

## HD 77361: A NEW CASE OF SUPER LI-RICH K GIANT WITH ANOMALOUS LOW $^{12}\text{C}/^{13}\text{C}$ RATIO

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Received 2009 July 20; accepted 2009 August 18; published 2009 September 1

### ABSTRACT

Results from high-resolution spectroscopic analysis of HD 77361 are reported. LTE analysis shows that HD 77361 is a K giant of atmospheric parameters:  $T_{\text{eff}} = 4580 \pm 75$  K,  $\log g = 2.5 \pm 0.1$ , and  $\xi_t = 1.40 \pm 0.5$  km s $^{-1}$ . We found that the atmosphere of HD 77361 is highly enriched in Li with  $\log \epsilon(\text{Li}) = 3.82 \pm 0.1$ . With this finding the total number of super Li-rich K giants ( $\log \epsilon(\text{Li}) \geq 3.3$  ISM value) known to date reached six. Contrary to first dredge-up, extra-deep mixing and the associated cool bottom processing, and other recent predictions for K giants on the red giant branch (RGB) luminosity bump phase, HD 77361 shows a very low value of  $^{12}\text{C}/^{13}\text{C} = 4.3 \pm 0.5$ , having, simultaneously, very large amount of Li. Also, HD 77361 is the only Population I low-luminosity ( $\log L/L_{\odot} = 1.66 \pm 0.1$ ) low-mass K giant ( $M = 1.5 \pm 0.2 M_{\odot}$ ) among the known super Li-rich K giants that has a very low  $^{12}\text{C}/^{13}\text{C}$  ratio. Results of HD 77361 further constrain our theoretical understanding of Li enhancement in the atmospheres of RGB stars.

*Key words:* stars: abundances – stars: evolution – stars: individual (HD 77361) – stars: late-type

### 1. INTRODUCTION

Stellar evolutionary models predict significant depletion of Li in the atmospheres of evolved stars in which the convection layer reaches much deeper regions where temperatures are such that Li is destroyed. Standard first dredge-up stellar models predict Li reductions by 1–2 mag in the low-mass stars ( $\leq 2.5 M_{\odot}$ ) at the end of the first dredge-up (Iben 1967a, 1967b) on the red giant branch (RGB) phase from the main-sequence maximum value of about  $\log \epsilon(\text{Li}) = 3.3$  (e.g., Lambert & Reddy 2004). The maximum amount of Li one would expect, depending on mass, metallicity, and the amount of Li on the main sequence, for a low-mass K giant is  $\log \epsilon(\text{Li}) < 1.5$  dex (Iben 1967a, 1967b). In fact, observations showed that most of the K giants of Pop I have much lower Li values (Brown et al. 1989; Mallik 1999) compared to the predictions suggesting significant depletion of Li during its pre-main-sequence and main-sequence phases, and to some extent, due to non-standard mixing (Charbonnel 1995). The consensus among the investigators of Li in RGB stars is that a K giant with  $\log \epsilon(\text{Li}) \geq 1.5$  can be termed Li-rich. A giant with  $\log \epsilon(\text{Li}) \geq 3.3$  (ISM value) may be termed super Li-rich.

Observations from different surveys reveal that Li-rich stars are very rare, and consist of just 1% of K giants (Brown et al. 1989) in the Galactic disk. Further, super Li-rich K giants are much more rare, and as of now there are just six (de La Reza et al. 1995; Balachandran et al. 2000; Drake et al. 2002; Reddy & Lambert 2005), including the one being studied here. To understand the distribution of Li-rich stars in terms of their mass and luminosity, Charbonnel & Balachandran (2000) located all the known Li-rich stars on the Hertzsprung–Russell (H–R) diagram, thanks to the accurate parallaxes from *Hipparcos* mission (Perryman et al. 1997). The study revealed that the ( $M/M_{\odot} \leq 2.0$ ) super Li-rich ( $\log \epsilon(\text{Li}) \geq 3.3$  dex) K giants are confined to a small region on the H–R diagram, the so-called luminosity bump:  $\log L/L_{\odot} = 1.45$ – $1.9$ ;  $\log T_{\text{eff}} = 4450$ – $4600$  K (Girardi et al. 2000). Also, these stars are found to have lower  $^{12}\text{C}/^{13}\text{C}$  ratios than the expected from the standard mixing theory. It is not well understood how the K giants with very deep convective envelope and efficient mixing, as suggested from the measured low values of  $^{12}\text{C}/^{13}\text{C}$ , possessed such high amounts of Li; almost 10 times larger than the ISM value. In the literature,

