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Beryllium abundance in lithium-rich giants*

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Abstract. About 2% of the Population I red giants show lithium abundances significantly larger than expected by dilution due to mixing by classical convection and, in some of them, the lithium abundance reaches values similar to (and even larger than) the Pop I value (meteoritic, open clusters etc.) around logN(Li) = 3.3. The classical convection predicts also a (smaller) dilution of beryllium and (an even smaller one) of boron.

Two main interpretations of the Li-rich giants are possible:

– the initial Li has been somehow preserved (perhaps by the inhibition of the classical mixing)
– on the contrary, a mixing, deeper than the classical one, took place in some (or all?) giants, leading to a dilution of the superficial lithium but sometimes overcompensating for it by an internal production of lithium, with transport to the surface (by the Cameron-Fowler mechanism).

In the first interpretation, Be (more robust than Li) is a fortiori preserved, in the second one, a mixing deeper than the classical one should dilute Be more than the classical Be dilution.

We have observed the Be II λ 3130.420 and 3131.066 Å lines in two Li-rich giants and three reference stars: one Li-poor giant and α Cen A and B. The observations were carried out at the ESO 3.6m telescope using the CASPEC spectrograph. By comparing the observed spectra with spectrum synthesis calculations we show that for the three giant stars the Be abundance is low, suggesting that, in these giants, Be is very depleted (>90%) from the initial Pop I value (logN(Be)$\sim$1.4). This result implies that the original Li in these stars must have been almost completely destroyed, and that the high Li abundances in the Li-rich red giants is most probably due to Li production in these stars.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: late-type

1. Introduction

The internal structure of the evolved stars is not well known. Lithium, Beryllium and Boron are fragile elements, selectively destroyed in the deep (hot) layers of the stars. Lithium is the most fragile element, and is preserved in a thin external layer. Beryllium is less fragile, and is preserved in a thicker zone, and boron in an even deeper zone. A mixing of the external layers with deeper ones will lead to a depletion of the fragile elements in the external layers. A shallow mixing will deplete essentially lithium, a deeper one will deplete also Be, and a still deeper one will even deplete B.

Gathering simultaneous data on both Be and Li is a powerful tool for a better understanding of stellar structure. Such a tool will be useful for the analysis of the intriguing problem of the spread of the lithium abundance in supergiants and giants: this spread is not understood and its study should help to check the processes of lithium depletion, and the possible lithium production in giants and supergiants. Observation of BeII lines in two Li-rich giants using IUE data of limited resolution and S/N gave encouraging indication that Be is not highly preserved in these giants (De Medeiros et al. 1997).

The galactic lithium production itself is an important pending problem (Matteucci et al. 1995, Lemoine et al. 1998), linked with the primordial nucleosynthesis. Sackmann & Boothroyd (1999) presented the first models for the production of Li in low mass normal red giants.

The intriguing problem of the lithium abundance spread in giants has been widely discussed in the literature since the work of Brown et al. (1989), without any satisfactory conclusion. A dilution by a factor of 60 is expected from the standard convective mixing model (Iben 1967) but the observations show that lower values of the lithium abundance are often found (even down by an additional factor of 50). In general terms, lithium is observed to be severely depleted in most giants.

More recent work (see Castilho et al. 1998 and references therein) has been successful in the discovery of a number of Li-rich stars. Let us note, that in some of them, the lithium reaches a value similar to (and even larger than) the lithium abundance generally observed for the Population I objects; those giants, through their wind could contribute to the enrichment of the interstellar medium.

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Several interpretations may be considered:

1- A combination of destruction in the MS phase with further dilution in the giant phase: An interpretation of the low Li abundance found in most giants could be that the depletion is the standard dilution, by classical convective mixing (Iben 1967), but that most stars have in addition suffered a previous lithium destruction in the main sequence phase:

a)- in the domain of the Boesgaard-Tripicco's dip (Boesgaard & Tripicco 1986) Li may be strongly destroyed (Balachandran 1990), but Be is only slightly depleted by the lithium dip's process (García López et al. 1995) so that the final Be abundance would be only slightly lower than predicted by the classical convection, provided that the line is observable.

b)- in a way similar to the (not yet well understood) solar lithium depletion on the main sequence. However, very few giants in the solar neighborhood will have solar masses, and even then the solar depletion of Be is moderate if existing at all (cf. Balachandran & Bell 1998). Here again, Be would be observable.

