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CARBON ISOTOPE RATIOS IN VERY LITHIUM-RICH K GIANTS

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ABSTRACT

High-resolution spectra were used to derive CNO abundances and the $^{12}C/^{13}C$ ratios for the very Li-rich K giants HD 19745 and HD 39853. O and $^{12}C/^{13}C$ are also obtained for comparison for the Li-rich K giant HD 787. Results from the literature for other very Li-rich giants were also gathered to allow for a more complete discussion. The three most Li-rich giants known, HD 19745, HD 39853, and HD 95799, with $\epsilon(Li) \geq 3.0$, show low $^{12}C/^{13}C$ values ($^{12}C/^{13}C \leq 15$), requiring an extra-mixing mechanism, whereas HD 9746 and HD 112127 with $\epsilon(Li) \sim 2.7$ show $^{12}C/^{13}C \sim 25$, following the standard first dredge-up predictions. The data for these five stars indicate that no clear correlation is found between $^{12}C/^{13}C$ and $\epsilon(Li)$ for the very Li-rich giants. An important conclusion is that, since for the three most Li-rich giants, $^{12}C/^{13}C$ is low, efficient mixing should have lowered both $^{12}C/^{13}C$ and Li abundances. The very high Li abundances actually found in these stars call therefore for an independent mechanism enriching the Li.

Subject headings: stars: abundances — stars: chemically peculiar — stars: evolution — stars: late-type

1. INTRODUCTION

About 1% of K giant stars present very strong Li I lines. This peculiarity is completely unexpected from the standard first dredge-up evolutionary theory, which predicts a strong Li depletion. Some of the Li-rich giants show Li abundances larger than that of the interstellar medium of $\epsilon(Li) = 3.1$ (Boesgaard & Steigman 1985) (the standard notation $\epsilon(Li) = \log N(Li) = \log [n(Li)/n(H)] + 12$, where n = number density of atoms, is adopted). This is the case of HD 19745, HD 39853, and HD 95799. The field star HD 19745, discovered in the survey for new T Tauri stars by Gregorio-Hetem et al. (1992), revealed itself to be the most Li-rich star known up to now, with an LTE Li abundance $\epsilon(Li) = 4.08$ (de la Reza & da Silva 1995). The star HD 39853, discovered by Gratton & D'Antona (1989), is a Population II K giant with $\epsilon(Li) = 2.92$. From non-LTE calculations the values are larger: 4.75 for HD 19745 and 3.90 for HD 39853 (de la Reza & da Silva 1995). HD 95799 has been recently detected by Luck (1994) and has an LTE Li abundance of $\epsilon(Li) = 3.22$.

The mechanism for Li enrichment on the surface of very low mass giant stars has not yet been identified. In this respect, it is interesting to investigate to what level the isotopic ratio $^{12}C/^{13}C$, which measures a deep mixture process in the star's interior, can be related to a strong Li enrichment. A simple eventual relation between Li abundance and $^{12}C/^{13}C$ can perhaps give us first insight on this mechanism. In the case of normal M giants, for example, Wallerstein & Morell (1994) showed that the relatively constant value of $^{12}C/^{13}C = 11.8 \pm 3.8$ for an ensemble of 23 giants is not correlated with their (low) Li abundances, which vary over a range of three orders of magnitude.

In the present Letter, we investigate if, in very Li rich giants, there is a correlation between the lithium abundance and $^{12}C/^{13}C$ ratio, and if $^{12}C/^{13}C$ follows the standard first dredge-up theory.

We present here the first measurements of CNO abundances and $^{12}C/^{13}C$ ratio for the very Li-rich giant HD 19745. We also remeasured the $^{12}C/^{13}C$ and CNO abundances for HD 39853 in order to compare our results to those of Gratton & D'Antona (1989). New measurements of the $^{12}C/^{13}C$ ratio and the N and O abundances for HD 787 are also shown.

The observations are presented in § 2, and the calculations of synthetic spectra are described in § 3. We present our results on $^{12}C/^{13}C$ in § 4. In § 5 the results are discussed, and in § 6 conclusions are given.

2. OBSERVATIONS

In the present work three Li-rich giants were observed at high resolution using the 1.4 m coudé auxiliary telescope (CAT) of ESO; the short camera focus of the coudé échelle spectrograph (CES), with CCD ESO 9 (1024 × 512 pixels), was used. Spectra of three regions, centered on λ6300, λ6470 and λ8000 were obtained in 1990 November. The resolving power of all spectra is 60,000 and their signal-to-noise ratio values are larger than 100. A reduction program, developed by ourselves at the Observatório Nacional, was used to reduce the two-dimensional spectra to one dimension, to convert from pixel to wavelength, and to normalize the spectra. Tests made later using the IRAF package gave the same results.