a different class of super Li-rich stars were reported. They are either massive ( $\geq 4 M_{\odot}$ ) weak *G*-band stars (Lambert & Sawyer 1984) or asymptotic giant branch stars (Smith & Lambert 1989) or low-mass metal-poor giants (Kraft et al. 1999; Monaco & Bonifacio 2008).

Li excess in K giants is one of the most puzzling stellar astrophysical problems to which, in the last two decades, great deal of research has been devoted. The high values of Li in the super Li-rich K giants are thought to be due to stellar nucleosynthesis and some kind of extra mixing (Denissenkov & Weiss 2000; Palacios et al. 2001; Denissenkov & Herwig 2004). At the luminosity bump on the RGB, the hydrogen burning shell passes the  $\mu$ -barrier or the mean molecular weight discontinuity that was created during the first dredge-up. This allows mixing between the cool outer layers and the hotter inner regions. This so-called extra-mixing theory associated with cool bottom processing was invoked for Li enhancement. For low-mass stars of solar metallicity at the luminosity bump, theoretical models (e.g., Denissenkov & Herwig 2004) are constructed to match the observed peak Li abundance of  $\log \epsilon(\text{Li}) \geq 3$  and low  $^{12}\text{C}/^{13}\text{C} \approx 15$ – $28$ . The theoretical results are, in general, in agreement with the observed values of super Li-rich K giants (Charbonnel & Balachandran 2000 and references there in). As star evolves from the bump region and moves up toward the tip of the RGB, Li drops sharply with the  $^{12}\text{C}/^{13}\text{C}$  ratio (Lambert et al. 1980).

HD 77361 is a bright field star of  $mv = 6.21$  with color  $B - V = 1.13$ . It is classified as a K1 III CN star (Houk 1982). This is one of the candidate K giants in our sample of 1800 stars that are selected from the *Hipparcos* catalog (van Leeuwen 2007) for a systematic search of Li-rich K giants. The Li-richness of the star is identified from the low-resolution spectra and later confirmed by obtaining series of high-resolution spectra. Full details of the survey and results are presented elsewhere. We note that for HD 77361, no previous spectroscopic analysis of either low- or high-resolution spectra is available. Results of very high Li abundance and the anomalously very low values of  $^{12}\text{C}/^{13}\text{C}$  ratios are quite puzzling given the low luminosity of HD 77361 and its location at the RGB bump region. This finding may further challenge the theoretical understanding of the stellar structure and mixing mechanism during the RGB phase.