2- Li production: Another interpretation would be that lithium is severely depleted in all giants, but that some variable Li production occurs in a few giants. The severe depletion would be produced by a mixing deeper than the classical convection (first dredge-up, standard model). This problem has been tackled by Charbonnel (1994; 1995) who finds a deep mixing in giants of small masses (smaller than about 2 $M_\odot$): this mixing should also dilute Be (more moderately); so that the Be observation could confirm (or infirm) this interpretation. The problem of the higher mass giants remains, but most Li-rich giants in the RGB seem to have small masses (da Silva et al. 1995).

3- Li preservation: An opposite interpretation would be a variable inhibition of the deep mixing: if the low level of Li observed in most of the giant stars is due to a mixing larger than the one predicted by the first dredge-up standard model, an inhibition of this mixing in a few of the giants could preserve their lithium. The Be would then be a fortiori preserved and observable. A simple preservation would not by itself explain the few red giants with a lithium abundance larger than the Pop I abundance.

The aim of this work is the determination of the Be abundance in Li-rich and Li-poor giants, in order to discriminate between the possible interpretations, obtaining also some information about the mixing in the red giants.

In Sect. 2 the observations and data reduction are reported, in Sect. 3 the calculations are described, in Sect. 4 the results are given, in Sect. 5 a discussion is presented and in Sect. 6 the conclusions are drawn.

2. Observations and data reduction

Observations were carried out using the 3.6m ESO telescope with the CASPEC Spectrograph equipped with the long camera centered at λ 3640 Å (order 156), covering the orders 131 to 190. The BeII λ 3130 Å lines are found at the order 181. The échelle grating of 31.6 l/mm and a *cross-disperser* of 300 l/mm were used. In all observations we employed the filter ESO # 4 (UG5) which is 90% transparent in the UV, and cuts light redder than 4200 Å in order to avoid light contamination by saturation in the redder orders. The CCD ESO # 37, a Tektronix TK1024 of 1024x1024 pixels, with pixel size of 24 μm was used as detector. The slit was chosen to have 180x350 μm, corresponding to 2.″4 on the sky, and (with a scale of 0.33″/pixel in the direction of the dispersion) to a resolving power R $\sim$ 32000. The slit was aligned in the direction of atmospheric dispersion (parallactic angle), corresponding to the position of the star at half the exposure time. An external Th-Ar lamp was necessary since the light of the internal lamp crosses a prism opaque in the UV.

The data were reduced using the IRAF ECHELLE package. Flatfield corrections were not applied because there was no lamp available for the UV; but we find by inspecting the spectrum of the B1 star that the reduction of such images can be performed without flatfield division, since the CCD response is smooth (see also Molaro et al. 1997). Spectra from different exposures were added by weighting them with $(S/N)^2$. The final S/N ratio for the giants goes from 40 to 20, due mainly to the low atmospheric transmission and low CCD sensitivity at these wavelengths. The spectrum of η Cen was inspected for telluric lines. The log of observations and final S/N ratios are given in Table 1.

Table 1. Log of observations

Target	m_v	Spec. type	Date	Exp. (min.)	S/N	Comments
α Cen A	-0.01	G2 V	26.06.97	2×5	180	ref. star
α Cen B	1.33	K1 IV	26.06.97	2×12	40	ref. star
HD 220321	3.97	K0 III	25.06.97	1×90	45	ref. giant
HD 148650	5.94	K3 III	25.06.97	6×90	20	Li-rich giant
HD 787	5.25	K4 III	26.06.97	4×55	25	Li-rich giant
η Cen	2.31	B1 V	25.06.97	2×10	40	B star

Table 2. Adopted stellar parameters for program stars

Star	T_{eff}	log(g)	[Fe/H]	v_{mt}	ref.
α Cen A	5800	4.40	0.10	1.0	1
α Cen B	5350	4.50	0.10	1.0	1
HD 220321	4490	2.73	-0.40	1.3	2
HD 146850	4000	1.50	-0.30	1.6	3
HD 787	3890	1.74	0.03	1.5	2

Note: 1 Primas et al. (1997), 2 McWilliam (1990), 3 Castilho et al. (1995)

3. Calculations

3.1. Stellar parameters and models

Stellar parameters for the program stars were adopted from the literature, as indicated in Table 2. Model atmospheres employed have been interpolated in tables computed with the MARCS code by Gustafsson et al. (1975) and Edvardsson et al. (1993). The α Cen A and B synthetic spectra were also computed with models by Kurucz (1992) and we obtain a very good agreement with the above calculations.

