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# Lithium in the intermediate age cluster NGC 3680: Following Li evolution along the C–M diagram*

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**Abstract.** We present an analysis of high resolution spectroscopic observations ($R \sim 30\,000$, $S/N = 60{-}150$) of 24 members of the intermediate age (∼1.5 Gyr) open cluster NGC 3680, covering all regions of the cluster colour-magnitude (C–M) diagram where cluster members are known to exist. These observations represent in many aspects challenges to our understanding of stellar interior and mixing. Four main sequence G stars have, within the errors, the same Li abundance, 0.3 dex lower than similar stars in the ∼1 Gyr younger Hyades but comparable with those observed in the coeval cluster IC 4651. The cluster shows a clear Li-dip located around the turn-off; two stars on the upper part of the turn-off are out of the dip and reach solar system meteoritic Li abundances. Just above the turn-off, in a very small range of magnitudes (∼0.2 in V), a factor of ∼5 Li depletion occurs. This sudden decrease explains puzzling results recently obtained on field subgiants but it is not at all reproduced by standard (e.g. no rotation, no diffusion) models, whereas it is in somewhat better agreement with the predictions of recent models which include rotational mixing and atomic diffusion. Out of the six cluster giants, one is probably a binary; of the remaining five single cluster members, three have a Li abundance log $n$(Li) $\sim 1.1$ while two have Li abundances from a factor 6 to more than a factor 30 lower than the other three. The star with no detected Li is the coolest and most luminous object in the sample and is most likely an AGB star; the other has instead a similar magnitude and effective temperature as the three more Li rich giants. The reasons for this difference in Li abundance among otherwise similar stars can be ascribed either to differential depletion during main-sequence or post-main sequence evolution, possibly induced by rotation, or to differences in the evolutionary status of these evolved stars. By comparing our results with those found for clusters of similar age and for field stars, we find that none of the possible scenarios gives a fully satisfactory explanation if the present population of NGC 3680 giants reflect the expected ratio of clump vs. first-ascent RGB stars. If the more abundant Li-rich giants in NGC 3680 are indeed clump giants, their relatively high Li content requires that Li is produced, or brought to the surface, between the tip of the RGB and the clump, which is not consistent with observations of the similar age cluster NGC 752, where the more abundant, presumably clump giants have low Li abundances. Finally, we have used our spectra to determine the metallicity of the cluster giants, finding [Fe/H] $= -0.17 \pm 0.12$. This value is in very good agreement with that derived from spectral indexes analysis, but substantially lower than the value inferred from Strömgren photometry.

**Key words.** stars: abundances – stars: evolution – open clusters: NGC 3680

## 1. Introduction

Despite the great progress made in the last ten years in the study of lithium evolution, the so-called Li problem is far from being solved. We do not fully understand how and when Li is produced nor how and when it is depleted. A definitive solution to this puzzle would allow us to answer several important questions related to primordial nucleosynthesis, chemical evolution of the Galaxy and mixing mechanisms in stellar interiors.

A full understanding of the Li problem requires a large observational effort, in order to properly sample the age, effective temperature, gravity and metallicity space; in this framework, observations of stars in clusters, i.e. in homogeneous samples of stars with approximately the same age and chemical composition, provide a unique, powerful tool. With the advent of efficient spectrographs coupled to 4 m class telescopes, it became possible to obtain high

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* Based on observations collected at ESO, la Silla, and at the VLT.

resolution, high signal to noise observations of late-type main-sequence stars in open and globular clusters to derive accurate Li abundances. In particular, Li observations in open clusters have flourished in the last years, producing a wealth of new results which allow a more comprehensive understanding of the Li evolution in Pop I stars, of the chemical enrichment of the Galaxy and of the mixing processes in the interior of stars (see e.g. Deliyannis 2000; Jeffries 2000; Pasquini 2000 for recent reviews). However, most studies have concentrated so far on the young galactic population (at ages younger than the Hyades), while observations of old Pop I cluster stars have been rather limited, with the noticeable exception of the ∼4 Gyr old cluster M 67 (Pasquini et al. 1997; Deliyannis et al. 1997; Jones et al. 1999). Very little work has been done in particular on Li abundances in intermediate age clusters, which represent the link between the Hyades and very old clusters like M 67. Intermediate age clusters are particularly well-suited to test current models that relate Li depletion in solar-type stars to mass, age, metallicity and initial angular momentum (e.g. Deliyannis 2000).

In the framework of a long-term program aimed at studying lithium in stars belonging to intermediate and old clusters, we carried out a lithium study of the open cluster NGC 3680. With an estimated age of 1.45 Gyr, NGC 3680 is an intermediate age cluster; its metallicity derived from photometry is comparable to the Hyades; the reddening towards the cluster ($E(B-V) = 0.05$) is fairly low and well established (Nördstrom et al. 1996, 1997). Most important, NGC 3680 is one of the best studied clusters: accurate photometry is available in the literature and cluster membership has been established by means of proper motion and radial velocity studies. The cluster is not much populated, and only 37 stars are classified as bona fide members, of which 17 are binaries. 13 additional stars are classified as possible cluster members (Nördstrom et al. 1996, 1997). This extremely detailed analysis eliminates typical uncertainties related to the study of clusters, such as, in our case, possible differences in Li abundances due to duplicity or non membership.

NGC 3680 is also interesting because it is of an ideal age to test stellar evolution and it has been used to show the relevance of core overshooting in intermediate mass stars (Nördstrom et al. 1997); however, in their analysis these authors had to use photometric abundance estimates; it is therefore important to have a spectroscopic confirmation of the metal abundance, which is the most relevant free parameter in their analysis. NGC 3680 is also an ideal target because a cluster of this age allows the simultaneous testing of a number of questions relevant to Li, like the age-dependence of Li abundance and its dispersion among G-type stars, the formation of the Li dip and the post main-sequence evolution of lithium.

## 2. Observations, data sample, and analysis

The main body of our data was obtained at ESO la Silla, using the CASPEC spectrograph (Randich & Pasquini 1997) at the ESO 3.6 m telescope and the EMMI spectrograph at the NTT telescope. The resolving power was $R \sim 30\,000$ and the signal to noise ratio ranged from 150 for the brightest sources to 60 for the faintest ones. Most observations were obtained with CASPEC, and the instrument was coupled to the Long Camera and used in the long slit mode with a sampling of 2 pixels per resolution element. While this mode allows the observation of several stars simultaneously, only the order containing Li was recorded, therefore our wavelength coverage was restricted to 40 Å around the Li I 6707 Å line. Finally, three stars were observed in June 2000 with the UVES spectrograph on VLT *Kueyen* (Dekker et al. 2000), with a resolving power $R = 40\,000$ and a $S/N$ ratio in excess of 100. All the $S/N$ ratios quoted in this section are per resolution element.

The final sample consists of 26 stars, covering the known cluster giants and the main sequence stars down to a temperature of ∼5800 K. Since the study of Nördstrom et al. (1997) has shown that this cluster is disrupting and no firm lower mass cluster members could be identified, our sample covers the whole extent of the cluster color-magnitude diagram. Since observations started in 1995, before the publication of the Nördstrom et al. detailed study, two of the 26 observed stars were later found to be cluster non-members (and will be excluded from our analysis), while six of them were members, but belonging to binary systems. Three single stars in the sample are classified as possible members, while the remaining 15 stars are firm cluster members; all of them are supposedly single stars, based on radial velocities. However, one of them is classified as a possible binary (star 4001 in Table 1) because of its suspicious position in the colour magnitude diagram, although it has constant radial velocity, consistent with cluster membership (Nördstrom et al. 1997). The data for the observed stars are summarized in Table 1. Photometry is taken from Nördstrom et al. (1996), as well as names, membership and binarity information. In Fig. 1 the colour magnitude diagram (filled symbols: $B-V$, open symbols: $b-y$) of the observed stars is shown. Triangles represent binaries, squares single members. Non-members are not plotted in the diagram, and, although their data are included in Table 1, they will be ignored in the rest of this work. With regard to the three possible members in our sample, we treated them as confirmed members; none of the results and conclusions discussed in the following section critically depend on their inclusion in the sample or not.