HD 19745 was also observed with CCD ESO 32 (512 × 512 pixels) on the long camera focus of the Cassegrain échelle spectrograph (CASPEC) on the ESO 3.6 m telescope. The spectral range covered was λ5440–λ6760, with gaps, and the resolving power was 50,000. For this work, we used the apertures centered at λ5630 and 6330. The IRAF reduction package was used to extract the normalized one-dimensional spectra in wavelength coordinates.

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[1] Observations collected at the European Southern Observatory, La Silla, Chile.

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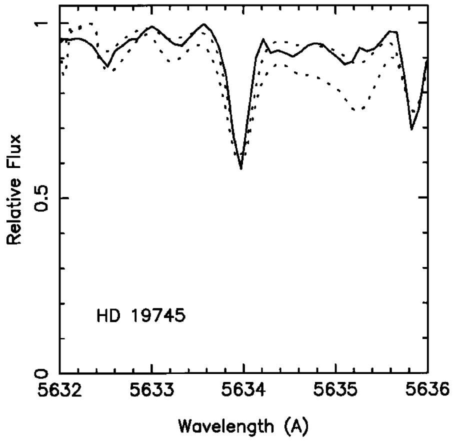

FIG. 1.—$C_2(0,0)$ λ5635 computed for [C/Fe] = 0.0 and +0.2. (observed spectrum, *solid line*; synthetic spectrum, *dotted line*) for HD 19745.

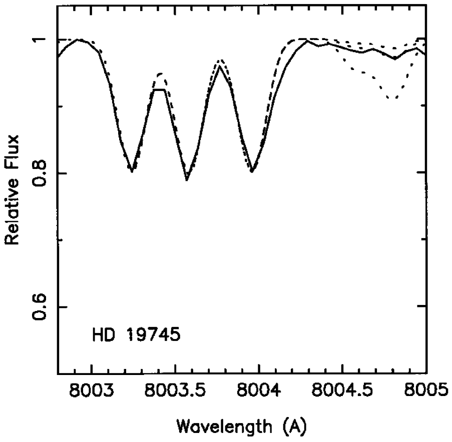

FIG. 2.—^{12}CN and ^{13}CN for isotopic ratios of $^{12}C/^{13}C = 4$, 15 and 30 (observed spectrum, *solid line*; synthetic spectrum, *dotted lines*) for HD 19745.

3. CALCULATIONS

To determine the $^{12}C/^{13}C$ ratios and CNO abundances, we have compared synthetic spectra with the observed ones. The calculations were made using the code for molecular lines by Barbuy (1982) and the same MARCS models (Gustafsson et al. 1975) used by de la Reza & da Silva (1995) to find the Li abundances of those stars. The carbon abundance was derived for HD 19745 using the $C_2(0,0)$ band head of the $A\,^3\Pi$–$X\,^3\Pi$ system at λ5635.5. Figure 1 shows the comparison between the observed and the synthetic spectra computed with [C/Fe] = 0.0 and +0.2. The nitrogen abundance was derived for HD 19745 and HD 39853 using the CN(6,2) λ6478.48 band head of the $A\,^2\Pi$–$X\,^2\Sigma$ red system (for the molecular data see Milone et al. 1991). The oxygen abundance was derived using the [O I] λ6300.31.

The $^{12}C/^{13}C$ isotopic ratio was derived from ^{12}CN and ^{13}CN lines in the λλ8003–8005 region. A description of molecular data is given in Barbuy et al. (1992). The CNO abundances and the $^{12}C/^{13}C$ ratios determined are reported in Table 1. In Figure 2 the ^{12}CN and ^{13}CN lines for HD 19745 computed with $^{12}C/^{13}C = 4$, 15, and 30 are shown together with the observed spectrum.