3.2. Atomic and molecular line lists

Several authors discussed the list of the absorption lines which are present in this crowded region, and chose different ways of fitting, correcting and merging the incomplete data available in the literature. Our list of atomic lines was built trying to adopt only the most reliable data, using the list of identified lines by Moore et al. (1966), and including the updated list and accurate data for Fe I by Nave et al. (1994). Oscillator strengths for atomic lines are adopted from Nave et al. (1994), Wiese et al. (1969), Fuhr et al. (1988) and Martin et al. (1988) whenever available otherwise they were obtained by fitting the solar spectrum. We used the solar atmospheric model by Edvardsson et al. (1993) and the Kurucz solar atlas (Kurucz et al. 1984) and the abundances are adopted from Grevesse et al. (1996).

The molecular lines of the following molecules were taken into account in the calculations: MgH ($A^2\Pi$-$X^2\Sigma$), C_2 ($A^3\Pi$-$X^3\Pi$), CN blue ($B^2\Sigma$-$X^2\Sigma$), CH ($A^2\Delta$-$X^2\Pi$), CH ($B^2\Delta$-$X^2\Pi$), CH ($C^2\Sigma$-$X^2\Pi$), OH ($A^2\Sigma$-$X^2\Pi$), NH ($A^3\Pi$-$X^3\Sigma$).

Franck-Condon factors with dependence on the rotational quantum number J as given in Dwiwedi et al. (1978) and Bell et al. (1979) were computed and adopted where possible. For vibrational bands for which such values were not available, we adopted a constant value kindly made available to us through computations by P. D. Singh (Singh 1998, unpublished).

For all molecular systems the line lists by R. Kurucz (CD ROM 18) were adopted, where we recomputed the 'molecular oscillator strengths', by recomputing their Honl-London factors using the formulae by Kovacs (1979), using the Franck-Condon factors as indicated above, and employing literature values for the electronic oscillator strengths $f_{\rm el}$. We have adopted the $f_{\rm el}$(CN blue) = 0.0338 (Duric et al. 1978), $f_{\rm el}(C_2)$ = 0.033 (Kirby et al. 1979), $f_{\rm el}$(CH) = 5.257E-3 for the ($A^2\Delta$-$X^2\Pi$) system (Brzozowski et al. 1976), $f_{\rm el}$(CH) = 2.5E-3 for the CH ($B^2\Delta$-$X^2\Pi$) system (Grevesse & Sauval 1973), and $f_{\rm el}$(CH) = 5.95E-3 for the CH ($C^2\Sigma$-$X^2\Pi$) (Lambert 1978), $f_{\rm el}$(OH) = 8.0E-4 and $f_{\rm el}$(NH) = 8.0E-3 (Grevesse & Sauval 1973) and dissociation potentials D_o(CN) = 7.65 eV, $D_o(C_2)$ = 6.21 eV, D_o(CH) = 3.46 eV, D_o(OH) = 4.392 eV, D_o(NH) = 3.47 eV (Huber & Herzberg 1979).

To fit the solar spectrum with the logN(Be)=1.15 (Grevesse et al. 1996), it was necessary to make slight modifications of the derived log *gf* values of the BeII lines. The adopted values are -0.308 for the λ 3130.420 Å line and -0.508 for the λ 3131.066 Å line. By calculating the synthetic spectrum with the Kurucz (1992) solar model, the BeII lines are adequately fitted with log *gf* -0.168 and -0.468 respectively. To fit the blue wing of the BeII λ 3131.066 Å (avoiding large modifications of the log *gf* of the surrounding lines, as found in the literature) we chose to include a FeI line at λ 3130.995 Å with χ_{ex}=3.00 eV and log(*gf*)=-3.30. The behaviour of this line in the fits of α Cen A and B proved to be appropriate.

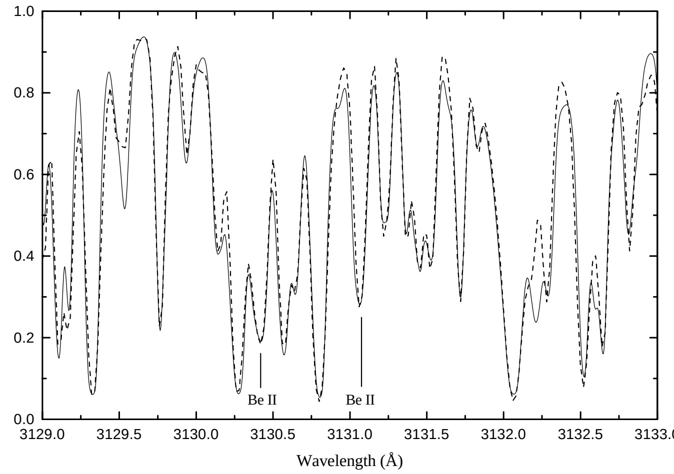

Fig. 1. Our synthetic spectra for the Sun (- - -), overimposed to the Kurucz Solar Atlas (—–).

