

New beryllium observations in low-metallicity stars^{*,**}

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Abstract. We present observations of the Be II 313.0 nm resonance doublet in 14 halo and old disk stars with metallicities ranging from $[\text{Fe}/\text{H}] = -0.4$ to ≈ -3.0 obtained with the CASPEC spectrograph of the ESO 3.6m telescope at a $\text{FWHM} \approx 8.6 \text{ km s}^{-1}$ resolution. Abundances are derived by means of the synthetic spectra technique employing Kurucz (1993) atmospheric models, with enhanced α -elements and no overshooting. The derived abundances together with those available in literature show that for $-2.7 < [\text{Fe}/\text{H}] < -0.8$ Be correlates linearly with iron $[\text{Be}] \propto 1.07(\pm 0.08)[\text{Fe}/\text{H}]$, giving strength to previous results. However, a steeper correlation is still possible at metallicities lower than $[\text{Fe}/\text{H}] < -1.4$ with $[\text{Be}] \propto 1.6(\pm 0.44)[\text{Fe}/\text{H}]$. When iron is replaced with oxygen, Be is found tracking closely oxygen up to solar values, without signs of breaking in correspondence of the onset of the Galactic disk.

No evidence of intrinsic dispersion is found, ought to the large errors involved in the Be abundance determinations, but for three stars (HD 106516, HD 3795, HD 211998) a significant upper limit in the Be abundance can be placed at ≈ 1 dex below the mean trend of the Be-Fe relation. For such stars non conventional mixing is required to explain Be depletion.

Be observations can be used to discriminate strongly Li-depleted stars. These are the stars which show less Li than that expected by high energy cosmic rays production as deduced from Be observations. The available Be observations imply that some of the stars which contribute to the scatter in the Li-Fe diagram are Li-depleted stars. This result strongly supports the use of the upper envelope of the Li-Fe diagram to trace the Li galactic evolution, and argues for a low value for the primordial Li against models which predict substantial Li depletion in halo and old disk stars.

Key words: stars: abundances – stars: Population II – Galaxy: evolution – cosmology: observations – cosmic rays

1. Introduction

The importance of beryllium stems largely from its unique origin. Be is probably a pure product of the galactic cosmic ray (GCR) nucleosynthesis, generated as the other light elements ${}^6,7\text{Li}$ and ${}^{10,11}\text{B}$ through the bombardment of ${}^{12}\text{C}$ and ${}^{16}\text{O}$ in the interstellar medium by energetic cosmic rays (Reeves, Fowler and Hoyle 1970; Meneguzzi et al 1971, Walker et al 1985). The process of ν -induced nucleosynthesis may produce significant amounts for ${}^7\text{Li}$, ${}^{10,11}\text{B}$ but only small amounts of ${}^9\text{Be}$ (Woosley and Weaver 1995). Standard Big Bang nucleosynthesis predicts negligible quantities of Be out of the primordial nucleosynthesis, namely $\text{Be}/\text{H} \approx 10^{-17}$ (Thomas et al 1994), but it has been suggested that baryon inhomogeneous Big Bang nucleosynthesis might produce enhanced quantities of Be up to four orders of magnitude relatively to the homogeneous case (Boyd and Kajino 1989; Malaney and Fowler 1989; Kajino and Boyd 1990). However, such inhomogeneities from the quark-hadron phase transition do not appear very probable (Kurki-Suonio et al 1990; Terasawa and Sato 1990; Mathews et al 1990; Jedamzik, Fuller and Mathews 1994; Thomas et al 1994). A primordial production of Be would appear as a *plateau* of the Be abundance in stars of low metallicities with analogy to what is observed for Li, and in a Be/B ratio significantly higher than that predicted by the spallation processes. However, the presence of such a *plateau* at low metallicities is not an unambiguous primordial signature, since it can be also produced by accretion onto the stellar surface while the star is passing through thick interstellar clouds, as shown by Yoshii, Mathews and Kajino (1995).

Beryllium was observed in the sun by Chmielewski et al. (1975) at a level of $[\text{Be}] = 1.15$ (i.e. $\text{Be}/\text{H} = 1.4 \cdot 10^{-11}$); here and after we will follow the notation $[\text{Be}] = \log(\text{Be}/\text{H}) + 12$. In a sample of young hot stars Boesgaard (1976) measured almost the same abundance of Be, namely $< [\text{Be}] > = 1.1 \pm 0.1$. The meteoritic value from carbonaceous chondrites is presumably the initial solar value and is $[\text{Be}] = 1.42 \pm 0.04$, which is about a factor of two higher than the presently observed solar value and

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** Tables 4 to 7 are available in electronic form only at the CDS via anonymous ftp 130.79.128.5 or <http://cdsweb.u-strasbg.fr/abstract.html>

also a factor of two higher than the mean of the stellar values (Grevesse and Noels 1993). Observations of Be in halo dwarfs began in the eighties with Molaro and Beckman (1984), Molaro, Beckman and Castelli (1984), Molaro (1987), showing that Be abundance in the past was lower than the solar one, which was not obvious at that time. Only recently has the technology become adequate for providing the required sensitivity and resolution at 313.0 nm and therefore accurate observations of the Be II lines became possible. The Be abundances in halo stars by Rebolo et al (1988), Ryan et al (1991), Ryan et al (1992), Gilmore et al (1991), Gilmore et al (1992), Boesgaard and King (1993) revealed a clear linear correlation with iron, while a steeper relation was expected. To account for this behaviour it has been suggested that spallation processes occur preferentially close to supernovae (Feltzing and Gustafsson 1994; Olive et al 1994; Tayler 1995). A preliminary analysis of the present data was already given in Molaro et al (1995a) and Primas (1995).

In this paper we present new observations and Be abundances for 14 halo and old disk stars. These new data, together with the data available from the literature, are used to investigate the evolution of Be.

2. Observations and data reduction

We used the CASPEC spectrograph at the ESO 3.6 m telescope to obtain ultraviolet spectra of our program stars. A log of observations and the available photometric data for the stars are given in Table 1. CASPEC is not normally used at these short wavelengths and a special instrument configuration had to be devised. To enhance resolution we used the long camera coupled with the blue cross-disperser. During observations alignment of the slit with the parallactic angle was maintained by rotating the adaptor to avoid slit losses due to the atmospheric dispersion. In order to minimize the red leak a UV filter was used in the optical path. A serious problem for this configuration is the acquisition of suitable calibration frames; in fact the light from the calibration lamps is fed into the spectrograph through a prism which is opaque in the UV, and hence no flat-field or Th-Ar can be obtained in the conventional way. The Th-Ar spectrum taken in this way is usable only longward of about 330.0 nm, and therefore we used an external Th-Ar lamp. This is mounted in the focal plane of the telescope and illuminates the spectrograph slit directly. Spectra of this “external” lamp had to be taken at the beginning and at end of each night, since the operation of mounting and dismounting the lamp, though simple, is time-consuming. The resolving power as measured from the emission lines of the Th-Ar lamp around the Be line region is of ≈ 35000 .

A similar approach could be used for flat fields, but, at present, a suitable UV flood-lamp is not available at ESO. The analysis of the first images acquired for this program convinced us that we could perform a meaningful reduction without flat-fielding. There is no fringing and the abundance analysis is done on normalized spectra, thus making the removal of the blaze effect not strictly necessary.

The spectra were reduced using the Echelle package in MIDAS. The major source of uncertainty in the calibration procedure is the background subtraction; in fact in the spectral region under study the orders are closely spaced and the inter-order region contains light coming from the tails of the adjacent orders. The background was taken to be the lower envelope of the signal in the inter-order region. We estimate the uncertainty of the background evaluation to be of the order of 10-15% of the background, from the RMS of in the inter-order, for most of our spectra, it can be higher for the low S/N spectra (e.g. HD 128279). This uncertainty introduces an error of the order of 10% in the level of the continuum. For instance in HD 3795 the average background per pixel is of 33 ADU, while the continuum is at 61 ADU, the RMS of the background is of 2.4 ADU, which is 8.6% of the continuum level. The effect of this error on the equivalent width of Be II lines is discussed in Sect. 5.1.

3. Model atmospheres

For the present investigation we used version 9 of the ATLAS code to compute the atmospheric models appropriate for metal-poor stars. This version of the ATLAS code (Kurucz 1993) differs from previous ATLAS versions mostly for the opacity and for the way in which the mixing-length convection is handled. In the ATLAS9 models the opacity distribution functions (ODFs), which account for the line opacity, were computed with a much larger number of atomic lines than in the previous versions and, for cool stars, molecular lines were also added. Continuous opacities were implemented by taking into account also the contribution of the OH and CH molecules. Convection is still based on the mixing-length approach, but two modifications have been made in ATLAS9; the first one allows for a horizontally averaged opacity and the second one allows for an approximate overshooting (Castelli 1996).

