The Ages of Stars
Proceedings IAU Symposium No. 258, 2008
E.E. Mamajek, D.R. Soderblom & R.F.G. Wyse, eds.

doi:10.1017/S1743921309031780

On the use of lithium to derive the ages of stars like our Sun

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Abstract. Along with chromospheric emission, lithium abundances are widely used to infer the ages of solar-like. We re-assess the validity and limits of this approach, based on new high quality Li measurements in seven open clusters observed with Giraffe on the ESO VLT.

Keywords. stars: abundances, stars: interiors, Galaxy: open clusters and associations: general

1. Introduction

Stars like our Sun† deplete lithium (Li) during their permanence on the main sequence, due to a mixing process that brings surface material down in the stellar interior where the temperature is high enough for Li burning to occur. Since the base of the convective zone of the Sun (and similar stars) does not reach the temperature needed for Li reactions, different extra-mixing processes have been proposed in the literature. Whereas no consensus has been reached on the nature of the extra-mixing mechanism, this can be very efficient, as indicated by the solar Li abundance. The Sun has in fact depleted a factor of $\sim$ 100 Li with respect to the initial meteoritic abundance. Also, the solar Li abundance is much lower than that of similar stars in young open clusters, such as the Pleiades.

Based on the assumption that the Sun and its Li content are representative of stars with similar age and temperature, and that Li abundance decreases as stars get older, the obvious conclusion was drawn that Li could be used to age date solar-type stars. Several papers in the 80's indeed focused on the determination of qualitative or even quantitative Li-age relationships. Among these works, we mention Herbig (1965), Skumanich (1972), Duncan (1981), Soderblom (1983), Boesgaard & Tripicco (1987). Note that all these studies were based on field stars and on a few young clusters such as the Pleiades (100 Myr), with a huge age gap. Noticeably, during the same years several examples of old (as indicated by the chromospheric emission levels and/or rotational velocities), but Li-rich stars were reported (Duncan 1981; Spite & Spite 1982; Pallavicini *et al.* 1987). Pallavicini *et al.* indeed concluded that *a high Li abundance is a necessary, but not sufficient condition for a star to be young.*

Whereas results on field stars might be affected by their uncertain age determination, similar findings were also reported for open clusters, whose age is more securely constrained. In particular, different studies (Spite *et al.* 1987; García López *et al.* 1988; Pasquini *et al.* 1997; Jones *et al.* 1999) pointed out that the Li distribution of solar-type

† In this paper we indicate as 'solar like' stars with temperature, but not necessarily mass, close to the solar value.

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

Cluster	age (Gyr)	[Fe/H]	N_{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

members of the solar age, solar metallicity cluster M 67 appears to be bimodal; along with stars showing an amount of Li depletion comparable to the solar one, several otherwise similar cluster members are present with a factor of about 10 higher Li. More recently, Randich *et al.* (2003) measured Li in 11 solar-like members of the 6–8 Gyr old NGC 188, finding that all the stars are 10–20 times more Li-rich than the Sun.

Both results are in agreement with those for field stars and evidence the existence of a population of old, but not necessarily Li-poor stars; in turn, this casts doubts both on the assumption that the solar Li is typical for a star of that age, and on the use of Li as an age tracer. In this context, we report here the results of a Li survey among a sample of open clusters well sampling the age-metallicity plane, aimed to put tighter constraints on the evolution of Li abundance with age and its possible dependence on metallicity,

2. The FLAMES survey

We have used the multiplex facility FLAMES on ESO VLT to perform a spectroscopic survey of a large sample of Galactic open clusters, addressing a variety of scientific goals (Randich *et al.* 2005; Pallavicini *et al.* 2006). In particular, we have used the Giraffe spectrograph 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 these were close enough to allow us to observe solar-type stars. In Table 1 we 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 span the age interval between ~0.7 and 8 Gyr and the metallicity range [Fe/H]= $-0.38 - +0.35$. After excluding radial velocity non members, each cluster sample typically consists of ~40–140 stars.

