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Lithium in M 67: evidence for spread in a solar age cluster*

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Abstract. We present high resolution observations of main sequence stars in the solar age, solar metallicity open cluster M 67. For the first time we show conclusively that a spread in lithium abundances exists among solar-type stars belonging to this cluster. This implies that standard models with only convection as a mixing mechanism can hardly account for the spread at each colour, and that the Li abundance is not a good age indicator for solar-type stars. The comparison of Li abundances in M 67 (age $\sim 4.7 \times 10^9$ yrs) with those in the younger Hyades cluster ($\sim 7 \times 10^8$ yrs) shows that the less depleted stars in M 67 have a Li content only $\sim$ 0.25 dex below similar stars in the Hyades. Considering the $\sim$ 4 Gyrs difference between the two clusters, this indicates that standard lithium destruction mechanisms are very inefficient (if present at all) in many solar-type stars during most of their main sequence lifetime. On the other hand, almost 40% of our sample stars show a significant Li depletion, with values comparable to the Sun. Our sample also includes one SB2 binary, for which a very high Li abundance was previously reported. We found an abundance significantly higher than in single stars, but our spectra are inconsistent with those previously published.

Key words: stars: abundances – open clusters: individual: M 67

1. Introduction

In his classical work, Skumanich (1972) showed that chromospheric activity, rotational velocity and lithium abundance in solar-type stars decreases with age. Subsequent work (e.g. Pallavicini et al. 1981, Noyes et al. 1984) demonstrated that the relationship between surface activity and age is indirect. Activity depends on stellar rotational velocity, and the relationship with age reflects the evolution of stellar rotation during main sequence lifetime: due to magnetic spin down, young single stars rotate faster than old ones and thus have a higher level of activity.

The dependence of Li abundance upon age is more intriguing. Since Li is easily destroyed in stellar interiors at temperatures above $\sim 2.5 \times 10^6$ K, depletion during main-sequence lifetime (and for the coolest stars also during pre-main sequence evolution) is expected for those stars with convective zones deep enough to mix surface material down the point where Li is burned. However the observations are in disagreement with the predictions of standard models even for the best studied and "well behaved" open cluster, the Hyades, unless *ad hoc* assumptions are made (Swenson et al. 1994).

Li observations of Pop I solar-type stars in the field gave more puzzling results: Duncan (1981), using Ca II emission as a proxy for age, pointed out the presence of stars with low chromospheric activity but high Li abundance. Pallavicini et al. (1987), using a smaller sample but higher quality data, confirmed Duncan's results, finding in addition that, whereas a general trend exists between chromospheric activity and stellar rotation, the same is not true for Li abundances, indicating that the problem is indeed with Li. In a detailed analysis of the Li-rich low-activity subgiant β Hyi, Dravins et al. (1993) suggested that lithium could be stored during main sequence evolution just below the convective zone, rather than destroyed, and that this Li-rich material could be brought back to the surface when a star evolves off the main sequence. In this interpretation, however, high Li abundances in old solar-type stars should be found only among evolved stars.

Pasquini et al. (1994), analyzing high quality data for a volume limited sample of nearby G dwarfs, showed that a large dispersion in Li abundances is present among stars otherwise similar to the Sun, and that this spread does not correlate with any of the measurable stellar parameters like absolute magnitude, effective temperature, and metallicity. This study also pointed out that old Li-rich stars are quite common and not limited to a few, exceptional cases.

To conclude, the question arises whether the Sun, which had an initial abundance N(Li) = 3.31 (in the usual logarithmic scale where N(H) = 12.0) and a present abundance N(Li) = 1.16 (i.e., a factor 100 lower, Grevesse et al. 1996) should be regarded as the 'standard' for stars of its mass, age and metallicity or

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rather if additional depletion mechanims, not account for in the standard models, need to be considered.

The results outlined above are based on field stars, for which distances, magnitudes and ages are poorly known; clearly, observations of an open cluster with solar age would allow determining whether a spread in Li abundance really exists among solar-type stars, with interesting consequences for our understanding of the relationship between Li abundance and age.