As far as convection is concerned, Castelli, Gratton and Kurucz (1996) have shown that the first modification of the mixing-length has negligible effects on the results, while the second one alters the whole structure of the models, mostly when T_{eff} is between 5500 K and 8000 K. Fig. 1 compares the T-log(τ_{Ross}) relations for $T_{\text{eff}} = 5750$ K, $\log g = 3.5$, and $[M/H] = -1.0$, with and without overshooting. The zone of formation of the Be II lines is around $\log(\tau_{\text{Ross}}) = -0.12$ where the temperature is higher for models with overshooting. While the different convection affects the whole structure, the different chemical composition due to the enhancement of the α -elements, mostly affects the structure of the deepest layers, as can be seen from the figure. The discrepancy between models with and without overshooting changes with $\log g$, T_{eff} and metallicity. The Kurucz solar model computed with overshooting fits the observations very well, but for other stars no overshooting models generally yield more consistent T_{eff} values when different methods are used to derive them, such as methods based on colors, Balmer profiles, and the infrared flux. A test on Procyon has also shown that, for this star, no overshooting models give parameters which are more consistent with the fundamental values, derived from model independent methods.

Table 1. Log of Observations and photometric data. Johnson photometry has been taken from SIMBAD, Strömrgren photometry from Hauck & Mermilliod (1990) and from Schuster & Nissen (1988) (in the second row, when available)

HD	V	(B - V)	(b - y)	m1	c1	β	E(b - y)	date	exp (sec)
3795	6.14	0.70	0.450	0.213	0.304	2.565	0.017	27-9-93	3000
6434	7.72	0.61	0.385	0.160	0.273	2.581	0.000	31-7-93	6300
			0.386	0.160	0.272	2.573	0.000		
16784	8.02	0.56	0.378	0.142	0.293	2.569	0.000	28-8-93	3600
			0.377	0.141	0.291	2.581	0.000		
25704	8.10	0.55	0.369	0.120	0.272	2.584	0.000	28-8-93	6600
			0.371	0.118	0.275	2.570	0.000		
76932	5.86	0.52	0.359	0.120	0.293	2.578	0.000	13-3-92	7200
			0.354	0.117	0.297	2.574	0.000		
106516	6.11	0.45	0.318	0.115	0.332	2.613	0.000	14-3-92	7200
			0.318	0.110	0.335	2.606	0.000		
128279	7.97	0.64	0.470	0.058	0.264	2.545	0.000	30-7-93	7200
140283	7.24	0.49	0.378	0.040	0.302	2.584	0.043	14-3-92	14400
			0.380	0.033	0.284	2.564	0.020		
160617	8.73	0.46	0.344	0.053	0.353	2.607	0.041	15-3-92	7200
			0.347	0.051	0.331	2.584	0.015		
166913	8.23	0.45	0.327	0.078	0.314	2.610	0.010	29-7-93	7200
200654	9.11	0.64	0.460	0.029	0.274	2.534	0.000	28-8-93	6600
			0.460	0.027	0.271	2.534	0.000		
211998	5.29	0.68	0.447	0.116	0.240	2.543	0.000	28-8-93	3600
			0.450	0.109	0.249	2.546	0.000		
218502	8.50							29-7-93	7200
219617	8.16	0.47	0.343	0.078	0.231	2.586	0.000	29-7-93	7200
			0.349	0.072	0.243	2.584	0.000		

On the basis of these results and also because the *ad hoc* inclusion of the overshoot in the ATLAS9 code is not really the physical overshoot (Freytag 1996), we decided to use for this investigation ATLAS9 models with the overshooting option switched off. We kept the same value $l/H_p=1.25$ adopted by Kurucz for the mixing-length to pressure height scale ratio, because we found that it well reproduces the solar irradiance also when overshooting is dropped. The choice of the mixing length in the range from 0.5 to 2.0 for the pressure scale height makes negligible differences (less than 0.01 dex) over the whole grid, and the adopted microturbulent velocity does not affect the derived Be abundance for the range of equivalent width under consideration.

We used the α -enhanced opacity distribution functions (ODFs) provided by Kurucz (1993a), which are obtained by assuming that all α elements are enhanced by 0.4 dex over iron. This is certainly a more realistic chemical composition for Pop II stars than the usual approach which uses the ODFs with solar-scaled abundances. Furthermore, for these ODFs the solar iron abundances is $\log(N_{Fe}/N_{tot})=-4.53$ (Hannaford et al 1992), instead of $\log(N_{Fe}/N_{tot})=-4.37$ (Anders and Grevesse 1989), which was used for all the ODF's for solar and solar-scaled abundances.

We selected the ODFs computed with a microturbulent velocity of 1 km s^{-1} to allow for very low microturbulent velocities, as can be found in some Pop II stars, instead of the 2 km s^{-1} of the Kurucz (1993a) grid. The grid covers the range from 4750 K to 6250 K in T_{eff} at steps of 250 K, from 2.50 to 4.75 in $\log g$ at steps of 0.25 and from -0.5 to -3.00 in $[\text{Fe}/\text{H}]$ at steps of 0.5. For all the models of this grid we also computed the emergent flux and the Johnson UBV and the Strömrgren *uvby* colour indices. Colour indices were then used to derive effective temperature and surface gravity for all the stars of our sample, except HD 218502 for which no observed photometric Johnson or Strömrgren indices have been found in the literature. Model parameters for the stars of our sample will be discussed in the next section.

In order to appreciate the differences with the Kurucz (1993a) grid we computed models for $T_{\text{eff}} = 5250, 5750, 6250$ K, $\log g = 3.0, 3.5, 4.0$ and metallicity $[\text{Fe}/\text{H}] = -1.0, -1.5, -2.5$ with the α enhanced ODFs and the overshooting option, and other models with the same parameters, but using the ODFs without α enhancement and overshooting.

For all these models, as well as for those from our grid and from the Kurucz(1993a) grid, we computed the curves of growth for the Be II 313.1065 nm line. Fig. 2 shows the different

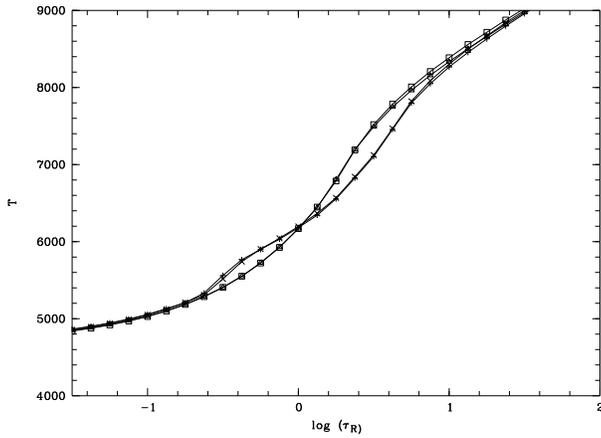


Fig. 1. Temperature structure for models with $T_{\text{eff}} = 5750$, $\log g = 3.50$ and metallicity $[\text{Fe}/\text{H}] = -1.0$: α enhanced with (x) and without (squares) overshooting; no α enhancement with (+) and without (triangles) overshooting

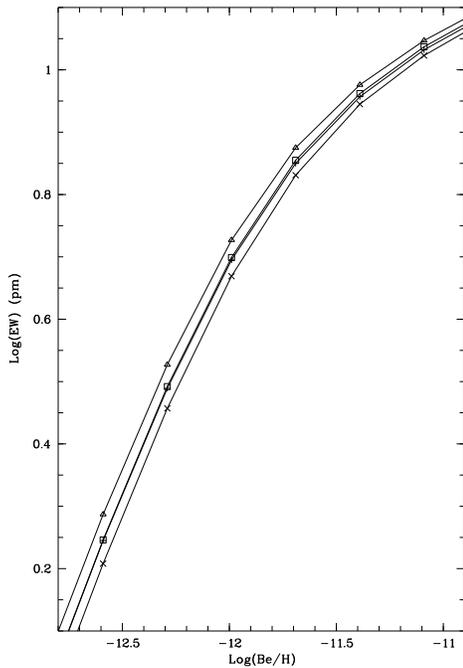


Fig. 2. Curves of growth for the Be II 313.1065 nm line for models with $T_{\text{eff}} = 5750$, $\log g = 3.50$ and metallicity $[\text{Fe}/\text{H}] = -1.0$: α enhanced with (x) and without (squares) overshooting; no α enhancement with (+) and without (triangles) overshooting

curves of growth for Be II 313.1065 nm corresponding to the same model parameters $T_{\text{eff}} = 5750$ K, $\log g = 3.5$, and $[\text{M}/\text{H}] = -1.0$ and to the different T - $\log(\tau_{\text{Ross}})$ relations displayed in Fig. 1.

In the very low metallicity domain, i.e. $[\text{Fe}/\text{H}] < -2.0$, the effect of α element enhancement is very small, of the order of 0.01 dex at most, with the α enhanced models yielding higher abundances. On the other hand, the effect of overshooting is not negligible and the models with overshooting yield abundances

which are higher by as much as 0.08 dex. This difference is almost constant at all temperatures.