The damping constants for the neutral element lines was calculated using tables of cross sections by Barklem et al. (1998 and references therein), and for the other lines they were determined by fitting the solar spectrum.

Therefore we have built an atomic and molecular data base, available upon request.

In Fig. 1 we show our synthetic spectra for the Sun, overimposed to the Kurucz Solar Atlas (Kurucz et al. 1984). No multiplicative or additive scaling was used in the Solar Atlas or the computed spectra.

3.3. Spectrum synthesis

An updated version of the code by Spite (1967), extended to include molecular lines by Barbuy (1982), where LTE is assumed, is used for the spectrum synthesis calculations. This code (FSYNTH) now includes atomic and molecular lines from UV to near-IR and the computations are made faster.

For α Cen A and B we calculated the synthetic spectra using the solar chemical composition, scaling to the adopted metallicity ([M/H]=0.1). Small changes for some element abundances ($\leq$0.15 dex) were applied in order to fit the spectra. For the giants we used published abundances available for some elements (Castilho et al. 1995 for HD 146850, and McWilliam 1990 for HD 787 and HD 220321) and solar composition for the other elements. A few elements for which the abundances were not available were slightly modified.

The uncertainties in Be abundance, as given in Table 3, are due to the S/N ratio. The intrinsic error in the abundance calculation is mostly due to the log *gf* and is estimated to be of 0.10 dex. We estimate that the uncertainties due to NLTE effects on the formation of the Be lines are small. The analysis of these effects for dwarfs by García López et al. (1995) shows that the NLTE corrections are lower than 0.1 dex, and for the subgiant HD 140283 it is even smaller, so that the NLTE cannot explain the difference between a dwarf like α Cen A and a giant. The main source of uncertainty is due to the relatively low S/N ratios.

Table 3. Be abundances (present work) and Li abundances (literature)

Star	logN(Be)	logN(Li)
α Cen A	1.20±0.1	1.37(1)
α Cen B	0.80±0.2	≤0.4(2)
HD 220321	0.40±0.3	≤-0.2(3)
HD 146850	−0,50±0.4	1.6 (1.9nlte)(4)
HD 787	0.00±0.4	2.2 (3.1nlte)(5)
Sun	1.15±0.1(6)	1.16±0.10(6)

Note: 1 King et al. (1997b), 2 Chmielewski et al. (1992), 3 Brown et al. (1989), 4 Castilho et al. (1995), 5 de la Reza & da Silva (1995), 6 Grevesse et al. (1996)

Table 4. Expected Li abundances from Be depletion

Star	present Be fraction	logN(Li) from solar [Be/Li]
Sun	0.0071	–
α Cen A	0.0079	1.21
α Cen B	0.0020	0.62
HD 220321	0.0013	0.41
HD 146850	0.0001	−0.49
HD 787	0.0005	0.01

4. Results

In Table 3 we report the presently derived Be abundances and literature values of Li abundances, including for reference the Be and Li abundances of the Sun according to Grevesse et al. (1996).

We observed α Cen A and B as comparison stars. The derived Be abundances agree within the uncertainties (illustrated in Fig. 3) with previous determinations of N(Be) = 1.21 and 0.61 (Primas et al. 1997) or N(Be) = 1.35 and 1.20 (King et al. 1997a). The determinations for the giants were made using the same techniques of data reduction, the same atomic and molecular constants, and the same grid of MARCS models.

The Be abundance estimated for the three red giant stars (Table 3) show that the Be abundance has been very depleted (by >90% i. e. by a factor of 10 or larger) from the initial Pop I value (logN(Be)= 1.4). By computing the Be abundance for HD 220321 and HD 787 using the atmospheric parameters used by Brown et al. (1989) $T_{\rm eff}$ = 4510 K and 4220 K; log(g)=2.3 and 1.5 and [Fe/H]=-0.32 and 0.07, we find Be abundances of logN(Be)= 0.1 and -0.2 respectively.

In Table 4 we show the present observed Be fraction (from Primas et al. (1997) for α Cen A and B and from Table 3 for the giants) with respect to the meteoritic value (2nd column), and the corresponding Li abundances (3rd column) deduced from the observed Be depletion by assuming the same depletion ratio of Be relative to Li as in the Sun. These estimations show large Li depletions for the three observed giants, that agree with the observed Li abundance for the low Li abundance giant HD 220321 but are in complete discordance with the two Li-rich giants.

