Astron. Astrophys. 356, L25–L29 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Evolution of lithium in solar–type stars: clues from intermediate age clusters*

S. Randich[1], **L. Pasquini**[2], **and R. Pallavicini**[3]

[1] Osservatorio Astrofisico di Arcetri, Largo Fermi 5, 50125 Firenze, Italy (randich@arcetri.astro.it)
[2] European Southern Observatory, Karl-Schwartzschild-Strasse 2, 85748, Garching bei München, Germany
[3] Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy

Received 12 January 2000 / Accepted 2 March 2000

Abstract. We present Li abundances for 14 solar–type stars in the intermediate age ($\sim$ 2 Gyr) clusters IC 4651 and NGC 3680. The $\log$ n(Li) vs. effective temperature distributions are compared with those of the similar age cluster NGC 752, of the younger Hyades (600 Myr) and of the older M 67 (4.5 Gyr) and NGC 188 (6–7 Gyr) clusters. Neither IC 4651 nor NGC 3680 show the dispersion in Li which is observed in M 67. The 2 Gyr clusters have very similar Li vs. $T_{\rm eff}$ distributions; in addition, stars in the upper envelope of the M 67 distribution have the same Li content as stars in the 2 Gyr clusters, suggesting that either they have not suffered any significant depletion between $\sim$ 2 and 4.5 Gyr or they had a much slower Li depletion. Mechanisms that lead to Li depletion on the main sequence are discussed in the light of these observations. None of the existing models seem to reproduce well the observed features.

Key words: Galaxy: open clusters and associations: individual: NGC 3680 – Galaxy: open clusters and associations: individual: IC 4651 – stars: abundances – stars: interiors

1. Introduction

Understanding the processes that lead to lithium destruction on the main sequence (MS) provides powerful diagnostics of stellar structure and evolution and of mixing mechanisms in stars.

Surveys of Li among cluster and field stars have shown that standard models (i.e., those that take into account convecting mixing only) are in contradiction with many of the observational features (see Deliyannis 2000; Jeffries 2000; Pasquini 2000, and references therein for recent reviews). Focusing on solar–type stars, at least two results in strong disagreement with model predictions have been found: *i)* these stars appear to deplete Li while on the MS, in spite of the fact that their convective zones bases are too cool to burn Li; *ii)* even more surprisingly, old, otherwise similar solar–type stars show different amounts of Li depletion. Solar–type stars in the solar age, solar metallicity cluster M 67 (4.5 Gyr) show a dispersion in Li abundances larger than a factor of 10 (Spite et al. 1987; García López et al. 1988; Pasquini et al. 1997; Jones et al. 1999), in contrast with the tight relationship between Li abundance and effective temperature (or mass) observed for single stars in the younger Hyades (age 600 Myr). The evolution from the Hyades to the age of the Sun seems to be ‘bimodal’, with a fraction ($\sim$ 60%) of stars depleting a relatively small amount of lithium, and another fraction, virtually similar to the other one as far as mass and chemical composition are concerned, that undergoes a severe Li depletion. It is important to mention that, whereas no Li data for other clusters coeval to M 67 are available, a similar behavior is observed among old solar-type stars in the field (e.g., Pasquini et al. 1994). The Sun with $\log$ n(Li) = 1.1 belongs to the class of Li-poor stars. In summary, not only we do not understand the mechanism(s) that lead to Li depletion on the MS, but these mechanism(s) seem to work differentially for otherwise similar stars.

As a possible solution for the dispersion observed among M 67 stars, Jones et al. (1999) speculated that the mixing is driven by MS spin–down and angular momentum loss; in this case, the dispersion in Li would be due to different initial rotation rates. If this were the case, a spread in Li should be seen already at ages of 2 Gyr or younger (e.g., Pinsonneault 1997). More in general, in order to explain the observational evidences, several models have been developed in the last decade, involving more complex physics or/and additional mixing processes; the validation of these models still needs strong observational support, in particular at ages intermediate between the Hyades and M 67 where very few data are available. Determining Li in a significant sample of stars in intermediate age clusters is thus extremely important: so far Li measurements for clusters of this age have been obtained only for very few objects in NGC 752 (Hobbs & Pilachowski, 1986).