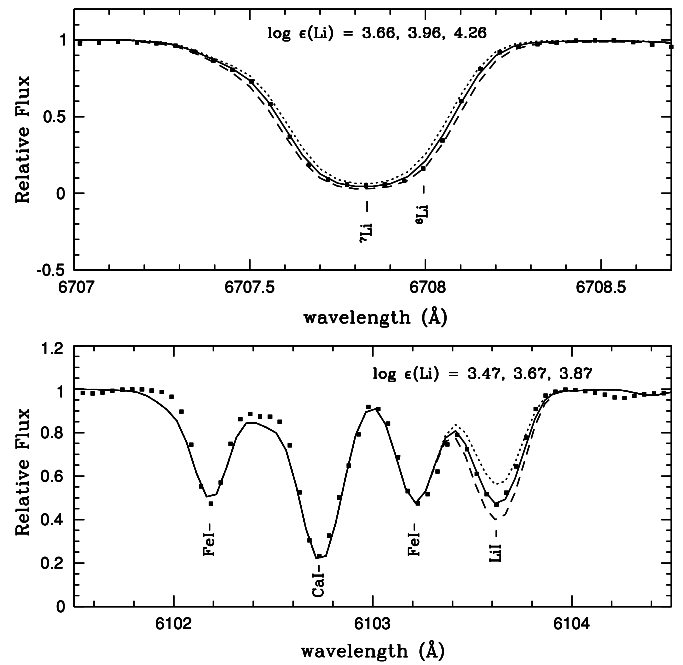
## 2. OBSERVATIONS

High-quality low-resolution spectra were obtained using the medium resolution Zeiss Universal Astro Grating Spectrograph (UAGS) and 1 K  $\times$  1 K TEK CCD mounted on the 1 m Carl Zeiss Telescope at Vain Bappu observatory, Kavalur. Followed by the detection of a very strong Li resonance line at 6707 Å in the low-resolution ( $R = \lambda/\delta\lambda = 6000$ ) spectrum of HD 77361, high-resolution spectra were collected from the 2.3 m Vainu Bappu Telescope (VBT) equipped with a fiber-fed coude echelle spectrograph (Rao et al. 2005) and 2 K  $\times$  4 K CCD. The final spectral resolution as measured from the arc spectrum is  $R \approx 60,000$ . Most of the spectra observed with VBT were under poor weather conditions, and hence of relatively poor quality ( $S/N \approx 100$ ) given the brightness of the star ( $m_v = 6.21$ ). Also, one set of high-quality ( $S/N \approx 500$ ) echelle spectra with resolution  $R \approx 55,000$  was obtained from the cross-dispersed echelle spectrometer mounted on the Harlan J Smith 2.7 m Telescope at McDonald Observatory. A standard Echelle reduction procedure was adopted using IRAF software.

## 3. ANALYSIS AND RESULTS

Local thermodynamic equilibrium (LTE) stellar model atmospheres computed by R. L. Kurucz<sup>1</sup> in 1994 with convection option on, and the revised radiative transfer code MOOG originally written by Sneden (1973), were adopted for the analysis. The standard procedure of requiring the same abundances from the neutral lines of different low excitation potentials was used for  $T_{\text{eff}}$  determination. Forty well separated and moderate strength ( $W_\lambda \leq 100 \text{ m}\text{\AA}$ ) Fe I and eight Fe II lines (Allende Prieto et al. 2002; Reddy et al. 2003) with accurate  $gf$ -values were used in the analysis. The spectroscopically derived  $T_{\text{eff}} = 4580 \pm 75 \text{ K}$  was found to be in good agreement with the photometric values, 4550 K ( $B - V$ ) and 4587 K ( $V - K$ ), which were determined using the Alonso et al. (1999) calibrations. The accurate parallaxes combined with the evolutionary tracks (Girardi et al. 2000) were used to determine the value of surface gravity of  $\log g = 2.5 \pm 0.1$ . This is consistent with the  $\log g$  value obtained by forcing Fe I and Fe II lines to yield the same abundance for a given  $T_{\text{eff}}$  but for varying  $\log g$  values. The value of microturbulence  $\xi_t = 1.4 \pm 0.5 \text{ km s}^{-1}$  was extracted by requiring to have the same abundance for a set of Fe I lines of different  $W_\lambda$ . The metallicity,  $[\text{Fe}/\text{H}] = -0.02 \pm 0.1$ , was determined from the mean abundance of Fe I and Fe II relative to the Sun (Lodders 2003). Radial velocity measurements made over a period of 20 days do not suggest variation in the velocity. The mean radial velocity relative to helio centric velocity was found to be  $R_v = -23.20 \pm 0.5 \text{ km s}^{-1}$ .

Abundances of Li, CNO elements, and  $^{12}\text{C}/^{13}\text{C}$  ratios were derived by matching the observed spectrum with that of the computed spectrum. The well tested line list (Reddy et al. 2002) in the region of Li resonance line 6707.8 Å was adopted. Hyperfine structure and the  $gf$  values of  $^7\text{Li}$  components of Li line at 6707.8 Å were taken from Hobbs et al. (1999). The computed spectrum was convolved with estimated values of microturbulence of  $1.4 \text{ km s}^{-1}$ , macroturbulence of  $3 \text{ km s}^{-1}$ , and rotational velocity of  $3 \text{ km s}^{-1}$ . A value of  $\log \epsilon(\text{Li}) = 3.96$  dex was obtained from the resonance line (Figure 1) assuming pure  $^7\text{Li}$  abundance. The Li line at 6103.6 Å, normally weak in the intermediate Li rich stars, is very strong ( $W_\lambda = 151 \text{ m}\text{\AA}$ ) in the spectrum of HD 77361. The compiled



