LITHIUM IN SOLAR-TYPE STARS OF THE OLD OPEN CLUSTER M67

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ABSTRACT. We present high resolution observations of main sequence stars in the solar age, solar metallicity open cluster M67 obtained with the 3.6m telescope and the CASPEC spectrograph at ESO. We show conclusively that a spread in lithium abundances exists among solar-type stars belonging to the cluster. Standard models with only convection as a mixing mechanism cannot account for this spread at each colour. The comparison of Li abundances in M67 (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 M67 have a Li content only ~ 0.25 dex below similar stars in the Hyades. Considering the ~ 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, which requires an extra mixing process in these stars. Our sample also includes one SB2 binary (S1045), for which a very high Li abundance was previously reported on the basis of similar resolution CTIO spectra (Deliyannis et al. 1994). We found an abundance significantly higher than in single stars, but our spectra are inconsistent with those previously published, whose lines appear strongly filled-in.

1. Introduction

The depletion of Lithium during main-sequence lifetime is still poorly understood. According to classical models, the Li abundance should depend only on mass, metallicity and age. However, observations of solar-type stars in the solar neighbourhood (Pasquini et al. 1994) showed that a large dispersion in Li abundances is present among stars with the same colour and, supposedly, the same age. Observations of stars in a solar-age old cluster allows addressing this question in a much better way than by using field stars. M67 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. Observations and data reduction

The observations were carried out at ESO, La Silla, in February 1995 using the CASPEC spectrograph at the 3.6m telescope. CASPEC was used in combination with the red crossdisperser, the long camera, the 31.6 lines/mm echelle grating and the Tektronix CCD ESO #37. A spectral range of 2400 Å was covered, with a dispersion of ~ 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 $\sim 20,000$.

In Table 1 the basic parameters of the observed stars are summarised, together with the measured Li equivalent widths. 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. For the SB2 binary S1045, the abundances of the individual components were derived by spectral synthesis using an updated version of the code of Gratton and Sneden (1990).

Table 1. Observed Stars. Columns 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		$\leq$22	5819	$\leq$ 1.63	
963	14.513	.706	.791	27	5662	1.68	Binary
976	13.095	.608	.718	$\leq$13	6024	$\leq$1.40	Var ?
982	14.122	.606	.714	$\leq$12	6032	$\leq$1.31	Binary
988	13.183	.574	.693	$\leq$12	6169	$\leq$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	$\leq$12	5797	$\leq$1.08	
1260	14.191	.625	.736	44	5954	2.23	
1283	14.115	.640	.744	32	5895	2.04	Var?

A few high resolution studies of Li in dwarf stars in M67 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 collected the published equivalent widths and we converted them to Li abundances by using the same procedure as for our data. The observations taken from the literature and reanalyzed in this way are summarised in Table 2.

Table 2. Reanalysed 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		$\leq$30	5819	$\leq$ 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	$\leq$15	5671	$\leq$ 1.09	747
I46	14.380	.709	.800	$\leq$13	5652	$\leq$ 0.811	746
I19	14.564	.684	.796	$\leq$12	5734	$\leq$ 0.797	991
F127	12.755	.559	.681	20	6233	2.03	995
F111	12.730	.554	.690	$\leq$21	6256	$\leq$ 2.086	986 Binary
F128	13.145	.566	.700	$\leq$28	6203	$\leq$ 2.232	2205
F132	13.095	.608	.718	$\leq$25	6024	$\leq$ 1.981	976 Var ?
F129	13.183	.574	.693	$\leq$12	6169	$\leq$ 1.49	988

3. Results

In Figure 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 symbols, while stars taken from the literature are indicated by open symbols. Circles identify those stars for which radial velocity measurements indicate duplicity, variability, or possible variability. 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. This spread is not related to the stellar magnitude, as shown by the lower panel of Fig. 1. Therefore, the presence of binaries cannot explain the observed scatter.

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 abundances for S1045 were reported by Deliyannis et al. (1994) who observed the star at CTIO and found for both components a Li abundance of N(Li) $\sim$ 3. However, they did not take into account in their analysis the binary nature of the star, which makes 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. We have reanalysed their spectrum with a spectral synthesis code and we have found a significantly lower abundance N(Li)=2.6, assuming two equal