Regarding CNO, for HD 19745 we found [C/Fe] = 0.0 and [N/Fe] = +0.1, showing a slight mixing signature. For HD 39853 and HD 787 the C_2 lines have not been observed yet. The CN(6,2) band head could be fitted adopting the literature values for the carbon abundances: [C/Fe] = +0.21 for HD 39853 (Gratton & D'Antona 1989) and −0.2 for HD 787 (Berdyugina & Savanov 1994); the nitrogen abundances derived are [N/Fe] = +0.1 and +0.3 for HD 787 and HD 39853, respectively, but for HD 39853 the determination is less accurate owing to a lower quality of the spectrum. For these two stars, the C and N values which fit the CN band head are indicative of mixing effects. As we shall see later, these values are compatible with the $^{12}C/^{13}C$ ratios for the three sample stars.

The oxygen abundances are solar for HD 787 and HD 19745, as expected for typical disk solar metallicity stars, and it is slightly overabundant for HD 39853, compatible with the moderate deficiency of this star.

4. $^{12}C/^{13}C$ RATIOS

The results on $^{12}C/^{13}C$ ratios in stars of different masses and at different evolutionary stages for several clusters by Gilroy (1989) and Gilroy & Brown (1991) have shown the following:

1. $^{12}C/^{13}C$ in stars more massive than $M/M_{\odot} \geq 2.2$ follows the predictions of the standard theory: from the base of the subgiant branch up to the point of inward maximum penetration of the convective envelope, the ratio falls from the solar value $^{12}C/^{13}C = 89$ to 22–28 and shows no further decrease.
2. For lower mass stars, the ratio decreases following the standard theory up to the point of maximum penetration of the convective envelope but continues to decrease for more evolved stars, reaching very low values at the tip of the red giant branch. Gilroy & Brown (1991) propose that this is caused by a continuing mixing due to turbulent diffusion or meridional circulation.

The lower the stellar mass and the metallicity, the more efficient is the extra-mixing process (Charbonnel 1994). After the completion of the first dredge-up, a discontinuity is built owing to the maximum penetration of the convective envelope. After this evolutionary point, low-mass stars show a degenerate helium core, which continues to grow owing to the shell hydrogen burning.

TABLE 1

ABUNDANCES OF LITHIUM IN LTE AND NON-LTE

Star	ϵ(Li)	[O/Fe]	[N/Fe]	[C/Fe]	$^{12}C/^{13}C$	$^{12}C/^{14}N$
HD 787	2.2/3.1	−0.0	0.1	(−0.2)	15	2
HD 19745	4.08/4.75	−0.0	−0.05	0.0	15	3.8
HD 39853	2.92/3.9	0.1(0.29)	0.3:(−0.03)	(0.21)	6(6.6)	3.3(8)

NOTE.—See de la Reza & da Silva 1995 (col. [2]) and abundance ratios obtained in the present work; values in parenthesis are from Berdyugina & Savanov 1994 for HD 787 and from Gratton & D'Antona 1989 for HD 39853.

TABLE 2

STELLAR PARAMETERS, ABUNDANCES, AND MASSES OF LITHIUM-RICH GIANTS

Star	Spectral Type	T_{eff}	log g	[Fe/H]	ϵ(Li)	$^{12}C/^{13}C$	$M(M_\odot)$	Reference
HD 787	K5	3980	1.70	−0.0	2.2	15	2.0(2.0)	1, 2, 3, 4, 5
HD 9746	K1	4420	2.30	−0.0	2.75	28	1.7(1.7)	3, 4, 6, 7
HD 19745	K0	4990	2.10	−0.0	4.08(4.75)	15	2.6	1, 4, 5
HD 30834	K3	4190	1.5	−0.17	1.8	13	2.0(2.0)	3, 4
HD 39853	K5	3900	1.16	−0.5	2.9(3.9)	6(6.6)	1.2(0.8)	1, 4, 5, 8
HD 95799	G8–K0	4800	2.00	−0.11	3.22	10	(2.7)	9
HD 108471	G8–K0	5010	2.80	−0.02	2.0	25	2.9(2.9)	3, 4, 7
HD 112127	K2	4340	2.10	+0.25	2.7	22	1.5(1.5)	3, 4, 7, 10
HD 120602	K0	5000	3.0	−0.07	2.0	16	2.8(2.8)	3, 4
HD 148293	K2	4640	2.5	+0.23	2.0	16	2.2(1.7)	2, 3, 4
HD 183492	K0	4700	2.4	+0.08	2.0	9	2.4(2.5)	3, 4

NOTE.—The Li abundances in parenthesis are non-LTE values. The mass values are taken from reference (9), those in parenthesis from reference (8), with the exception of star HD 95799.