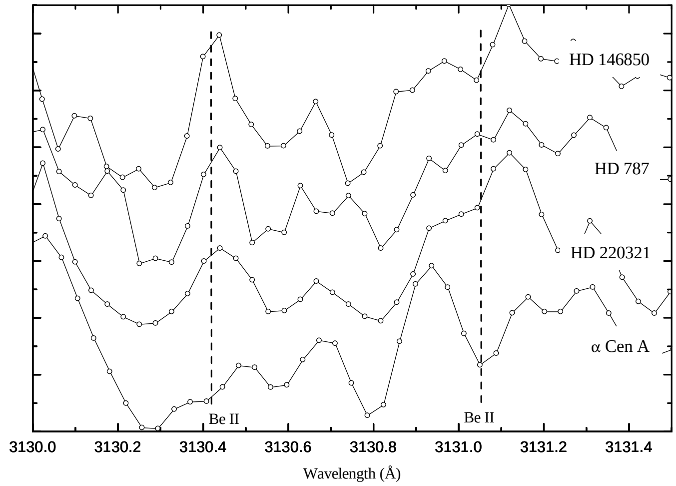

Fig. 2. Comparison between α Cen A (bottom) where we can see the Be II lines and the other three giants where the lines are nearly absent.

It is important to note however that this Li/Be depletion ratio is correct for dwarfs of solar mass (as shown by the agreement of the computations with the observed values for α Cen) - the ratio may be different for giants -, and that Balachandran & Bell (1998) have found that the solar Be abundance is, in fact, not depleted with respect to the meteoritic value of N(Be) = 1.42 dex. In this case the Li depletion with respect to Be will be even larger.

Our results for Be show good agreement with recent calculations by C. Charbonnel, carried out for giants of [Fe/H] = 0.0 and -0.5 and masses between 1.2 and 2.0 $M_\odot$, where mean values of Be/Be$_\odot$ $\sim$ 0.1 and Li/Li$_\odot$ $\sim$ 0.05; our depletions for Li are larger than predicted by the models, but an extra Li depletion is expected.

In Fig. 2 we compare the observed spectrum of α Cen A, where we can see the Be II lines, to the other three giants where the Be II lines are essentially absent.

In Figs. 3 to 7 we show the Be spectral region together with synthetic spectra for different Be abundances respectively for α Cen A and B, HD 220321, HD 146850 and HD 787.

5. Discussion

The small Be abundance found in the Li-rich giants suggests a Be depletion, since the Be depletion found in the giants is larger than the one found in the region of the dip. Moreover, it is not likely that these two stars had by chance a low Be initial abundance, in spite of the fact that the Be abundance in Pop I stars shows some spread. Therefore, Be is not preserved, and its depletion should be due to a rather deep mixing, implying that the original Li in these stars must have been strongly depleted, as in the case of HD 220321. As a consequence, the high Li abundance found in the two Be-poor Li-rich giants analysed here (and in all Li-rich giants) is due to a further Li production (cf. Sackmann & Boothroyd 1999).

Recently, two Hyades giants have been analyzed by Duncan et al. (1998). They have a lithium depletion by a factor of 120,

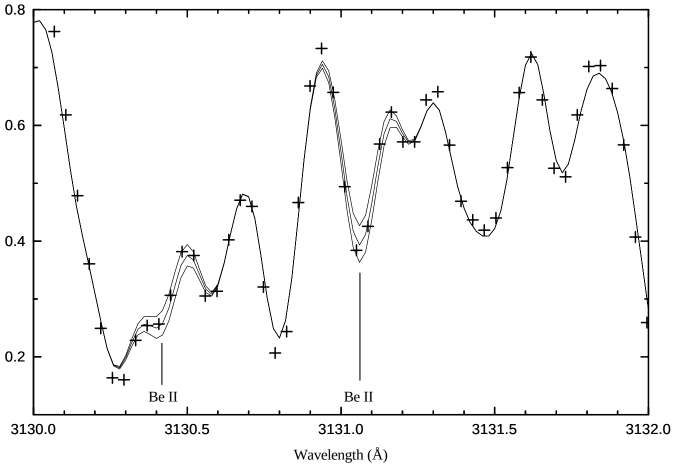

Fig. 3. α Cen A (+ + +), synthetic spectra with logN(Be) = 1.10, 1.20, 1.30 (—–). The best fit with logN(Be)=1.20 agrees with logN(Be)=1.21 from HST observations (Primas et al. 1997).

