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A new set of HST boron observations

I. Testing light elements stellar depletion*

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Abstract. A sample of 7 new stars ranging in metallicity from [Fe/H]=-2.0 to [Fe/H]=-0.75 has been analyzed in the boron spectral region. The spectra were observed with the Goddard High Resolution Spectrograph (GHRS) of the *Hubble Space Telescope* (HST). The targets were selected on the basis of their lithium and beryllium abundances in order to investigate in a more complete way light element depletion and internal mixing by comparing all 3 elements Li, Be, and B at once in the same objects. Four stars out of 7 are characterized by strongly depleted Li and Be abundances, compared to stars of similar characteristics. We find that 2 of them (HD 2665 and HD 3795) are also significantly B-depleted. Two others (HD 106516 and HD 221377) have normal or near normal B abundances despite being depleted by a factor $\geq$10 in both Li and Be abundances. These stars place strong constraints on the nature and depth of the mixing processes responsible for their light element abundances. Two other stars, HD 94028 and HD 194598, are found to have normal B abundances, despite a 0.3 dex difference in their Be abundances claimed by Thorburn & Hobbs (1996). We consider the reported Be difference unconfirmed. The 7th star belonging to this cycle of HST observations is HD 160617. Although subjected to a separate analysis (Primas et al. 1998a), it has also been included here because of the remarkable aspect of its low B, probably low Be, and completely normal Li. No stellar destruction mechanism can explain this. Rather, chemical inhomogeneities in the halo could be the cause.

Key words: line: profiles – stars: abundances – stars: Population II – Galaxy: halo

1. Introduction

The study of variations in the chemical composition of stars caused by nuclear reactions and/or internal mixing mechanisms is one of the basic ingredients of stellar evolution studies, and it allows us to probe and eventually better constrain our knowledge of stellar interiors. Among the several chemical elements that can be successfully analyzed in stellar atmospheres, the light elements Li, Be, and B play a fundamental role in this application providing some of the strongest benchmarks for testing stellar structure models. They can be generated by only few different physical processes, such as thermonuclear reactions in the early universe (^{7}Li, e.g. Reeves et al. 1990), galactic cosmic-ray (GCR) spallation reactions (^{6}Li, ^{9}Be, ^{10}B, ^{11}B, e.g. Reeves et al. 1970, Meneguzzi et al. 1971), stellar processes (but only some ^{7}Li during the AGB and perhaps RGB stellar phases, e.g. Smith & Lambert 1989), and maybe (still under debate) ν-spallation (^{11}B) in supernovae (e.g. Woosley et al. 1990). They cannot be produced in stellar interiors, because of the low temperature threshold at which they burn, and in fact they are easily destroyed by proton-α reactions in the outer layers of stellar atmospheres, at the low burning temperatures $\approx$ 2.5×10^6, 3.5×10^6, and 5.0×10^6 K respectively. Thus Li, Be, and B sample mixing to different depths of a stellar atmosphere. The analysis of their abundances can offer important insights on the mixing present in these surface layers.

The first stellar structure (so-called *standard*) models (e.g. Bodenheimer 1966, Deliyannis et al. 1990) considered convection as the only mixing agent, but as more data were gathered, it became clear that convection could *not* be the only mixing process active in stellar interiors. The long-standing problem of explaining the low surface abundance of lithium in the Sun ($\approx$ a factor 140 below its meteoritic value) represents just one of the first difficulties faced by this class of models. Low mass main-sequence (MS) stars in open clusters represent one ideal laboratory for testing different theoretical scenarios since observed depletion pattern is a complex function of mass, composition, and age (e.g. Pinsonneault 1997). The measurement of

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light element abundances in metal-poor stars provides another important constraint on the allowed classes of models. Only by determining and comparing all 3 light elements LiBeB in the same objects can we overcome the fact that the initial abundance of light elements in the oldest stars (clearly a quantity of great interest) is uncertain.

The main atomic transitions used to analyze spectroscopically Li, Be, and B fall at 6707Å, 3130Å, and 2500Å respectively. Because of that, lithium is the element which has been studied most widely, while only between the end of the 1980 s and the beginning of this decade has the availability of higher quality UV sensitive detectors and the launch of the *Hubble Space Telescope* made possible the start of rigorous analyses of Be and B respectively. After several independent analyses of Li, Be, and B in both disk and halo stars spanning a wide range in metallicity (e.g. Spite & Spite 1982, Rebolo et al. 1988, García-Lopez et al. 1995, Molaro et al. 1997, Duncan et al. 1997), the importance of studying all 3 light elements in the same objects became clear. With larger and more reliable samples of stars, covering the whole range of observable metallicities, the overview of all 3 light elements can allow us to achieve a deeper knowledge of the (different) processes with which these elements form and are destroyed, and of their evolution during subsequent epochs. We present here the analysis of B abundances in a set of 6 new halo stars. Combined with the samples analyzed by Duncan et al. (1997) and Primas et al. (1998a), this sums to a total of 17 halo and disk stars, analyzed in a consistent way, for which LiBeB are known. A few more stars, observed by other investigators, also have all 3 light elements now determined: 2 stars recently analyzed by García-Lopez et al. (1998) and 9 F-type stars analyzed by Boesgaard et al. (1998).

2. Observations and data reduction

This new set of boron spectra was observed during HST Cycle 6 and the spectral range covers a window of approximately 40Å centered around the 2 main resonant atomic transitions of neutral boron at λ 2496.772 and λ 2497.725. The main purpose of the project was to observe the B region in a small group of halo and old disk stars, characterized by peculiarities in their Li and/or Be contents (e.g. unusually low abundances compared to stars of similar metallicities, different abundances between "twin" stars). Therefore our selection criteria relied mainly on choosing potentially interesting candidates according to the LiBe pattern already available. As in our previous HST B analyses (Duncan et al. 1997, 1998a) the Large Science Aperture (LSA) combined with the G270M grating on the Goddard High Resolution Spectrograph (GHRS) was chosen. Such an instrumental set-up gives a resolution of ≈25,000 at the wavelengths of interest. The targets range from V=6.1 mag to V=8.7 mag. The exposure times were estimated from the spectra previously observed by us with the same instrumental configuration. Table 1 summarizes the technical details related to this set of observations, including the visual magnitude, total exposure time, number of counts per diode, and resulting S/N per pixel (1 pixel = 1/4 diode) for each target.

Table 1. Log of the HST GHRS observations.

Star	V mag	Exp. Time sec	Counts per diode	S/N per pixel
HD 2665	7.5	4896	2800	26
HD 3795	6.1	1795	2300	24
HD 94028	7.9	9574	21400	73
HD 106516	6.1	1740	16000	63
HD 160617	8.7	7616	12800	56
HD 194598	8.4	6798	12500	56
HD 221377	7.2	4896	14400	60

Data reduction was performed following the standard HST procedure, using the IRAF stsdas package, combining the quarter-stepped, FP-SPLIT data within each visit with the tasks poffsets and specalign, which performs a generalized least-squares solution for the photocathode granularity and the true spectrum. 2 stars only were observed without the FP-SPLIT option switched on (HD 3795 and HD 106516), and they have been reduced with the IRAF task mkmultispec that combines wavelength and flux information. The reduced spectra were then normalized with respect to the continuum level computed by spectral syntheses, by matching several reference points. The most line-free part of the spectrum just shortward of 2500Å usually used to normalize B spectra is populated by lines in more metal-rich stars. Only the spectrum of HD 160617 ([Fe/H]=−1.80) was normalized by assigning a value of 1 to this line-free portion, as indicated by the spectrum syntheses. The final spectra, reduced and normalized, are shown in Fig. 1.

3. Abundance analysis

The severe crowding of spectral lines that characterizes the near-UV region and the presence of blends, one of which is very close to the bluer B I line (which the B determinations rely on), require the use of spectrum synthesis techniques when analyzing B abundances. For this purpose, the latest Kurucz model atmospheres and the ATLAS and SYNTHE codes (Kurucz 1993), in the modified version running on UNIX SPARC stations (implemented by Steve Allen, University of California at Santa Cruz) were chosen. The computation of a synthetic spectrum requires 3 inputs: a grid of model atmospheres, a list of the atomic and molecular lines present in the spectral region of interest, and the determination of the main stellar parameters of the objects under investigation, *i.e.* effective temperature, gravity, and metallicity, in order to select the closest model atmosphere in the available grid. Each of these introduces different uncertainties, which must be carefully taken into account.