In the low metallicity domain (i.e. $[\text{Fe}/\text{H}]$ between -2.0 and -1.0) the effect of overshooting is of the same order of magnitude as in the very low metallicity regime, but the effect of α enhancement begins to be notable in particular for the cool models. Models with enhanced α -elements yield higher abundances of the order of 0.08 dex at $T_{\text{eff}} = 5250$ K, but of only 0.03 dex at $T_{\text{eff}} = 6000$ K and less than 0.01 dex at $T_{\text{eff}} = 6250$ K. No overshooting in the models implies lower abundances, while α enhancement implies higher abundances so that there is some compensation between the two effects. The result of these opposite behaviours is that while our models yield abundances larger than those of the Kurucz 1993a grid at low-temperatures, the reverse is true at the high temperature end.

For solar metallicities there is little or no difference in the Be abundances with respect to the implementation of overshooting in the models. This is because metal-poor models have convective zones which start at much shallower depths (D'Antona and Mazzitelli 1984).

Our models yield abundances which are identical within few hundredths of a dex to those obtained using Kurucz 1979 models and are therefore directly comparable with the Be literature values which are obtained mostly using those models. This also implies that the much larger number of lines included in the computations of the ODFs implemented in version 9 of the ATLAS code has relatively small effects on the temperature structure of the models. We stress that our choice of switching off overshooting makes the present analysis consistent with the older grids of models which make use of either Gustafsson-Bell or old (i.e. computed with version 8 or earlier ones of the ATLAS code) Kurucz models.

In conclusion, the differences in Be abundances found at low metallicities when using the Kurucz 1993a models, with respect to the Kurucz 1979 ones, are due to the presence of overshooting. The low effect on the metal-poor stars of the increased blanketing in the new models is explained by the small importance of the new lines in the metal poor stars. In fact, the large number of atomic lines added for computing the new ODFs arise from high-excited states and are therefore weak lines in solar metallicity stars. The effect of the molecular lines has still to be investigated. The abundances derived from lines whose depth of formation is close to the top of the convection zone, as for Be II and also for Li I, are quite sensitive to the assumptions made on overshooting (Molaro et al 1995b,c).

This extensive theoretical grid allowed us to perform an efficient comparison between observed and computed quantities (spectra and colours) and also to experiment the effects of small changes in the atmospheric parameters on the derived abundances. In addition to the models of the grid, more models were computed with atmospheric parameters appropriate for our program stars (see next section), including a small number of models with $[\text{Fe}/\text{H}] = -0.5$ for which we used ODFs with solar-scaled abundances rather than with α enhanced, the other assumptions being the same as the more metal-weak models.

Table 2. Atmospheric parameters for the program stars

HD	T_{eff}^1	T_{eff}^2	$\log g^3$	$\log g^4$	$\log g^5$	$\log g^6$	[Fe/H] ⁷	[Fe/H] ⁸	[Fe/H] ⁹
3795	5464	5420 ^a	4.05	4.00	3.63±0.24		-0.25	-0.73 ^a	
6434	5623	5671±79	4.21	4.25	4.25±0.22	4.08±0.14	-0.54	-0.54 ^b	-0.68
16784	5747	5564±71	4.00	3.88	3.80±0.22	3.68±0.13	-0.67	-0.75 ^c	-0.63
25704	5829	5884 ^b	4.19	4.00	4.23±0.20		-0.93	-0.85 ^b	
76932	5932	5965 ^b	4.15	4.00	4.18±0.17		-0.78	-0.82 ^b	
106516	6211	5995±68	4.23	3.98	4.00±0.14	3.97 ±0.13	-0.75	-0.70 ^d	-0.86
128279	5200	5165 ± 77	2.95	2.95	2.88±0.14	2.98 ±0.13	-2.22	-2.50 ^e	-1.97
140283	5864	5814±44	3.66	3.58	3.48±0.10	3.27 ±0.09	-2.00	-2.75 ^f	-2.36
160617	6144	5664±84	3.82	3.13	3.08±0.16	3.29 ±0.23	-1.80	-2.05 ^f	-1.76
166913	6213	5955±109	4.16	3.85	3.73±0.18	4.45 ±0.19	-1.32	-1.80 ^g	-1.31
200654	5208	5522±119	2.78	3.15	3.13±0.17	3.56 ±0.21	-2.65	-3.13 ^f	-2.38
211998	5243	5338±65	3.57	3.65	3.55±0.26	3.26 ±0.12	-1.43	-1.54 ^h	-1.40
218502		6000 ⁱ				3.80 ⁱ		-1.96 ⁱ	
219617	5960	5815±76	4.36	4.23	4.05 ±0.18	3.44 ±0.14	-1.32	-1.63 ^h	-1.08

¹ from (B – V); ² from Balmer lines, Fuhrmann et al (1993); ³ from c1 photometric temperatures (T_{eff}^1) and photometric metallicities ([Fe/H]⁴); ⁴ from c1 spectroscopic temperatures (T_{eff}^1) and photometric metallicities ([Fe/H]⁷); ⁵ from c1 spectroscopic temperatures (T_{eff}^1) and spectroscopic metallicities ([Fe/H]⁸); ⁶ spectroscopic from Axer et al (1994) with T_{eff} of column 2 and metallicities of column 8; ⁷ photometric metallicities; ⁸ spectroscopic metallicities from literature; ⁹ spectroscopic metallicities from Axer et al (1994) with the T_{eff} of column 3. ^a Pasquini et al (1994), ^b Edvardsson et al (1993), ^c Ryan & Norris (1991), ^d Spite et al (1994), ^e Peterson et al (1990), ^f Nissen et al (1994), ^g Magain (1989), ^h Gratton (1989), ⁱ Luck & Bond (1985) ^l Pilachowski et al (1993)

Non-LTE effects have been shown to be negligible in the sun by Chmielewski et al (1975). For metal-poor stars absolute NLTE corrections to the Be abundances have been shown to be lower than 0.1 dex by Garcia Lopez et al (1995) and Kiselman & Carlsson (1995).

4. Atmospheric parameters

The appropriate model-atmosphere for the sample stars is specified by T_{eff} , $\log g$ and metallicity.

Ten stars out of our 14 star sample have been studied by Fuhrmann et al (1994) who determined T_{eff} from the Balmer profiles of a large sample of G-dwarfs. Surface gravities and spectroscopic metallicities from Axer et al (1994) are given in column 7 and 10 of Table 2. The Axer et al gravities and metallicities are spectroscopically derived assuming the Fuhrmann et al (1994) temperature, thus forming a set of homogeneously derived stellar parameters.

A photometric estimate of the effective temperature may be derived from the (B – V) index, which is almost independent of gravity between 5750 K and 6250 K. For each star we interpolated our UVB grids for an assumed metallicity and gravity to obtain the T_{eff} corresponding to the observed (B – V). For the reddened stars, we dereddened the observed (B – V) indices by using the relation $E(B - V) = E(b - y)/0.74$ from Crawford & Mandwewala (1976), and the $E(b - y)$ value derived below.

These photometric temperatures may be found in column 2 of Table 2.

For a sample of seven subdwarfs, Castelli, Gratton and Kurucz (1996) showed that T_{eff} derived from H_{α} profiles computed with models similar to those used in this paper (namely ATLAS9 models with the overshooting option switched off) may differ from 10 K to 200 K from those derived by Axer et al. (1994). The differences between the photometric determinations of T_{eff} based on our models and the effective temperatures adopted for computing the Be abundances are of the same order, except for HD 160617, HD 200654, HD 166913, and HD 106516 for which the differences are 480 K, 314 K, 258 K, and 216 K respectively. For HD 160617 and HD 166913 Magain (1989) derived T_{eff} equal to 5910 K and 6030 K respectively. The above differences would reduce to 234 K and 183 K respectively.

We derived also a photometric surface gravity for the stars with available Strömgen photometry. The synthetic Strömgen indices have been computed from our grid of fluxes with α enhancement and no overshooting, as described in the previous section. The use of Kurucz (1993) synthetic colours yields $\log g$ being generally 0.1 to 0.2 dex lower than our estimates.

The observed c1 indices were taken from the electronic version of the Hauck & Mermilliod (1990) catalogue supported at CDS and corrected for reddening using the intrinsic colour calibration of Schuster & Nissen (1989), which is most appropriate for late-F and G-type metal-poor stars. For each star we iterated their equation (1) until the change in $(b - y)_0$ was less

than 0.0001 mag. The derived reddening is always very small, as expected since our stars are nearby, yet non-zero in a few cases. For those stars for which $E(b - y)$ has small negative values we imposed $E(b - y) = 0.000$. Also for the stars with $\beta < 2.55$, which lie outside the range of the calibration, we assumed zero reddening.

The surface gravities were derived by comparing the theoretical and observed c_0 for an assumed effective temperature and metallicity. For the reddened stars c_0 was dereddened by means of the relation $E(c) = 0.2E(b - y)$ (Crawford 1975).

Column 4 of Table 2 gives the surface gravities derived from the photometric temperatures of column 2 and photometric metallicities of column 8. In columns 5 and 6 the Fuhrmann et al temperature is assumed instead, but while in column 5 the photometric metallicity of column 8 is assumed, in column 6 the “best” literature value of column 9 is taken. To be brief, errors on the photometrically derived $\log g$ are given only in column 6, the others being comparable.