As is well known, the effective temperature is the most critical parameter in the determination of the Li abundance, since the Li doublet is rather insensitive to gravity and metallicity but strongly dependent on $T_{\rm eff}$. We based our temperature calibration on the infrared flux semi-empirical method; more specifically, $T_{\rm eff}$ for main sequence stars have been derived using the $B-V$ calibration of Alonso et al. (1996), while for the evolved stars the effective temperature scale of Alonso et al. (1999) was adopted. A reddening $E(B-V) = 0.05$ has been assumed

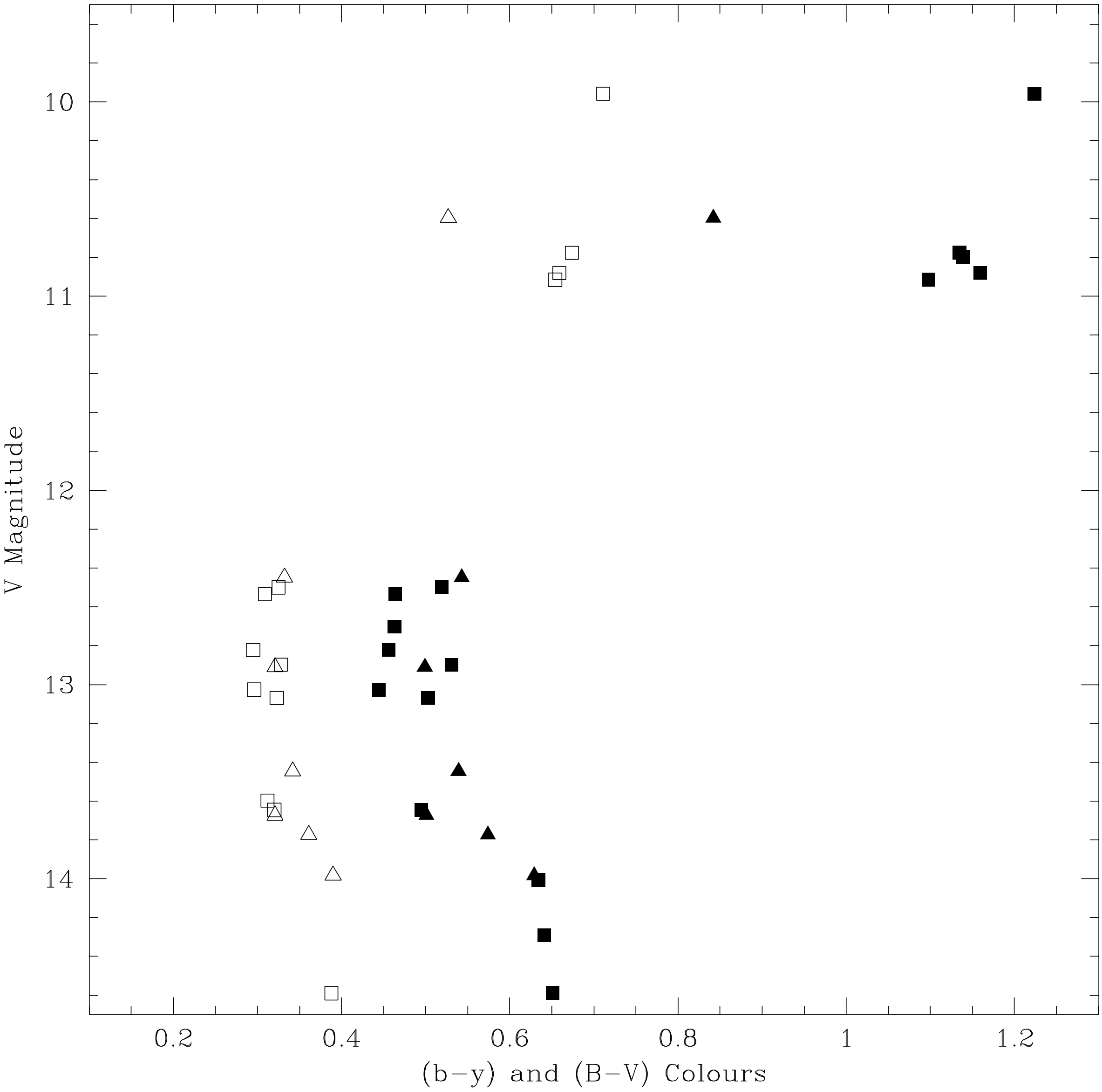


**Fig. 1.** Colour-Magnitude diagram for the observed stars. The stars are plotted vs. the $b-y$ (open symbols) and $B-V$ (filled symbols) colours. Single stars (both firm and possible members) are plotted as squares, binaries as triangles. The $b-y$ and $B-V$ sequences are clearly separated, with the $b-y$ sequence being the bluer one.

following Nördstrom et al. (1997), with a dispersion of only 16% among the single cluster members. The relative uncertainty on $T_{\rm eff}$ resulting from the adopted scale and the measured photometry and reddening can be estimated in $\pm$100 K. Note that for a typical G-type star a $\pm$100 K error translates into an error in Li abundance of $\pm$0.1 dex. As far as the absolute $T_{\rm eff}$ scale is concerned, a larger error on $T_{\rm eff}$ has to be realistically assumed; for the giants in the $(B-V) \sim 1$ colour range, for instance, Alonso et al. (1999) show that comparing different calibrations with their own, differences of up to $\pm$150 K (peak to peak) can be found. We also mention that the Alonso et al. scales depends somewhat on the assumed metallicity. To this purpose we used the photometric metallicity derived by Nördstrom et al. (1997). As we will see in the next section, this is $\sim$0.25 dex higher than what we infer from our spectra. If the latter metallicity is assumed, the effective temperatures would be systematically lower by 100 K and 60 K for the dwarfs and giants respectively. The resulting Li abundances would be $\sim$0.1 dex lower if this scale were adopted. Since the NGC 3680 data will be used to compare our results with those obtained for other clusters, we also note that our adopted scale for dwarfs coincides to better than 10 K with that used by Soderblom et al. (1993) in their study of the Pleiades cluster.

Equivalent widths for the Li I 6707 Å and the Ca I 6717 Å lines are also given in Table 1. At our resolution, the Li line is blended with the Fe I 6707.4 line, therefore the equivalent widths given in Table 1 refer to the blend of these lines and this has to be taken into account when converting the Li EWs of Table 1 into abundances (see below).

**Table 1.** Sample stars. Column 1: name (Nördstrom et al. 1996); Col. 2: $V$ magnitude; Col. 3: $B-V$ colour; Col. 4: $b-y$ colour; Col. 5: $v \sin i$; Col. 6: $T_{\rm eff}$; Col. 7: Li Equivalent Width (in mÅ including the 6707.4 Å blend); Col. 8: Ca I Equivalent Width (in mÅ); Col. 9: Li abundance; Col. 10: Membership and binarity flag. Colours, membership, binarity and $v \sin i$ are from Nördstrom et al.

| Name | $V$ | $B-V$ | $b-y$ | $v \sin i$ | $T_{\rm eff}$ | Li EW | Ca EW | $N$(Li) | Flag |
|---|---|---|---|---|---|---|---|---|---|
| 1031 | 9.957 | 1.224 | 0.711 | 1.1 | 4508 | 48 | 235 | <-0.5 | MB,E44 |
| E13 | 10.776 | 1.135 | 0.674 | 1.2 | 4668 | 104 | 224 | 1.05 | MB |
| E53 | 10.796 | 1.139 | // | 1.8 | 4661 | 97 | 229 | 1.05 | MB |
| 1050 | 10.880 | 1.159 | 0.659 | 1.5 | 4624 | 55 | 207 | 0.3 | MB,E41 |
| 4036 | 12.499 | 0.519 | 0.325 | 15.7 | 6410 | 41 | 96 | 2.68 | MB |
| E43 | 12.535 | 0.464 | 0.309 | 22.0 | 6655 | <30 | 90 | < 2.7 | MB |
| 3017 | 10.915 | 1.098 | 0.654 | 0.3 | 4738 | 104 | 223 | 1.20 | MB,E26 |
| 4028 | 12.700 | 0.463 | // | 27.1 | 6670 | 93 | 100 | 3.40 | MB(?) |
| E10 | 12.822 | 0.456 | 0.295 | 48.2 | 6693 | 75 | 70 | 3.30 | MB |
| E4 | 12.897 | 0.531 | 0.328 | 17.4 | 6353 | <20 | 100 | < 2.21 | MB |
| 1032 | 13.026 | 0.444 | 0.296 | 25.5 | 6756 | <11 | 91 | < 2.30 | MB |
| 4003 | 13.068 | 0.503 | 0.323 | 12.1 | 6481 | <12 | 93 | <1.89 | MB |
| E30 | 13.597 | // | 0.312 | 15.5 | 6595 | <7 | 92 | <1.85 | MB |
| 3012 | 13.646 | 0.495 | 0.320 | 27.1 | 6517 | <13 | 104 | <2.0 | MB |
| 4114 | 14.006 | 0.634 | // | 8.6 | 5942 | 60 | 100 | 2.52 | MB(?) |
| 1009 | 14.290 | 0.641 | // | 1.9 | 5916 | 57 | 110 | 2.46 | MB? |
| E70 | 14.589 | 0.651 | 0.388 | 1.0 | 5879 | 49 | 124 | 2.34 | MB |
| 4001 | 10.596 | 0.842 | 0.527 | 1.4 | 5233 | 30 | 182 | <0.8 | MB,SB?,E34 |
| 4053 | 12.447 | 0.543 | 0.332 | 43.7 | 6307 | 50 | 99 | 2.72 | MB,SB1 |
| 2003 | 12.909 | 0.499 | 0.321 | 17.7 | 6499 | 28 | 94 | 2.52 | MB,SB1 |
| 4004 | 13.446 | 0.539 | 0.342 | 11.9 | 6324 | 10 | 100 | <1.50 | MB,SB2 |
| 3013 | 13.673 | 0.501 | 0.321 | 10.2 | 6490 | 10 | 91 | 1.73 | MB, SB1 |
| 3014 | 13.773 | 0.574 | 0.361 | 6.1 | 6178 | <8 | 111 | <1.27 | MB, SB1 |
| 3011 | 13.982 | 0.629 | 0.390 | 1.6 | 5961 | 52 | 117 | 2.47 | MB, SB1 |
| 1001 | 13.129 | 0.478 | 0.312 | 19.2 | 6595 | 51 | 85 | 2.97 | NM,SB1 |
| 3001 | 12.796 | 0.459 | 0.304 | 16.8 | 6684 | 78 | 103 | 3.29 | NM |