M 67 is an ideal target for this study, because the cluster has been extensively observed for proper motions (Sanders 1977, Girard et al. 1989) and thus a reliable membership list exists; moreover, accurate CCD photometry has been obtained (Montgomery et al. 1993), and surveys for detecting the presence of binaries have been carried out (Latham et al. 1993). Finally, the cluster age (about 4.7 Gyrs) and the solar metallicity (Fe/H ~ 0) (Janes and Phelps 1994) offer the possibility of making a direct comparison with the Sun. A few observations of Li in this cluster have been carried out (Hobbs and Pilachowski 1986, Spite et al. 1987, Garcia Lopez et al. 1988), suggesting that a spread in Li abundances may be present among solar-type stars belonging to the cluster. We present here new observations of G-type stars in the cluster which extend those carried out in the past and allow addressing the question of the Li spread on a firmer statistical basis.

2. Sample selection and observations

Sample stars were selected according to two criteria. First we chose objects with a membership probability higher than 90% in the proper motion studies of Sanders (1977) and Girard et al. (1989). Second, we made an effort not to include known binaries in our sample: therefore, in all but one case (see Sect. 4.2) we chose stars that were not catalogued as binaries in the literature. We anticipate, however, that some of our objects turned out to be either binaries or radial velocity variables on the basis of later surveys. We will flag those stars in the following discussion.

The observations were carried out at ESO, La Silla, in February 1995 using the CASPEC Spectrograph at the 3.6m telescope (Randich and Pasquini 1996). CASPEC was used in combination with the red crossdisperser, the long camera and the 31.6 lines/mm echelle grating. Coupling the long camera with the Tektronix CCD ESO #37, which has 24 μm square pixels, a spectral coverage of 2400 Å was covered, with a dispersion of $\sim$ 0.080 Å/pixel in the lithium region.

Due to the cluster declination, the combined telescope plus instrument image quality was not very good, and a slit width of 2 arcsec had to be used, giving a resolving power of $\sim 20,000$. This resolution corresponds to a FWHM for unblended calibration lines of $\sim$4 pixels. Stars with V=14 were observed for 1.5 hours, giving a typical signal to noise (S/N) ratio of about 50 per pixel.

In the reduction phase, one of the largest uncertainties is given by the subtraction of the interorder light. For this reason, the spectra were reduced (and normalized) in two independent ways, with two different background subtractions, finding that the differences in the measured Li equivalent widths were at most of 7 mÅ, in good agreement with what expected from the resolution and the S/N ratio.

In Table 1 the basic parameters of the observed stars are summarized, together with the measured Li equivalent widths. Note that at our resolution, the Li feature at 6707.81 Å cannot be separated from a nearby 6707.44 Fe line, whose contribution is thus included in the equivalent widths given in Table 1. This contribution will be subtracted before converting equivalent widths to Li abundances (see Sect. 3). Note that for star S1045 (the only double line spectroscopic binary in the sample) the measured equivalent widths of each component include, in addition to the 6707.44 blend, any contribution coming from the other component of the binary system. The abundances for this binary were derived using spectral synthesis (cfr. Sect. 4.2).

The photometry from Montgomery et al. (1993) available for all but one object (S958) has been consistently adopted. In Table 1 stars are numbered according to Sanders (1977). Although, as mentioned in the previous section, we tried to avoid known binaries, some may still be present in the sample. After the observations were taken, Dr. Mathieu kindly provided us with his latest results from a radial velocity survey of the cluster (Mathieu and Latham 1996, in preparation); it turned out that some of our target stars are either binaries or show radial velocity variations. These objects have been flagged in the last column of Table 1.

3. Li abundances

Lithium abundances were derived using the curves of growth of Soderblom et al. (1993a). The contribution of the 6707.44 Fe line to the Li blend was subtracted using the empirical correction of the same authors. In a few cases we also performed spectral synthesis of a 20 Å region centered at Li, using an updated version of the synthetic code by Gratton and Sneden (1990), finding results that were in excellent agreement with those obtained using the Soderblom et al. (1993a) curves of growth and empirical correction for the Fe blend. Such an agreement is to be expected since both analysis are based on similar codes and on the Bell et al. (1990) model atmosphere. Balachandran (1995) pointed out how a simplified treatment of the Li doublet may result in overabundance estimates for large Li equivalent widths. Since our synthetic code uses a list of lines where the two components of the Li doublet are taken into account separately, our abundance estimates are correct also for high Li values.