We derived photometric metallicities for the stars with available Strömgen photometry (i.e. all except HD 218502) derived from Schuster & Nissen’s (1989) calibration. The values are given in column 8 of Table 2.

The result of a search for spectroscopic determinations of the metallicity in literature is reported in column 9 of Table 2. It is worth noting that when comparing the 3 different sources for metallicities only in a few cases is the disagreement larger than 0.5 dex: namely HD 128279, HD 166913, HD 200654 and HD 219617.

A direct check of the gravity is possible for HD 140283 which has a measured parallax from where Nissen et al (1994) estimate $\log g = 3.39 \pm 0.15$; this value is consistent with all four values reported in Table 2. On the other hand, remarkable disagreements up to about 0.7 dex are found between the spectroscopic and photometric gravities for HD 166913 and HD 219617. However, this is not so uncommon, for instance, for HD 76932 the gravities in the literature show a very large spread ranging from the 3.5 of Bessel et al (1991) to 4.37 of Edvardsson et al (1993). For HD 166913 there is a considerable uncertainty in the atmospheric parameters. Laird (1985) gives $T_{\text{eff}} = 6120$ and $\log g = 4.43$. Fuhrmann et al and Axer et al give $T_{\text{eff}} = 5955$ and $\log g = 4.45$, whereas from the photometry we deduce a $\log g = 3.8$. This uncertainty in the atmospheric parameters represents a major source of uncertainty in the Be abundances.

For our analysis we adopted the effective temperature provided by Fuhrmann et al (1994) and the surface gravity of Axer et al (1994) whenever available. For these stars the metallicity of the adopted model was that of Axer et al (1994), rounded to the nearest 0.5 dex. For HD 3795, HD 25704 and HD 76932, which are not included in the paper of Fuhrmann et al (1993), we adopted the photometric gravity derived by using the literature metallicity reported in column 6 in Table 2. For these stars the effective temperature has been taken on the basis of a critical analysis of the literature. These temperatures are close to our photometric estimates. For HD 218502, which lacks the necessary photometry, we took gravity and T_{eff} from Luck & Bond (1985).

Table 3. Beryllium abundances

HD	Teff	Log g	[Fe/H]	[Be]
3795	5420	3.60	-0.73	< -0.48
6434	5671	4.08	-0.68	0.81 ± 0.22
16784	5564	3.68	-0.63	0.19 ± 0.21
25704	5884	4.20	-0.85	0.39 ± 0.24
76932	5965	4.15	-0.82	0.79 ± 0.21
106516	5995	3.97	-0.86	< -0.76
128279	5165	2.98	-1.97	-0.75 ± 0.30
140283	5814	3.27	-2.36	-0.91 ± 0.17
160617	5664	3.29	-1.76	-0.90 ± 0.27
166913	5955	4.45	-1.31	0.54 ± 0.15
		3.73		$0.23^a \pm 0.15$
200654	5522	3.56	-2.38	-0.56 ± 0.22
211998	5338	3.26	-1.40	< -1.05
218502		3.80	-1.96	-0.56 ± 0.22
219617	5815	3.44	-1.08	-0.56 ± 0.20
		4.05		$-0.16^b \pm 0.20$

^a if $\log g = 3.73$; ^b if $\log g = 4.05$

5. Be abundances

The beryllium abundances are derived from the Be II $2^2S - 2^2P_0$ resonance lines. While the Be II 313.1065 nm line is unblended, the Be II 313.0420 nm line is blended with OH 313.0281 nm, V II 313.0257 nm and CH 313.0370 nm, and hence the abundance of these elements affects the appearance of the whole feature. We therefore determined the Be abundance from the spectral synthesis of the 312.6 - 313.4 nm region. A work in progress is analysing the whole 310-350 nm range available which shall, eventually, lead to the determination of the abundances of C, N, O, Ca, Ti, V, Cr, Zn.

Model atmospheres with the appropriate atmospheric parameters were computed for each star as described in Sect. 4. We used the equivalent width and the model-atmosphere as input to version 9 of the WIDTH code (Kurucz 1993a) to derive a first estimate of the Be abundance. This abundance and the model-atmosphere were then used as input to the SYNTH code (Kurucz 1993b) to synthesize the whole region from 312.6 nm to 313.4 nm. This synthetic spectrum and the observed spectrum, which was shifted in wavelength so that the lines appeared at their laboratory position, were superimposed on the same plot. These plots were visually inspected and then the abundances of several elements, including Be, were changed in order to obtain the agreement between observations and computations. These abundances were used to compute a new synthetic spectrum and the whole procedure was iterated until the agreement was judged satisfactory. We imposed also the requirement that the blended Be II 313.0420 nm line should be reproduced with the same abundance of the Be II 313.1065 line.

The results of this analysis are given in Table 3. For the stars HD 166913 and HD 219617 for which the difference between the photometric and spectroscopic gravities is particularly large we derived the abundance for both gravity values.

5.1. Errors

The process of abundance determination is complex and the estimate of the error is by no means straightforward. Errors in $\log g$, T_{eff} and metallicity will affect the derived abundances. Microturbulence is unimportant since for our stars the Be II lines are essentially weak lines. Given the measured equivalent width of the Be II 313.1065 line, we interpolated our grid of curves of growth to estimate the Be abundance for our adopted parameters and for $\log g = \log g \pm \sigma(\log g)$.

The errors in photometrically derived surface gravities are reported in Table 4 (available electronically). To compute the total $\sigma(\log g)$ we have assumed an error of 0.008 mag on c_1 , the error in T_{eff} provided by Fuhrmann et al (1994) or ± 100 K for the stars not included in that paper, an error of ± 0.3 dex in metallicity and an error in the reddening equal to the reddening value, which is appropriate for slightly reddened stars. For all parameters, in case of asymmetric errors we assumed the largest one in absolute value. Column 5 of Table 4 gives the uncertainty in $\log g$ due to random errors in the photometry, column 6 that due to the uncertainty in reddening, column 7 that due to the uncertainty in T_{eff} and column 8 that due to the uncertainty in metallicity. Finally the square root of the sum of the squares of these four uncertainties was taken as the total uncertainty on $\log g$ and given in column 9.

For the errors in T_{eff} and metallicity we proceeded in the same fashion. For HD 218502, for which $\log g$ has been taken from the literature, we arbitrarily assumed an error in $\log g$ of ± 0.25 dex. The results and the total error on [Be] due to errors in the atmospheric parameters are given in column 5 of Table 5 (available electronically). As expected, the largest error comes from the uncertainty in $\log g$. These errors ought to be considered as 1σ errors.

In column 6 of Table 5 we give an estimate of the error associated with the noise in the data, based on several synthetic spectra computed with different Be abundances. This uncertainty is summed with the uncertainty associated with the atmospheric parameters and given in the last column of Table 5. Both the uncertainty in the background subtraction and the uncertainty in the continuum placement will affect the equivalent width of the lines. The effect will be larger, in percentage, for stronger lines in which wings are important. In our whole sample the Be II lines may be considered weak lines. As discussed in Sect. 2, uncertainty in the background may lead to an error in the continuum level of 10% for the average quality spectra in our sample. Trials have shown that this will affect the measured equivalent width by no more than 0.5 pm. On top of this, there may be an error in the placement of the continuum due to the lack of line-free regions. This error may not be easily estimated for the more metal-rich stars, while it can be done for the most metal-poor stars, for which, with the aid of synthetic spectra, we

may locate regions which are almost line-free. In these cases the error on the placement of the continuum is of the order of 2%. Garcia Lopez et al (1995) estimate these errors to be of the order of 0.05-0.10 dex in Be abundances for an uncertainty of 2% in continuum placement. Such error is not included in our estimates.

HD 128279 shows an inconsistency between the two Be II lines: the fainter line is apparently present, while there is no evidence for the stronger line. Since this is the coolest star of our sample ($T_{\text{eff}} = 5165$ K), and Garcia Lopez et al (1995) have shown that for stars cooler than ≈ 5200 K the observed feature at the position of the Be II 313.1 line is probably contaminated by Mn I λ 313.1037 nm, we checked if such a line could be also responsible for the feature observed at 313.1 nm in our spectrum of HD 128279. In order to explain the solar spectrum Garcia Lopez et al increased by 1.5 dex the $\log gf$ value in Kurucz's line lists. However, even with this $\log gf$ we are not capable of reproducing the observed feature.

6. The Boesgaard and King sample

Boesgaard & King (1993) published a considerably large data set of Be abundances in halo and old disk stars. As it appears from the discussion given in section 2 our abundances may not be directly compared to those of Boesgaard & King (1993), who employed ATLAS 9 models with overshooting. There is a further peculiarity in that their published curves of growth yield abundances which are some 0.03 dex larger than those obtained from the Kurucz 1993a grid. We suspect that this is due to the fact that BK used a preliminary version of the 1993 grid, which was slightly different from the official 1993 release.

Since the models adopted by them are different from the ones employed in the present study we have recomputed the Be abundances for all of their halo stars, where the differences between the models are important, adopting their original equivalent widths and atmospheric parameters.

The new abundances worked out with models that account for the α -element enhancements and without the overshooting are given in Table 6 (available electronically) and are typically ≈ 0.1 dex lower than originally estimated by Boesgaard and King (1993).