Since the Ca I 6717 Å line is a good temperature tracer, in Fig. 2 we plot the Ca I equivalent width as a function of the $(B-V)$ and $(b-y)$ colours. The relationships are tight; this shows the quality of the data and the cleanness of the sample (binaries with a secondary having impact on the Li spectral region would clearly show up in this diagram as outliers). We note that one giant (star 1050, cf. Table 1) seems to deviate in the Ca EW vs. $(B-V)$ diagram, but not in the $(b-y)$ one; we suspect that the $(B-V)$ photometry for this star is slightly too red and we will come back to this point in the discussion.

Li abundances for our sample dwarfs and turn-off stars were derived from the equivalent widths listed in Table 1 using the line-to-line abundance code described by Carretta & Gratton (1997). Kurucz (1995) model atmospheres, including overshooting, were used. The measured Li equivalent widths were first corrected for the contribution of the Fe I 6707.4 Å blend, which was estimated with the procedure outlined by Soderblom et al. (1993). For the giants a full spectral synthesis was carried out, since the analytical correction for the Fe I 6707.4 Å line is not valid for giant stars. The same code and class of atmospheric models were used.

The high $S/N$ spectra of the cluster giants were used also to estimate the cluster metallicity; the same line-to-line abundance code and model atmospheres used for deriving log $n$(Li) were employed. We used seven Fe I lines which are within about ±20 Å from the Li doublet; namely, $\lambda\lambda$ = 6699.14, 6703.57, 6704.48, 6710.32, 6713.74, 6725.36, 6726.67 Å. Note that for a couple of stars it was not possible to measure the EWs of all these lines and thus a subset of them was used. *gf*-values were estimated from an inverse abundance analysis of the solar spectrum assuming a solar iron abundance $\log\epsilon({\rm Fe})_\odot = 7.52$; solar EWs were retrieved from King et al. (2000) or directly measured on the solar flux spectrum of Kurucz et al. (1984). As to stellar parameters, we obviously assumed the same $T_{\rm eff}$ employed in the Li analysis; $\log g$ values were inferred assuming a cluster turnoff mass equal to 1.8 $M_\odot$ and using the expression given by Gilroy (1989); namely:

$$\log g/g_\odot = \log(M/M_\odot) + 4\ \log(T_{\rm eff}/T_{\rm eff\odot}) + 0.4(M_{\rm bol}/M_{\rm bol\odot}) \quad (1)$$

Bolometric magnitudes were in turn estimated from $V$ magnitudes and the bolometric corrections of Johnson (1966). An initial microturbulence $\xi = 2$ km s$^{-1}$ was assumed which was then changed until no EW vs. $\epsilon$(Fe)

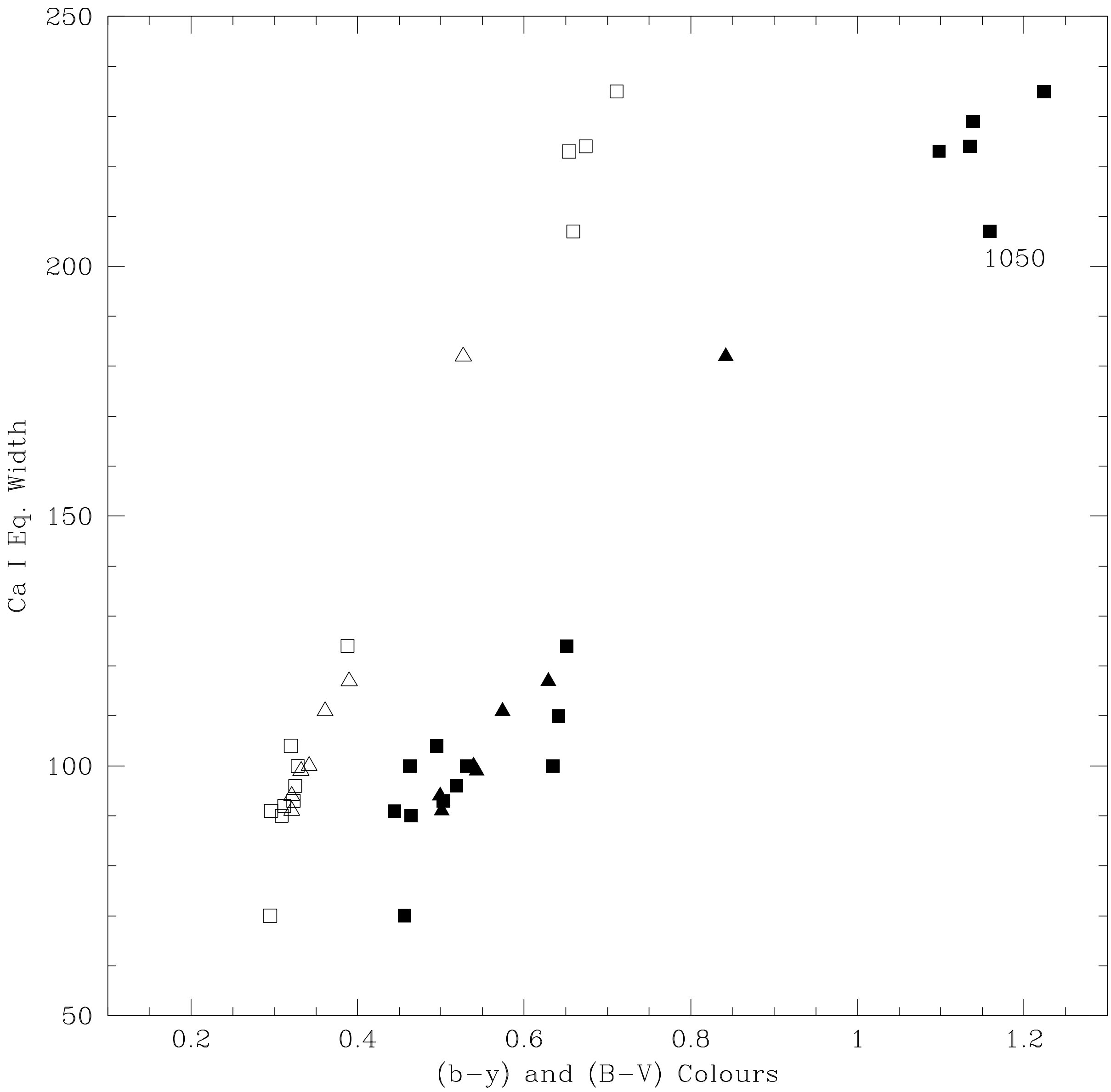


**Fig. 2.** Equivalent widths of the Ca I 6717 Å line vs. colours for the sample stars. The stars are plotted vs. the $B-V$ colour (filled symbols) and the $b-y$ colour (open symbols). Squares: cluster single members and possible members; triangles: binaries.

trend was present. We mention that a fully self-consistent analysis would require us to simultaneously adjust $T_{\rm eff}$ by also imposing a slope equal to zero in the EW vs. excitation potential (EP) plane. Although we did not carry out such an analysis and decided to keep $T_{\rm eff}$ fixed, with our final assumed parameters we nevertheless find slopes equal to zero in both the log $n$(Fe) vs. EW and log $n$(Fe) vs. EP diagrams. The final values of the input stellar parameters are listed in Table 2, while the EWs of the Fe I lines for the six giants are listed in Table 3. For each star the final iron abundance was derived as the average of $\epsilon$(Fe) from the single lines used in the analysis, with the same weight given to all lines. The average metallicity, expressed as [Fe/H], is listed in the last column of Table 2.