How the uncertainties on the derived Li abundances depend on stellar parameters has been extensively discussed elsewhere (e.g. Pasquini et al. 1994). It is well known that the effective temperature is the most critical parameter. In this work we have used the T_{eff} vs. B$-$V calibration of Böhm-Vitense (1981). The same calibration was also used by Balachandran (1995) in her study of Li-dip stars in M 67 and in her critical reassessment of published data of Li in cluster stars. The reddening was fixed to E(B-V)=0.04 (Cayrel de Strobel 1990). We note however that in order to study the Li scatter in a cluster the choice of the temperature scale is not important, since to this purpose absolute abundances are not needed. A comparison of measured equivalent

Table 1. Observed Stars. Column 1-8 give: 1) Sanders (1977) number, 2) apparent V magnitude, 3) B-V colour, 4) V-I colour, 5) measured equivalent width (in mÅ) for the Li+Fe blend, 6) effective temperature, 7) Li abundance, 8) binary flag.

Name	V	B-V	V-I	E.W.	T_{eff}	N(Li)	Comments
958	14.54	.66	/	≤22	5819	≤ 1.63	
963	14.513	.706	.791	27	5662	1.68	Binary
976	13.095	.608	.718	≤13	6024	≤1.40	Var ?
982	14.122	.606	.714	≤12	6032	≤1.31	Binary
988	13.183	.574	.693	≤12	6169	≤1.49	
1011	13.821	.627	.803	47	5946	2.28	Var
1045	12.540	.591	.703	72+55	6100+6100	2.95+3.05	SB2 *
1055	13.795	.586	.699	45	6117	2.39	
1064	14.04	.660	.759	49	5819	2.16	Var
1075	13.837	.598	.658	58	6066	2.49	
1252	14.067	.643	.729	45	5883	2.20	
1255	14.486	.666	.774	≤12	5797	≤1.08	
1260	14.191	.625	.736	44	5954	2.23	
1283	14.115	.640	.744	32	5895	2.04	Var?

widths will result more accurate, because it will avoid adding the uncertainties involved in passing from measured quantities to abundances. In such a relative comparison, only two sources of uncertainties are present: errors in measured equivalent widths and errors in photometry. The first can be estimated in 5 mÅ. For the photometry, the differences (standard deviation) may be as large as a few hundreds of magnitude as estimated from a comparison of the results of different authors for the same object (cfr. Figs. 2-6 in Montgomery et al. 1993). However, by using the same source of photometry for all stars as we did (see previous section), these systematic errors are minimized. Montgomery et al. (1993) showed an internal accuracy (standard deviation) of ~ 0.003 mag for (B-V)and (V-I) and of ~ 0.002 mag for V for the magnitude and colour ranges of our sample stars.

A few high resolution studies of Li in dwarf stars in M 67 exist in the literature (Hobbs and Pilachowski 1986, Spite et al. 1987, Garcia Lopez et al. 1988). 17 stars belong to the magnitude/colour range we are interested in. In order to combine the published data with our sample thus doubling it, we followed the same approach of Balachandran (1995), i.e. we collected the published equivalent widths and we converted them to Li abundances by using the same procedure as for our data. The resulting abundances are therefore on one scale. The photometry from Montgomery et al. (1993) was available for all but one object (I160) and this photometry was adopted as for our data. The observations taken from the literature and reanalyzed in this way are summarized in Table 2. As in Table 1, the listed equivalent widths include the contribution of the 6707.44 Å Fe line to the Li blend. When the same star was observed by more than one author, the smaller upper limit has been adopted. Three of the published stars were also observed by us: we were able to give lower upper limits for two of them (S958, S976), while for the third (S988), the published upper limit could only be confirmed.

As already mentioned, uncertainties on the Li abundances are dominated by the uncertainty on the effective temperature whereas for warmer stars errors in the measured equivalent widths become also relevant. An error in T_{eff} of 150 K translates in an error in the Li abundance of 0.12 dex. Errors on the equivalent widths of 5 mÅ translates into Li uncertainties that depend on both the effective temperature and the equivalent width itself, and which are typically of 0.06 to 0.1 dex.

Table 2. Reanalyzed data from the literature. Columns 1 to 8 give: 1) original identification, 2) V magnitude, 3) (B-V) colour, 4) (V-I) colour, 5) Li equivalent width, 6) effective temperature, 7) Li abundance, 8) Sanders numbers and radial velocity flag.