It is worth noting that in the case of HD 84937, for which ${}^6\text{Li}$ has been detected by Smith et al (1993), the decrease in the Be abundance makes a larger ${}^6\text{Li}/{}^9\text{Be}$ ratio. The new ratio becomes 56, which is much larger than the GCR ratio ${}^6\text{Li}/{}^9\text{Be}(\text{p+CNO}) \approx 5$ showing clearly the effect of α - α fusion reactions in the production of ${}^6\text{Li}$.

As discussed in section 3 the models used here are consistent with both old Kurucz models and Bell-Gustafsson models so that there is no need for revision of the other Be analysis.

7. Results

Our Be measurements together with all the Be observations from the literature reported in Table 7 (available electronically)

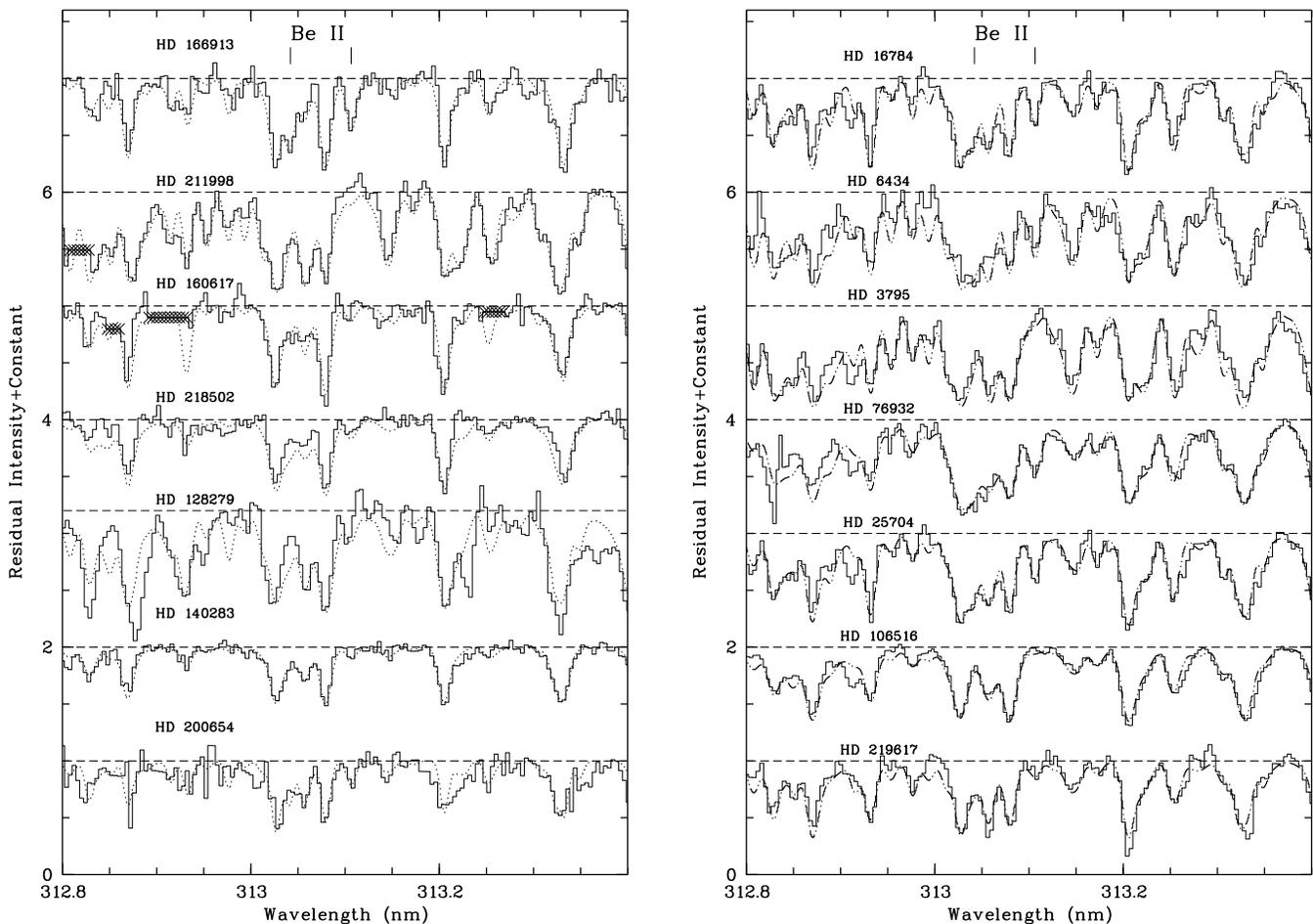


Fig. 3. All the data is displayed, solid lines are the observed spectra, dotted lines are the synthetic spectra, the dashed line above each spectrum represents the level of the continuum. The crosses on the spectra of HD 160617 and HD 211998 indicate cosmic ray hits which have been removed for display purposes

are displayed in Fig. 4. The data points are from Rebolo et al (1988), Ryan et al (1991, 1992), Gilmore et al (1991, 1992), Boesgaard and King (1993), Garcia Lopez et al (1995). To compute $[\text{Be}/\text{Fe}]$ we used the meteoritic Be value from Grevesse and Noels (1993). The use of the solar value of Chmiliwsky et al (1975) will offset all the data points by $+0.3$ dex. From Table 7 we may single out the extreme case of HD 189558 for which the difference between the Boesgaard and King (1993) and Rebolo et al (1988) determinations is about 1 dex with almost the same stellar parameters in both analyses. Also striking is the case of HD 200654, since the upper limit of Gilmore et al (1992) is in sharp contrast with the detection given here. The appearance of their spectrum is different from the observations shown here (Gilmore private communication), and it may be that our data were flagged by noise. Stellar parameters for HD 200654 are also rather uncertain in literature. Nissen et al (1994) derive $T_{\text{eff}} = 5090$ K, $\log g = 2.7$ and $[\text{Fe}/\text{H}] = -3.0$, which are the parameters adopted by Gilmore et al (1992) to compute the Be abundance. If so the star is a subgiant with a T_{eff} which allows Be dilution. The Fuhrmann et al temperature

is 5522 K, significantly hotter, and the gravity from Axer et al (1994) is 3.56, so that the dilution is marginal according to standard models. In Fig. 4 are also reported the Be abundances for the stars HD 166983 and HD 219617 for which spectroscopic and photometric gravities differ considerably. For most stars in our sample the choice of the different metallicities and gravities given in Table 2 move the points along a constant $[\text{Be}/\text{Fe}]$ which does not make a big difference, with the notable exceptions of HD 219617 and HD 160617, which are shifted from the “Be-weak” zone towards the “Be-normal” strip. For instance HD 219617 would have $[\text{Be}/\text{Fe}] = 0.12$ instead of -0.9 if its metallicity were $[\text{Fe}/\text{H}] = -1.63$ and $\log g = 4.05$ instead of -1.08 and 3.44 as provided by Axer et al (1994). HD 160617 would have $[\text{Be}/\text{Fe}] = -0.27$ instead of -0.56 if we take $[\text{Fe}/\text{H}] = -2.05$ and $\log g = 3.08$. The high value found by Gilmore et al (1992) which would give $[\text{Be}/\text{Fe}] = 0.21$ follows from a particularly high value for the gravity, namely $\log g = 3.8$. These two stars are potentially Be weak stars depending on the real stellar parameters. Considering the errors involved in the Be abundance determination, the whole dispersion of the points along the Be-Fe relation may be

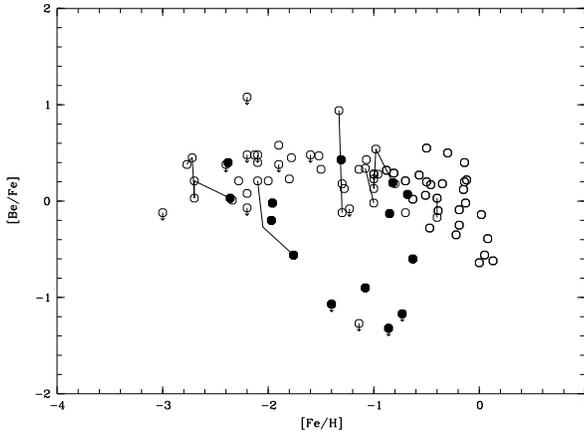


Fig. 4. [Be/Fe] versus [Fe/H]. Open octagons are from Table 7 with the exception of the data from Boesgaard and King (1993) from Table 6. Filled octagons are this paper

due to observational errors, with the notable exception of three stars which will be discussed later on.

8. Discussion

Reeves, Fowler and Hoyle (1970) first suggested that spallation reactions between cosmic rays, and the interstellar medium are responsible for the production of the light elements Li, Be and B together with their isotopes. A straightforward integration over the galactic life of the present rate of elemental production, i.e. assuming constant flux and shape of high energy cosmic rays, accounts for both solar Be and B abundances and their ratios, with the remarkable failures of Li abundance and of isotopic boron ratio. While for lithium a number of other sources including the primordial one are viable, for the B isotopes a *carrot* of low energy cosmic rays was postulated by Meneguzzi et al (1971).