Errors in the final iron abundance for each star were estimated as follows: we assumed that the standard deviation of the mean abundance from all the analyzed lines would provide a reasonable approximation for random errors due to uncertainties in equivalent widths and atomic parameters ($\sigma1$). On the other hand, random errors due to uncertainties in atmospheric parameters ($\sigma2$) were estimated by changing one of the parameters and leaving the others unchanged. We found that errors of 200 K, 0.3 dex, and 0.3 km s$^{-1}$ in $T_{\rm eff}$, $\log g$, and $\xi$ correspond to $\Delta\epsilon$(Fe) = 0.15, 0.07, and 0.075 dex respectively (note that a conservative error of 200 K is assumed, although random errors in $T_{\rm eff}$ should not exceed 100 K). This reflects a total error $\sigma2 \simeq 0.18$ dex. The final errors on metallicity listed in Table 2 were conservatively estimated as $\sigma = \sigma1 + \sigma2$. External errors due to both systematic errors in atmospheric parameters and to uncertainties in e.g. model atmospheres are more difficult to estimate. In

**Table 2.** Metallicity determination. Column 1: star name Col. 2: $T_{\rm eff}$; Col. 3: Log $g$; Col. 4: microturbulence; Col. 5: derived Fe abundance.

| Name | $T_{\rm eff}$ | Log($g$) | $\xi$ | Log(Fe/H) |
|---|---|---|---|---|
| 1031 | 4508 | 2.0 | 1.70 | 7.24 ±0.32 |
| 1050 | 4624 | 2.4 | 1.90 | 7.11 ±0.29 |
| 3017 | 4738 | 2.5 | 1.90 | 7.22 ±0.26 |
| 4001 | 5233 | 2.4 | 1.90 | 7.45 ±0.35 |
| E13 | 4668 | 2.3 | 1.95 | 7.30 ± 0.25 |
| E53 | 4661 | 2.3 | 1.95 | 7.24 ± 0.26 |

order to put our inferred metallicity for NGC 3680 on the same scale as other clusters, we derived iron abundances for two Hyades giants (VB71 and VB28) observed during the commissioning of FEROS at the ESO 1.5 m telescope (Kaufer et al. 1999). The $S/N$ ratio of the spectra well exceed 100 and the FEROS resolving power is $R \sim 50\,000$. The metallicity analysis was carried out in the same way as for the NGC 3680 stars, i.e., by deriving stellar parameters in the same fashion and using the same atomic parameters, abundance code, and model atmospheres. The derived metallicities for these Hyades stars, once compared with the canonical value of the Hyades metallicity, will be used in the following to put our metallicity for NGC 3680 on the same scale.

## 3. Discussion

### 3.1. Fe abundance

The determination of the metal content of NGC 3680 is an interesting result, beyond the Li study, since metallicity is crucial for dating the cluster by comparing the colour magnitude diagram with theoretical isochrones.

The results in Table 2 show a high internal consistency among the measured Fe abundances; four of the stars show values confined between [Fe/H] = 7.22 and 7.30, while two (stars 4001 and 1050) slightly depart ($\sim$0.14 dex) from the others. Although, given the errors involved, this difference is not significant, we point out that one of these stars (4001) is classified as a possible binary, while the other (E41) would have a metallicity perfectly matching the others if a $(b-y)$ scale was adopted; this, in combination with Fig. 1 may suggest that the $(B-V)$ for this star is slightly ($\sim$0.02) overestimated.

We estimated the cluster metallicity as the average of the metallicity of the single giants; we obtain $\log\epsilon({\rm Fe}) = 7.25 \pm 0.12$ or $[{\rm Fe/H}] = -0.27 \pm 0.12$, excluding 4001 and 1050 from the sample. Note, however, that including these two stars the mean value remains the same. The metallicity of NGC 3680 results significantly (i.e. more than 1 sigma) under-solar. As discussed by Nordström et al. (1997), several determinations of the cluster metallicity have been carried out in the literature. In particular Nissen (1988) obtained $[{\rm Fe/H}] = 0.09 \pm 0.08$ from $uvby - {\rm H}_\beta$ photometry of 32 F–type dwarfs, while Nordström et al. themselves obtained from their single members sample $[{\rm Fe/H}] = 0.11 \pm 0.05$. Friel & Janes (1993) instead estimated the cluster metallicity from a calibration of spectroscopic indices finding $[{\rm Fe/H}] = -0.16 \pm 0.05$.

The usually quoted metallicity for the Hyades is [Fe/H] = +0.13 (e.g., Boesgaard & Friel 1990), although other studies report slightly larger or smaller values ranging from +0.12 to +0.16 (e.g., Boesgaard & Budge 1988; Cayrel et al. 1985). We found an average metallicity for the two Hyades giants of [Fe/H] = +0.06, i.e., 0.07 dex below the canonical value (and in the range 0.06–0.10 dex below other determinations of the Hyades metallicity). This in turn suggests that our external error should be of the order of $\sim$0.1 dex, likely underestimating the metal abundance. In other words, taking this fact into account, our best estimate for the metallicity of NGC 3680 is [Fe/H] $\sim -0.17$ in very good agreement with that of Friel & Janes (1993), but much below the values inferred from Strömgren photometry. In order to bring our [Fe/H] value in agreement with the latter ones, our temperature scale would be wrong (more specifically, too cold) by more than $\sim$400 K, which we regard as very unlikely. Note that a discrepancy between Strömgren-based and spectroscopic-based metallicities is not an unusual finding, although the reasons are still poorly understood.

The metallicity we have derived may have important implications for the determination of the cluster age. In particular, since it is much below the value used by Nordström et al. it may have consequences for their interpretation of the C–M diagram. As mentioned above, only by adopting a much hotter temperature scale and/or by assuming a higher reddening would we be able to obtain such a high metallicity; but the adoption of a different reddening would also be inconsistent with the Nordström findings. In brief, a lower metallicity, such as the one found by us and by Friel & Janes (1993), indicates an older age for the cluster with respect to the 1.45 Gyr estimated by Nordström et al. Computations kindly provided to us by L. Girardi, using the Padua tracks (Girardi et al. 2000) indicate that with our spectroscopic metallicity the cluster age would increase by 20%, giving therefore an age of $\sim$1.74 Gyrs for NGC 3680.

### 3.2. Li abundances

Since we have observed stars both below and above the turn-off, a classical Li-$T_{\rm eff}$ diagram is not very useful, because it is degenerate with respect to mass, i.e. stars with different masses may correspond to the same $T_{\rm eff}$. For this reason, in the following we will use a Li vs. $V$ magnitude diagram, which approaches rather well the Li-mass plane. In Fig. 3 log $n$(Li) vs. visual magnitude is plotted; filled squares and triangles represent cluster single members and binaries, respectively.