We present here Li abundances for a sample of solar–type stars in the open clusters IC 4651 and NGC 3680. These clusters,

Send offprint requests to: S. Randich

* Based on observations carried out at the European Southern Observatory, La Silla, Chile

Table 1. The sample

IC 4651

name (1)	$(B-V)_0$	EW(Li I) (mÅ)	T_{eff} (K)	log n(Li)	RV info. (2)
EG 7	0.56	70 ± 15	6061	2.7 ± 0.12	S
EG 45	0.57	44 ± 7	6016	2.4 ± 0.12	S
AT 38	0.54	35 ± 8	6122	2.4 ± 0.06	
AT 39	0.54	49 ± 10	6114	2.6 ± 0.06	
AT 1108	0.53	47 ± 10	6189	2.6 ± 0.06	SB
AT 1109	0.62	61 ± 15	5814	2.4 ± 0.08	
AT 1225	0.51	64 ± 7	6235	2.8 ± 0.08	S
AT 2207	0.59	44 ± 10	5908	2.3 ± 0.08	
AT 2105	0.54	48 ± 10	6110	2.5 ± 0.08	S
AT 3226	0.58	49 ± 8	5967	2.4 ± 0.06	NM
AT 4226	0.62	31 ± 10	5795	2.1 ± 0.08	

(1) From Eggen (1971) and Anthony-Twarog et al. (1988). Photometry comes from the latter source.
(2) Information on radial velocities (membership and binarity) was kindly provided by Dr. B. Nordström.

NGC 3680

name	$(B-V)_0$	EW(Li I) (mÅ)	T_{eff} (K)	log n(Li)	RV info.
23	0.58	46 ± 5	5971	2.41 ± 0.04	SB1
60	0.59	48 ± 6	5924	2.38 ± 0.05	M?
70	0.60	42 ± 5	5884	2.28 ± 0.04	M
4114	0.58	51 ± 6	5951	2.44 ± 0.05	M?

(1) Star numbers, colors, and information on membership/binarity were taken from Nordström et al. (1997).

for which metallicities close to solar have been derived (Friel 1995), have estimated ages of 1.5 – 2 Gyr (e.g., Meynet et al. 1993; Friel 1995); these data, therefore, allow us to address the problem of Li depletion from the age of the Hyades to that of M 67 and to put observational constraints on the mechanisms responsible for MS Li depletion and on their timescales.

2. Observations and analysis

The observations of both clusters were carried out at ESO, La Silla. Most of IC 4651 stars were observed during three observing campaigns in June 1997, June 1998, and May 1999. The 3.6 m telescope with the CASPEC spectrograph was used; the standard grating (31.6 lines/mm), the red cross-disperser, the long camera, and ESO CCD #37 (1024×1024 24μ pixels) were employed. A few additional IC 4651 spectra were taken in sparse observing runs with FEROS at the 1.5 m ESO telescope and with CASPEC. The spectra of NGC 3680 were obtained using CASPEC. Different slit widths (from 1.4 to 2 arcsec) were used in the various CASPEC runs due to different seeing conditions. Correspondingly, we obtained spectra with resolving powers ranging from $R \sim 20,000$ to $R \sim 30,000$. The FEROS spectra have resolution $R = 48,000$. The S/N of the spectra is in the range $\sim$ 30 to 60.

Data reduction for the CASPEC spectra was performed using the ECHELLE context within MIDAS and following the usual steps. FEROS spectra were reduced using the FEROS data reduction pipeline.