New recent observations of abundances for Be, ^7Li , ^6Li , and B in halo stars have allowed a better definition of the evolution abundance curves for the light elements. In the past Be was always lower than in the sun, showing a progressive decrease with the decreasing of the stellar metallicity. The measures by Rebolo et al (1988), Ryan et al (1991) and Gilmore et al (1991, 1992) revealed a linear increase of Be with the metallicity.

The precise correlation between Be and Fe contains clues which reveal the process responsible for Be synthesis. Spallation reactions may occur when p and α particles collide with the CNO atoms at rest in the ISM, or when the fast CNO nuclei of the cosmic rays collide with the p and α . The second process produces fast light elements which may escape from the Galaxy; this has been generally assumed to produce a modest contribution to the synthesis of the light elements.

If the former mechanism is the dominant one and the cosmic rays are produced by supernovae, then the Be abundance is expected to be proportional to the square of the metallicity. To account for the linear behaviour of Be versus Fe, Ryan et al

(1990) and Gilmore et al (1991) suggested that Be is synthesized in the immediate surroundings of supernovae by spallation of fast nuclei of C and O ejected by the supernovae against the protons of the interstellar medium. This idea has been also further elaborated by Feltzing and Gustafsson (1994) and Tayler (1995).

8.1. Be-Fe correlation

The Be abundances derived in this paper versus [Fe/H] together with all Be observations available in literature are shown in Fig. 5. When stars evolve off the main sequence, the surface abundances of Be dilute considerably because of the deepening of the surface convection zones into Be-free layers. Standard models predict significant depletion on the subgiant branch when $T_{\text{eff}} \leq 5700\text{-}5500$ K (Deliyannis et al 1990, Chaboyer 1993). This has important implications for the interpretation of Be observations of some of the stars in our list, namely HD 3795, HD 128279, HD 140283, HD 160617, and possibly HD 200654. No detectable Be is found in some of the subgiants, showing that considerable Be depletion must have occurred in these stars. To avoid contamination of the sample abundance from evolution effects we have cleaned the sample from evolved stars ($\log g \leq 3.6$) unless their T_{eff} is > 5750 K. As a precaution we kept only the stars for which all parameters from different authors or derived by the different means fulfill the requirements of gravity and metallicity. The Be data show a considerable scatter for $[\text{Fe}/\text{H}] > -0.8$, which is probably due to stellar depletion, thus for safety we considered only stars with lower metallicity. Moreover, we rejected HD 219617 for which we have a $\Delta[\text{Fe}/\text{H}] = 0.6$ dex, HD 189558 because of the large (1 dex) difference of Be abundance between two different sources, HD 166913 for the large discrepancy in the gravity. We also did not consider the upper limits for Be and took the weighted average of the Be abundances for stars for which multiple measures are available (4 stars: HD 64090 and HD 94028, HD 76932, HD 134169).

After this cleaning we are left with a sample of 19 stars (see Fig. 5) in the interval $-2.7 < [\text{Fe}/\text{H}] < -0.8$, for which we performed a χ^2 analysis taking into account errors both in the Be abundances and in metallicity. The latter are assumed to be ± 0.1 dex for all the stars. The analysis gives:

$$[\text{Be}] = 1.81(\pm 0.114) + 1.07(\pm 0.08)[\text{Fe}/\text{H}].$$

with a reduced χ^2 of 0.72 corresponding to a goodness of fit $Q = 0.78$. The correlation between Be and Fe is thus slightly steeper than the $[\text{Be}] \propto 0.8[\text{O}/\text{H}]$ originally found by Gilmore et al (1992) from only six determinations, but it is slightly more gentle than the $[\text{Be}] \propto 1.256[\text{Fe}/\text{H}]$ derived by Boesgaard and King (1993). In general the new Be abundances and the repeated analysis of the halo stars ($[\text{Fe}/\text{H}] < -1.0$) by Boesgaard and King (1993) support a tight linearity between Be and Fe.

If we confine the χ^2 fit to the data points with $[\text{Fe}/\text{H}] < -1.4$ we obtain:

$$[\text{Be}] = 2.89(\pm 0.96) + 1.57(\pm 0.436)[\text{Fe}/\text{H}]$$

With a reduced χ^2 of 0.39 and $Q=0.87$. If we confine to $[\text{Fe}/\text{H}] < -1.6$, which practically means not considering one more star, we obtain $[\text{Be}] = 4.40 \pm 3.91 + 2.28 (\pm 1.26) [\text{Fe}/\text{H}]$.

This might suggest that in the early galaxy a steeper increase of Be with the metallicity is still possible. However, the small number of data points does not allow firm conclusions. The large error we get in the slope makes it marginally consistent with a slope of 1.

Be spallation involves mainly oxygen, because of its larger spallation cross sections with protons, and several authors discussed the behaviour of Be with respect to oxygen (Gilmore et al 1991; Boesgaard and King 1993). However, oxygen abundances are not always available for the sample stars, and if available they often do not have the desired accuracy. Therefore, instead of using the measured oxygen abundances for the data sample we investigate the Be versus O correlation by using the O-Fe parametrization which has been deduced by general observations of halo and disk stars, namely we took $[\text{O}/\text{Fe}] = 0.5$ for $[\text{Fe}/\text{H}] < -1.0$, and $[\text{O}/\text{Fe}] = -0.5 [\text{Fe}/\text{H}]$ for $[\text{Fe}/\text{H}] > -1.0$. The Be abundances versus oxygen are shown in Fig. 6. The analysis for stars with $[\text{O}/\text{H}] < -0.6$, which corresponds to $[\text{Fe}/\text{H}] \leq -0.8$, gives:

$$[\text{Be}] = 1.38 (\pm 0.13) + 1.13 (\pm 0.11) [\text{O}/\text{Fe}]$$

with a reduced χ^2 is 0.59 and a goodness of fit $Q=0.76$.

A fit to the whole sample gives a linear relation with a similar slope, slightly offset, but with an inferior goodness of fit ought to the dispersion in the Be data at disk and solar metallicities. It is worth noticing that if oxygen is increasing towards lower metallicities, as suggested by some observations, then the correlation would result steeper. Assuming $[\text{O}/\text{Fe}]$ increases linearly towards lower metallicities from $[\text{O}/\text{Fe}] = 0.5$ at $[\text{Fe}/\text{H}] = -1.0$ up to $+1.0$ at $[\text{Fe}/\text{H}] = -3.0$, the fit now gives a correlation:

$$[\text{Be}] = 1.13 (\pm 0.11) + 1.38 (\pm 0.13) [\text{O}/\text{Fe}]$$

with a reduced χ^2 of 0.39 and a goodness of fit $Q=0.94$. opening the possibility to a faster increase of Be at lower metallicities. In Fig. 6 the crosses and open squares show the different behaviours with $[\text{O}/\text{Fe}]$ constant and increasing towards lower metallicities.

The fit obtained for the stars with $[\text{O}/\text{H}] < -0.6$ intercepts the upper envelope of $[\text{Be}]$ abundances and the meteoritic value. This is also true considering the Be versus $[\text{Fe}/\text{H}]$, where the extrapolation at $[\text{Fe}/\text{H}] \approx 0$, is about 0.2 dex above the meteoritic value. If the dispersion observed at solar metallicities is due to stellar depletion, in opposition to an intrinsic pristine dispersion, then the upper envelope of the $[\text{Be}]$ abundances is more representative of the evolution abundance curve of Be. And if this is the case, from Fig. 6 it is clear that the Be abundance tracks oxygen closely and $[\text{Be}/\text{O}]$ remains always at about the solar value at any metallicity. This is a remarkable output if we consider that that Be production is related to quantities such as the flux of cosmic rays and the amount of astration which do not affect oxygen production.