3.1. Model atmospheres

Independently of the authorship, the physics behind modeling stellar atmospheres developed from common grounds: it usually assumes that stellar atmospheres can be represented in first approximation by horizontal, flat, parallel layers where physi-

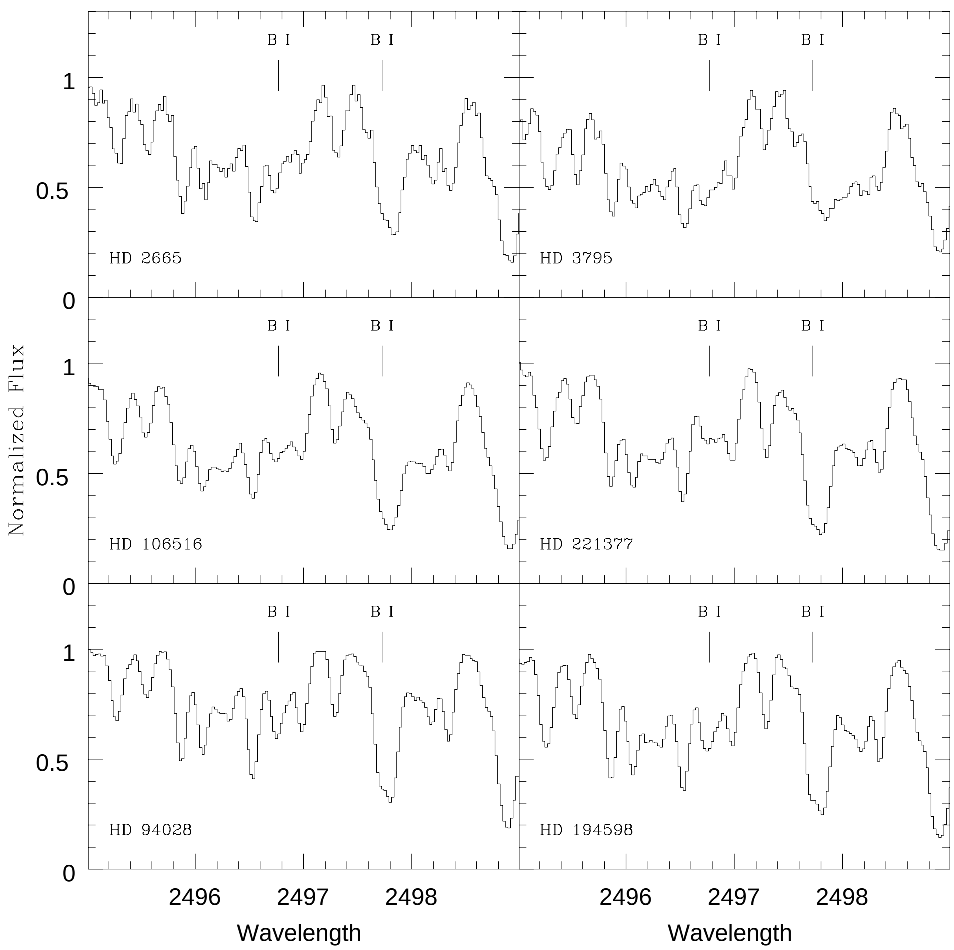

Fig. 1. Reduced and normalized observed spectra of the program stars.

cal principles like hydrostatic equilibrium, conservation of the energy flux, and local thermodynamic equilibrium, hold. Further assumptions consider the state of the gas, opacity sources, convection and turbulence. In the Kurucz's ATLAS code, convection is treated by means of the mixing-length theory, and the mixing-length to the pressure scale-height ratio *l/h* is equal to 1.25. The abundances are scaled solar for all the elements. Except for iron, for which the more recent determination by Holweger et al. (1995) was selected ($\log N(Fe)/N_{tot} = -4.53$), the Anders & Grevesse (1989) compilation of solar abundances has been otherwise adopted. Therefore, the solar boron abundance used in this work is $\log N(B)/N_{tot}=-9.44$.

The version of the grid of models released by Kurucz on CD-ROM #13 (1993) incorporates additional blanketing (a total of nearly 60 million atomic and molecular features), a larger number of the sources of the continuum and line opacities, and overshooting. The fact that at the very beginning this so-called "approximate-overshooting" at the top of the convection zone had been tested only for the solar spectrum, triggered further tests at lower metallicities. Specifically related to light element analyses, Molaro and collaborators (1995) showed that Li abundances $\approx$0.1 dex higher result from the new treatment of convection, while Primas (1996) estimated $\approx$0.07–0.05 dex (at metallicities of -1.0 and -3.0 respectively) higher abundances in the case of beryllium, compared to the old version of models (Kurucz 1979). When comparing abundances determined by different groups of investigators and addressing issues like the presence of dispersion among the observed data, extra (further) attention must be spent in checking which version of model atmospheres has been used: differences on the order of $\approx$0.1 dex (in Li and Be) can be easily accounted for only by different grids of models.

In order to be as much unaffected as possible by this uncertainty, we decided to analyze all our stars with Kurucz (1993) models computed with (OV) and without (NOV) overshooting, in order to estimate the influence of this new treatment of convection on the final B abundances. Although it is likely that neither of the two versions of models (with or without overshooting) is the correct one (non-overshooting seems also quite unrealistic), in this way we can have a broader picture when we make comparisons between different samples of abundances. However, our discussion in Sect. 4 will rely on the "non-overshooting" B abundances since Castelli et al. (1997) have clearly shown that, except for the Sun, the Kurucz model atmospheres calculated with the overshooting option switched off give much more consistent parameters. Also, several curves of growth run specifically for Li and Be have shown that the Kurucz model atmospheres without overshooting give quite similar numbers to what the OSMARCS (Edvardsson et al. 1993) model atmospheres calculate (see García-Lopez et al. 1998 for a detailed comparison of B abundances using both OSMARCS and Kurucz NOV models).

3.2. List of lines

The final list of atomic and molecular lines adopted during this analysis derives from the list compiled by Duncan et al. (1998b), that had been originally taken from the official list of atomic and hydrides lines of Kurucz (1993, LOWLINES, CD-ROM #1). Slight adjustments to the oscillator strengths of some of the lines around the boron doublet were then made. These modifications, required in order to improve the overall fit, were tested on a large sample of halo and disk stars, spanning a wide range in T_{eff}, log g, and metal content (5000÷6750 K, 2.5÷4.5 dex, −2.85÷+0.10 dex respectively), including the high resolution HST spectrum of Procyon (Lemke et al. 1993).

B abundances are usually derived from the λ 2496.772 line because the redder component of the doublet is severely blended. However, a Co I line at 2496.708Å also affects the bluer B line. At this resolution and S/N such a blending is difficult to resolve. A very high resolution analysis by Edvardsson et al. (1993) of the metal-poor star HD 140283 partially resolved the Co-B blend and determined a B abundance which is in very good agreement with what we found for this same star, but from a much lower resolution spectrum (see Duncan et al. 1997). This agreement make us confident that the Co should not be dominant in the 2496.772 Å line. As a further proof, we have decided to compute all the syntheses also without boron (see Figs. 2, 3, 4), in order to have an idea of the strength of the Co contribution. More recently, in their analysis of RR Lyrae stars, the metal-poor star HD 140283, and a variety of more metal-rich objects, Peterson et al. (1998) introduced the hyperfine structure (*hfs*) of 2 cobalt lines at $\lambda\lambda$ 2495.55 and 2496.708. By taking advantage of the fact that the λ 2495.55 line is unblended, they first constrained the Co abundance by fitting the bluer cobalt line, and then re-derived the B abundance from the λ 2496.772 line. Here, a similar approach has been applied for the first time in a systematic analysis of metal-poor stars. By finding that a strong change (±0.3 dex) in the Co abundance affects very much the unblended Co I line at 2495.55Å but produces a much smaller change in the redder Co I transition at 2496.708Å, we conclude that the influence of this Co blending is not an important source of error and that the line is likely to be mostly boron. On the average, the difference in the final B abundances is on the order of +0.1 dex when the Co *hfs* is taken into account.