Name	V	B-V	V-I	E.W.	T_{eff}	Li	Comments
I29	13.488	.627	.735	55	5946	2.38	758 Binary
I160	14.54	.66	/	≤30	5819	≤ 1.90	958
III22	13.198	.620	.737	19	5974	1.725	1292 Binary
III042	13.698	.635	.739	63	5914	2.438	1314
III043	13.308	.631	.733	49	5930	2.304	1092
I11	13.06	.567	.667	45	6199	2.502	998,F106 Var
I9	13.183	.581	.687	38	6138	2.36	994
I20	13.430	.560	.589	67	6230	2.756	990 Binary
II13	13.673	.660	.728	12	5819	0.971	1256
I48	14.052	.703	.787	≤15	5671	≤ 1.09	747
I46	14.380	.709	.800	≤13	5652	≤ 0.811	746
I19	14.564	.684	.796	≤12	5734	≤ 0.797	991
F127	12.755	.559	.681	20	6233	2.03	995
F111	12.730	.554	.690	≤21	6256	≤ 2.086	986 Binary
F128	13.145	.566	.700	≤28	6203	≤ 2.232	2205
F132	13.095	.608	.718	≤25	6024	≤ 1.981	976 Var ?
F129	13.183	.574	.693	≤12	6169	≤ 1.49	988

The correction for the 6707.44 blend varies between $\sim$7 mÅ for the hottest star to $\sim$10 mÅ for the coolest. The uncertainty in this estimate is smaller than the typical errors in the measurement of the equivalent widths.

4. Discussion

4.1. The spread

As outlined in the introduction, the main aim of the present work was to establish whether a real spread in Li abundances exists among main sequence stars in a solar-age, solar-metallicity cluster like M 67. The most appropriate way of investigating this issue, is first to look at the distribution of stars in a colour-equivalent width diagram; these are measured quantities and thus much less affected by errors than effective temperatures and Li abundances.

In Fig. 1 (upper panel) the Li equivalent widths are shown as a function of (B-V) colour. In the figure stars observed by us are represented with filled squares, while stars taken from the literature are indicated by open squares. Circles identify those stars for which radial velocity measurements indicate duplicity, variability, or possible variability (cf. Tables 1 and 2). We caution that some of the sample stars were not included in the Mathieu and Latham (1996) survey, therefore the number of possible binaries has to be considered as a lower limit.

From Fig. 1 it is clear that a large spread in the measured equivalent widths is present at each colour, well above the uncertainty of the equivalent width measurements. The spread is seen at all colours, indicating therefore that the observed spread is neither limited to the warmer stars (where it could indicate the presence of Li-gap stars, Boesgaard and Tripicco 1986, if these stars have not yet evolved off the main-sequence, contrary to what expected, cf. Balachandran 1995), nor to the cooler ones.

On the other hand, we know that the colour-magnitude diagram (CMD) of M 67 shows a large spread in magnitudes at each colour. It is therefore necessary to investigate whether the Li spread is related to the spread in the CMD. If, for example, the spread were caused by contamination from binaries, low equivalents widths could be due to dilution from the continuum of the secondary star: Li poor stars therefore should be located, on average, above the cluster main sequence.

Fig. 1 (lower panel) shows the V vs. B–V colour–magnitude diagram for the stars in Tables 1 and 2. Both upper limits and detections have been included in the figure. Known binaries are indicated. The figure clearly shows that the stars with upper limits in Li are uniformly distributed in the CMD, indicating that the spread is not linked to the stellar magnitude, at least not in a straightforward way. Fig. 1 also shows that no trend in Li is present among the binaries, and that the number of Li-poor binaries is basically the same as that of the Li-rich ones.

Fig. 2 is the same as Fig. 1, but for the (V-I) colour. The same pattern as in Fig. 1 is seen, leading to the same conclusions.

To conclude, the presence of binaries cannot fully explain the observed scatter in Figs. 1 and 2. As an example, in Fig. 3 the spectra of two pairs of supposedly single stars having similar colours but different Li lines are plotted. Clearly, the Li abundances are different, while no major difference is seen for the other lines, indicating that the scatter in Li is real.

Standard models, where the depletion of Li is due only to convective mixing, are unable to explain this spread, since for a given age, effective temperature, and metallicity, the Li abundance should be the same. Clearly this is not the case and other processes must affect Li depletion for solar-type stars in M 67.