Moving from left to right in the figure, we can follow with very good approximation stars with increasing main-sequence mass, while the six separated most luminous points to the right represent the giants well detached

**Table 3.** Fe I equivalent widths used for metallicity determinations.

| Star | λ 6699.14 Å | λ 6703.57 Å | λ 6704.48 Å | λ 6710.32 Å | λ 6713.14 Å | λ 6725.36 Å | λ 6726.67 Å |
|---|---|---|---|---|---|---|---|
| 1031 | 20 mÅ | 99 mÅ | 17 mÅ | 114 mÅ | 46 mÅ | 43 mÅ | 67 mÅ |
| 1050 | 17 mÅ | 88 mÅ | 11 mÅ | 91 mÅ | 35 mÅ | 38 mÅ | 59 mÅ |
| 3017 | 15 mÅ | 95 mÅ | — | 84 mÅ | 34 mÅ | 40 mÅ | 63 mÅ |
| 4001 | 18 mÅ | 70 mÅ | 10 mÅ | 67 mÅ | 35 mÅ | 29 mÅ | 53 mÅ |
| E13 | 20 mÅ | 96 mÅ | 16 mÅ | 98 mÅ | 44 mÅ | 44 mÅ | — |
| E53 | 16 mÅ | 98 mÅ | 16 mÅ | 90 mÅ | 44 mÅ | 46 mÅ | 65 mÅ |

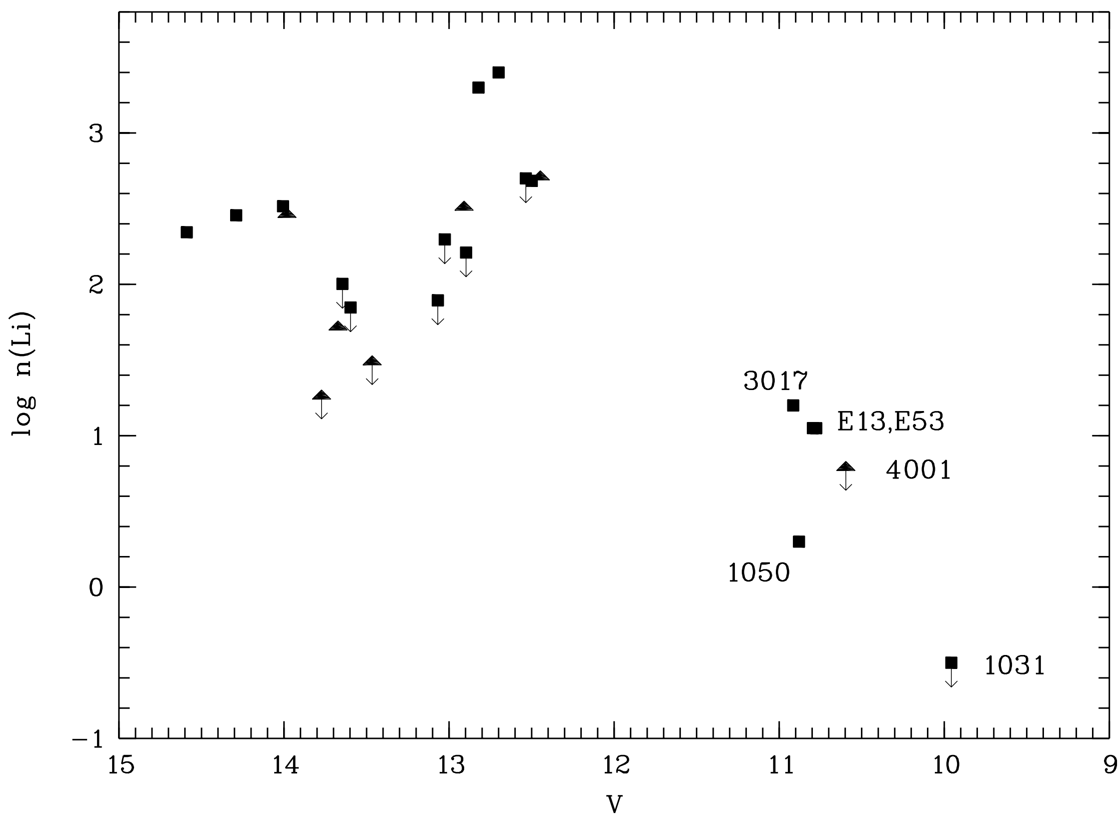


**Fig. 3.** Li abundance vs. visual magnitude for the observed stars. Symbols as in Fig. 2.

from the bulk of the main sequence and turn-off stars. The four G-type main sequence stars (one single member, one SB1 member and two possible members) with $V \leq 14$ show a behaviour typical of Hyades-age G-type stars, with a Li abundance log $n$(Li) $\sim 2.45$, but no presence of a significant scatter.

An abrupt, strong decrease of the Li abundance for stars brighter than $V \sim 13.8$ shows the presence of the well known Li dip (Boesgaard & Tripicco 1986). In NGC 3680 the dip shows up in the region just below the turn-off and it includes stars as hot as 6500 K and as bright as $V \sim 13.0$. We note however that, due to the absence of stars in the range $V = 13.8{-}14.0$ (and $T_{\rm eff}^{\rm MS} \sim 6000{-}6200$ K) it is not possible to determine accurately the red edge of the dip. This unfortunately prevents us from investigating whether the Li dip in NGC 3680 fully overlaps in $T_{\rm eff}$ and mass with the ones observed in other clusters (Balachandran 1995). Stars brighter than $V \sim 12.9$ are then already out of the dip, on the blue side of it: they are too hot for the Li dip depletion mechanism to work.

As for giants, the measured Li abundances show a more puzzling picture. We observe, as expected from standard dilution, that giants (interpreted here as RGB stars) are diluted in Li and only a very low Li upper limit is obtained for 1031 located at the tip of the observed RGB. However, of the four giants sharing a very similar location in the C–M diagram (cf. Fig. 1), 3 have a Li abundance a factor 5 to 6 higher than the fourth one. A comparison of the spectra of the stars 1050 and 3017 is shown in Fig. 4; the comparison shows that the difference in the strength of the Li feature is real and not due to possible measurement uncertainties.

For sake of clarity, in the following subsections we will separately discuss the stars belonging to the three different regions of the colour-magnitude diagram.

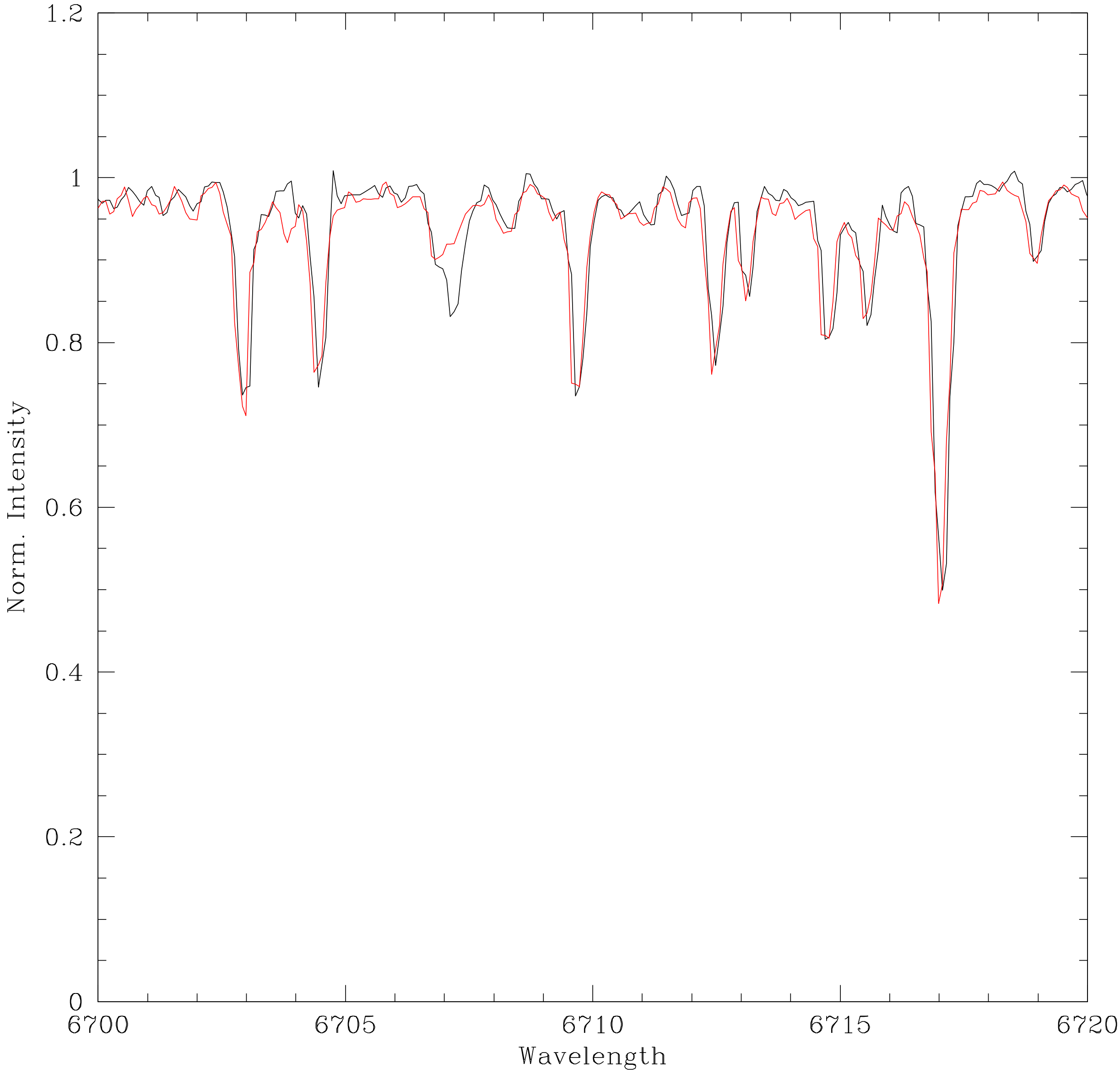


**Fig. 4.** Comparison of the spectra in the Li region of the stars 1050 = E41 (red line) and 3017 = E26 (black line). While the spectra are very similar in all features, the difference in the Li line is striking.