**Figure 1.** Comparison of observed spectrum with the spectrum computed using the LTE model atmospheres in the wavelength region of the Li resonance line at 6707.8 Å and the excited line at 6103.6 Å.

line list from Kurucz's line database was used for computing the spectrum in the vicinity of the Li excited line at 6103.6 Å. For a Li abundance of  $\log \epsilon(\text{Li}) = 3.67$  dex, the synthetic spectrum matches well with the observed spectrum (Figure 1). The significant difference between the abundances of Li lines at 6707 Å and 6103 Å is due to severe non-LTE effects ( $\Delta(\text{LTE} - \text{NLTE}) = 0.16$  dex for the 6707 line and  $-0.16$  dex for the 6103 line) acting in the opposite directions (Carlsson et al. 1994; Lind et al. 2009). The LTE abundances, and the abundances after correcting NLTE effects, are given in Table 1. Corrected values of Li from the two lines agree very well (Table 1). A Li abundance of  $\log \epsilon(\text{Li}) = 3.82$  for HD 77361 is the straight mean of Li abundances, after non-LTE corrections, from the two Li lines at 6103 Å and 6707 Å. The same analysis is duplicated for the comparison star HD 19745, and the results obtained are consistent with the previous studies (Reddy & Lambert 2005).

The  $^{12}\text{C}/^{13}\text{C}$  ratio is proved to be a very sensitive parameter of the stellar mixing process. Measuring the  $^{12}\text{C}/^{13}\text{C}$  ratio along with the Li abundance has an obvious advantage in understanding the RGB mixing process. As shown in Figure 2, the  $^{13}\text{C}^{14}\text{N}$  lines at 8004.6 Å together with a few  $^{12}\text{C}^{14}\text{N}$  lines in the same region were used for deducing the  $^{12}\text{C}/^{13}\text{C}$  ratio. The abundance of carbon isotope  $^{12}\text{C}$  was derived by matching the observed spectrum with that of the computed spectrum of the C I line at 5380 Å and C<sub>2</sub> Swan system features at 5086 Å and 5135 Å. The mean abundance of the three lines  $\log \epsilon = 8.45 \pm 0.05$  was used to determine the N abundance from CN lines in the 8003 Å region. The oxygen abundance was determined from the two forbidden lines at 6300 Å and 6363 Å. The line list and the procedure adopted are very similar to those used in our earlier studies (Reddy & Lambert 2005). Abundances of CNO and  $^{12}\text{C}/^{13}\text{C}$  ratio are given in Table 1. The quoted errors in the abundances are the quadratic sum of uncertainties due to the uncertainties in the model parameters.

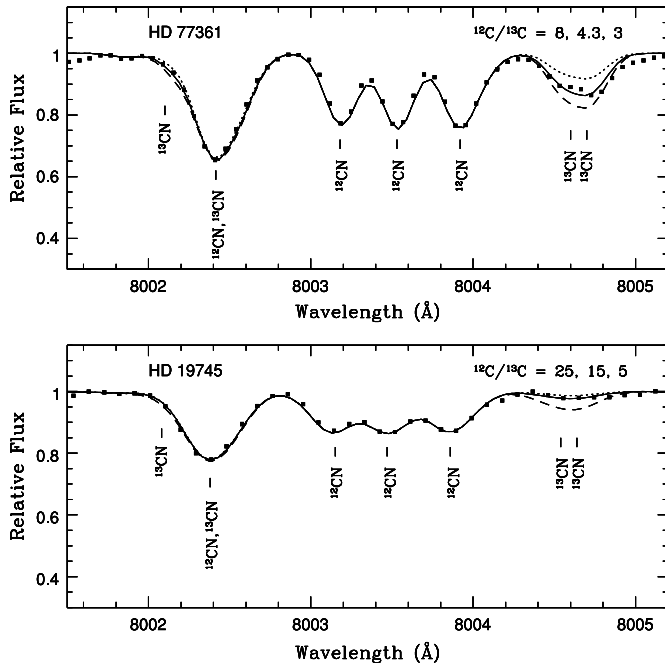
Accurate *Hipparcos* parallaxes ( $\pi = 9.25 \pm 0.43$  mas) are available for HD 77361 (van Leeuwen 2007). Mass ( $1.5 M_\odot$ )