3.3. Stellar parameters

A fundamental step for an accurate analysis of chemical abundances is the determination of the stellar parameters. Near-UV spectra do not allow spectroscopic determinations of T_{eff} and log g as is usually done in the optical where several unblended neutral and ionized iron and other metal lines are available. But fortunately all our targets had already been subjected to high-resolution spectroscopic analyses in different spectral regions, and accurate and very consistent values can be found in the literature. Also, a remarkable improvement in the determination of the gravity parameter was achieved after the Hipparcos mission. Nissen et al. (1997) have determined a new set of gravities for 54 metal-poor stars, the parallaxes of which have an accuracy better than 20%. Whenever possible, our initial sets of stellar parameters were chosen from this work (HD 94028, HD 160617, and HD 194598). Pasquini et al. (1994) and Molaro et al. (1997) analyzed spectroscopically HD 3795, finding very similar temperatures (5420 K), metallicities (−0.70 dex), and slightly different gravities (4.0 and 3.6 dex respectively). A good agreement was found among different literature sources for HD 2665 and HD 221377 (e.g. Gratton & Sneden 1987, Gilroy et al. 1988, Deliyannis et al. 1995), while HD 106516 is characterized by the most dispersed literature values of T_{eff} and log g. Fuhrmann et al. (1994) determined 5995/3.97/−0.86, while Alonso et al. (1996) and Gratton et al. (1998) found respectively 6208/4.5/−0.78 and 6267/4.6/−0.66. Because of this discrepancy, we decided to start to analyze it by using 2 models characterized by 6000/4.0/−1.0 and 6250/4.5/−1.0 respectively. The latter turned out to have too high T_{eff} and log g values in order to achieve a satisfactory fit, while the former set of parameters worked very well. A similar good agreement was also found by using a model with averaged T_{eff} and log g values (T_{eff}=6125 K and log g=4.25 dex). Table 2 reports the B abundance determined with this "average" model. When the 6000/4.0/−1.0 model is used a ≈0.10 dex lower B abundance is found. The slightly broader lines of HD 106516 compared to the other stars of the sample, required the inclusion of a rotational velocity as high as $V_{ROT}\approx$8km s^{-1}(also reported in SIMBAD), in order to achieve a good match between observed and calculated features.

Table 2. Our final B abundances (LTE and NLTE) computed with models with and without overshooting using the stellar parameters given in column #2 (T_{eff} in kelvin, g in cm s^{-1}, abundances in units dex, and ξ in km s^{-1}).

Star	T_{eff}/log g/[Fe/H]/ξ	log ϵ(B)$_{LTE}$	log ϵ(B)$_{NLTE}$
Models without Overshooting (NOV)			
HD 2665	5100/2.65/−2.00/2.0	0.26	0.49
HD 3795	5420/3.60/−0.72/1.4	1.10	1.19
HD 94028	5950/4.30/−1.50/1.5	1.22	1.52
HD 106516	6125/4.25/−0.90/1.5	1.42	1.67
HD 160617	5900/3.75/−1.80/1.5	0.27	0.67
HD 194598	5950/4.30/−1.15/1.5	1.35	1.57
HD 221377	6200/3.75/−0.92/1.5	1.36	1.65
Models with Overshooting (OV)			
HD 2665	5100/2.65/−1.96/2.0	0.20	0.42
HD 3795	5420/3.60/−0.75/1.4	1.12	1.21
HD 94028	5950/4.30/−1.45/1.5	1.27	1.57
HD 106516	6125/4.25/−0.80/1.5	1.49	1.72
HD 160617	5900/3.75/−1.80/1.9	0.37	0.77
HD 194598	5950/4.30/−1.15/1.5	1.39	1.61
HD 221377	6250/4.00/−0.95/2.0	1.50	1.79

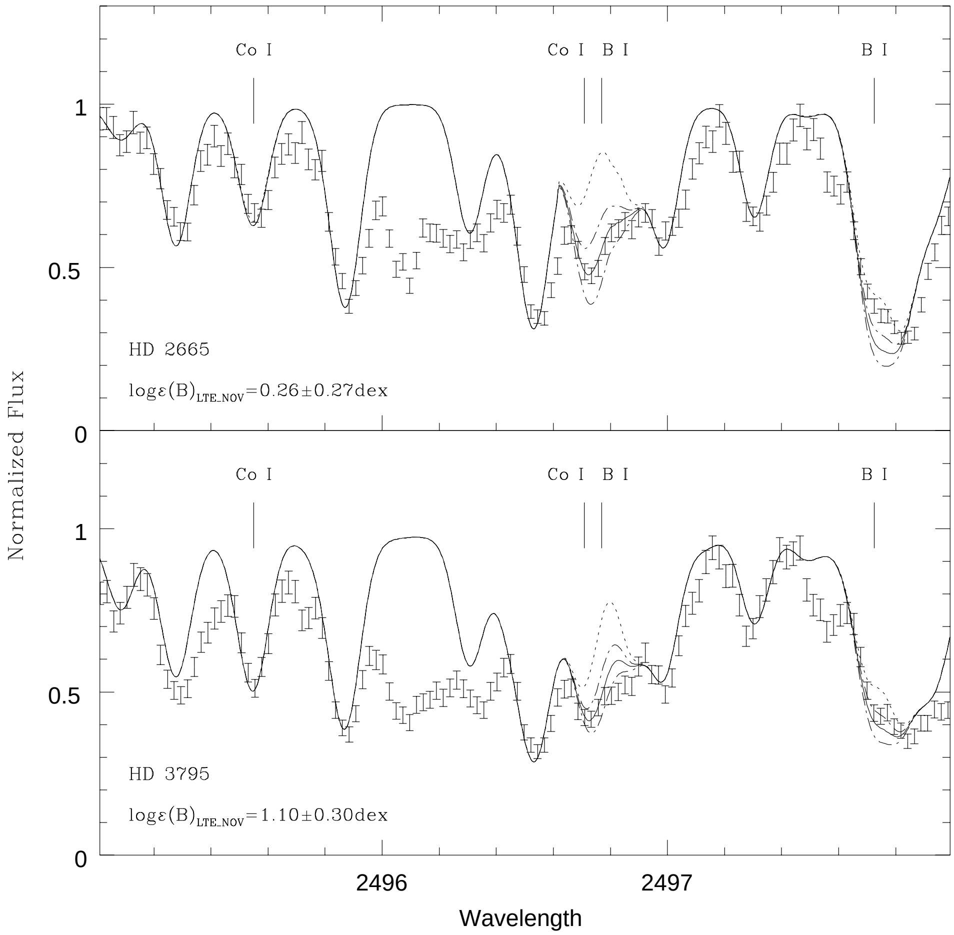

Fig. 2. Best-fits for HD 2665 and HD 3795. The observed data are represented by photon statistics error bars. Overplotted are also spectrum syntheses computed with no boron (dotted line) and with ± "the net final error" (dot-dashed line) as reported in Table 3. Each panel is labeled accordingly.

After this first selection of parameters, slight changes were then allowed in T_{eff}, log *g*, and [Fe/H] (well within the uncertainties associated to each of them) in order to select the best-fit. By running several spectrum syntheses, we more or less confirmed our initial literature-based choices: because of the excellent agreement thus found, no further attempt was made to use different empirical methods to determine stellar parameters, mainly because such a procedure would have not guaranteed any higher accuracy. Table 2 gives the final stellar parameters (in column #2) for which our best-fits were obtained (see Figs. 2, 3, 4), and the resulting B abundances (LTE and NLTE) computed by making use both of models with and without overshooting.

Microturbulence has usually been assumed constant in this kind of analyses (≈1.5–2 km s^{-1} for all halo stars) mainly because the sensitivity of boron abundance to this stellar parameter is found to be negligible. But despite of the fact that boron is what we want to determine, any analysis based on spectrum synthesis calculations usually tries to achieve a "good *overall* fit", *i.e.* the final choice of the best-fits relies on fitting also the adjacent lines. And if boron lines do not show any significant change associated with different microturbulent velocities, many other lines in their proximity do. Furthermore, at higher metallicities the boron lines also start to show some dependence on ξ. Keeping in mind that the boron abundance is more sensitive to the selected effective temperature and metallicity than to the other stellar parameters, we tried to quantify how much a possibly different value of microturbulence affects our final choice of T_{eff} and/or [Fe/H], and in turn our final estimate of the boron content. We ran several syntheses, starting from the value of ξ=1.5 km s^{-1}, and then changing it according to different values found in the literature (it is worth remembering that ξ is usually determined in high-resolution spectroscopic analyses of optical spectra as the value that minimizes the dependence on equivalent widths of the abundance determined from unblended neutral iron lines). We found that in order to maintain the goodness of our fits, slight adjustments in T_{eff}, log *g*, and [Fe/H] must be allowed when adopting different ξ values. Although these changes have always been found to be smaller than the uncertainties we associated with them, we considered this an extra source of uncertainty and took it into account in estimating the net errors to be associated with our B abundances (see Table 3). Although it does not make any substantial difference, the boron abundances reported in Table 2 have been all computed with the microturbulent velocities there specified (column #2). A detailed description of these tests, with the resulting curves of growth showing the dependence of both B and Co on microturbulence, as on the other stellar parameters, will be reported in Primas & Duncan (1998b).