### *3.3. Main sequence stars on the cool side of the dip*

One of the goals of this project was to investigate whether the behaviour of lithium in intermediate-age G stars is similar to that observed in the old cluster M 67 and in old field stars, which shows a large spread in Li among otherwise similar stars (Pasquini et al. 1994, 1997), or is closer to the very tight log $n$(Li) vs. $T_{\rm eff}$ relationship observed in the 0.6 Gyr old Hyades. The lithium pattern in the solar-type stars of NGC 3680 was already investigated by Randich et al. (2000) in conjunction with a study of the similar age cluster IC 4651. We refer to that paper for a detailed discussion and summarize here only the main conclusions. Randich et al. (2000) showed that solar-type stars in both clusters show no signs of differential depletion, and discussed several current theoretical models to explain the main-sequence evolution of Li between the age of the Hyades and that of M 67. Although various studies have suggested that slow rotationally-induced mixing could occur in MS stars and be responsible for Li depletion (see Deliyannis 2000 and reference therein for a detailed discussion of the supporting evidence), Randich et al. (2000) showed that none of the currently available models can fully reproduce Li depletion in MS stars between the age of the Hyades and M 67. The Li abundance in NGC 3680 and IC 4651 MS stars is $\sim$0.3 dex below the Hyades, indicating that a mild depletion did indeed take place in the $\sim$1 Gyr following the Hyades age; in addition, the data indicate that differential Li depletion on the main-sequence should occur between the age of NGC 3680/IC 4651 and that of M 67, unless the two intermediate-age clusters and M 67 started with very different initial conditions (e.g. different initial angular momentum distributions).

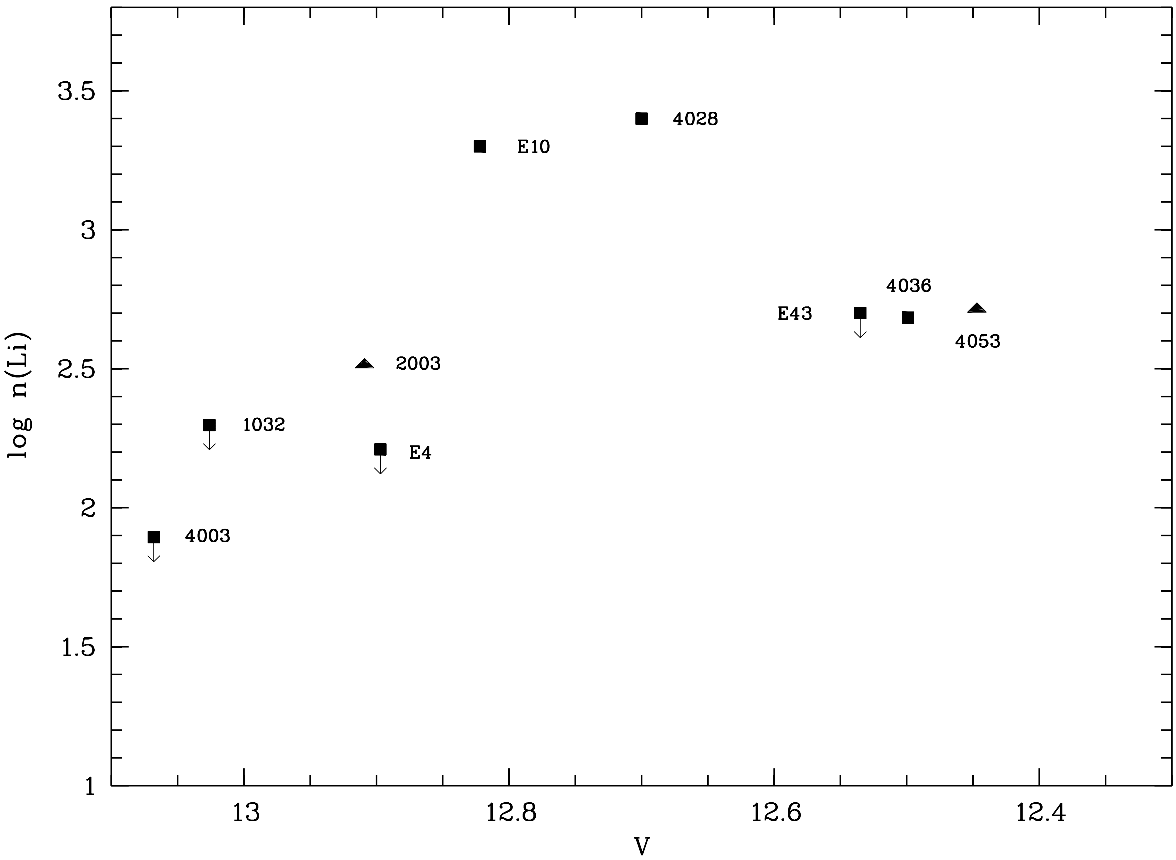


**Fig. 5.** Li abundance vs. $V$ magnitude for the stars on the blue side of the Li dip. Filled squares and triangles represent cluster single stars and binaries, respectively.

### *3.4. The turnoff: The Li dip and hotter stars*

Our observations clearly show the presence of a Li dip in NGC 3680, in spite of the fact that it consists mostly of upper limits. We also notice that the data for all stars are consistent, irrespective of their single or binary nature. On the blue side, the Li dip extends up to $V = 12.9$ and $T_{\rm eff} = 6500$ K, with stars E4 and 2003 defining the blue edge of the Li dip region.

Figure 5 is similar to Fig. 3, but only the region of the turn-off is shown in order to follow in more detail the lithium pattern on the blue side of the dip. Stars 4028 (a possible member) and E10 with magnitudes 12.7 and 12.8, respectively, have Li abundances which are very close to the initial solar system value. There are no doubts that these stars are completely out of the dip, on the hot side of it. It is likely therefore that their Li represents the original Li abundance of the cluster (we will discuss later the much less plausible possibility that their present Li abundance is enhanced with respect to the original one).

Within a very small magnitude variation (an increase of $\sim$0.2 magnitudes), the Li abundance drops to values which are 0.6–0.7 dex lower than the meteoritic one (stars 4036, 4053 and E43). These stars, which are just evolving off the main sequence, were born as hot stars on the MS and it is reasonable to assume that they left the MS with the original meteoritic Li abundance. They appear to have already depleted a considerable fraction of their original Li (a factor 4–5). This result is in sharp contrast with what is expected from standard post-MS evolutionary models, which do not predict any substantial Li dilution before the first dredge up (Charbonnel & Talon 1999, hereafter CT99). This cluster therefore represents a powerful keystone for the interpretation of the results obtained on field subgiants by Randich et al. (1999) and Do Nascimento et al. (2000): it indeed shows that small differences in the physical parameters of main-sequence stars may correspond to large differences in Li abundances in the early stages of post main-sequence evolution. Rather than being due to real structural changes in otherwise very similar stars, these differences likely represent main-sequence effects that have caused a dispersion. This readily explains why the Li-$T_{\rm eff}$ relationship found for field subgiants did not reveal any evident, regular pattern, even if stars with parallaxes from *Hipparcos* were used.

Our observations, although based only on a few data points, allow a quantitative comparison with more complex evolutionary models, like those developed by CT99 which include the effects of rotational mixing and atomic diffusion, for stars of various masses and MS rotational velocities. NGC 3680 has a turn-off mass around 1.8 $M_\odot$ (Nördstrom et al. 1997), therefore our observations can be compared with the 1.85 $M_\odot$ case of CT99 (their Fig. 6

and Table 1). According to the CT99 models, a rotating ($v_{\rm rot} > 100$ km s$^{-1}$) 1.85 $M_\odot$ star would leave the main sequence with a temperature of ∼7000–7100 K at an age of 1.2–1.3 Gyrs and with a Li abundance a factor of 5 lower than its initial value. The age estimate for NGC 3680 (1.45 Gyr) is fully consistent with these stars being slightly evolved and having a mass close to the one assumed; we can therefore take the CT99 1.85 $M_\odot$ models as guidelines for the analysis of NGC 3680. We note that a lower metallicity and older age, as proposed in this paper for NGC 3680, would not change appreciably the turnoff mass, therefore the comparison still applies even if the new metallicity and age were adopted.