<sup>1</sup> <http://kurucz.harvard.edu/>

**Table 1**  
Abundances of Li and CNO Elements for HD 77361 and HD 19745

Star	[Fe/H] <sup>a</sup>	[C/Fe] <sup>a</sup>	[N/Fe] <sup>a</sup>	[O/Fe] <sup>a</sup>	log $\epsilon(\text{Li})_{\text{LTE}}$		log $\epsilon(\text{Li})_{\text{NLTE}}$	$^{12}\text{C}/^{13}\text{C}$
					Li 6103 Å	Li 6707 Å		
HD 77361	-0.02 ± 0.1	0.01	0.076	0.039	3.67 ± 0.10	3.96 ± 0.14	3.82	4.3 ± 0.5
HD 19745	-0.05 ± 0.1	0.00	0.047	0.017	3.91 ± 0.12	3.69 ± 0.27	3.77	15 ± 2

**Note.** <sup>a</sup> Adopted solar values are recommended abundances from Lodders (2003).



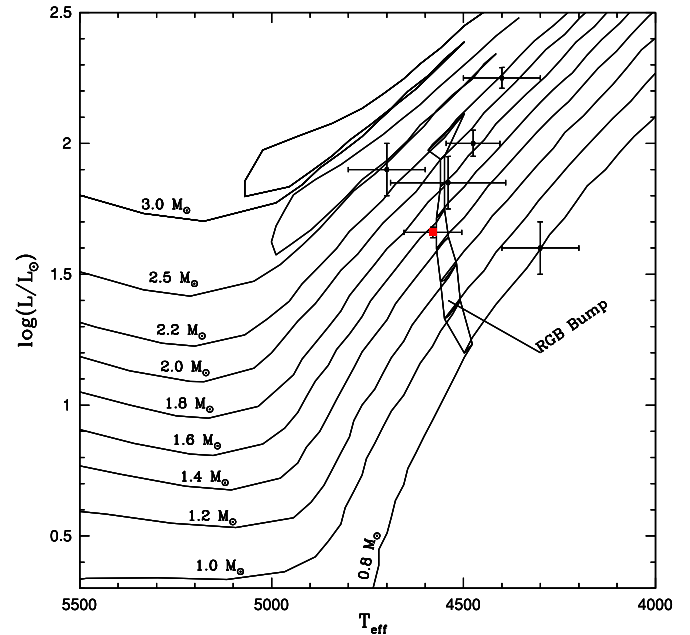
**Figure 2.** Comparison of synthetic and observed spectra for HD 77361 and the template star HD 19745 in the wavelength region of 8000 Å. The ratio of  $^{12}\text{C}/^{13}\text{C}$  is derived using the  $^{13}\text{C}^{14}\text{N}$  lines at 8004.6 Å.

and luminosity ( $\log L/L_{\odot} = 1.66$ ) were obtained combining the parallax information with photometry and evolutionary tracks (Girardi et al. 2000) of solar metallicity. Four stars in the table lack parallax information for which values of mass and luminosity were derived by combining spectroscopy and photometric information (Balachandran et al. 2000; Drake et al. 2002; Reddy & Lambert 2005). HD 77361, along with the known super Li-rich stars, is shown in the H–R diagram (Figure 3). All the six K giants occupy the region just around the RGB luminosity bump which is marked in Figure 3.

#### 4. DISCUSSION

Results of five super Li-rich K giants are given along with HD 77361 in Table 2. Values of other stars are taken from the literature. For the most Li-rich K giant HD 233517, unfortunately, the  $^{12}\text{C}/^{13}\text{C}$  ratio is not available, probably due to its very high rotation of  $v \sin i = 17 \text{ km s}^{-1}$ . Generally, the  $^{13}\text{C}^{14}\text{N}$  lines at 8004.6 Å, often used for the carbon isotopic ratio, is weak and gets smeared out in the spectra of high-rotation stars.