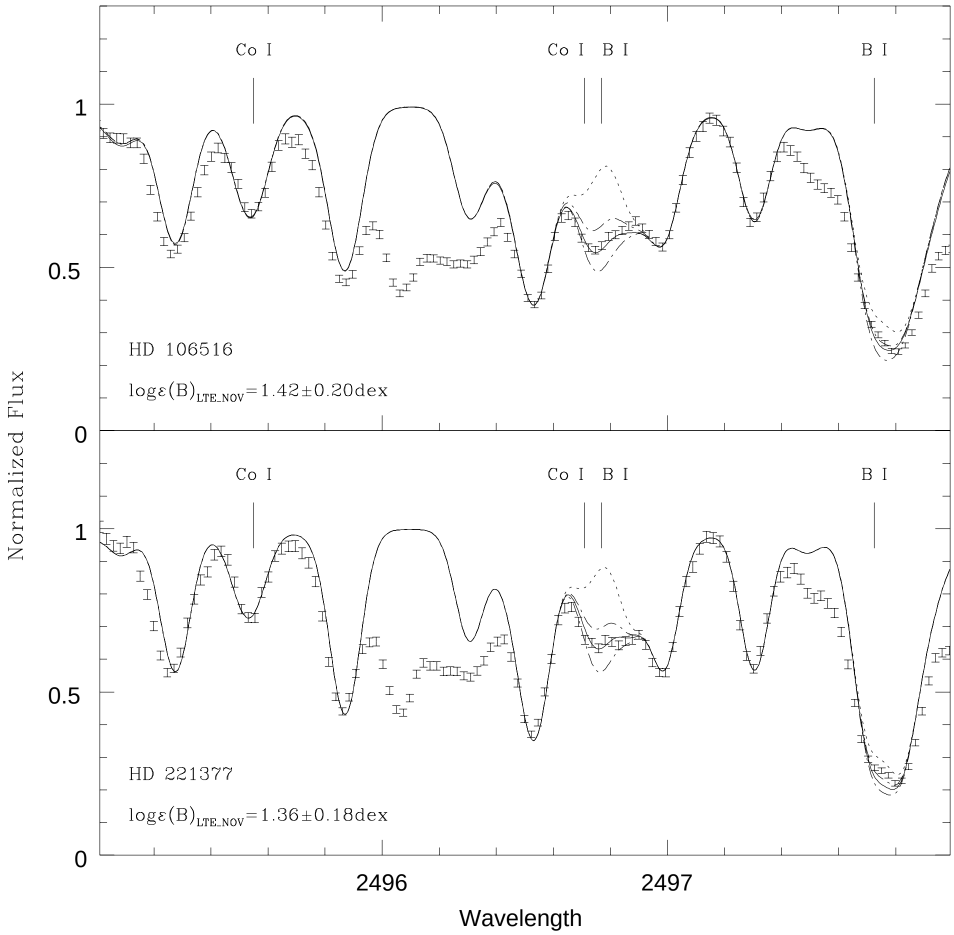

Fig. 3. Best-fits for HD 106516 and HD 221377. The observed data are represented by photon statistics error bars. Overplotted are also spectrum syntheses computed with no boron (dotted line) and with ± "the net final error" (dot-dashed line) as reported in Table 3. Each panel is labeled accordingly.

Table 3. Uncertainties affecting B abundances (all units dex).

Star	T_{eff} ± 75 K	log *g* ± 0.2 dex	[M/H] ± 0.10 dex	ξ ±0.5 km s^{-1}	Continuum ± 2.0%	Photon statistics	Total Error
HD 2665	±0.09	±0.08	±0.15	±0.06	±0.10[a]	±0.15	±0.27
HD 3795	±0.10	±0.10	±0.15	±0.05	±0.10[a]	±0.18	±0.30
HD 94028	±0.11	±0.02[b]	±0.12	±0.05	±0.08	±0.06	±0.20
HD 106516	±0.12	±0.06	±0.10	±0.08	±0.05	±0.05	±0.20
HD 160617	±0.08	±0.03[c]	±0.15	–	±0.06	±0.08	±0.21
HD 194598	±0.11	±0.02[b]	±0.10	±0.04	±0.06	±0.06	±0.20
HD 221377	±0.06	±0.04	±0.12	±0.08	±0.05	±0.07	±0.18

[a] ±5%; [b] ±0.07 dex; [c] ±0.13 dex

3.4. Uncertainties

We followed the same approach described in Duncan et al. (1997) in order to estimate the total uncertainty to be associated with our B abundances. Errors mainly depend on the uncertainties associated with the stellar parameters T_{eff} (±75 K), log *g* (±0.2 dex), metallicity (±0.1 dex), and microturbulence (±0.5 km s^{-1}), and statistical errors were quantified by taking into account the placement of the continuum (±2%) and the photon statistics in the points defining the line itself. In the case of the 3 stars for which Hipparcos-based gravities are available, the sensitivity of B to log *g* was tested for changes of ±0.06 dex for HD 94028 and HD 194598, and ±0.13 dex for HD 160617 (as reported by Nissen et al. 1997). Due to the slight dependence of boron on gravity, even a change of ±0.2 dex would practically not affect the final estimate of the net error. In the case of the two worst spectra (HD 2665 and HD 3795) the sensitivity of the B abundances to a change of ±5% in the continuum location was assumed. By summing quadratically all these different sources of error, final net errors ranging from ±0.18 dex to ±0.30 dex resulted (Table 3).

These estimates do not include the systematic uncertainty related to NLTE effects and to the procedure followed to derive them. The NLTE B abundances given in Table 2 have been

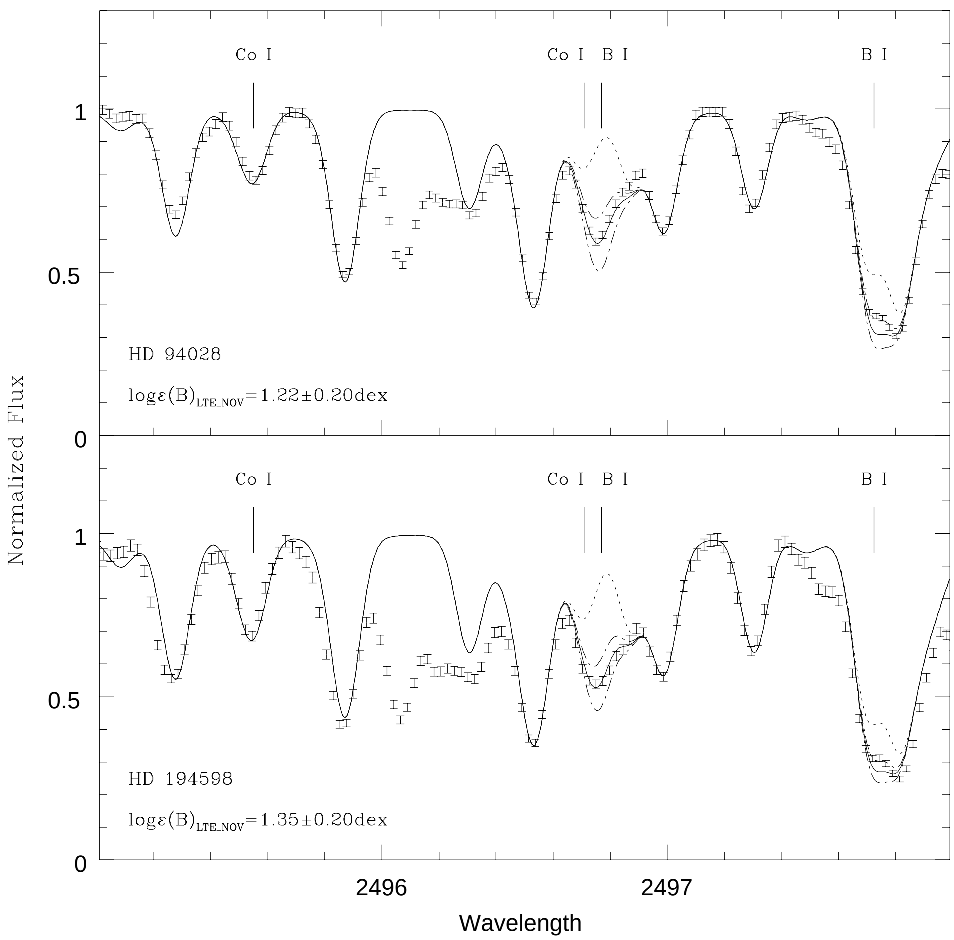

Fig. 4. Best-fits for HD 94028 and HD 194598. The observed data are represented by photon statistics error bars. Overplotted are also spectrum syntheses computed with no boron (dotted line) and with ± "the net final error" (dot-dashed line) as reported in Table 3. Each panel is labeled accordingly.

derived by interpolating in $T_{\rm eff}$, log g, [Fe/H], and LTE B abundances the NLTE corrections computed by Kiselman & Carlsson (1996). Although the statement made by García-Lopez et al. (1998) is *in principle* correct, *i.e.* that NLTE corrections calculated via the Kiselman & Carlsson code should apply only to the LTE abundances calculated via the OSMARCS models, *in practice* we expect corrections to be quite similar between OSMARCS models and those of Kurucz without overshooting, since the run of physical variables with depth in those two sets of atmospheres are not so different.