It clearly appears that the large drop in Li abundance in such a tiny magnitude range as observed in NGC 3680 is not consistent with the classical models: it would require in fact that the strong dilution predicted to occur at the first dredge-up is "anticipated" in the stellar evolution and it already occurs when the star is ∼1000 K hotter than at the first dredge up. Rotating models with an initial rotational velocity of about 100 km s$^{-1}$ or higher could better reproduce the observed behaviour, since they predict the right amount of Li depletion at the end of the main sequence phase; however, even the rotating models are not fully consistent with the observations and they are difficult to prove with the data at hand. These models (CT99) predict that Li destruction inside the star already occurs during the *Main Sequence* phase in the rapidly rotating stars, although very little Li depletion may be observable during the MS; their effects start to appear only at the early phase of the post-main sequence evolution and the dispersion in Li abundances in this phase should be related to the rotational velocity on the main-sequence.

Looking at the same problem from another perspective, while the CT99 models could explain the lower Li abundance observed in stars E43, 4036 and 4053, they fail to explain the very high Li observed in stars 4028 and E10, which are just slightly fainter and have comparable rotational velocities. Different rotational rates do not seem to be the right explanation, since all these stars have similar (and rather fast) rotational rates: stars 4036, 4053, and E43 have $v \sin i$ of 15.7, 43.7, 22 km s$^{-1}$; E10 and 4028 of 48 and 27.1 km s$^{-1}$ respectively. It seems quite possible that stars like 4053 and E10 most probably had a high $v \sin i$ when younger, while this is not as clear for the other stars. The study of younger clusters may help in understanding this point; stars of ∼1.8 solar masses in the younger Hyades show rotational velocities in the range of 40–120 km s$^{-1}$ (Gaigé 1993); therefore a high MS rotational velocity for 1.8 $M_\odot$ stars can be expected, at least in a statistical sense. While this supports the view that NGC 3680 turnoff stars may be consistent with rapid main sequence rotators (as expected by the CT99 models), the actual rotational velocities observed for the stars in our sample pose the problem of why the observed Li abundances do not reflect the observed $v \sin i$ distribution. A cluster with a larger membership would be of great help in order to understand this point.

In conclusion, whereas the rotating models of CT99 might better represent the general observed behaviour (at least they could reproduce the drop in Li abundance observed at the tip of the turnoff) with respect to "standard" models, they still need additional fine tuning; the quantity and quality of the observations available require that a fully self-consistent model, reproducing simultaneously the colour-magnitude diagram, the rotational velocities, and the abundance pattern, is developed. The Li data we are presenting, together with the accurate work made recently on this interesting cluster (Nordström et al. 1996, 1997), represent a unique test for stellar evolutionary models.

For sake of completeness we mention that alternative solutions could also be found to solve this puzzle, but they have to invoke ad-hoc conditions such as, for instance, the possibility that the Li abundance in stars E10 and 4028 does not represent the pristine cluster abundance, and that these two stars were rather enriched in Li through, e.g. radiative acceleration. Burkhart & Coupry (2000) showed that this may indeed occur in a few stars in open clusters. However, beside the fact that these stars are always more than 1000 K hotter than our targets, and any theory will have to struggle to predict such an enrichment for the NGC 3680 stars, we note that the treatment of the errors in the derivation of the Li abundances for hot A-type stars is not trivial (small equivalent widths, large ionization correction, full treatment of the line structure, NLTE effects) and that the mean value and scatter ($\log n(\mathrm{Li}) = 3.45 \pm 0.15$) found by these authors for A-type stars is compatible with the meteoritic value plus the uncertainties related to the abundance determination, thus questioning the reality of such Li enriched stars. Although we cannot exclude that stars E10 and 4028 are enriched in Li with respect to the pristine cluster abundance, the observational evidence in favour of this possibility is rather weak and we regard it as very unlikely.

### 3.5. Climbing the Red Giant Branch

The situation for the giants is also complex; given their temperatures and luminosities, all the stars should have passed the first dredge-up phase; it is not clear however if all of them are first-ascent RGB stars or if "clump" stars are present.

The assumption that these are all first-ascent RGB stars might indeed be wrong. Simulations of a 1.6 Gyr old cluster using the Girardi et al. (1999) evolutionary tracks show in fact that the ratio of clump to RGB giants is about 4. In our case, this would imply that 3 out of 4, or even all of the giants at $(B-V) \sim 1.15$ in the C–M diagram of Fig. 1, should be clump giants, although it is not too safe to do statistics with such low numbers. Three of these stars have a rather high Li content ($\log\ n(\mathrm{Li}) \sim 1.1$), one has a Li content at least 5 times smaller.

The most luminous star of the sample shows only a low upper limit; we do not know if this star is at the top of the RGB or along the AGB. The same theoretical models would indicate that an AGB star is favored. Note that the RGB in NGC 3680 is not well defined and is scarcely populated. Star 1031 (the giant with no detectable Li) is only $\sim$200 K cooler than the "clump" giants at $(B-V) \sim 1.1$. This small temperature difference is not consistent with the star being at the tip of the RGB and its very low Li abundance is also not consistent with the decline of Li abundance along the RGB typically observed in cluster and field giants (see later and Pilachowski 1986; Brown 1989; Mallik 1999).

Observations of Li abundances for two other clusters with similar ages as NGC 3680 are published in the literature: NGC 752 (Pilachowski et al. 1988), and NGC 7789 (Pilachowski 1986). Both show some similarities to NGC 3680, and it is worth recalling the main results. NGC 752 shows a well developed clump, and among the 11 cluster members observed by Pilachowski et al. (1988) two have Li abundances similar to the high Li giants of NGC 3680, while for the other 9 only upper limits (log $n$(Li) $< 0.3$–$0.5$) could be obtained. Pilachowski et al. (1988) interpreted the two Li rich stars as if they were first-ascent RGB stars, while the stars showing upper limits were interpreted as being the genuine clump stars. The fact that they outnumber the ones with detected Li is in agreement with the expected ratio of clump vs. first-ascent RGB stars.

In NGC 7789, Li was detected at values of log $n$(Li) $\sim 1.4$ in stars just above the clump. Li abundances were observed to decrease strongly with increasing magnitude along the well-developed RGB of NGC 7789. Only upper limits (unfortunately rather high, log $n$(Li) $\sim 1$) could be obtained for the clump giants (Pilachowski 1986).

Possible ways to understand the behaviour of Li in the NGC 3680 giants (and in the other intermediate age clusters observed so far) can be separated in three cases:

1) Differential dilution along the RGB: according to the same models (CT99) which we have used to interpret the observations of stars around the turnoff, during the MS more lithium destruction would occur inside a rapid rotator; even if no significant Li depletion is expected to show up at the surface of MS stars on the hot side of the dip, this would affect later evolutionary phases when the rotating model would dredge-up material from the so-called "Li-free" region. Therefore, variations in Li abundances from star to star at the end of the first dredge-up are expected, since most probably not all stars started with the same rotational velocity. The observed difference in Li abundances (about a factor 5) would be really at the extremes of what is predicted, suggesting that star 1050 must have been a very fast MS rotator (100 $\mathrm{km\,s^{-1}}$), whereas the other three giants probably had a much lower MS rotational velocity. This is possible, but cannot be proven; in addition, since the observed rotational velocities of all giants are similar, such a hypothesis would require that all stars, while having large differences in rotation on the main sequence, would converged at very similar rotation values after evolving out of it. This implies a braking mechanism which is more effective for more rapidly rotating stars, which is not unlikely.

We note that this hypothesis could explain both the difference in depletion between the 4 giants with detected Li and the absolute amount of the depletion (a factor $\sim$1000 for star 1050 and more than a factor 100 for the others) from the original meteoritic value. Against this hypothesis is the fact that the CT99 models also predict for 1050, if it were a much more rapidly rotating star than the other giants, a substantially higher luminosity and somewhat higher temperature, which is not observed.