For instance, rather than by convection, Li depletion could be caused by mixing mechanisms which depend on the stellar angular momentum, as suggested, among others, by Pinsonneault et al. (1990), Michaud & Charbonneau (1991) and Charbonnel et al. (1994). These mechanisms add an extra parameter –either rotational velocity or the initial angular momentum– and since this parameter is likely to be different from one star to the other, a spread in Li abundances can easily be produced. Alternatively, Li depletion in Pop I stars could basically follow the standard models (as suggested by Spite and Spite 1982) and the Li-rich stars at each colour could be the ones in which the standard convective mixing operates. In the Li-poor stars, an extra depletion occurs, It is unclear, however, what this mechanism might be.

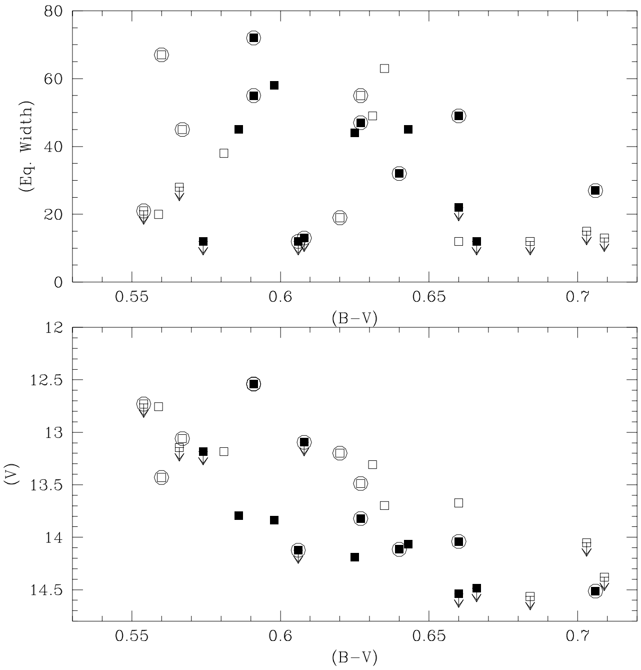

Fig. 1. (upper panel) Li Equivalent widths vs. B-V colour for M 67. Filled squares, our observations. Open squares, data taken from literature. Circles indicate known binaries or radial velocity variables. (lower panel) Colour-magnitude diagram for the same stars as in the upper panel. Symbols are as above. Stars with upper limits in Li are marked with arrows.

It is also possible, at least in principle, that small differences exist in the interior of otherwise similar stars, leading to different amounts of Li depletion. For instance, Swenson et al. (1994) have pointed out that Li depletion may strongly depend on the abundance of certain key elements, like oxygen, which can modify stellar atmospheric opacities and thus lead to different amounts of convective mixing. One could hyphotesize that the spread in Li among solar-type stars in M 67 is produced by differences in the abundances of other elements. It is difficult to understand how these differences could be present in a cluster; on the other hand, differences in CN-CH have been observed among main sequence stars belonging to the globular cluster 47 Tuc (Briley et al. 1994) which suggests that some chemical inhomogeneities may originate before the ascent of the red giant branch.

At the moment we cannot discriminate between these different hypotheses. We can broadly estimate the fraction of Li-rich

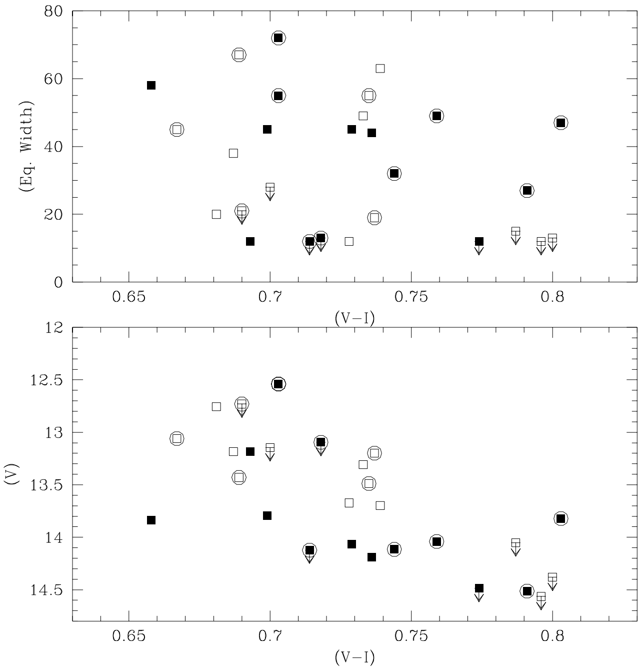

Fig. 2. (upper panel) Li equivalent widths vs. V-I colour for M 67. Filled squares, our observations. Open squares, data taken from literature. Circles indicate known binaries or radial velocity variables. (lower panel) Colour-magnitude diagram for the same stars as in the upper panel. Symbols are as above. Stars with upper limits in Li are marked with arrows.