It is clear from Table 2 that HD 77361 is a super Li-rich, and the third most Li-rich, K giant amongst the six super Li-rich K giants known so far. The derived luminosity ( $\log L/L_{\odot} = 1.66$ ) and  $T_{\text{eff}} = 4580 \text{ K}$  place HD 77361 at the RGB luminosity bump. The most striking from the results shown in Table 2 is the very low  $^{12}\text{C}/^{13}\text{C}$  ratio of HD 77361. The other super Li-rich stars have significantly higher values of  $^{12}\text{C}/^{13}\text{C}$  ratios.



**Figure 3.** Location of super Li-rich K giants in the H–R diagram. Evolutionary tracks of solar metallicity of masses 0.8–3  $M_{\odot}$  are plotted. HD 77361 (red square) and the RGB luminosity bump region are marked.

It is puzzling that HD 77361 has a  $^{12}\text{C}/^{13}\text{C}$  ratio that is close to the CN equilibrium value, but continues to have a peak value of Li on its surface. Another important point to be noticed is the location of super Li-rich stars. All are very close to the expected luminosity bump region for a given stellar mass. Results of HD 77361 strengthen the argument that the changes to the stellar structure of low-mass stars at the bump region are the main cause for the sudden reduction in the  $^{12}\text{C}/^{13}\text{C}$  ratio, and the enhancement of Li on the surface of RGB stars.

It is known that at the RGB bump the hydrogen burning shell moves past the so-called  $\mu$ -barrier. In the absence of the  $\mu$ -barrier, the convective zone reaches a much deeper level dredging up the hydrogen burning products to the surface altering abundances of Li, C, N, and  $^{13}\text{C}$  much more severely compared to the predictions of the standard first dredge-up scenario. This is known as extra mixing (Sweigart & Mengel 1979; Charbonnel et al. 1998) which is different from the ordinary convective mixing. The extra mixing is invoked to explain the observed, in general, low values of Li and  $^{12}\text{C}/^{13}\text{C}$  ratio at or above the RGB bump (Lambert et al. 1980; Gratton et al. 2000). The exact mechanism for the extra mixing is still an issue to be worked out.

For the Population I stars of low-mass ( $M/M_{\odot} \leq 2.5$ ) theoretical models of extra mixing predict final  $^{12}\text{C}/^{13}\text{C}$  ratios as low as 10 when star evolves to the RGB tip. Boothroyd & Sackmann (1999) demonstrated that deep circulation mixing at the base of convective envelope and the associated cool bottom

**Table 2**

Values of Stellar Parameters (Metallicity,  $T_{\text{eff}}$ , Mass, Luminosity) and the Surface Abundances Values of  $\log \epsilon(\text{Li})$  and Carbon Isotopic Ratios of HD 77361 are Given Along with the Known Super Li-rich K Giants

Star	[Fe/H]	$T_{\text{eff}}$	$M^*/M_{\odot}$	$\log L/L_{\odot}$	$\log \epsilon(\text{Li})$	$^{12}\text{C}/^{13}\text{C}$	Ref.
HD 77361	$-0.02 \pm 0.1$	$4580 \pm 75$	$1.5 \pm 0.2$	$1.66 \pm 0.1$	$3.82 \pm 0.10$	$4.3 \pm 0.5$	This paper
HD 233517	-0.37	$4475 \pm 70$	$1.7 \pm 0.2$	2.0 <sup>a</sup>	$4.22 \pm 0.11$	...	1
IRAS 13539-4153	-0.13	$4300 \pm 100$	$0.8 \pm 0.7$	1.60 <sup>a</sup>	$4.05 \pm 0.15$	20	3
HD 9746	-0.06	$4400 \pm 100$	$1.92 \pm 0.3$	2.02	$3.75 \pm 0.16$	$28 \pm 4$	1
HD 19745	-0.05	$4700 \pm 100$	$2.2 \pm 0.6$	1.90 <sup>a</sup>	$3.70 \pm 0.30$	$16 \pm 2$	3
IRAS 13313-5838	-0.09	$4540 \pm 150$	1.1	1.85 <sup>a</sup>	$3.3 \pm 0.20$	$12 \pm 2$	2

**Note.** <sup>a</sup> *Hipparcos* astrometry is not available and values of luminosities and masses are derived from spectroscopy.