Lithium abundances were obtained in the same fashion as in Jones et al. (1999) for M 67. Namely, effective temperatures were derived from dereddened $B-V$ colors using the relationship of Soderblom et al. (1993). Reddening values E(B–V)$= 0.05$ and 0.083 were assumed for NGC 3680 and IC 4651, respectively. Abundances were derived from measured equivalent widths (EWs) using the curves of growth (COGs) of Soderblom et al. (1993). When the Li I 6707.81 doublet was blended with the Fe I λ 6707.44 line, we estimated the contribution of the latter using the prescription of Soderblom et al. (1993). Information on the sample stars together with our Li measurements are given in Table 1. We carried out a similar analysis for NGC 752 and NGC 188, using the published Li EWs (from Hobbs & Pilachowski 1986, 1988) and the most updated sources for photometry and membership. Hyades data from Thorburn et al. (1993) were also re-analyzed in a consistent way. We stress therefore that the Li abundances used in this letter are all on the same abundance scale.

Besides dwarf stars, we observed giants and turn–off stars in the two clusters; these data will be used to address different issues and they will be presented in a separate paper.

3. Results

In Fig. 1 we plot $\log$ n(Li) vs. effective temperature for IC 4651 and NGC 3680 together with the Hyades, NGC 752, M 67, and NGC 188. Four major features are evident in the figure: **1.** The three about coeval clusters, IC 4651, NGC 3680, and NGC 752,

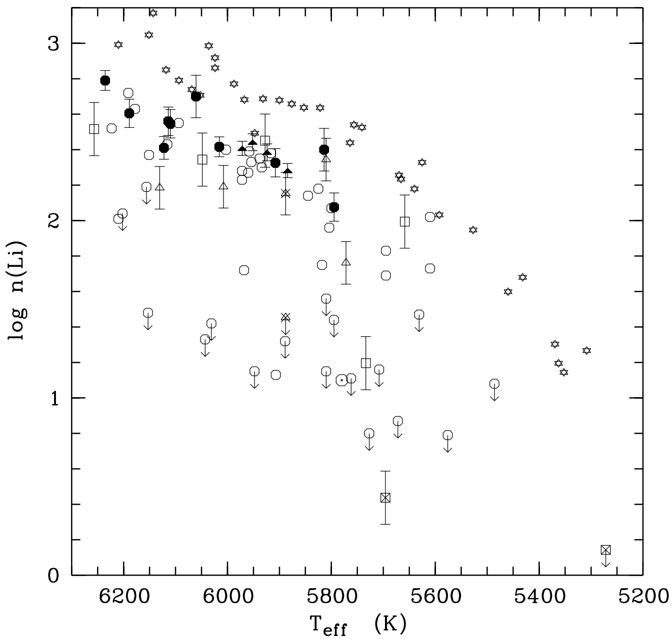

Fig. 1. $\log$ n(Li) vs. $T_{\rm eff}$ for our sample stars in IC 4651 and NGC 3680 (filled circles and triangles, respectively), the Hyades (stars), M 67 (open circles), NGC 752 (open squares), and NGC 188 (open triangles). M 67 data have been taken from Jones et al. (1999). The SB2 binary S1045 is not included in the figure. Possible non–members in NGC 752 and NGC 188 are indicated as crossed symbols. Errors in $\log$ n(Li) take into account only errors in EWs. The Sun is also shown in the figure.

have very similar Li vs. $T_{\rm eff}$ distributions, with only a couple of IC 4651 stars lying somewhat above the average trend (but within 1σ error bar from it). Their average Li at a given $T_{\rm eff}$ is about 0.4 dex (or a factor 2.5 in abundance) below the Hyades; **2.** if we consider the upper envelope of the Li vs. $T_{\rm eff}$ patterns, it is evident that the less Li depleted stars in M 67 have very similar abundances as the stars in the ~ 2 Gyr clusters. The NGC 188 (age 6–7 Gyr) sample is too small and the error bars too large to allow definite statements, but there might be an additional slight Li decrease with respect to M 67; **3.** *none* of the three intermediate age clusters shows any significant dispersion for stars warmer than $\sim$ 5800 K; there are no stars cooler than this in NGC 3680 and IC 4651, while the three NGC 752 stars cooler than 5800 K have significantly different Li abundances (but one is possibly a non–member); **4.** as now well known, a large fraction of stars in M 67 have suffered much more Li depletion than stars defining the upper envelope of this cluster.