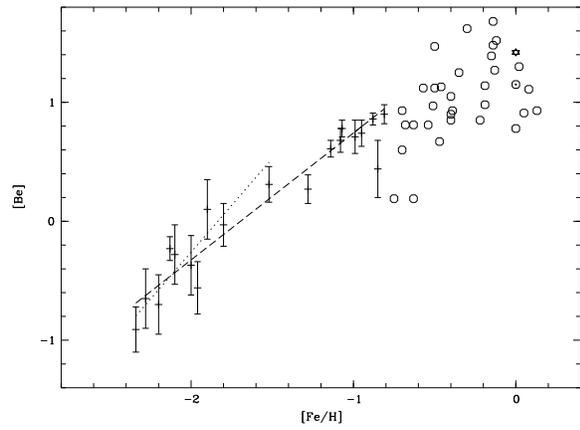


Fig. 5. $[\text{Be}]$ versus $[\text{Fe}/\text{H}]$ for a selected sample of stars as described in the text. Dashed line is for the fit of stars with $[\text{Fe}/\text{H}] < -0.9$, dotted line for $[\text{Fe}/\text{H}] < -1.4$

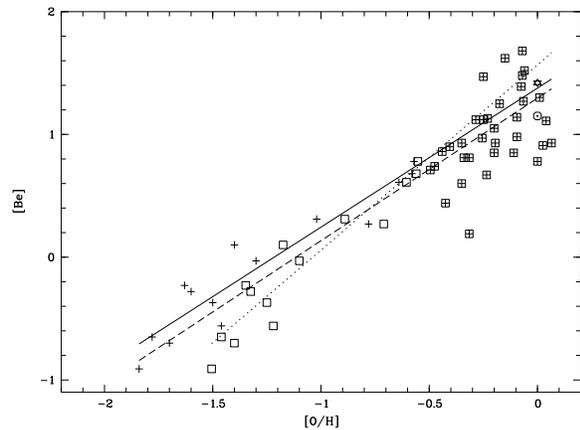


Fig. 6. $[\text{Be}]$ versus $[\text{O}/\text{H}]$. Crosses are for $[\text{O}/\text{Fe}] = +0.5$ in the halo, while squares are for increasing oxygen towards lower metallicities as described in the text. Continuous line is the fit for crosses with $[\text{O}/\text{H}] < -0.6$ and dashed line for all the sample. Dotted line is the fit of the squares for $[\text{O}/\text{H}] < -0.6$ and then extrapolated towards solar values

Alternative nucleosynthesis for Be such as that caused by the flood of neutrinos passing through the mantle and helium core during explosions of massive stars might also result in a linear output. Malaney (1992) suggested that ^9Be might be produced by $^7\text{Li}(t,n)^9\text{Be}$ in the helium shell of low-metallicity stars. However, no appreciable fraction of the solar abundance of ^9Be is made in such a way, and the ejected abundance of ^9Be in metal deficient stars, is quite small if compared with other isotopes like ^{11}B . The process of ν -induced nucleosynthesis may produce interesting amounts for ^7Li , $^{10,11}\text{B}$, but only small amounts of ^9Be (Woosley and Weaver 1995).

8.2. Primordial Be

The possibility of primordial production of Be in a strongly inhomogeneous universe was explored by Malaney and Fowler (1988), Boyd and Kajino (1989) and Thomas et al (1993). Be-

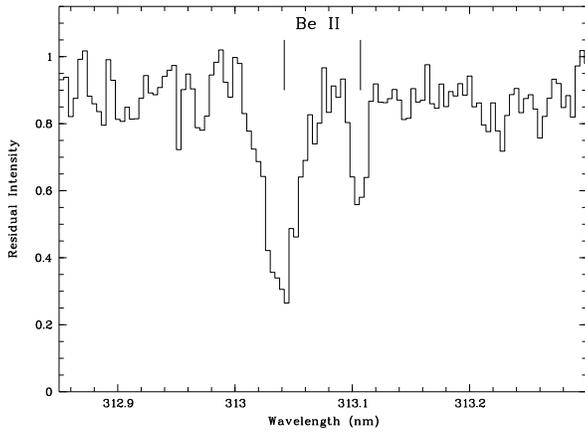


Fig. 7. Residual spectrum after division of HD 76932 with HD 106516 spectra

sides the fact that, on theoretical grounds, large inhomogeneities are unlikely to occur, the presence of a plateau of Be at low metallicities such as the Spite plateau for Li would be a strong case for primordial Be production, although not totally univocal as argued by Yoshii, Mathews and Kajino (1995). In Fig. 5 in correspondence of the most metal-poor objects, there is no evidence for a *plateau* in the Be abundances analogous to that observed for Li abundances, at least down to $[\text{Fe}/\text{H}]=-2.5$ and $[\text{Be}]=-1.0$. Boesgaard (1995) argued that a plateau at $[\text{Be}]$ about -1.0 is plausible but far from conclusive for the lowest metallicity stars HD 140283 and BD+3 740.

HD 140283 plays a special role in the existence of a plateau at low metallicities. Our determination differs from the previous ones mainly for the higher T_{eff} and the inclusion of α enhanced opacities in the atmospheric model. As already discussed, a further difference with respect to the Boesgaard and King (1993) analysis concerns overshooting. If the star is a relatively cool subgiant with $T_{\text{eff}}=5660$ K, as taken by Boesgaard and King (1993) and Gilmore et al (1992), standard stellar evolution models predict ^9Be depleted by ≈ 0.3 dex (Chaboyer 1994). Thus the values $[\text{Be}]=-0.97\pm 0.25$ (Gilmore et al 1992) and -0.78 ± 0.14 , (Boesgaard and King 1993) should be increased correspondingly, producing a flattening of Be-Fe relation at the lowest edge. On the other hand for the T_{eff} used here no post-main sequence depletion is expected and the measured abundance $[\text{Be}]=-0.86$ should reflect the protostellar one. It is the precise value of T_{eff} which determines whether the evolution correction has to be applied or not.

A remarkable prediction of inhomogeneous BBN is a large Be/B ratio of the order of about ≈ 100 . So far B has been measured in only three stars (HD 19445, HD 140283 and HD 201891) with boron showing a linear behaviour with iron as Be does. The B/Be ratios have been used to derive information on the origin of the two elements (Walker et al 1993, Olive et al 1994, Fields et al 1995). Most of the arguments rely on HD 140283, which has the more reliable boron determination. The LTE $[\text{B}] = -12.16\pm 0.14$ by Duncan, Lambert and Lemke (1992) coupled with the $[\text{Be}]=-0.97\pm 0.25$ (Gilmore et al 1992) or the

$[\text{Be}] = -0.78\pm 0.14$, (Boesgaard and King 1993) results in a very low B/Be ratio, i.e. lower than 6. The result is exacerbated if a post-main sequence correction of 0.3 dex to the Be abundance should be applied to HD 140283 when the cooler temperature is adopted, with $\text{B}/\text{Be} \approx 3$. The upwards revision of the Be abundance may be balanced by the revision of B abundance by non-LTE effects. Edvardsson et al (1994) and Kiselman (1994) have repeated the analysis of the B abundance taking into account non-LTE effects, leading to an upwards revision of ≈ 0.5 dex, i.e. 0.34 ± 0.2 . Therefore, taking into account both revisions, the B/Be ratio becomes ≈ 9 , still leading to a marginal conflict with the B/Be ratio of 10-20 predicted by GCR production. However, for the T_{eff} we have adopted here (5814 K) no post main sequence dilution is expected and with our value $[\text{Be}]=-0.86$ the B/Be ratio becomes 17, once non-LTE effects for B are accounted for. This ratio is in good agreement with the GCR predictions and does not require additional sources either for boron or beryllium.

8.3. Be-depleted dwarfs

Be is destroyed in warm stellar interiors and its presence in stellar atmospheres has important bearings for the study of the stellar outer layers (Bodenheimer 1966). Standard models predict negligible Be depletion in dwarfs with $T_{\text{eff}} \geq 4900$ K, in which the base of the convection zones is not hot enough to burn beryllium, and in subgiants with $T_{\text{eff}} > 5700-5500$ (Deliyannis et al 1990, Deliyannis and Pinsonneault 1990).

In fact, observations by Garcia Lopez et al (1995) in Pop I Hyades dwarfs show a plateau in the Be abundances down to $T_{\text{eff}} \approx 5200$ K, with a decline afterwards. In these stars Li is partially depleted implying that the mixing mechanism operating below the convection zone must be efficient enough in transporting material down to the Li burning layer ($T=2.5 \times 10^6$ K), but not to the Be burning layer ($T=3.5 \times 10^6$ K).

Extra mixing due to diffusion and rotation may amplify the elemental depletion if compared to the standard model. Rotationally induced mixing leads to a Be depletion strongly dependent on the T_{eff} and on the degree of initial angular momentum (Deliyannis and Pinsonneault 1990). We verified that accounting for such a depletion does not destroy the linear Be-Fe relation, but this may be due to the small number of hot halo stars available. It will be interesting to repeat the test when more such stars are available.

No detectable Be is found for HD 106516, HD 211998, HD 3795. The corresponding upper limits are far below the mean trend of the Be-Fe relation. HD 106516 is a dwarf with temperature 5995 K and no depletion is predicted by standard models for such a temperature. The upper limit in the Be is about 1 dex below the average Be-Fe relation. HD 106516 is a star with properties very similar to HD 76932. They have the same metallicity, gravity and almost the same effective temperature. HD 106516 may actually be 300 K hotter than HD 76932 according to the colour temperatures in column 2 of Table 2, but also slightly more metal-rich, according to the metallicities of Edvardsson et al (1993) (column 9 in Table 2). Whichever the case the

only remarkable difference between their spectra is the lack of Be lines in HD 106516. This can be appreciated from Fig. 7 where the spectrum resulting from the division of the two stars is shown. In the division of their spectra all the spectral features cancel out with the exception of the BeII lines of HD 76932, which clearly show up in Fig. 7. Note that a 300 K increase in the temperature of HD 106516 would result in an increase of only 0.03 dex in the [Be] abundance. HD 106516 shows also no Li (Hobbs & Duncan 1987) and therefore the two elements are consistently depleted. If we consider the high temperature of this star, it is likely that rotationally induced mixing or diffusion may be responsible for the elemental depletion of both Li and Be.