REFERENCES.—(1) de la Reza & da Silva 1995; (2) McWilliam 1990; (3) Berdyugina & Savanov 1994; (4) de la Reza & Drake 1995; (5) this work; (6) Fekel & Balachandran 1993; (7) Brown et al. 1989; (8) Gratton & D'Antona 1989; (9) Luck 1994; (10) Wallerstein & Sneden 1982.

Charbonnel (1994) concludes that the extra-mixing process is only efficient when the hydrogen-burning shell reaches the discontinuity in molecular weight. Still, according to Charbonnel, the extra-mixing process may be close to the mechanism proposed by Zahn (1992), who considers an interaction between meridional circulation and turbulence, induced by rotation. Other information given in Gilroy & Brown (1991) and Charbonnel (1994) is that post–He flash stars do not show modified $^{12}C/^{13}C$ ratios relative to pre–He flash.

4.1. *Data for* Li-*rich giants*

As pointed out by Gilroy (1989) and Charbonnel 1994), it is important to know the star's mass to understand the behavior of $^{12}C/^{13}C$. For this reason special care was taken to choose the masses of the Li-rich K giants discussed below and listed in Table 2. In this table, with other data, we present ϵ(Li), $^{12}C/^{13}C$ ratios, and masses of our three program stars and some other Li-rich K giants, taken from the literature. We selected all giants with LTE $\epsilon(\mathrm{Li}) \geq 2.0$, and we measured $^{12}C/^{13}C$ ratios for those with $\epsilon(\mathrm{Li}) \geq 3.0$. The masses were derived by de la Reza & Drake (1995) plotting the stars on the log T_{eff} versus log $L/L_\odot$ solar metallicity evolutionary tracks published by Maeder & Meynet (1988). L and T_{eff} values are adopted from the literature. Note that the mass now derived for HD 19745 is considerably higher than the value given by de la Reza & da Silva (1995). The derived masses are compatible with the literature estimations. The mass of HD 95799 should be in error; the published mass of 2.7 $M_\odot$ is the turnoff mass of the cluster NGC 3532; however, the star is located nearby this cluster but is not a member.

Figure 3 shows a plot of the $^{12}C/^{13}C$ ratio as a function of mass, in solar units, for the stars of Table 2 together with the stars studied by Gilroy (1989). In terms of $^{12}C/^{13}C$, it appears that the Li-rich giants behave in a similar way to Gilroy's sample. Therefore, as pointed out by Gilroy, an extra-mixing mechanism is required to explain the lower values of $^{12}C/^{13}C$ relative to the standard theory. Nevertheless, the stars HD 19745, HD 95799, HD 120602, with $M/M_\odot > 2.2$, show low $^{12}C/^{13}C$, in contrast with Gilroy's massive stars.

In Figure 4 are plotted $^{12}C/^{13}C$ ratios versus ϵ(Li). No clear correlation is found, but the very Li-rich stars (log $\epsilon(\mathrm{Li}) > 2.8$) show low $^{12}C/^{13}C$. As low $^{12}C/^{13}C$ means that mixing was very effective, the high Li abundances found for the stars of Table 2 are even more unexpected.

5. DISCUSSION

In the case of normal M giants, Wallerstein & Morell (1994) showed that the relatively constant value $^{12}C/^{13}C = 11.8 \pm 3.8$ for an ensemble of 23 M giants (by grouping their eight sample stars together with 15 stars measured by Smith & Lambert 1990 and Luck & Lambert 1982 is not correlated with their normal (low) Li abundances. Those authors suggest that a Li enrichment (in this case, a modest one) could be due to a superficial mixture process, not sufficiently deep to modify the $^{12}C/^{13}C$ ratio.

For normal K giants, the isotopic ratio is not constant, ranging from 30 to 4 (Gilroy 1989). On the other hand, the range of Li abundances, including the richest stars, is much larger than the three orders of magnitude of M giants.