The analysis was carried out as described in Sestito & Randich (2005) and Randich *et al.* (2009). Briefly, effective temperatures (T_{eff}) were derived employing the calibration T_{eff} vs. B–V of Soderblom *et al.* (1993a) for solar metallicity stars or that of Alonso *et al.* (1996) for stars with metallicity different from solar.

At our resolution, the Li I 670.8 nm feature is blended with the Fe I 670.74 nm line. The contribution of the latter to the Li feature was estimated using the analytical expression of Soderblom *et al.* (1993b) in the case of solar metallicity clusters; for clusters with over-/under-solar metallicity we instead measured the equivalent width of the Fe line on a grid of synthetic spectra with the appropriate metallicity and different temperatures. Finally, Li abundances (log n(Li)) were computed from deblended equivalent widths and using curves of growths of Soderblom *et al.* (1993b).

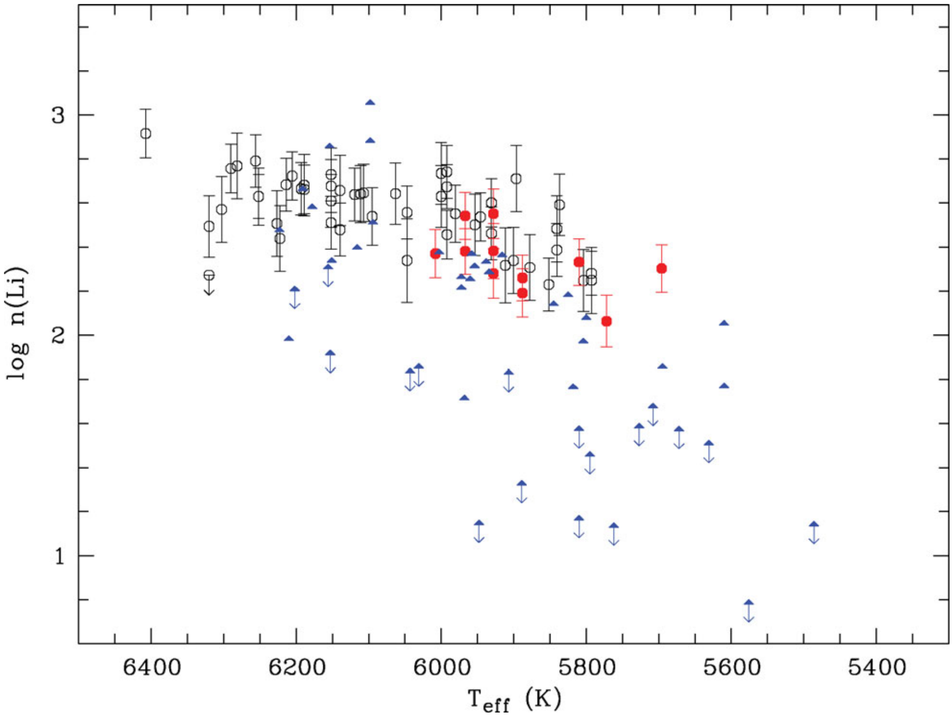

Figure 1. Li abundances (in the usual scale log n(Li)=log n(Li)/n(H)+12) as a function of effective temperature for Be 32 (open circles-present sample), NGC 188 (filled circles), and M 67 (filled triangles). Li abundances for NGC 188 and M 67 have been retrieved from Sestito & Randich (2005) and had been derived in the same fashion as for the sample clusters.

3. Li vs. temperature

In Figs. 1, 2, 3 we compare the log n(Li) vs. T_{eff} distributions of three of the sample clusters (Be 32 –Fig. 1; Mel 66 –Fig. 2; Cr 261 –Fig. 3) with data from the literature for M 67 and NGC 188. All the five clusters are as old as the Sun or older.