As far as a possible missing UV opacity is concerned, we have decided not to quantify such an effect until more tests and results become available. The recent paper by Balachandran & Bell (1998) has raised this as an issue, but their finding has not been investigated yet in other stars than the Sun nor in other spectral regions than at 3130Å.

4. Results and discussion

The importance of studying the light elements lithium, beryllium, and boron is at least twofold: they are useful probes of stellar interiors and useful tools in better constraining the chemical evolution of the Galaxy. On one side, since Li, Be, and B cannot survive in deep stellar interiors because they burn at progressively higher temperatures at densities found in F and G stars near the base of the surface convection zone, they are a powerful diagnostic for testing stellar structure models. On the other, the analysis of their abundances in different types of stellar objects represents an additional test for the standard Big Bang nucleosynthesis theory (homogeneous vs. inhomogeneous), and can further constrain the GCR spallation scenario, where both Be and B are believed to originate. Here, the derived B abundances will be discussed, together with the Li and Be literature data, with the aim of testing predictions of depletion and/or internal mixing.

The discussion of the results has been divided in 3 parts so that the stars could be grouped according to the motivation that triggered their selection and to the findings of this work. Table 4 combines our NOV LTE and NLTE B abundances with Li and Be determinations collected from the literature (the corresponding references are listed at the bottom of the table). Li and Be abundances have been adjusted in order to match our adopted stellar parameters and in order to take into account effects due to the type of models (with or without overshooting) used by the other investigators, according to the extensive analyses of how Li and Be depend on stellar parameters and model atmospheres (see Molaro et al. 1995 and Primas 1996, respectively). On the average, the following corrections were applied: ≈+0.08 dex in Li for a $\Delta(T_{\rm eff})$=+100 K, and ≈ -0.06 dex and +0.11 dex in Be for $\Delta(T_{\rm eff})$=+100 K (for $T_{\rm eff}$

Table 4. NOV LiBeB abundances for all the stars analyzed in this work and in Duncan et al. (1997) (T_{eff} in kelvin, g in cm s^{-1}, and abundances in units dex).

Star	T_{eff}	log *g*	[M/H]	log $\epsilon(Li)^{a}_{LTE}$	log $\epsilon(Be)^{b}_{LTE}$	log $\epsilon(B)_{LTE}$	log $\epsilon(B)_{NLTE}$
HD 2665	5100	2.65	−2.00	<0.90	< −1.70	0.26	0.49
HD 3795	5420	3.60	−0.72	<0.65	< −0.48	1.10	1.19
HD 19445	5870	4.50	−2.20	2.10	−0.93	0.49	0.8
HD 64090	5350	4.50	−1.80	1.22	−0.16	1.02	1.20
HD 76932	5900	3.50	−1.00	2.06	0.57	1.80	1.97
HD 94028	5950	4.30	−1.50	2.21	0.45	1.22	1.52
HD 106516	6125	4.25	−0.90	<1.50	< −0.68[c]	1.42	1.67
HD 140283	5640	3.60	−2.60	2.10	−1.19	−0.14	0.32
HD 142373	5900	4.00	−0.45	2.44	1.10	2.04	2.12
HD 160617	5900	3.75	−1.80	2.22	−0.73/−0.47	0.27	0.67
HD 184499	5700	4.00	−1.00	1.36	0.80	1.60	1.73
HD 194598	5950	4.30	−1.15	2.10	0.14/0.31	1.35	1.57
HD 201891	5870	4.50	−1.15	1.98	0.52[c]	1.60	1.78
HD 221377	6200	3.75	−0.92	<1.45	< −0.95	1.36	1.65
BD+3°740	6125	3.50	−2.75	2.05	−1.56	0.16	0.99
BD+26°3578	6150	4.00	−2.35	2.11	−0.75	0.08	0.72
BD−13°3442	6250	3.75	−3.00	2.18	−1.44	−0.10	0.82

[a] *References:* Bonifacio & Molaro (1997), Hobbs & Duncan (1981), Molaro et al. (1995), Pasquini et al. (1994), Pilachowski et al. (1993), Rebolo et al. (1988), Ryan et al. (1992)
[b] *References:* Boesgaard & King (1993), Boesgaard (1996), Deliyannis et al. (1995), Gilmore et al. (1992), Molaro et al. (1997), Primas (1996) Thorburn & Hobbs (1996)
[c] Average value between determinations from 2 different investigations (see text for more details)

<5500 K only) and Δ(log *g*)=+0.25 dex respectively. The correcting factors required to put all the abundances on the same "non-overshooting" scale (keeping in mind that the old Kurucz, the new non-overshooting Kurucz and the OSMARCS models give very similar results) are the numbers previously given in Sect. 3.1 (*i.e.* −0.10 dex and ~ -0.06 dex for Li and Be abundances respectively). For 2 stars (HD 106516 and HD 201891) the Be abundances given in Table 4 represent values that have been averaged between two similar but slightly different determinations (< -0.6 dex and < -0.76 dex in the case of HD 106516, and +0.40 dex and +0.64 dex for HD 201891). For 2 others, two different Be abundances are reported because the detected differences are relevant to the interpretation of the results. One is HD 160617 (see Primas et al. 1998a), and the other is HD 194598, that will be discussed in Sect. 4.3. How this new set of boron determinations behaves as a function of metallicity is displayed in Fig. 5, where both LTE and NLTE NOV B abundances are plotted (*upper* and *lower* panel respectively). The open symbols represent the data set analyzed by Duncan et al. (1997), but all the B abundances have been re-synthesized with non-overshooting models and taking into account the *hfs* of the two cobalt lines (cf Peterson et al. 1998). We found that the use of NOV model atmospheres is responsible for corrections to the B abundances ranging between −0.03 dex and −0.13 dex, whereas the introduction of the Co *hfs* accounts for corrections ranging between +0.05 dex and +0.10 dex. The chi-squares fits super-imposed on the data have been taken from Duncan et al. (1997). They still fit the observed trend very well, because the abovementioned correcting factors affect the B abundances in opposite directions, and practically cancel out (except for HD 19445 and BD−13°3442 for which the applied corrections do not compensate and slightly different B abundances are found with respect to the Duncan et al. analysis). A forthcoming paper (Primas et al. 1998c) will re-discuss in detail the evolutionary trend of boron in the light of our new set of abundances, making use of a more robust statistical analysis. The discussion that follows is based on the NLTE NOV B abundances only.

4.1. Li-poor, Be-poor, B-poor stars: HD 2665 and HD 3795

These are the 2 coolest objects of our sample. HD 2665 is a metal-poor giant star (T_{eff}=5100 K, log *g*=2.65, [Fe/H]=−2.0), for which both Li and Be have upper limits only. Pilachowski et al. (1993) determined log ϵ(Li)<0.9, while Deliyannis et al. (1995) found log $\epsilon(Be) < -1.64$ (where log ϵ(X)=log(N(X)/N(H)) + 12, with logN(H)=12). It is expected that such a star has undergone both Li and Be *dilution*: as a star evolves past the turnoff (until which point its light elements were preserved in the outermost layers only) its surface convection zone deepen beyond these boundaries, thus diluting the surface abundances with light-element-free material (Iben 1967). Our B measurement (log $\epsilon(B)_{NLTE\_NOV}$=0.49±0.27 dex, Fig 5) indicates that the star still has boron, although approximately 0.5–0.6 dex less than other objects at similar metallicities. We can infer that its B content might also have been affected by dilution. Theoretical calculations of dilution factors of light elements have been performed for ^{6}Li, ^{7}Li, ^{9}Be, but they have never been severely tested because of the paucity of Be detec-