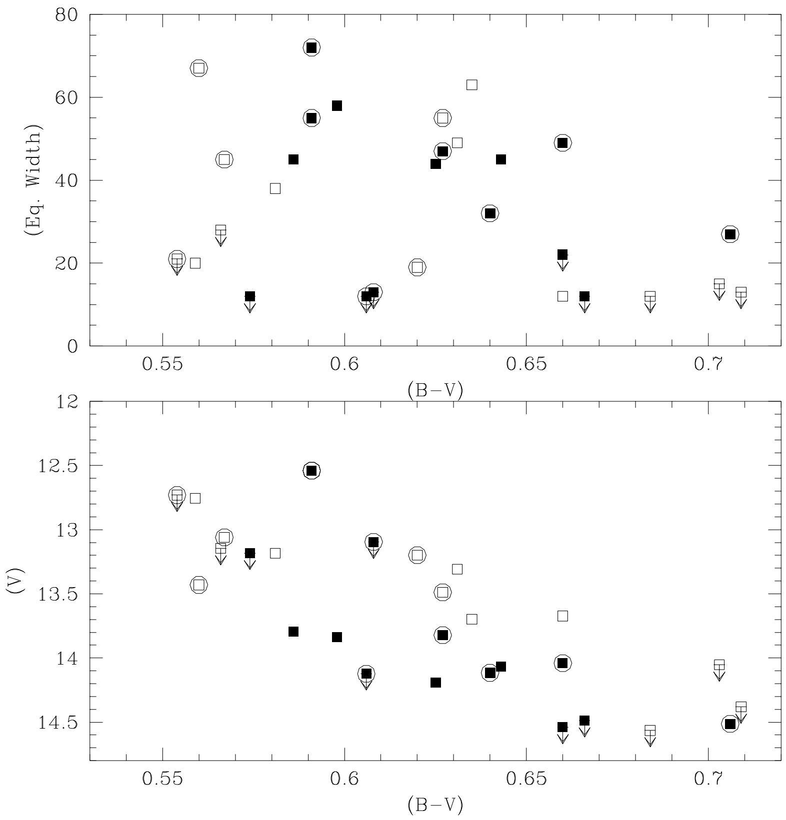

Fig. 1. (upper panel) Li equivalent widths vs. B-V colour for M67. Filled squares, our observations. Open squares, data taken from literature. Circles indicate known binaries or radial velocity variables. (lower panel) Colour-magnitude diagram for the same stars as in the upper panel. Symbols are as above. Stars with upper limits in Li are marked with arrows. Note the large spread in equivalenth widths at each colour.

stars with T_{eff}=6100 K. The lower Li abundance derived by us from the CTIO spectrum is not significantly higher than for other stars in M67.

To check this point, we reobserved S1045 at ESO, and we obtained by spectral synthesis a Li abundance N(Li) $\sim$ 3 for both stars, a result quite different from that obtained by fitting the CTIO spectrum, but in agreement with the original Li abundance quoted by Deliyannis et al. (1994). Direct comparison of the CTIO and ESO spectra shows that the two are inconsistent, with the CTIO spectrum showing a strong filling-in of all lines with respect to our CASPEC spectrum. This, together with neglecting the contribution of the other component to the Li equivalenth widths, conspired to produce a Li abundance that is in agreement with our more accurate analysis.

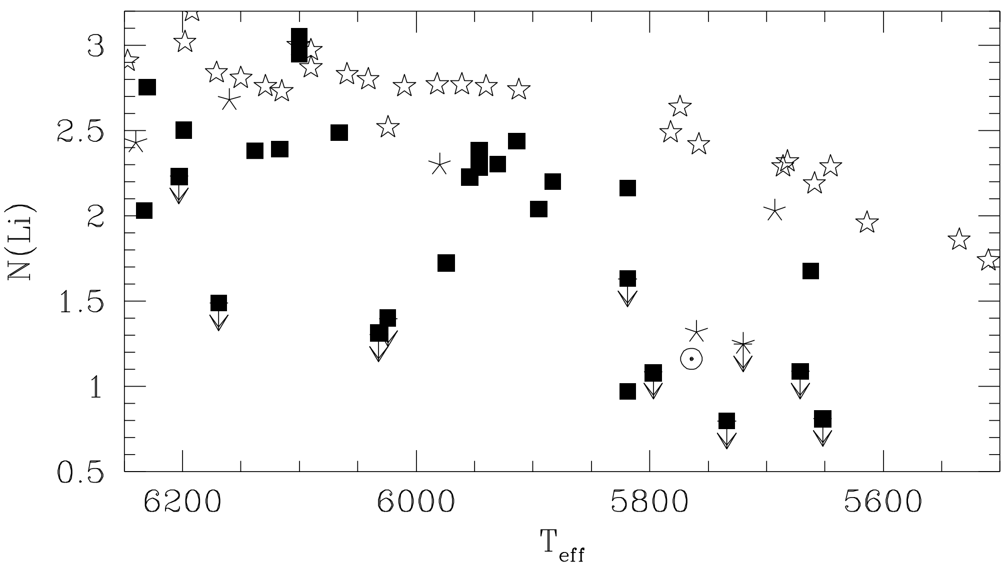

Fig. 2. Li abundances vs. effective temperatures for solar type stars in clusters of different ages: M67 (4.7 Gyr, filled squares), Hyades (0.8 Gyr, stars), NGC752 (2 Gyr, starred). The position of the Sun is also indicated. Note the much larger scatter in Li abundances of M67 stars with respect to the Hyades and the similar value of the *maximum* Li abundance in the two clusters.

The high abundance inferred from our spectrum indicates that the initial Li abundance in M67 must 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.

In Figure 2 Li abundances for M67 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. Fig. 2 shows that:

1. The upper envelope of the M67 stars follows closely the Hyades distribution, with only $\sim$0.25 dex offset for the warmer stars.
2. Although the NGC752 sample consists of only seven stars, no significant difference is evident between the distribution of Li abundances in M67 and in NGC752.
3. If the high abundance measured in S1045 is representative of the initial abundance of M67, a depletion of at least a factor 4 occurred for the other stars of M67.
4. The Li abundances among the M67 stars cover a range of more than one order of magnitude, from values comparable to the present solar value (N(Li)=1.1), up to N(Li)$\sim$ 2.5.

The similarity between the Hyades curve and the M67 upper envelope shows that *for* *some stars* Li depletion depends very 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 is based on the assumption that the initial Li content of M67 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.

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 M67 and possibly in the 2 Gyr old cluster NGC752. Whether this depletion is produced by mechanisms related to rotation and/or angular momentum loss (e.g. Pinsonneault et al. 1990, Michaud and Charbonneau 1991, Charbonnel et al. 1994), or by some other, yet unknown, extra depletion mechanism, cannot yet be definitely established.

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