The comparison of the three figures clearly shows that both the upper envelope of the Li vs. T_{eff} distribution and the maximum Li abundance is similar in the five clusters; however, each of the three clusters Be 32, Mel 66, and Cr 261 behaves in a different way. The distribution of Be 32 is similar to that of NGC 188: at variance with M 67, it is characterized by no dispersion and all stars have a Li abundance more than a factor of 10 larger than the Sun. Vice versa, most members of Mel 66 are heavily Li depleted and only five stars (out of 53) have log n(Li)> 2. Finally, Cr 261 exhibits an intermediate behaviour, more similar to the pattern of M 67: a fraction of stars have a Li content similar to the Sun, while another fraction shows a much higher Li. As to the other four sample clusters, three show almost no dispersion and all their members are Li-rich, while a scatter is observed in NGC 6253.

In conclusion, our results confirm on solid grounds and based on large number statistics that old stars are not necessarily Li poor as the Sun is. 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 ones are present. Based on the

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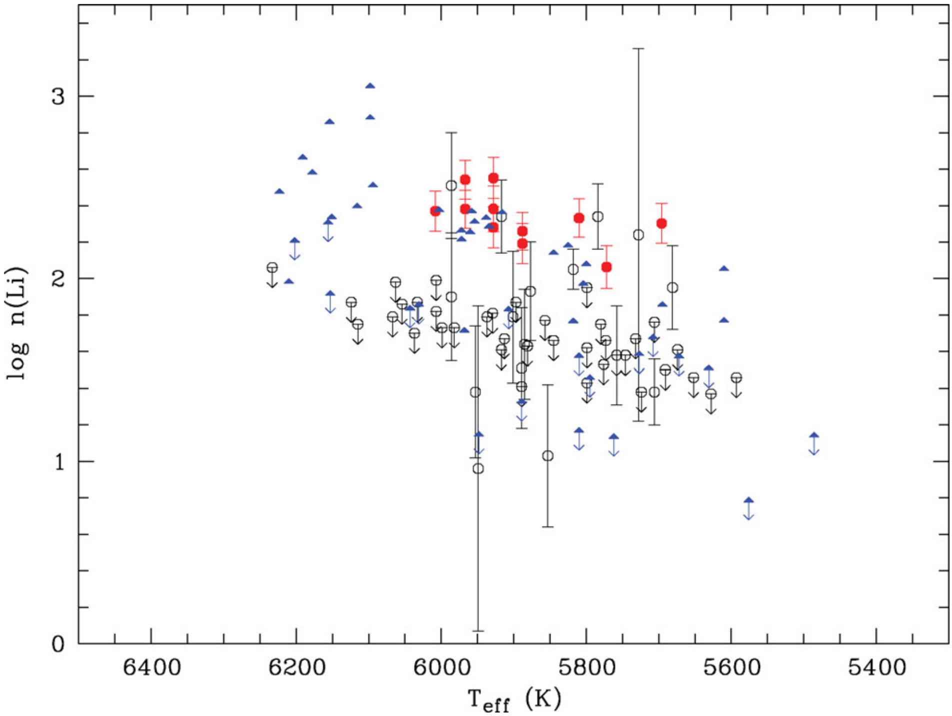

Figure 2. Same as Fig. 1, but NGC 188 and M 67 are compared to Melotte 66.

whole sample, we find that the Li patterns do not seem to depend on obvious cluster properties, such as, for example, metallicity.

4. Evolution of Li with age

In Fig. 4 we summarize the results on the evolution of Li with age, plotting the average Li abundance as a function of age; for each cluster we considered stars in the temperature interval 5750 K $\leqslant T_{\rm eff} \leqslant$ 6050 K. Open symbols denote clusters from the literature re-analyzed by Sestito & Randich (2005), while filled symbols indicate the present sample. Symbols at the same age do not indicate different clusters, but the average of the upper and lower envelopes of the Li vs. $T_{\rm eff}$ distribution of clusters characterized by a dispersion. The Sun is also plotted in the figure. Fig. 4 shows that solar-type stars undergo very little depletion (less than a factor of 2) up to 100 Myr. Then, they suffer continuous depletion 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†. Another fraction of the stars, including the Sun, instead continue depleting Li at a very fast rate ($\alpha = -1.63 \pm 0.08$).