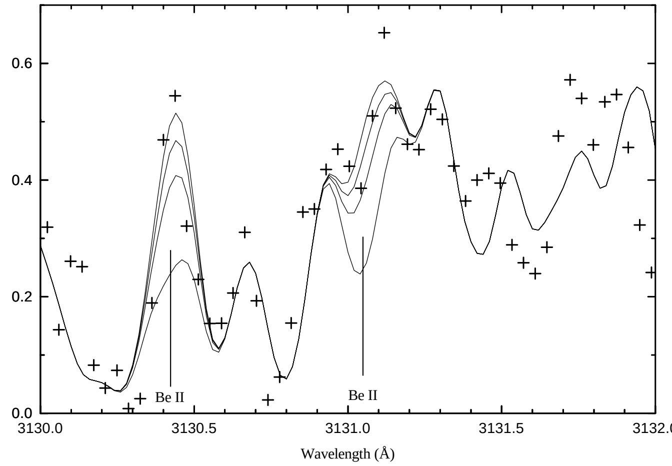

Fig. 6. HD 146850: Observed spectrum (+ + +) and synthetic spectra (—–). computed with Be abundances: logN(Be) = −1.0, −0.5 (best fit), 0.0, and 1.2.

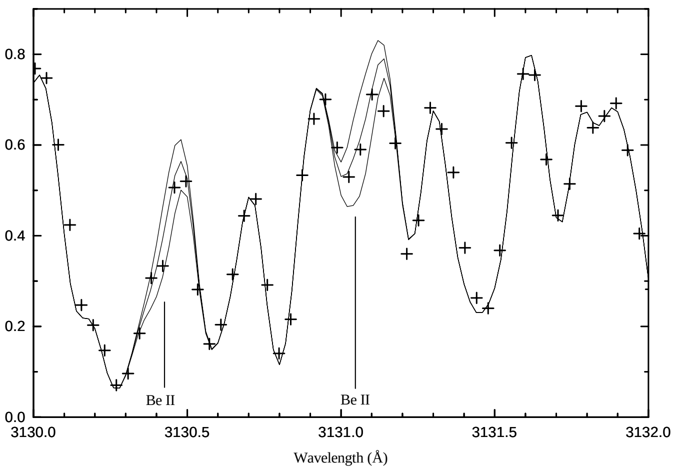

Fig. 4. α Cen B (+ + +) together with synthetic spectra for three Be abundances: logN(Be) = 0.50, 0.80 (best fit) and 1.10 (—–).

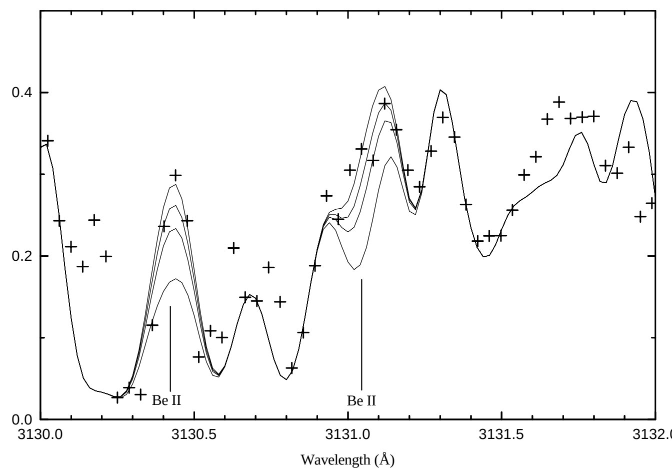

Fig. 7. HD 787: Observed spectrum (+ + +) and synthetic spectra (—–) computed with Be abundances: logN(Be) = −0.4, 0.0 (best fit), 0.4 and 1.2.

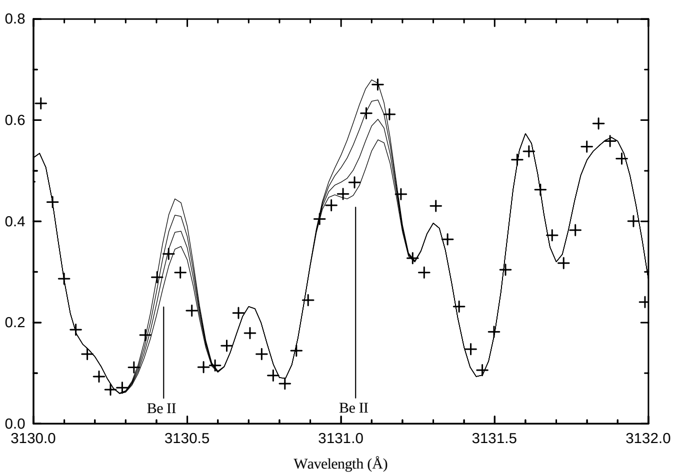

Fig. 5. HD 220321: Observed spectrum (+ + +) and synthetic spectra (—–) computed with Be abundances: logN(Be) = 0.1, 0.3, 0.5 and 0.7. A best fit is for logN(Be) = 0.4