First of all, any discussion relating $^{12}C/^{13}C$ with a Li enrichment mechanism is difficult, since such a mechanism is not known. Only for giants with masses $4 < M/M_\odot < 6$, which have already reached the asymptotic giant branch stage, an efficient mechanism for enrichment in Li was proposed by Sackmann & Boothroyd (1992). This is based on the transport of internal

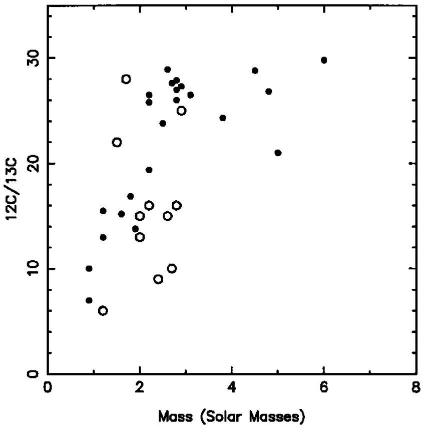

FIG. 3.—$^{12}C/^{13}C$ vs. stellar mass for the Li-rich giants of Table 3 (*open circles*) and cluster's giants of Gilroy (1989) (*filled circles*).

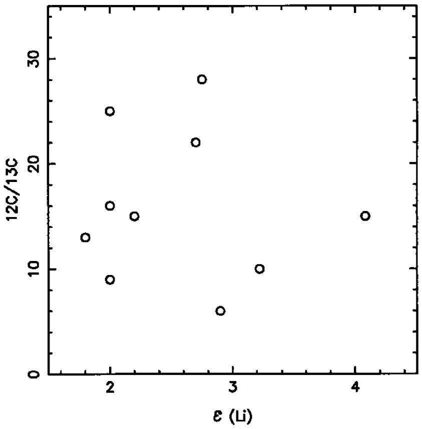

FIG. 4.—$^{12}C/^{13}C$ vs. ϵ(Li) for the Li-rich giants of Table 3.

^7Be, produced from ^3He (Cameron & Fowler 1971) and transported to the surface by successive He flashes through convective diffusion.

Nevertheless, with the data obtained, we can try here to examine the conditions or constraints for that enrichment. Several authors have discussed the different Li enrichment mechanisms (Gratton & D'Antona 1989; Brown et al. 1989; Fekel & Balachandran 1993; de la Reza & da Silva 1995), which can be summarized as follows: (1) external contamination, (2) preservation of the original Li content, and (3) internal fresh Li production by the ^7Be mechanism.

In any case, taking into account that the very Li-rich K giants are only 1% to 2% of K giant stars, we can consider that the Li-rich giant phenomenon should correspond to a short phase of stellar evolution. Now, how is this mechanism related to $^{12}C/^{13}C$ ratios?

Lambert, Dominy, & Sivertsen (1980) carried out the first study trying to relate ϵ(Li) and $^{12}C/^{13}C$ ratios. In a sample of 47 G and K giants showing essentially normal Li abundances, those authors found a correlation between the two quantities—giants with a low $^{12}C/^{13}C < 15$ showed low Li abundances—indicating that, for that sample of stars, convective mixing brings CN cycle fresh ^{13}C to the surface and transports Li to deeper zones, where it is destroyed.

For the present sample, such correlation is not seen: the most Li-rich stars HD 19745, HD 39853, and HD 95799 have very low $^{12}C/^{13}C$ ratios. Note, however, that HD 39853 shows the lowest mass and metallicity, in which case lower $^{12}C/^{13}C$ ratios are expected (§ 4.1), and that the mass values of HD 19745 and HD 95799 are very uncertain.

On the other hand, it has been found that Li-rich K giants seem to be related to variable mass-loss phenomena by de la Reza & Drake (1995). In fact, Gregorio-Hetem, Castilho, & Barbuy (1993) have shown the very different behavior of Li-rich giants with respect to ordinary K giants in their *IRAS* colors, connected to dust shells. But, interestingly, a few Li-rich giants, like HD 39853, present no dust shell. This apparently paradoxical situation can be interpreted in a scenario in which dust shells are ejected in episodic mass-loss events.

In conclusion, the values of $^{12}C/^{13}C$ for Li-rich giants indicate, at least for those having the highest Li abundances, that an extra mixing mechanism has lowered their $^{12}C/^{13}C$ ratios. It might be concluded, since convective mixing is expected to destroy Li (Iben 1967a, b), that some mechanism producing fresh Li occurs.

6. CONCLUSIONS

We have shown that an extra-mixing relative to first dredge-up predictions has occurred in the most Li-rich K giants. Since such mixing processes are expected to destroy the original surface Li, this reinforces the idea that an efficient Li producing mechanism is acting in these stars. Several questions remain open, however. Which is this mechanism? If it is the ^7Be mechanism, can it work for these low-mass stars? How is this mechanism related to a variable mass loss and dust envelopes?

To make further progress in this subject, it would be desirable to derive more accurate masses for these stars.

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