The reason why otherwise similar stars deplete Li at different rates after 1 Gyr is so far not understood. However, this empirical evidence allows us to draw definitive conclusions on the use of Li to derive the age of solar-type stars. Namely, Li is a good

† This plateau value is surprisingly similar to the Spite plateau of Pop. II stars.

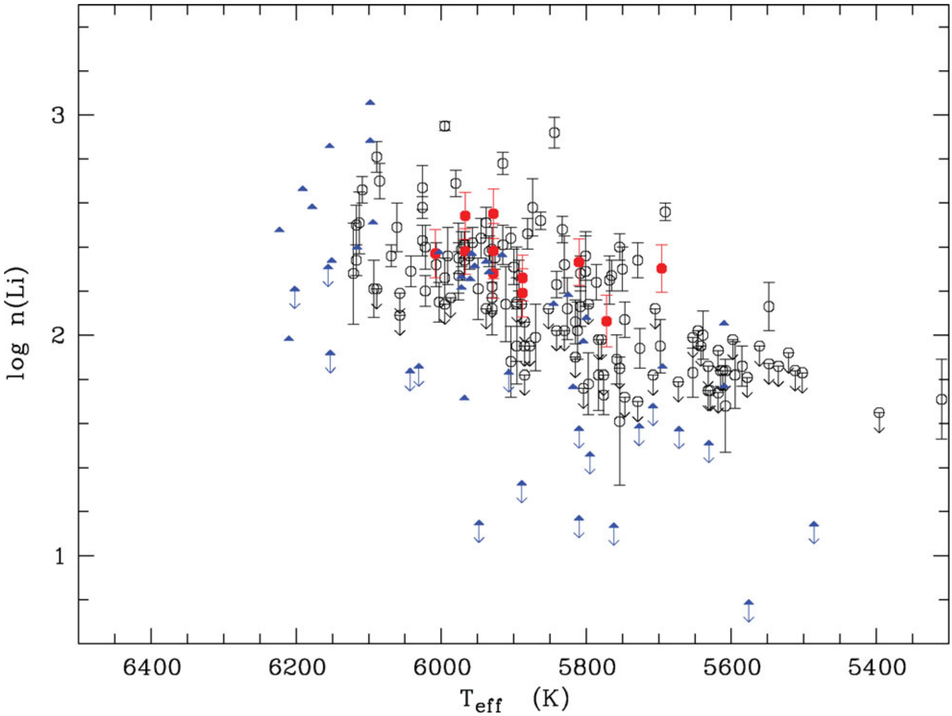

Figure 3. Same as Figs. 1 and 2, but NGC 188 and M 67 are compared to Collinder 261.

age tracer for these stars up to about 1 Gyr. After that, a 'low' solar-like Li abundance is indicative of an old age, plus, possibly, a peculiar evolution. Vice versa, a 'high' Li content ($\sim$ 10 times the solar value) only allows deriving a lower limit to the star age. A Li abundance log n(Li) $\sim$ 2.4 does not allow discerning whether a star is 1 or 8 Gyr old. These conclusions should be kept in mind when using Li to derive the ages of field stars, in particular of exo-planet host stars.