Under the assumption that all the clusters had the same initial Li abundance, the four points listed above in turn suggest that: **i.** Li depletion among solar–type stars older than the Hyades is a single function of age up to $\sim$ 1.5–2 Gyr and $T_{\rm eff} \sim$ 5800 K; **ii.** the mechanism which drives Li depletion between the Hyades and the 2 Gyr old clusters appears to saturate, or to considerably slow down, at ages of 2 Gyr. If stars continued to deplete Li at the same rate as between the Hyades and the 2 Gyr clusters, one would expect a maximum Li abundance (in the range $\sim 6100 < T_{\rm eff} < 5800$ K) of the order of $\log$ n(Li)~ 2.1 at the M 67 age and of the order of ~ 1.95 at the NGC 188 age. Both clusters show a higher maximum Li abundance; the alternative hypothesis can be made however that Li-rich M 67 stars suffered a slower overall Li destruction than inferred from younger clusters; **iii.** Li depletion appears to stop or to slow down only for a fraction of the stars, while the other fraction suffers significant additional depletion. Additional depletion may start at ages younger than 2 Gyr for stars cooler than 5800 K. On the other hand, we cannot exclude that the Sun itself at 2 Gyr still had a Li abundance a factor of 10 higher than its present value.

Before trying to interpret these results, we must check whether and to which extent the lack of a major dispersion among the IC 4651 and NGC 3680 clusters may be due to low number statistics. 37 M 67 members are included in the 6200 $\geq T_{\rm eff} \geq 5800$ K range: excluding the SB2 binary S1045, 11 of them ($\sim$ 30%) are Li–poor, 23 ($\sim$ 62%) are Li-rich, and one has a very high Li upper limit. The IC 4651 + NGC 3680 merged sample in the same temperature range contains 14 stars; more specifically, our sample contains about half of the total population of solar–type stars in IC 4651 and all the presently known solar–type stars in NGC 3680. In order to have a similar fraction of Li-poor/Li rich stars as in M 67 one would have to assume that all the Li-rich stars fell in our (unbiased) sample or, viceversa, that most of the stars that were not observed by us are Li-poor. Whereas this possibility cannot be entirely excluded, it would represent a very unusual coincidence.

4. Constraints on MS Li depletion mechanism(s)

Basically four possible processes have been suggested in the literature for Li depletion on the MS: namely, microscopic diffusion, mass loss, and slow mixing either induced by rotation or driven by gravity waves.

a) Diffusion is a slow mechanism and could in principle explain the smooth decay of the maximum Li abundance between the Hyades and the 2 Gyr clusters, as well as the lack of a star-to-star scatter up to at least 2 Gyr. Diffusion has been shown to be able to explain Li in the Sun, where He diffusion is validated by heliosismology (Vauclair 1998). However, diffusion is probably far too slow: model calculations suggest that due to the increasing depth of the convective zone, below 6400 K the diffusion timescales are very large, comparable to the evolutionary timescale, and thus no significant Li depletion should occur before the star reaches the very end of its MS lifetime (Michaud 1986). In addition, it would be difficult to explain the “saturation” of Li depletion that seems to occur for clusters older than 2 Gyr. **b)** Mass loss has been shown not to be able to reproduce the Hyades Li vs. $T_{\rm eff}$ distribution (Swenson & Faulkner 1992) and, according to the same authors, it would be even more difficult to reproduce the NGC 752 pattern; by extension, it is reasonable to expect that diffusion would not be able to account for the IC 4651 and NGC 3680 Li patterns. In any case, contrary to diffusion, mass loss is probably a too fast mechanism to account for the slow decrease of the maximum Li abundance. **c)** Both rotation (due to angular momentum loss) and waves driven mixing mechanisms are rather slow processes and, in this sense, have the right timescales to explain the decay between the Hyades and the 2 Gyr clusters. **c1)** Montalbán & Schatzman (1996) were able to reproduce the Hyades pattern at 600 Myr with somewhat simplified models including gravity waves and a certain amount of PMS depletion; the speculation therefore can be made that the distribution of older clusters may be fitted as well. However, it is not clear whether this mechanism would saturate or not; **c2)** as to rotational mixing, quoting from Pinsonneault (1997), "Theoretical models of rotational mixing in solar analogs produce a rate of depletion that decreases with age as stars spin down". Thus, it is plausible that Li destruction eventually stops (or becomes very slow) when stars are completely spun-down. However, whereas "The existence of a dispersion is a prediction of rotational mixing", our results indicate that a significant dispersion develops only very late during MS evolution. In Fig. 2 we show again $\log$ n(Li) vs. $T_{\rm eff}$ for IC 4651, NGC 3680, NGC 752, and M 67. The rotationally induced mixing isochrones at 1.7 and 4 Gyr of Deliyannis & Pinsonneault (1997; see also Stephens et al. 1997) for two initial rotational velocities are also shown in the plot. The figure indicates that the virtually null Li destruction for Li-rich stars observed between the 2 Gyr clusters and M 67 is not predicted by the models and, more in general, that the upper envelopes of the observed distributions are not well reproduced by the isochrones corresponding to initial velocities of 10 km/sec, too much Li depletion being predicted by the latter models. In addition, as the figure shows, the models predict that a large difference in Li between stars with initial velocities of 10 and 30 km/sec should be present already at ages of $\sim$ 1.7 Gyr. On the other hand, the 4 Gyr model with an initial rotational velocity of 30 km/sec fairly well reproduces the lower envelope of M 67.