2) Different Li abundances on the main sequence: although these stars may all have suffered standard Li dilution along the RGB, they might have started with different Li abundances on the main-sequence. Variations in Li abundance for main sequence stars on the blue side of the dip have been reported in the literature (Bourkhart & Coupry 1989, 1998, 2000), but they are limited to a few objects. Observations of hot stars in young clusters (with ages up to that of the Hyades) do not support this interpretation since very little scatter is present among main-sequence stars on the hot side of the dip (e.g. Thorburn et al. 1993; Bourkhart & Coupry 2000). No significant scatter is also observed among main-sequence G stars on the cool side of the dip in intermediate clusters as old as NGC 3680 and IC 4651 (Randich et al. 2000).

3) Evolutionary effects: This might be the most natural hypothesis, and it needs to be developed in some detail, because several possibilities may exist.

a) The easiest interpretation is that the Li rich stars are first-ascent RGB stars and the Li poor ones are clump stars. This hypothesis has been proposed for NGC 752 by Pilachowski et al. (1988), but it is unlikely it can hold for NGC 3680, because on the basis of stellar evolution principles the Li poor (clump) stars should largely outnumber the Li rich ones (RGB), which is the opposite of what is observed. Unless the "clump" stars have somehow disappeared in NGC 3680, it is unlikely that most of the observed giants in this cluster are first crossing RGB stars (but we stress once again that the RGB of NGC 3680 is scarcely populated and not well defined).

b) If we accept that most of the giants in NGC 3680 belong to the clump, clearly our results show that the NGC 3680 clump stars possess a considerable amount of Li (log $n$(Li) $\sim 1.1$), much larger than that believed to exist in similar stars in NGC 752 (for which only upper limits log $n$(Li) $< 0.5-0.3$ were observed, Pilachowski et al. 1988). If this is the pristine Li depleted during the post-main sequence evolution, then stars 1050 and 1031 (which have much lower Li) are necessarily AGB stars, and this would be in rough agreement with what expected from stellar evolution. If correct, this interpretation would imply that the NGC 3680 stars have maintained a considerable (for a giant star) amount of Li along the whole RGB, which does not appear to be consistent with the results obtained for other clusters and for field giants (Brown et al. 1989; Gilroy 1989; Mallik 1999).

The observations of NGC 7789 by Pilachowski (1986) show in fact that stars along the RGB loose most of their Li, arriving at levels below log $n$(Li) = 0 at the tip of the RGB (note that the RGB is well developed in NGC 7789 and was followed by Pilachowski along its full length). In addition, observations of field giants (Brown et al. 1989, Mallik 1999) do not show cool giants with Li above log $n$(Li) = 1.2 in the RGB region above the clump, while a rather interesting enhancement of stars with considerable Li (log $n$(Li) > 1.2) is present in the region of the H–R diagram corresponding to the 1.6–2 $M_\odot$ clump stars (Mallik 1999). We cannot be sure, however, when using field starts, that all these are genuine clump stars as opposed to first crossing RGB stars.

c) A third possibility exists, which could explain the observations, but it would require a quite strong change in our understanding of the Li evolution in giants: between the tip of the RGB and the clump, Li could be produced or brought to the surface. Although we cannot push this argument beyond the present speculation, we note that the presence of a short-lived episode of Li production during the post main sequence evolution, accompanied by the subsequent release of a shell, has been advanced on several occasions (De la Reza et al. 1979; Charbonnel & Balachandran 2000) to explain the formation of super Li-rich giants, and the tip of the RGB could be a possible location for such a dramatic event to occur. On the observational side, a way of proving this hypothesis is to determine the Li abundance in the clump stars of NGC 7789; if this would be higher than that observed in stars at the top of the RGB, this hypothesis would receive a strong observational support. We note however that the data available for NGC 752 would argue against this possibility if most of the giants in NGC 752 are indeed clump giants, as assumed by Pilachowski et al. (1988). Also note that the freshly synthesized lithium in super Li-rich giants should have been rapidly destroyed afterwards in order to explain the observed abundance log $n$(Li) $\sim$ 1. This fact and the extreme rarity of super Li-rich giants (e.g. Brown et al. 1989) make this possibility interesting, but unlikely.

In brief, we can divide the possible interpretations into two main groups: in the first, the stars must have started with different Li abundances on the MS or they must have depleted Li differently (by dilution or destruction) during the RGB phase or in the early evolution out of the main-sequence. The effect of rotation on the depletion mechanism(s) could be the cause of differential Li depletion. This cannot be proven with the data we have at hand.

Alternatively, the differences observed might be due to the different evolutionary status. The most obvious interpretation, in this case, is that 1050 is a clump star (and 1031 is an AGB star), while the others are first-ascent RGB stars: they are still diluting the initial Li, while 1050 has completely diluted it on the RGB. However, as mentioned above, the expected number of clump to RGB stars in a cluster with the age of NGC 3680 leads us to the opposite conclusion that most of the giants in NGC 3680 are clump stars, unless clump stars have somehow disappeared from this scarcely populated cluster. In this case, with stars 1050 and 1031 post-clump stars that have possibly suffered a second mixing episode, we could easily understand the observations. However, the observed high Li content of the clump stars (log $n$(Li) $\sim$ 1) is much higher than expected from the observations of stars at the tip of the RGB in NGC 7789 and of field giants, requiring that fresh Li is produced, or brought to the surface, in clump giants of NGC 3680. Although interesting, this is a hypothesis that remains to be proven. Moreover, it is not consistent with the observations of NGC 752 which suggest instead that most of the giants in this cluster are indeed clump giants with quite low Li abundances. Observations of more clusters in the same age range are required to discriminate between these various possibilities.

## 4. Conclusions

This study has shown how powerful the detailed analysis of Li can be in a well-studied open cluster. For the first time we were able to follow the details of the Li evolution along the C–M diagram of an intermediate age cluster. Whereas some of our results seem definitive and explainable, others still present question marks. NGC 3680 unfortunately is left with a limited numbers of single members, and more Li observations, in addition to those of the isotopic ratios (e.g. $C^{12}/C^{13}$) in clusters more densely populated than NGC 3680, would help in answering them.

Our main conclusions can be summarized as follows:

- Solar-type stars in NGC 3680 show no appreciable spread; they have a Li content which is $\sim$0.3 times lower than in the Hyades, but similar to what is observed in the coeval cluster IC 4651. It is important to recall in this context that the evolution of Li in solar-type stars between the age of the Hyades and that of old clusters like M 67 cannot be reproduced by any of the existing models (Randich et al. 2000).
- The cluster presents a very well determined, clean Li-dip in the region of the turn-off. The stars at the tip of the turnoff are out of the dip and reach meteoritic Li abundances; however, just $\sim$0.2 magnitude brighter stars already show a Li depletion of a factor of 5. This result puts firm constraints on models: none of the existing ones seem able to reproduce these observations, although we find that the CT99 models for rapidly rotating stars can at least reproduce the overall amount of dilution/depletion at the end of the main sequence phase.
- Also puzzling are the results for the giant stars, two of which have Li abundances from 5 to more than 30 times lower than the remaining three. Whereas for one star the very low upper limit found for Li can be explained with its lower temperature and higher luminosity, which suggests that it may be an AGB star, for the other one (star 1050), which has the same position

in the C–M diagram than the three giants with higher Li, no definitive explanation can be found.

Theoretical models predict that clump stars should largely outnumber RGB stars in this cluster. If this holds true for the small number of stars surviving in NGC 3680, the observations suggest that clump stars in NGC 3680 have a considerable amount of Li (log $n$(Li) $\sim 1.1$). This would require either that the stars did not destroy completely their Li along the RGB (which is not supported by both observations of RGB stars in the similar age cluster NGC 7789, Pilachowski et al. 1986, and of field giants, Brown 1989; Mallik 1999), or that Li is destroyed along the RGB but again produced, or brought to the surface, in the clump phase. Although interesting, this second possibility contrasts with observations of NGC 752, which suggest instead that clump stars have low Li abundances (log $n$(Li) $< 0.5$–$0.3$). Moreover, it is difficult to reconcile with the extreme rarity of super Li-rich giants and with the much higher Li abundance of these stars in comparison with the clump giants of NGC 3680.

– We have measured the metallicity for the giants stars using seven lines around the Li 6707 Å region. We find that the cluster giants consistently show a Fe abundance [Fe/H] $= -0.27$, which we correct to [Fe/H] $= -0.17 \pm 0.12$ after a comparison of the abundances derived by us for the Hyades giants with the Hyades canonical value ([Fe/H] $= 0.13$). This metallicity is much lower than that deduced by Strömgren photometry by an amount which is out of any reasonable uncertainty. This implies that the cluster age should be revised (in the sense of a 20% older age) with respect to the 1.45 Gyr found by Nordström et al. (1997).

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