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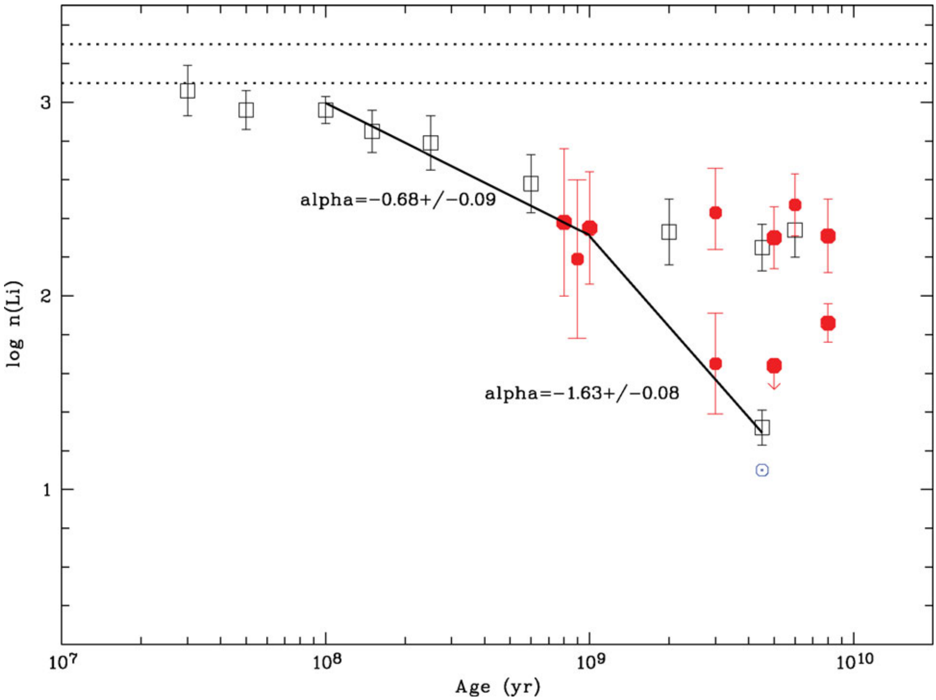

Figure 4. Average Li abundance as a function of age for solar-type stars (5750 K $\leqslant$ $T_{\rm eff}$ $\leqslant$ 6050 K). Open symbols indicate clusters from Sestito & Randich (2005), while filled circles denote the present sample. Error bars indicate the 1σ deviation from the average. Symbols 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 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.

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Discussion

E. Mamajek: This is a question for Sofia and the previous speaker (Deliyannis). Why is the Sun so weird (Li poor)? Follow up: Are exoplanet host stars also anomalously Li poor?

S. Randich: 1) Actually we do not know – several people have suggested that it could be because of the fact that the Sun hosts a planetary system. 2) Yes, on average they are.

R. Mathieu: Following on Marc Pinsonneault's thought regarding the effect of planets on disks and thus lithium enrichment, might binary companions play the same role? Of order one-third of stars in NGC 188 and M67 are spectroscopic binaries, and presumably undetected wider binaries are also present.

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S. Randich: Yes, I agree.

L. Hillenbrand: I also wanted to ask about the bimodality in N(Li) vs. age. Are there additional clusters in the 1–10 Gyr age range that might someday be placed on this figure to test bimodality vs. scatter between the two limits defined by 1) the flat relation and 2) the solar track?

S. Randich: Yes, there are a few clusters within reach. But I think that the observational pattern is now rather well defined. We should try understanding what could be the reason of bimodality, before aiming for more observing time.

C. Deliyannis: What is your favorite Galactic Li production mechanism?

S. Randich: AGB stars with a superwind.

M. Pinsonneault: You've demonstrated that Li depletion is highly variable, making Li a poor age diagnostic for field stars. There is also a theoretical framework in which Li depletion is expected for stars which truncated their accretion disks early.

S. Randich: OK. Thanks for mentioning this.

N. Panagia: Judging from your last plot I would conclude that the "normal" Li depletion is slowly evolving with time (less than a factor of 10 in 10 Gyr) whereas "exceptional" stars evolve faster (due to rotation?).

S. Randich: Yes, the majority of stars shows slowly evolving Li and converge towards a plateau at old ages.

H. Richer: Have people looked for planets or binary companions to the lithium-depleted stars?

S. Randich: We do have a program (just started) to do that. The PI is Luca Pasquini.

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