HD 3795 has $\log g = 3.6-3.9$, and $\text{Be} < -0.5$, at a metallicity where the Be is typically > 0.5 . Li has been measured at less than 0.60 by Pasquini et al (1994), i.e. more than 1.5 dex below the Spite plateau, and considering that T_{eff} is ≈ 5400 K, convection might have depleted Li according to the standard theory. However, we do not expect that Be has been depleted at this temperature. Therefore, other mechanisms should be at work in depleting Be from the atmosphere of this star.

HD 211998 has $T_{\text{eff}} = 5338$ K, no Be and Li measured with $[\text{Li}] = 1.1$ (Maurice et al 1984), i.e. ≈ 1 dex below the plateau value. According to Deliyannis and Pinsonneault (1990), since Li burns at lower temperatures, any significant destruction of Be would imply Li to have been completely destroyed. Thus in this case both the absence of Be and the behaviour of Be and Li are at odds with the predictions of standard stellar evolution theory. However, HD 211998 might be a post turn off star since $\log g = 3.26 \pm 0.12$ from Axer et al (1994), and 3.5 ± 0.26 in the photometrical derived gravity as reported in the fourth column of Table 2. The presence of Li would be consistent with HD 211998 being an evolved star, since many subgiants show lithium at this level (Pilachowski et al 1993; Pasquini and Molaro 1996). Be dilution is also expected to be about 0.8 dex and therefore it will be very interesting to see whether the real Be abundance is very much below the present upper limit.

The cool ($T_{\text{eff}} \approx 5000$ K) halo dwarf Groombridge 1830 (HD 103095) has a Be abundance by at least a factor 2-3 below the mean trend and Li has been detected in this star with $[\text{Li}] = 0.27 \pm 0.06$ (Boesgaard and King 1993; Deliyannis et al 1994). Various possibilities such as an intrinsically low beryllium abundance, mass loss or slow mixing have been discussed by Deliyannis et al (1994).

The three new stars given here together with Groombridge 1830 are the first cool Be-poor stars, and measurements of light elements, including boron, are potentially very important because they can help to discriminate among the various mechanisms for light element depletion proposed for cool stars so far.

9. The Li/Be ratio

The comparison between observed abundances and their theoretical ratios is a good test of models of elemental nucleosynthesis. Since Be has probably a univocal source in the GCR,

observations of Be help to constrain the degree to which ${}^7\text{Li}$, ${}^6\text{Li}$, ${}^{11}\text{B}$ and ${}^{10}\text{B}$ may have been produced in cosmic ray collisions rather than in stellar sources, neutrino nucleosynthesis, α - α reactions, and in the Big Bang. The amount of Li produced by spallation of high energy cosmic rays can be inferred from the observed Be by taking the theoretical $({}^6\text{Li}+{}^7\text{Li})/{}^9\text{Be}$ derived by Steigman and Walker (1992). The presence of ${}^6\text{Li}$ has to be considered because, observationally, it cannot be split from ${}^7\text{Li}$. However, ${}^6\text{Li}$ is rather fragile and is not expected to survive in halo stars cooler than ≈ 6300 K (Brown and Schramm 1988). Since ${}^6\text{Li}$ has been detected in HD 84937, which has $T_{\text{eff}} \approx 6200$ K (Smith et al 1993), we take the $({}^6\text{Li}+{}^7\text{Li})/{}^9\text{Be} = 13.1$ only for stars hotter than 6200 K and ${}^7\text{Li}/{}^9\text{Be} = 7.6$ for the cooler stars, which should have had their original ${}^6\text{Li}$ depleted and therefore not contributing to the Li EW at 670.7 nm. These ratios hold strictly for a relative chemical composition of the solar type and for the present day spectral distribution of the cosmic rays. However, changing the chemical composition to account for the enhancement of O relative to C and N in the past would not significantly affect the results shown here.

The Li abundance for the stars for which Be has been measured are given in Table 7. The amount of Li_{GCR} is negligible for low metallicity, where the primordial fraction and α - α fusion reactions are the overwhelming sources for ${}^7\text{Li}$. Li_{GCR} is about 1% at $[\text{Fe}/\text{H}] \approx -2.5$ and 10% at $[\text{Fe}/\text{H}] = -2.0$. For $[\text{Fe}/\text{H}] > -1.0$ it becomes progressively more important and comparable to that of other sources. It might be possible that the GCR contribution to present day Li is in fact greater than what is generally assumed (i.e. $\approx 10\%$). The relative contributions are related to the detailed synthesis of the two elements during the evolution of the Galactic disk, and the global uncertainty of these predictions leave enough room for such a possibility.

It is remarkable that at $[\text{Fe}/\text{H}] > -1.0$ in several cases Li_{GCR} exceeds the Li which is actually observed. The most probable explanation is that in these stars Li has been largely depleted. Li burns at lower temperatures than Be and therefore these are probably the stars in which Li has been depleted, but not Be. The sun itself should be one of these cases, with $2.3 \leq [\text{Li}]_{\text{GCR}} \leq 2.52$, which is much greater than the measured value, i.e. $[\text{Li}] = 1.16$. Thus, Be determinations offer a powerful way to pick up stars where strong Li depletions occurred. In fact there are four stars that have temperatures between 4900 K and 5500 K. For stars within this temperature range standard models predict Li depletion by stellar convection, but not for Be, and this shows the reliability of this approach to get information on Li depletion. These stars are shown in Fig. 8 as crossed squares. Of course the method fails at lower metallicities where most of the Li is supplied by other sources, or when Be may be also depleted. It is reliable only to discriminate stars with large Li depletions, and these place therefore a lower limit to the number of real cases.

It is interesting to note that these objects where $\text{Li}_{\text{GCR}} > \text{Li}_{\text{obs}}$ occupy a well specified region in the $[\text{Li}]-[\text{Fe}/\text{H}]$ diagram. They are shown as crossed circles in Fig. 8 and these are the points which contribute to the dispersion in the Li data at metallicities $[\text{Fe}/\text{H}] > -1.0$. The remaining stars are those which are

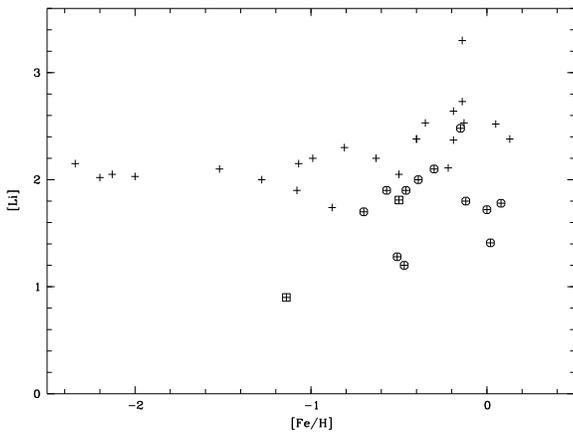


Fig. 8. [Li] versus [Fe/H]. Octagons show stars which are likely Li depleted, and squares point dwarfs with $5600 > T_{\text{eff}} > 5000$ K for which Li is expected depleted but not Be

not depleted at all or only moderately, and are preferentially located on the upper envelope of the Li-Fe diagram. This implies that the dispersion observed in the Li abundances is due to stellar depletion rather than to intrinsically different protostellar Li abundances. It also strongly suggests that the envelope of the data points in Fig. 8 is actually tracing the increase of Li during the Galactic life from the primordial plateau value up to the present values, with strong implications on the primordial origin of Li. Depletion mechanisms of Li, such as those of rotational mixing or diffusion, which are currently invoked to deplete an original high primordial Li, should have been highly tuned not only to reproduce a flat plateau for $[\text{Fe}/\text{H}] < -1.0$, but also to make a differential depletion at higher metallicities which may reproduce a monotonic increase of Li from the halo value to solar metallicities.

10. Conclusions

Observations at high resolution of 14 metal poor stars are analyzed for deriving the Be abundance through the 313.1 nm BeII resonance lines. The analysis has led to the following main conclusions:

- the Be abundance is subject to a small dependence of the order of ≈ 0.1 dex, from the atmospheric model used due to the particular treatment of overshooting and/or of the α -elements enhancement in the chemical composition of the atmosphere;
- the stellar parameters remain rather uncertain and in particular the surface gravity which is responsible for the main component of the error associated with the Be abundance;
- after retaining the best Be determinations in the literature and after homogenization to the same set of atmospheric models, Be shows a tight correlation with Fe with a slope of 1, although a steeper correlation cannot be ruled out at lower metallicities;
- after replacing Fe with O, by using the parametrization which comes from the general study of the metal poor stars,

Be shows a strong correlation with oxygen which holds up to solar values, without showing evidence of any break at the formation of the Galactic disk;

- no evidence of any primordial Be plateau is found at least down to $[\text{Fe}/\text{H}] = -3.0$
- few stars are significantly Be deficient, and if they are confirmed to be truly dwarfs, the absence of Be needs to be explained;
- it is shown in which way combined Li and Be observations can be used to pick up stars which suffered strongly Li depletion. These stars occupy a specific region in the Li versus [Fe/H] diagram, supporting the interpretation of the diagram in terms of a galactic enrichment of Li from a low Li primordial value of $[\text{Li}] \approx 2.2$;

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