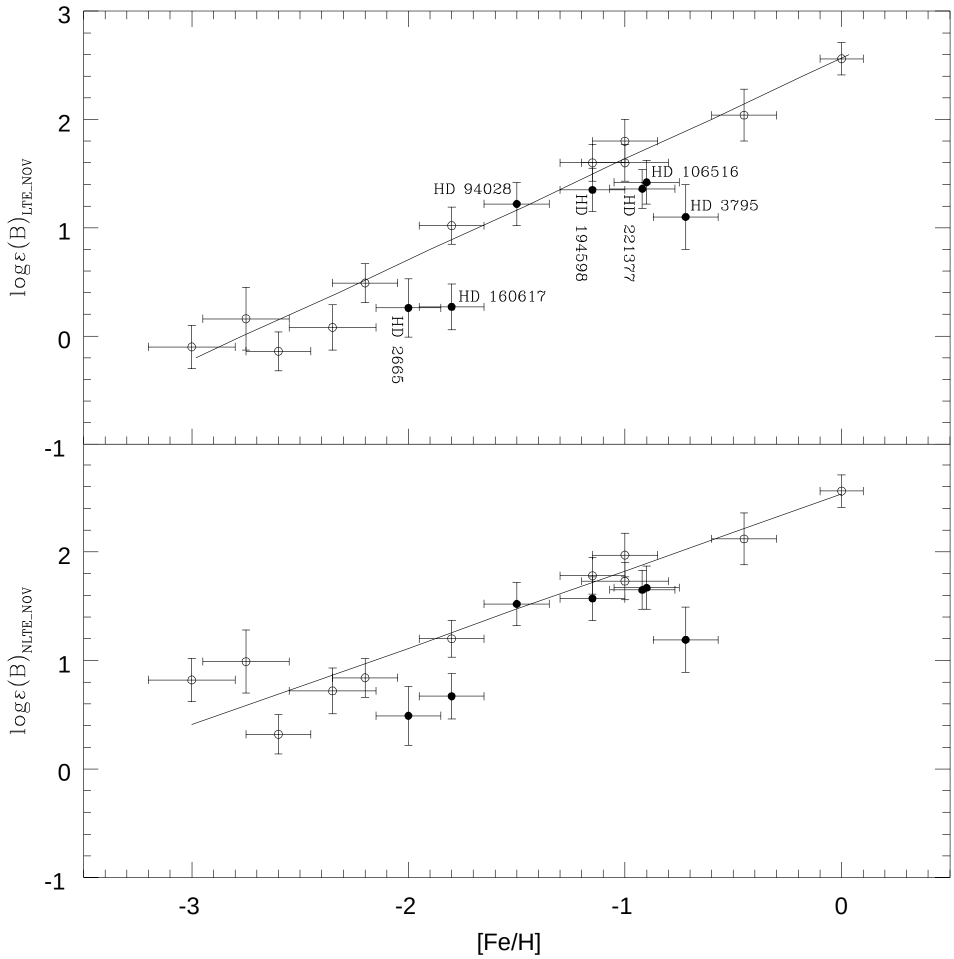

Fig. 5. [B] vs. [Fe] for all the stars analyzed in this work (filled symbols) and in Duncan et al. (1997, open symbols). LTE boron abundances are plotted in the upper panel; NLTE boron abundances are plotted in the bottom panel. The linear chi-squares-fits determined by Duncan et al. (1997) have been superimposed.

tions in subgiant stars. According to Deliyannis et al. (1995) calculations, a star of this effective temperature is predicted to have diluted its lithium content by -1.2 dex and its beryllium by -0.9 dex. When these factors are applied to the abovementioned upper limits, a Spite-plateau Li abundance is found and the star falls back on the mean evolutionary trend observed for Be. If predicted factors for boron were available, it would then be possible to test whether dilution alone explains this star, or whether "additional mixing" is required. From a static model we have roughly estimated an expected dilution factor for boron; this is -0.5 dex, consistent with our observations. We stress the need for theoretical calculations to include also B, and not only Li and Be.

HD 3795 is a subgiant star, with a metallicity characteristic of the galactic disk ([Fe/H]≈ -0.75). Pasquini et al. (1994) and Molaro et al. (1997) assigned upper limits to its Li and Be abundances respectively ([Li]$<$0.65, [Be]< -0.48). The star falls well below the Li Spite-plateau and the Be evolutionary trend, indicating that both elements are strongly depleted. Although a star of these characteristics might have already started to deplete its lithium content by convection (as predicted in standard models), at this effective temperature ($\approx$ 5420 K) no Be (and consequently no B) depletion is expected. We measured a low B content (log ϵ(B)$_{NLTE\_NOV}$=1.19$\pm$0.30 dex) at least a factor of 5–6 below the mean trend. *Non-standard* stellar structure models seem to be the only plausible solution. The star then becomes an excellent case to further constrain what different destruction scenarios predict.

4.2. Li-poor, Be-poor, possibly B-poor stars: HD 106516 and HD 221377

HD 106516 is a subdwarf with a metallicity [M/H]=$-$1.00, to be identified as a disk star according to the kinematical classification of Nissen & Schuster (1997). No light elements depletion is expected according to its evolutionary status and effective temperature ($\approx$6000 K). But its Li content has been measured as an upper limit (log ϵ(Li)$<$1.50, Hobbs & Duncan 1981), and it has been identified as a Be-poor star by both Molaro et al. (1997) and Stephens et al. (1997) (log ϵ(Be)< -0.76 and < -0.60 respectively). These abundances represent deficiencies of $\geq$ 0.7 dex and $\geq$1.5 dex respectively, compared to stars of similar metallicity. Once again, such results make it very difficult to find a plausible explanation without invoking *non-standard* stellar structure scenarios, rotationally induced mixing and diffusion having been suggested as the most likely ones. The B abundance we determine (log ϵ(B)$_{NLTE\_NOV}$=1.67 $\pm$0.20 dex) falls slightly below the linear evolutionary trend of [B]$_{NLTE}$ vs. [Fe].

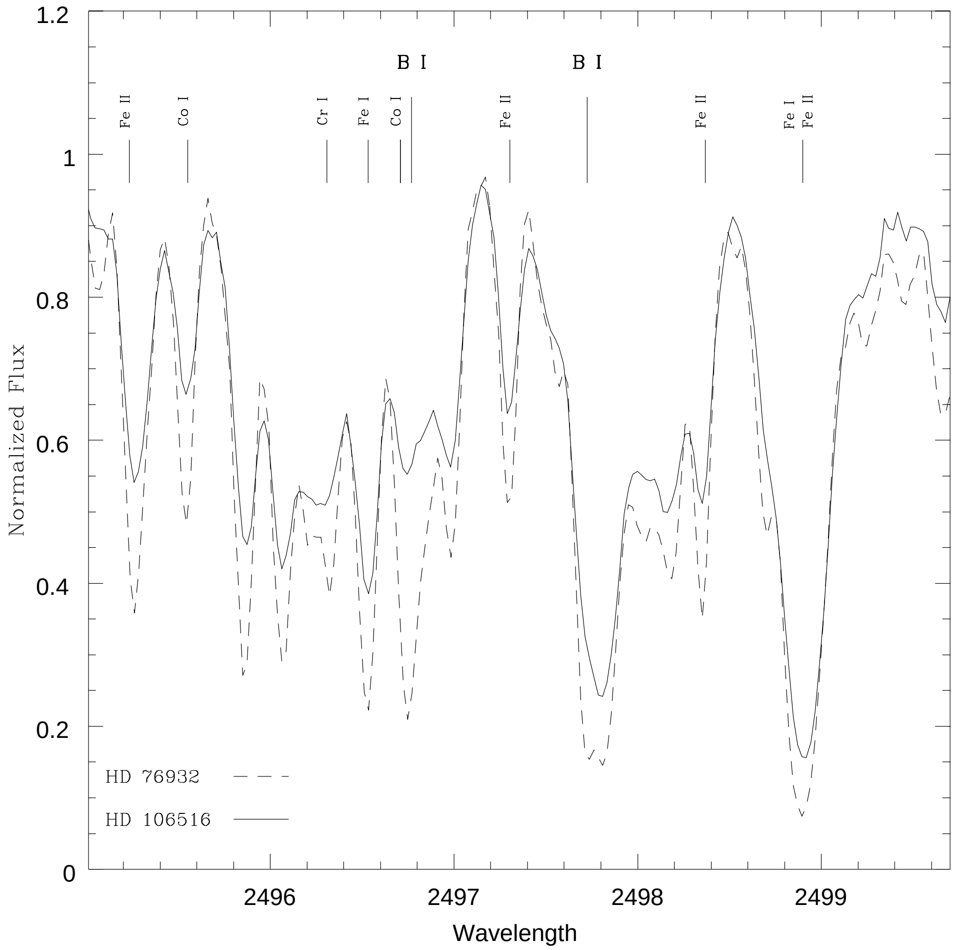

Fig. 6. Overplot of the observed spectra HD 76932 (dashed line) and HD 106516 (continuous line).