similar to the solar depletion. In fact, in the sample of Brown et al. (1989) the depletions are generally even larger. The boron is found depleted by a factor of 10: the mixing responsible for the lithium depletion has been deep enough for depleting significantly the boron, implying a Be depletion by an even larger factor. In fact, a NLTE analysis of the lithium abundance shows a depletion of only $\approx$ 80. This analysis suggests that the relatively moderate lithium depletion in the Hyades giants has been obtained by a deep mixing, deep enough for depleting Boron and, a fortiori Be (the three depletions of Li, Be and B are found compatible with the Yale model of stellar evolution by Pinsonneault et al. 1992).

Both results concur to suggest that rather deep mixing occurs generally in Li-poor giants, implying depletions of Li, Be and B. The occurrence of a high Li abundance in Be-poor giants suggests some lithium production, compensating (and sometimes overcompensating) the previous depletion.

Except for the Li abundance, the Li-rich giants are normal red giants. No correlation was found between mass, rotation or $^{12}C/^{13}C$ ratio and Li abundance (da Silva et al. 1995; De Medeiros et al. 1996a). Observations with the CORAVEL spectrometer indicate that HD 146850 is a binary system, very probably with a double-lined behaviour, noting however that this was not detectable in our spectroscopic observations (Castilho et al. 1997). A projected rotational velocity $V \sin i$ of 2.8 km s^{-1} is found for this star, which seems to be the first known Li-rich giant presenting indication of binarity. The rotational velocity for HD 146850 can be considered normal in comparison with the observed rotation for giant stars. As shown by De Medeiros et al. (1996b) the mean rotational velocity for K3 III giants (the assigned spectral type for HD 146850) is near 2.0 km s^{-1}. For the other two lithium-rich stars of our sample, CORAVEL observations show no sign of binarity.

These facts suggest that the Li-rich giants are not a particular class of stars, but ordinary low mass stars, observed during a short phase of their evolution, when Li is created (Castilho 1995). Sackmann & Boothroyd (1999) demonstrated that ^{7}Li can be created in low mass red giant stars via the Cameron-Fowler mechanism, due to non-classical deep mixing and the associated "cool bottom processing" yielding photospheric abundances like the ones observed in the Li-rich red giants. Observed Li abundances in red giants can even reach values larger than the Pop I value, such as the case of HD 19745 (de la Reza & da Silva 1995). If indeed all low mass red giants go through a phase of Li production in the RGB (that could be cyclic), together with an increase in mass loss seen in the IRAS colour diagram (Gregorio-Hetem et al. 1993, de la Reza et al. 1996), and since some of them reach a lithium abundance larger than the Pop I abundance, they could be an important source of Li enrichment in the Galaxy.

6. Conclusion

The observations presented here suggest that the lithium abundance distribution observed in the red giants is best explained by a classical mixing, deep enough for depleting B, Be and Li, and probably deep enough for inducing (sometimes, or in delimited evolutionary phases) a variable lithium production, confirming the computations of extra-mixing in low-mass giants published by Charbonnel (1998) and of cool bottom processing in such stars recently presented by Sackmann & Boothroyd (1999). However, in the limited telescope time attributed to this project, it was possible to observe only two Li-rich giants, and owing to the importance of a better understanding of extra mixing processes in stars, and lithium production in the Galaxy, the observation of some more Li-rich giants would be desirable.