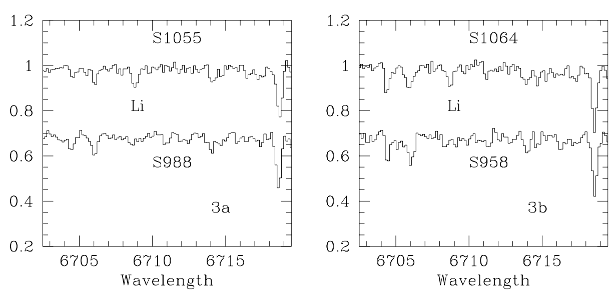

Fig. 3. CASPEC spectra in the Li region of pairs of stars with similar colours but different Li abundances. In each panel, the continuum of one of the star is shifted vertically with respect to the other for clarity reasons.

vs. Li-poor solar-type stars in M 67: this fraction may approach 40%, a percentage very similar to that observed among field G dwarfs (Pasquini et al. 1994).

We think that it is quite worrying that the CMD of M 67 is so scattered. Binaries can only partially explain the spread in magnitude of the CMD of this cluster. Even in our subsample, stars exist that have similar colours, but large differences in magnitude, and they are most likely single. It seems that in this old cluster it is hard to find two stars that are real “twins”.

4.2. S1045

One of our sample stars, S1045, is worth to be discussed separately, since this star is a known double-lined spectroscopic binary with similar components and a 7.6 day orbital period (Latham et al. 1993).

Li observations of S1045 were reported by Deliyannis et al. (1994) (hereafter we refer to these observations as CTIO), who found in both components a Li abundance of N(Li) $\sim$ 3, higher than the average Li abundance of M 67 stars. They interpreted this result as a strong support to the theory of rotationally induced mixing.

Deliyannis et al. (1994), however, do not seem to have taken in full account in their analysis the binary nature of this star: the spectra of the two components in fact were separated by $\sim$ 2.6 Å, making the Li line of one component (star 1) blended with the Fe 6705 Å line of the other component (star 2) and the Li line of star 2 blended with the 6710Å Fe line of star 1. Since they attributed the measured equivalent widths only to Li, their abundances are expected to be overestimated.

The CTIO digitized spectrum of S1045 was re-analysed by us using the same spectral synthesis code used by Randich et al. (1993) in their study of RS CVn binaries. By fitting this spectrum with two equal stars with T_{eff} = 6160 K and N(Li) = 2.96 (the first case in Table 2 of Deliyannis et al.), we obtained the synthetic spectrum shown in Fig. 4, which is clearly a non acceptable fit to the observed spectrum. In the same figure, the separate contributions of the two stars are also plotted, to show the severe blending of the Li and Fe lines. Note that, under the assumption of equal stars, each of the two components contribute to half of the total flux: the continua are therefore at the 0.5 level. A good fit of the CTIO spectrum was obtained assuming two equal stars with T_{eff}=6100 K and N(Li)=2.6. The latter value is significantly less than estimated by Deliyannis et al., while the temperature is the one adopted by us from the B-V calibration (cf. Table 1) and it is within the range of models considered by Deliyannis et al. (see their Table 2). The lower Li abundance derived by us from the CTIO spectrum is not significantly higher than for other stars in M 67.

To check this point further, we have reobserved S1045 at ESO on February 23, 1995. The results from our best fit are given in Tab. 1: a Li abundance of $\sim$ 3 for both stars was derived, a result quite different from that obtained by fitting the CTIO spectrum. Our CASPEC spectrum together with the best fit is shown in Fig. 5.

Why did we obtain different results from the CTIO and ESO spectra ? From a direct comparison of these spectra (which have similar resolution and similar separation between the two components), the reason from the discrepancy is clear (see Figs. 4 and 5): the CTIO spectrum shows a strong filling-in of all lines with respect to our CASPEC spectrum. The reasons for this filling-in remain unclear: either some scattered light was present in the CTIO spectrum, or some physical process makes the stellar continuum varying. Migrating spots are unlikely, because they should be exceptionally large, and such strong variations are not observed even in the most active stars (Pallavicini et al.