Because of the uncertainties associated with B measurements, we cannot be certain that this lower location of HD 106516 with respect to the mean trend is significant. Further information could be provided by differential comparison with stars of similar atmospheric characteristics but potentially different boron. Fig. 6 attempts to do this by comparing the observed spectra of HD 106516 and HD 76932, which are roughly similar. HD 76932 is about 200 K cooler, which is the main reason its lines are deeper. The almost constant difference observed in the lines strength clearly confirms that these 2 stars have different temperatures, and maybe slightly different gravities. A careful inspection shows that the difference is strongly emphasized at the B I 2496.772Å position only, suggesting a probable lower content of boron in HD 106516. But the correct interpretation of this star may well be different. The star has been recently found to be a single-lined spectroscopic binary, with a long period (>150 days) and low eccentricity (Carney 1998). The star appears to be a blue straggler from its colours, envisaging a mass transfer scenario. This could explain its low Li and Be abundances. The knowledge of its B abundance may constrain further which depths of its atmosphere have been involved in such mass transfer event (the B preservation layer evidently not).

The subdwarf HD 221377 ([Fe/H]=−1.00) has been analyzed by Rebolo et al. (1988) in the Li region, and by Boesgaard & King (1993) in the Be spectral region. The low lithium (log ϵ(Li) < -1.45), together with the low beryllium (log ϵ(Be)< -0.99), made Boesgaard & King conclude that some depletion mechanism must be already active in the photospheric layer where Be is normally preserved. These authors showed a differential comparison of the observed Be spectra of this star and HD 76932 (like we did above for B in HD 106516), and suggested that only with some "extra" depletion mechanism at work in HD 221377 could the observed differences be explained. The B abundance we determine (log $\epsilon(B)_{NLTE\_NOV}$=1.65±0.18 dex) is essentially identical to that derived for HD 106516. Again, the star falls just slightly below the linear evolutionary trend of boron (see Fig. 5). This suggests that its B content has not been severely depleted as Be, although (as previously found for HD 106516) a much more pronounced discrepancy between HD 221377 and HD 76932 is observed again at the wavelength of the bluer B I line (easy to check by noticing the similarity between the spectral features of HD 106516 and HD 221377 in Fig. 3). A more suitable comparison star is desirable.

4.3. HD 94028 vs. HD 194598

HD 94028 and HD 194598 were selected mainly because despite their twin nature and similar Li abundances

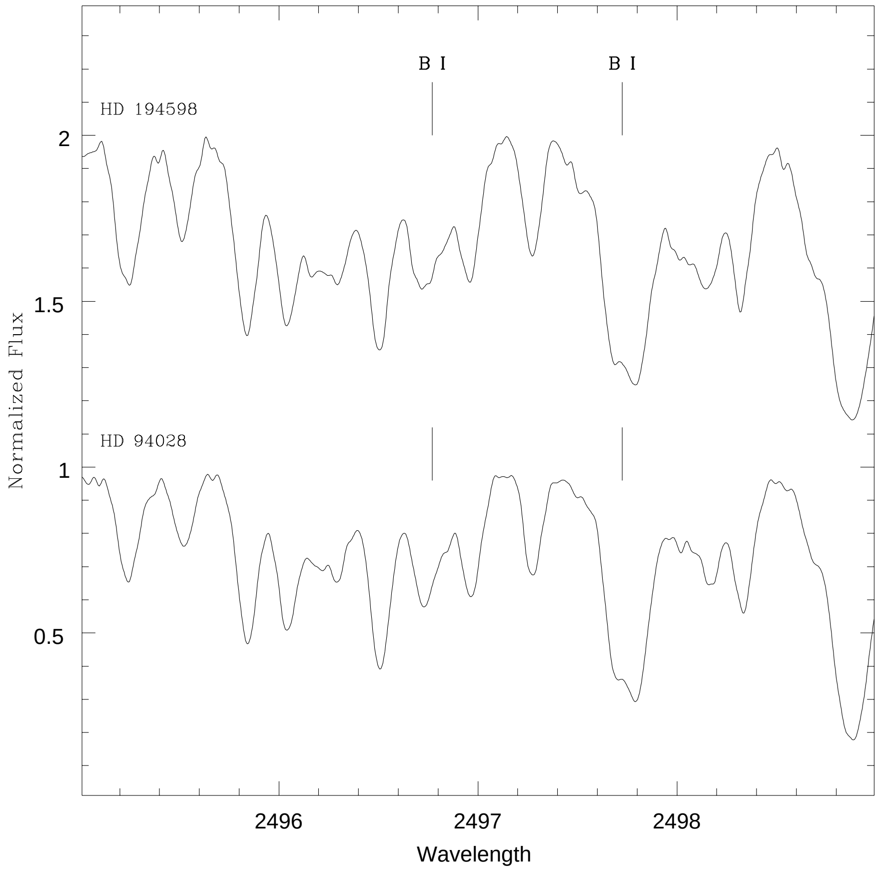

Fig. 7. The observed spectra of HD 94028 and HD 194598 are compared (the identification of the stars is marked).

(log ϵ(Li)=2.25±0.10 and 2.15±0.06 respectively, Bonifacio & Molaro 1997), they were found to differ by 0.3 dex in their Be contents by Thorburn & Hobbs (1996, hereafter TH96; see their Fig. 10). Whatever might cause the Be abundances to be slightly different does not affect Li, as would be anticipated for light element depletion. TH96 tentatively concluded that the Be contrast between these two stars indicates inhomogeneity in their initial Be content rather than different internal processing. If B was proved to be lower in HD 194598 by the same factor as Be, while Li is not depleted, then the mechanism of B and Be production – rather than stellar depletion – could be implicated more firmly as the cause. However, we find a quite similar content of boron in these 2 stars (log ϵ(B)$_{NLTE\_NOV}$=1.52±0.20 dex in HD 94028 and log ϵ(B)$_{NLTE\_NOV}$=1.57±0.20 dex in HD 194598), although models that differ in metallicity by 0.3 dex were used in the spectrum synthesis analysis (no satisfactory fit could be achieved with the parameters adopted by TH96 for HD 94028). This 0.3 dex difference in [Fe/H] has also been found in other spectroscopical analyses. The 2 observed spectra are plotted in Fig. 7. Apart from slight differences due to the different metal content of the 2 objects, the net contrast revealed by TH96 in their Be spectra is clearly not present in the B spectral region. The interpretation of only a Be deficiency, with no Li or B deficiency, would be extremely challenging. The suggestion made by TH96 about inhomogeneity in the initial Be content was waiting to be proved or disregarded by verifying their B content. Our finding seems to disprove it, unless different mechanisms are responsible for the production of Be and B, resulting in less Be than B. Depletion mechanisms had already been discarded because of the normal lithium detected in both stars. But it is important to mention that a previous Be analysis of the same two stars did not detect any significant difference in their Be content. Boesgaard & King (1993) measured equivalent widths of the λ3130 line of 51mÅ and 43mÅ in HD 94028 and HD 194598 respectively, while TH96 found 50mÅ and 25mÅ. Despite of the fact that such a discrepancy might be explained by how these two investigations have handled the placement of the continuum in HD 194598, it clearly suggests the need for re-observing the Be spectral region (at least in HD 194598). Until then, any discussion can be only speculative. If ^{11}B is produced also by ν-spallation in supernovae shock waves (e.g. Woosley et al. 1990), then the difference observed in Be and likely due to cosmic-ray spallation could have been canceled out because of this extra-mechanism intervening in the production of boron. It seems however quite difficult to explain and justify why two otherwise similar objects should have been affected by different ν-spallation contributions. Furthermore, ν-spallation has not yet gained a clear role in the global scenario of light elements abundances, the neutrino yields being under strong debate (e.g. Vangioni-Flam et al. 1996, 1998). Measuring the isotopic boron ratio in HD 194598 might shed new light on this hypothesis, as well as re-observing the 2 stars at 3130Å. HD 94028 and HD 194598 may well turn out to be very similar in their contents of all 3 light elements Li, Be, and B.

