leqslant 6000$ K (right-hand panel). Open circles are Hyades, Praesepe, Coma members from Boesgaard *et al.* (2002, 2003, 2004b), while filled circles denote M 67, IC 4651, IC 2391 and NGC 2516 members from Randich *et al.* (2007). Finally, open squares are solar mass field stars from Boesgaard *et al.* (2009). The position of the Sun is also shown. The horizontal lines bound the range of initial Be abundances in the different scales, while the vertical line indicates the initial Li abundance.

abundances is lower than for Li (see also Primas, these Proceedings). For this reason, until very recently much fewer surveys of Be have been performed, mostly focusing on bright F-type stars in the field and in the closest clusters (Hyades, Come Ber, Ursa Major, Pleiades). These measurements have shown that such stars undergo Be depletion (a Be dip has indeed been identified) and show a tight Be vs. Li correlation holds (Boesgaard *et al.* 2004a and references therein).

4.1. *Beryllium in solar-type stars*

As mentioned, the Sun has suffered a large amount of Li depletion. Until 10 years ago it was commonly believed that it had also undergone some (a factor of two) Be depletion. Balachandran & Bell (1998) performed a new analysis of the near-UV solar spectrum, correctly taking into account continuous opacity. They showed that the Sun has instead not depleted any Be, implying that mixing in the solar photosphere is more superficial than previously supposed.

The availability of state-of-the art high resolution spectrographs with high near-UV efficiency has made it possible to measure Be not only in bright stars in close-by clusters, but also in fainter members of more distant, old clusters (Randich *et al.* 2002, 2007; Smiljanic *et al.* 2009). In particular, Be has been measured in solar-analogs in two clusters older than the Hyades: IC 4651 (2 Gyr) and M 67. Furthermore, in a very recent paper Boesgaard & Krugler (2009) present Be measurements for the one solar mass stars of the sample of Lambert & Reddy (2004). All these new data give us the possibility to study the behaviour of Be depletion in old stars similar to our Sun.

In Fig. 3 I show Li vs. Be abundance for members of different clusters in two temperature regimes, as indicated in the caption. The figure evidences distinct behaviors for stars in the two subsamples. Namely, stars warmer than 6000 K in both young and old clusters deplete some amount of Be and a clear correlation between Li and Be abundances is present, in agreement with the results of Boesgaard and collaborators. I mention that Be depletion was also found by Smiljanic *et al.* (2009) among F-type stars in IC 4651. On the other hand, virtually all the stars in the range $5700 \leqslant T_{\rm eff} \leqslant 6000$ K, including the Sun, show, within the errors, the same Be abundance. While some star-to-star dispersion is present, possibly due to the adoption of different abundance scales and to non-uniform initial abundance, the stars in the right-hand panel of the figure do not follow any Be vs. Li correlation. These stars span two orders of magnitude in Li abundances, they have different ages and metallicities, but they share the same Be content. The Sun also has a very similar Be abundance. I stress that stars in the old M 67 have virtually the same Be abundance as members of the 50 Myr old IC 2391 and the 100 Myr old NGC 2516 clusters. Also, stars in M 67 showing different amount of Li depletion have the same Be content (see also Randich *et al.* 2002, 2007). This in turn implies that *i.* solar-type stars do not deplete any beryllium at least up to the solar and M 67 age, in spite of the fact that they do deplete lithium; *ii.* at variance with the warmer star regime, where Be depletion is correlated to Li depletion, the mixing mechanism responsible for MS Li depletion in this temperature range is rather shallow and does not extend deep enough to cause also Be depletion.

5. Concluding remarks

I conclude by answering the five questions raised in the introduction.

Observations of solar-type stars in open clusters strongly suggest that the solar Li content is not typical. Whereas stars showing the same severe Li depletion as the Sun are found in the field and in clusters, otherwise similar old stars are present with a factor of at least ten higher Li. Part of the old open clusters so far observed show a dispersion similar to M 67, while the Li distribution in other clusters is very narrow. Solar-type stars deplete Li on the MS up to an age of about 1 Gyr; afterward, depletion either stops or becomes considerably more efficient, like in the Sun. The reasons why otherwise similar stars deplete Li at different rates after 1 Gyr and why similar cluster behave differently is so far not understood. The hypothesis that the Li behaviour might be related to the presence of a planetary system (Israelian, these Proceedings) is very tempting. In any case, this empirical evidence suggests that Li is a good age tracer for these stars up to about 1 Gyr. After that age , a 'low' solar-like Li abundance is indicative of an old age, plus, possibly, a peculiar evolution. Viceversa, a 'high' Li content ($\sim$ 10 times the solar value) only allows inferring a lower limit to the age.

Li vs. $T_{\rm eff}$ patterns and the presence of severely depleted stars do not depend on the cluster metallicity. I mention however that metallicity affects stellar structure and a given effective temperature corresponds to lower masses for lower metallicities (and viceversa). Therefore, similar Li vs. $T_{\rm teff}$ distributions do not correspond to similar Li vs. mass patterns, if the metallicity of the clusters is not the same (see Randich *et al.* 2009).

Finally, Be observations in solar-type stars in old clusters show that, like the Sun, they do not deplete any Be, in spite of the fact that they deplete [different amount of] Li. This indicates that the mixing process must be a shallow one.

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