In summary, both diffusion and mass loss can probably be excluded as processes affecting in a major way Li depletion on the MS. If any, diffusion may have some effect between M 67 and NGC 188, if the maximum Li abundance in the latter cluster is really slightly below that of M 67. Gravity waves are a viable mechanism, but they cannot reproduce the spread observed in M 67; more work needs to be carried out on model calculations to check whether they could fit the intermediate age cluster patterns. Rotational mixing has in principle the requirements to meet the observational constraints, but currently available models do not fit quantitatively the observational data. In order to get a better agreement between observations and models, the latter ones should predict an even slower Li depletion for stars with low initial velocities (of the order of 10 km/sec –models with even lower initial velocities should also be computed) and, furthermore, they should predict no (or very small) additional depletion after 2 Gyr for these stars (it is conceivable that stars starting their MS lifetimes with low rotational velocities should have a small degree of internal differential rotation by that age). In order to reproduce the lack of a spread at 2 Gyr, stars that start their MS lifetimes as rapid rotators should deplete the same amount of Li as initially slow rotators up to $\sim$ 2 Gyr; afterwards rotation driven mixing should become much faster.

The above discussion is based on the assumption that the three middle–aged clusters are representative of stars at 2 Gyr,

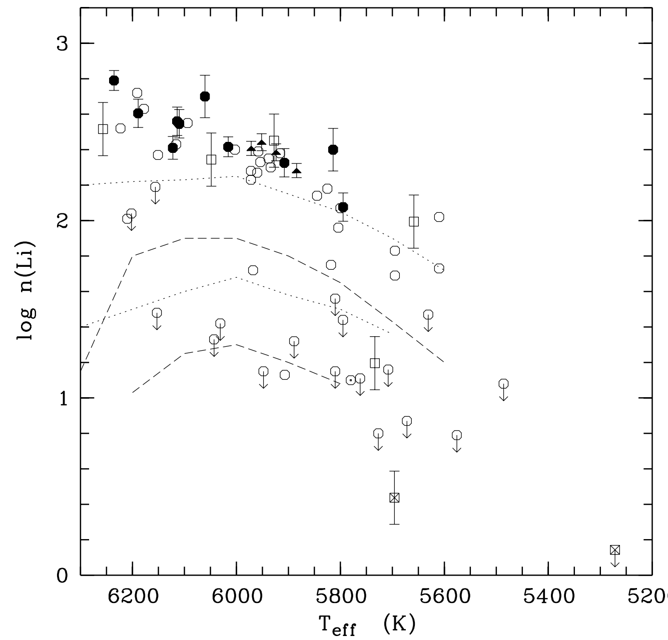

Fig. 2. $\log$ n(Li) vs. $T_{\rm eff}$ for IC 4651, NGC 3680, NGC 752, and M 67. Symbols are the same as in Fig. 1. Dotted and dashed curves represent the 1.7 Gyr and 4 Gyr isochrones for models with rotationally induced mixing; upper and lower curves at the same age denote models with initial rotational velocities of 10 and 30 km/sec, respectively.