4.4. The anomalous Li-Normal, probable Be-low, B-low HD 160617

Since this star is discussed in detail in Primas et al. (1998a), here we will just briefly comment on the remarkable result found for HD 160617. This metal-poor ([Fe/H]=-1.80) subgiant star is characterized by a normal "Spite-plateau" Li abundance, its Be is likely to be lower than stars of similar metallicities (the precise amount of which being uncertain), but its boron is low. No destruction mechanism is able to account for such a pattern. Rather, the cause may be found in inhomogeneous production of light elements by CR spallation, depending on the galactic region where the star actually formed. Recent developments of the theoretical scenario responsible for Be and B formation in the Galaxy (e.g. Vangioni-Flam et al. 1998, Ramaty et al. 1997) indicate that (isolated) regions around massive-star supernovae might play a more important role in spallation than previously realized. This might account for different amounts of spallation in different regions of the Galaxy. A factor that must be taken into account is that HD 160617 is extremely rich in nitrogen (by a factor of $\sim$50, cf Laird 1985). The hypothesis that the star formed out of N-rich proto-stellar material seems to be the most plausible explanation for the N-overabundance. How N overabundance could affect spallation reactions between protons and α-particles and CNO nuclei (but now with N being much more abundant than usually considered) still needs to be investigated. An interesting *coincidence* is that one of the possible candidates responsible for such N-rich gas at these early epochs of the Galaxy is super-massive stars (pop III objects?, see Spite & Spite 1986), which naturally end their quite short lives in supernovae explosions.

5. Conclusions

Seven new halo and disk stars ranging in metallicity from [Fe/H]=-2.0 to -0.75 have been analyzed at 2500Å with the aim of measuring their B abundances. The analysis was performed via spectrum synthesis, by using model atmospheres computed with and without overshooting, giving our preference to the latter ones. NLTE corrections were then applied to the LTE B abundances thus determined. The whole discussion was based on such non-overshooting (NOV) NLTE B abundances. Li and Be abundances were already available from the literature for all our targets, so we could test implications for light elements depletion and internal mixing. The lack of specific theoretical calculations for boron represents the strongest limitation in discussing the results. We hope that future developments of stellar structure models and light elements depletion isochrones will extend their predictions also to boron. The main findings can be summarized as follows:

- Among the 4 stars known to be Li- and Be-poor (compared to stars of similar metallicities), 2 of them were found to be substantially B-poor. HD 2665 is a metal-poor giant star for which dilution is able to account for the observed depletion factor of all 3 light elements. The case of the subgiant HD 3795 is different: additional non-standard mixing is required to explain the low Li, Be, and B abundances.
- Another Li- and Be-poor star of the sample (HD 221377) shows a probable B depletion, which would also require non-standard mixing for its explanation. This probable B-depletion strongly constrains the extra-mixing at disk metallicities. The observed pattern of its LiBeB abundances qualitatively confirms what one should expect according to their burning temperatures: Be is substantially depleted (a factor of $\geq$30) before mixing starts to penetrate the layer where B is preserved. Quantitatively, these numbers will strongly constrain extra-mixing models.
- Taken together, HD 3795 and HD 221377 place strong constraints on possible depletion mechanisms. Both have a B content (actual values, and not just limits, were determined) that is not as low as their Li and Be abundances. HD 3795 shows the most depletion of the 2 (in B), and it is a subgiant with a deeper convection zone (which presumably augments any extra mixing process).
- A similar scenario to HD 221377 was found for HD 106516, but in this case the interpretation of its light element abundances might be different in the light of the recent finding that the star is a single-lined spectroscopic binary, that has likely undergone mass transfer (Carney 1998). Its low Li and Be abundances could be thus explained and the normal B content we determine may become an useful constraint on the depth to which the mass transfer has affected the star.
- HD 94028 and HD 194598 have been found to have comparable amounts of boron, despite a 0.3 dex difference in Be claimed by TH96. Because these 2 stars have also very similar Li abundances, we stress the need for re-observing the Be spectral region of this pair of objects (or at least HD 194598), before starting to interpret what could be a very exotic scenario.
- HD 160617 turned out to be the most critical object of the entire sample, being characterized by a lower B content with respect to other stars with similar stellar parameters, *but* normal Li. Such a scenario is not predicted by any destruction and/or mixing mechanism. It suggests that stars very similar in their stellar characteristics can have different amounts of boron (and beryllium), which becomes a strong indication of a spatially different efficiency in producing beryllium and boron in the Galaxy.

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References

Alonso A., Arribas S., Martínez-Roger C., 1996, A&AS 117, 227
Anders E., Grevesse N., 1989, Geoph. and Cosmochim. Acta 53, 197
Balachandran S., Bell R., 1998, Nat 392, 791

Bodenheimer P., 1966, ApJ 144, 103
Boesgaard A.M., King J.R., 1993, AJ 106, 2309
Boesgaard A.M., 1996, Light Element Abundances in the Halo. In: Morrison H., Sarajedini A. (eds.) Formation of the Galactic Halo....Inside and Out. PASPC, vol. 92, 327
Boesgaard A.M., Deliyannis C.P., Stephens A., King J.R., 1998, ApJ 492, 727
Bonifacio P., Molaro P., 1997, MNRAS 285, 847
Carney B., 1998, private communication
Castelli F., Gratton R.G., Kurucz R.L., 1997, A&A 318, 841
Deliyannis C.P., Demarque P., Kawaler S.D., 1990, ApJS 73, 21
Deliyannis C.P., Boesgaard A.M., King J.R., et al., 1995, preprint
Duncan D.K., Primas F., Rebull L.M., et al., 1997, ApJ 488, 338
Duncan D.K., Rebull L.M., Primas F., et al., 1998a, A&A 332, 1017
Duncan D.K., Peterson R.C., Thorburn J.A., et al., 1998b, ApJ 499, 871
Edvardsson B., Andersen J., Gustafsson B., et al., 1993, A&A 275, 101
Fuhrmann K., Axer M., Gehren T., 1994, A&A 285, 585
García-Lopez R.J., Severino G., Gomez M.T., 1995, A&A 297, 787
García-Lopez R.J., Lambert D.L., Edvardsson B., et al., 1998, ApJ 500, 241
Gilmore G., Gustafsson B., Edvardsson B., Nissen P.E., 1992, Nat 357, 379
Gilroy K.K., Sneden C., Pilachowsky C.A., et al., 1988, ApJ 327, 298
Gratton R.G., Sneden C., 1987, A&A 178, 179
Gratton R.G., Carretta E., Clementini G., et al., 1998, preprint
Hobbs L.M., Duncan D.K., 1981, ApJ 317, 796
Holweger H., Koch M., Bard A., 1995, A&A 296, 233
Kiselman D., Carlsson M., 1996, A&A 311, 680
Kurucz R.L., 1979, ApJS 40, 1
Kurucz R.L., 1993, CD-ROM # 1,13,18
Iben I. Jr., 1967, ARA&A 5, 271
Laird J.B., 1985, ApJ 289, 556
Lemke M., Lambert D.L., Edvardsson B., 1993, PASP 105, 468
Meneguzzi M., Audouze J., Reeves H., 1971, A&A 15, 337
Molaro P., Primas F., Bonifacio P., 1995, A&A 295, L47
Molaro P., Bonifacio P., Castelli F., et al., 1997, A&A 319, 593
Nissen P.E., Schuster W.J., 1997, A&A 326, 751
Nissen P.E., Høg E., Schuster W.J., 1998, In: Proceedings of the Hipparcos Venice '97 Symposium. ESA SP-402, in press
Pasquini L., Liu Q., Pallavicini R., 1994, A&A 287, 191
Peterson R.C., Carney B.W., Smith H., 1998, submitted to ApJ
Pilachowski C.A., Sneden C., Booth J., 1993, ApJ, 407, 699
Pinsonneault M.H., 1997, ARA&A 35, 557
Primas F., 1996, In: The Challenge of Be Observations. Ph.D. Thesis, University of Trieste
Primas F., Duncan D.K., Thorburn J.A., 1998a, ApJ 506, L51
Primas F., Duncan D.K., 1998b, A&AS, in preparation
Primas F., Duncan D.K., Beers T.C., 1998c, in preparation
Ramaty R., Kozlowski B., Lingenfelter R.E., Reeves H., 1997, ApJ 488, 730
Rebolo R., Beckman J.E., Molaro P., 1988, A&A 192, 192
Reeves H., Fowler W.A., Hoyle F., 1970, Nat 226, 727
Reeves H., Richer J., Sato K., Terasawa N., 1990, ApJ 355, 18
Ryan S.G., Norris J.E., Deliyannis C.P., 1992, ApJ 388, 184
Smith V.V., Lambert D.L., 1989, ApJ 345, 75
Spite F., Spite M., 1982, A&A 115, 357
Spite F., Spite M., 1986, A&A 163, 140
Stephens A., Boesgaard A.M., King J.R., et al., 1997, ApJ 491, 339
Thorburn J.A., Hobbs L.M., 1996, AJ 111, 2106 (TH96)
Vangioni-Flam E., Cassé M., Fields B.D., et al., 1996, ApJ 468, 199
Vangioni-Flam E., Ramaty R., Olive K.A., et al., 1998, A&A 337, 714
Woosley S.E., Hartmann D.H., Hoffman R.D., Weaver T.A., 1990, ApJ 356, 272