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References

Balachandran S., 1990, ApJ 354, 310
Balachandran S., Bell R.A., 1998, Nat 392, 791
Barbuy B., 1982, Ph.D. Thesis, Univ. Paris VII
Barklem P.S., O'Mara B.J., Ross J.E., 1998, MNRAS 290, 102
Bell R.A., Dwiwedi P.H., Branch D., Huffaker J.N., 1979, ApJS 41, 593
Boesgaard A.M., Tripicco M.J., 1986, ApJ 303, 724
Brzozowski J., Bunker P., Elander N., Erman P., 1976, ApJ 207, 414
Brown J.A., Sneden C., Lambert D.L., Dutchover E., 1989, ApJS 71, 293
Castilho B.V. 1995, MsC Thesis, IAG, Universidade de São Paulo
Castilho B.V., Gregorio-Hetem J., Barbuy B., 1995, A&A 297, 503
Castilho B.V., Gregorio-Hetem J., Barbuy B., 1997, Journal of Astronomical Data 3, 1
Castilho B.V., Gregorio-Hetem J., Spite F., Spite M., Barbuy B., 1998, A&AS 127, 139
Chmielewski Y., Friel E., Cayrel de Strobel G., Bentolila C., 1992, A&A 263, 219
Charbonnel C., 1994, A&A 282, 811
Charbonnel C., 1995, ApJ 453, L41
Charbonnel C., 1998, Space Science Rev. 84, 199
da Silva L., de la Reza J.R., Barbuy B., 1995, ApJ 448, L41
de la Reza J.R., da Silva L., 1995, ApJ 439, 917
de la Reza R., Drake N., da Silva L., 1996, ApJ 456, L115
De Medeiros J. R., Lèbre A., de Garcia Maia M.R., Monier R., 1997, A&A 321, L37
De Medeiros J.R., Melo C.H.F., Mayor M., 1996a, A&A 309, 465
De Medeiros J.R., Da Rocha C., Mayor M., 1996b, A&A 314, 499
Duncan D.K., Peterson R.C., Thorburn J.A., Pinsonneault M.H., 1998, ApJ 499, 871
Duric N., Erman P., Larson M., 1978, Phys. Scripta 18, 39
Dwiwedi P.H., Branch D., Huffaker J.N., Bell R.A., 1978, ApJS 36, 573
Edvardsson B., Andersen J., Gustafsson B., et al., 1993, A&A 275, 101
Fuhr J.R., Martin G.A., Wiese W.L., 1988, Atomic Transition Probabilities: Iron through Nickel. Journal of Physical and Chemical Reference Data vol. 17, suppl. no. 4
García López R.J., Rebolo R., Pérez de Taoro M.R., 1995, A&A 302, 184
García López R.J., Severino G., Gomez M.T., 1995, A&A 297, 787
Gregorio-Hetem J., Castilho B.V., Barbuy B., 1993, A&A 268, L25
Grevesse N., Sauval J., 1973, A&A 27, 29
Grevesse N., Noels A., Sauval J., 1996, In: Holt S.S., Sonneborn G. (eds.) ASP Conf. Ser. 99, p. 117
Gustafsson B., Bell R.A., Eriksson K., Nordlund A., 1975, A&A 42, 407
Huber K.P., Herzberg G., 1979, Constants of Diatomic Molecules. van Nostrand Reinhold, New York
Iben I. Jr., 1967, ApJ 147, 624
King J.R., Deliyannis C.P., Boesgaard A.M., 1997a, ApJ 478, 778
King J.R., Deliyannis C.P., Hiltgen D.D., et al., 1997b, AJ 113, 1871
Kirby K., Saxon R.P., Liu B., 1979, ApJ 231, 637
Kovacs I., 1979, Rotational Structure in the Spectra of Diatomic Molecules. Am. Elsevier Pub. Co.
Kurucz R.L., 1992, In: Barbuy B., Renzini A. (eds.) IAU Symp. 149, Kluwer Acad. Press, p. 225
Kurucz R.L., Furenlid I., Brault J.W., Testerman L., 1984, Solar Flux Atlas from 296 to 1200 nm, NSO, Tucson, Atlas no. 1
Lambert D.L., 1978, MNRAS 182, 249
Lemoine M., Vangioni-Flam E., Casse M., 1998, ApJ 499, 735

McWilliam A., 1990, ApJS 74, 1075

Matteucci F., D'Antona F., Timmes F.X., 1995, A&A 303, 460

Martin G.A., Fuhr J.R., Wiese W.L., 1988, Atomic Transition Probabilities: Scandium through Manganese. Journal of Physical and Chemical Reference Data vol. 17, suppl. no. 3

Molaro P., Bonifacio P., Castelli F., Pasquini L., 1997, A&A 319, 593

Moore C.E., Minnaert M.G., Houtgast J., 1966, The Solar Spectrum from 2935 to 8870 Å. Second Revision of Rowland's Preliminary Table of Solar Spectrum Wavelengths, N.B.S. Monog. 61, Government Printing Office, Washington, D.C.

Nave G., Johansson S., Learner R.C.M., Thorne A.P., Brault T.J., 1994, ApJS 94, 221

Pinsonneault M., Deliyannis C.P., Demarque P., 1992, ApJS 78, 181

Primas F., Duncan D.K., Pinsonneault M.H., Deliyannis C.P., Thorburn J.A., 1997, ApJ 480, 784

Sackmann I.-J., Boothroyd A.I., 1999, ApJ 510, 217

Spite M., 1967, Ann. Astrophys. 30, 211

Wiese W.L., Martin G.A., Fuhr J.R., 1969, Atomic Transition Probabilities: Sodium through Calcium. NSRDS-NBS 22