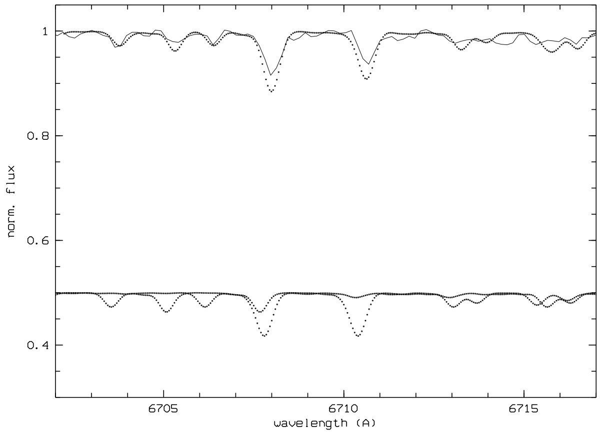

Fig. 4. CTIO spectrum of the SB2 binary S1045 (solid line) with overplotted the results of a spectral synthesis fit (dotted line) using the parameters of case 1 of Deliyannis et al. (i.e. two equal stars with T_{eff} = 6160 K and N(Li)=2.96). The fit is clearly unacceptable. The separate contributions of the two stars to the fit are also shown. Each star contributes to half of the total flux: the continua are therefore at the 0.5 level. Note the strong contamination of the Li line of both stars by Fe lines of the other star.

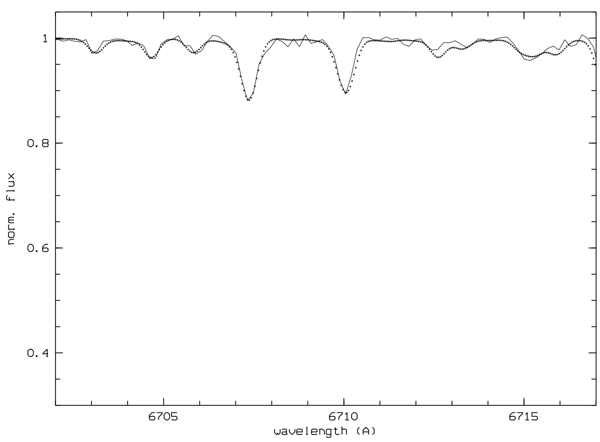

Fig. 5. ESO spectrum of the SB2 binary S1045 (solid line) with overplotted our best fit listed in Table 1 (dotted line).

1993). The existence of a third companion cannot be excluded, although it is unlikely that this hypothetical companion contributes only to the continuum, with no other spectral signature.

In summary, the case of S1045 is puzzling. The two existing high quality, high resolution spectra are inconsistent.

The high abundance inferred from our spectrum would indicate that the initial Li abundance in M 67 should have been at least as high as N(Li) $\sim$ 3. This value is close to the initial Li abundance in the solar system and is close to the maximum abundance measured in young clusters like the Pleiades, the Hyades and Praesepe. Thus, S1045 must have suffered very little depletion (if any!) during its main sequence lifetime.

4.3. Comparison with other clusters

In Fig. 6 Li abundances for M 67 stars are plotted (filled squares), together with the Li abundances for the Hyades (open stars) and for the 2 Gyr old cluster NGC752 (starred), as compiled by Balachandran (1995). The Sun is also shown in the plot. The stellar effective temperature scales used by Balachandran (1995) and in this work are the same, thus the abundances are on the same relative scale and should not be affected by major systematic uncertainties.

The fact that we have been able to prove the presence of a scatter in Li abundances among the stars of M 67 allows us to investigate the evolution of Li with age under a novel perspective. For sake of simplicity we refer to the M 67 stars with a low Li content as "overdepleted" (but equivalently we could consider the M 67 stars with high Li content at each colour as "underdepleted").