while M 67 is representative of stars at the solar age. In other words, we gave for granted that the M 67 and the middle–aged clusters had similar initial properties (in particular a similar distribution of rotation rates) and that M 67 at 2 Gyr had a similar Li distribution as the intermediate clusters or, viceversa, that the latter clusters would show at the M 67 age a Li pattern similar to that of M 67. However, we cannot exclude that M 67 and the intermediate age clusters were characterized by different initial conditions and, consequently, underwent a different rotational history and Li evolution. For example, the intermediate age clusters may have had a very small initial rotational spread with most of the stars being very slow rotators (but available rotational data for young clusters do not support this ideas); or, as originally suggested by García López et al. (1988), there may have been more than one burst of star formation within M67. Obviously, additional intermediate age and old clusters should be observed in order to test these hypotheses.

Acknowledgements. We are grateful to Drs. J. Andersen and B. Nordström for providing information on radial velocities and membership for IC 4651 prior to publication. We thank the referee, Dr. F. Spite, for useful comments on the manuscript.

References

Anthony-Twarog, B.J., Mukherjee, K., Caldwell, N., and Twarog, B.A. 1988, AJ 95, 1453

Deliyannis, C.P. 2000, in: Stellar Clusters and Associations: Convection, Rotation, and Dynamos, ASP Conf. Ser., eds. R. Pallavicini, G. Micela, and S. Sciortino, in press

Deliyannis, C.P., and Pinsonneault, M.H. 1997, ApJ 488, 833
Eggen, O.J. 1971, ApJ 166, 87
Friel, E.D. 1995, ARA&A 33, 381
García López, R.J., Rebolo, R., and Beckman, J.E. 1988, PASP 100, 1489
Hobbs, L.M., and Pilachowski, C. 1986, ApJ 309, L17
Hobbs, L.M., and Pilachowski, C. 1988, ApJ 334, 734
Jeffries, R. 2000, in: Stellar Clusters and Associations: Convection, Rotation, and Dynamos, ASP Conf. Ser., eds. R. Pallavicini, G. Micela, and S. Sciortino, in press
Jones, B.F., Fisher, D., and Soderblom, D.R. 1999, AJ 117, 330
Meynet, G., Mermilliod, J.-C., & Maeder, A. 1993, A&AS 98, 477
Michaud, G. 1986, ApJ 302, 650
Montalbán, J., & Schatzman E. 1996, A&A 305, 513
Nordström, B., Andersen, J., and Andersen, M.I. 1997, A&A 322, 460
Pasquini, L. 2000, IAU Symp. 198, ASP Conf. Ser., eds. M. Spite, L. da Silva, and J.R. de Medeiros, in press
Pasquini, L., Liu, Q., and Pallavicini, R. 1994, A&A 287, 191
Pasquini, L., Randich, S., and Pallavicini, R. 1997, A&A 325, 535
Pinsonneault, M.H., 1997, ARA&A 35, 557
Soderblom, D.R., Jones, B.F., Balachandran, S., et al. 1993, AJ 106, 1059
Spite, F., Spite, M., Peterson, R.C., Chaffee, F.H.Jr. 1987, A&A 171, L8
Stephens, A., Boesgaard, A.M., King, J.R., and Deliyannis, C.P. 1997, ApJ 49, 339
Swenson, F.J., and Faulkner, J. 1992, ApJ 395, 654
Thorburn, J.A., Hobbs, L.M., Deliyannis, C.P., and Pinsonneault, M.H. 1993, ApJ 415, 150
Vauclair, S. 1998, Space Sci. Rev. 84, 265.