Fig. 6 shows that:

- The upper envelope of the M 67 stars follows closely the Hyades distribution, with only $\sim$0.25 dex offset (this difference may be larger for cooler stars).
- Although the NGC752 sample consists of only seven stars, no significant difference is evident between the distribution of Li abundances in M 67 and in NGC752.
- If the high abundance measured in S1045 is representative of the initial abundance of M 67, the initial solar system abundance (N[Li]=3.31, Grevesse et al. 1996) is not exceptional for the solar age and metallicity, but is shared by other coeval systems in the Galaxy. In addition, this would imply that a depletion of at least a factor 4 occurred for the other stars of M 67.
- The Li abundances among the M 67 stars cover a range of more than one order of magnitude, from values comparable to the present solar value (N[Li]=1.1), up to N[Li]$\sim$ 2.5. The fact that the Sun lies on the lower envelope of the M 67 distribution suggests that the Sun represents a quite normal case of "overdepleted" star 4 Gyrs old. Considering the M 67 sample and the sample of field G stars of Pasquini et al. (1994), the same behaviour is shared by $\sim$ 40% of the solar metallicity, solar age stars.
  Among the observed stars very few have Li abundances with intermediate values. In other words, the distribution of Li abundances in M 67 stars could be bimodal (although our statistics is not sufficient to prove it). A similar behaviour was observed among field G stars by Pasquini et al. (1994). If the low Li abundances are produced by a mechanism of extra depletion, this mechanism must be very efficient, when in force.

The observational evidences summarized above clearly show that Li abundance is not a good tracer of stellar age, at least for stars older than the Hyades. Different Li depletion mechanisms seem to operate for different stars of the same mass, which makes the interpretation of Fig. 6 in terms of evolution of Li abundance with age not straightforward.

The similarity between the Hyades curve and the M 67 upper envelope shows that *for some stars* Li depletion depends very

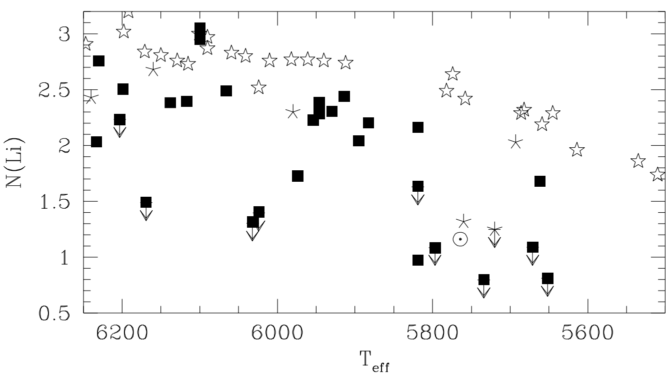

Fig. 6. Li abundances vs. effective temperatures for solar type stars in clusters of different ages: M 67 (4.7 Gyr, filled squares), Hyades (0.8 Gyr, stars), NGC752 (2 Gyr, starred). The position of the Sun is also indicated.

weakly on age during most of their main sequence lifetime: their Li content does not substantially change between an age of $\sim$ 0.8 Gyr and $\sim$ 4.7 Gyr. This result is also supported by sparse observations of the 6 Gyr old cluster NGC188 (Hobbs and Pilachowski 1988), in which several stars were found with a Li content as high as N[Li]=2.3. This suggests that Li depletion is not very efficient for many stars during main sequence lifetime. This conclusion assumes that the initial Li content of M 67 was as high as suggested by our analysis of S1045, i.e. N(Li) $\sim$ 3, a value comparable to the initial Li abundance in the Hyades and in the solar system. This conclusion would not be correct only in case the initial Li abundance in M 67 was much higher than in the Hyades, a possibility which at the moment is not supported by any observational evidence.

Conversely, for about 40% of the stars, a drastic Li depletion occurs. This depletion seems to start only after the first $\sim$ 1 Gyr of permanence on the main sequence. G stars strongly depleted in Li are in fact not observed in the Hyades and in the coeval Praesepe cluster (Soderblom et al. 1993b), while they are present in M 67 and possibly in the 2 Gyr old cluster NGC752. Is this depletion produced by mechanisms related to rotation and/or angular momentum loss, or by some other, yet unknown, extra depletion mechanism ? As mentioned in Sect. 4.1, we cannot yet discriminate between the various possibilities. The fact that S1045 has the highest Li abundance of any star in M 67 may indicate that rotation is relevant in the Li evolution, but the present data cannot firmly demonstrate it. The observed separation between "overdepleted" and "underdepleted" stars may, on the other hand, be of not easy interpretation in the framework of rotational theories, if this separation is as sharp as suggested by the presently available data (but the statistics is too low to be sure that the distribution is really bimodal). In fact, if different levels of Li depletion are produced by different amounts of angular momentum loss (and associated rotation-induced turbulence) one would expect to observe a continuous distribution of Li abundances rather than a bimodal distribution, unless the initial stellar angular momenta were unevenly distributed. Also, the absence of a spread in the Hyades argues against this mechanism.

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