**References.** (1) Balachandran et al. 2000; (2) Drake et al. 2002; (3) Reddy & Lambert 2005.

processing brings down the first dredge-up prediction of  $^{12}\text{C}/^{13}\text{C} \approx 28$  to the lowest final value of 10 closer to the RGB tip for a star of  $1.5 M_{\odot}$  with solar metallicity. Similar results from the recent computations based on enhanced extra mixing triggered by external sources (Denissenkov & Herwig 2004) and mean molecular weight inversion or  $\delta$ -mixing (Eggleton et al. 2008) predicted final values of  $^{12}\text{C}/^{13}\text{C} \approx 10$ –14 for low-mass Pop I stars. However, in all the models, stars at the RGB bump region are expected to have  $^{12}\text{C}/^{13}\text{C}$  ratios at about 15 or more.

Earlier suggestions of planet or dwarf companion merger (Alexander 1967; Brown et al. 1989; Siess & Livio 1999) with the parent stars or addition of Li-rich material from the nearby novae ejections (Gratton et al. 1989) cannot explain the localization of super Li-rich stars on the H–R diagram. If the Li enhancement in the K giant is due to the external sources like planet engulfment or accretion of novae material, it could happen anywhere on the RGB phase. Absence of low-mass super Li-rich giants below or above the RGB bump simply means that Li enhancement is related to changes in the internal stellar structure and the mixing process that are associated with the luminosity bump. Depletion of Li starts once again, from the peak Li abundance at the RGB bump, as stars evolve toward the RGB tip. Observations show, in general, very low Li abundances ( $\log \epsilon(\text{Li}) = -1.0$ – $-1.5$  dex) in K giants between the bump and the RGB tip. As discussed by de La Reza et al. (1997) and calculated by Denissenkov & Herwig (2004) the super Li-rich phase on the RGB seems to be very short (a few million years), and all the low-mass stars, perhaps, experience this phase.

Another suggestion one can infer from the results shown in Table 2 is that the absence of correlation between Li enhancement and the  $^{12}\text{C}/^{13}\text{C}$  ratio. It seems Li enhancement in the K giants at the bump is independent of the  $^{12}\text{C}/^{13}\text{C}$  ratio, and hence longevity or the extent of the deep mixing process. Sackmann & Boothroyd (1999) suggest that Li can be enhanced on the surface as long as fast deep mixing is ensured, and in fact they have predicted high values of Li toward the RGB tip (not at the RGB bump) where  $^{12}\text{C}/^{13}\text{C}$  values are low. On the other hand, Palacios et al. (2001) hypothesized that the surface  $^7\text{Li}$  enhancement is the precursor for the extra mixing. Given the very low value of  $^{12}\text{C}/^{13}\text{C}$  ratio for the HD 77361, one may suggest that erasing the  $\mu$ -barrier, and hence the free mixing of material between the hydrogen burning shell and the bottom of the convective outer layer, seems to be providing a conducive environment for the enhancement of surface Li abundance.

It is understood that Li is produced in the inner layers of the stars through the Cameron & Fowler (1971) mechanism. Sustaining the Li production and dredging up the Li-rich material to outer layers to the observed levels is still an unsolved

problem. For safe transportation of  $^7\text{Be}$  produced in the inner layers via  $^3\text{He}(\alpha, \gamma)^7\text{Be}$  to cooler regions, so that  $^7\text{Li}$  could be produced and mixed up with the photosphere, a few possibilities were explored. Palacios et al. (2001) suggested a Li-flash scenario for high Li-abundance. In this scenario,  $^7\text{Be}$  diffuses outward where Li can be produced via  $^7\text{Be}(e^-, \nu)^7\text{Li}$  and forms the so-called lithium burning shell. Energy release from the destruction of  $^7\text{Li}$  by proton as well as from production of  $^7\text{Li}$  destabilize the Li burning shell leading to a runaway situation. This in turn leads to the enhanced meridional circulation and hence the observed Li enhancements. In this scenario Li enhancement precedes the  $^{12}\text{C}/^{13}\text{C}$  reduction. This explains the localization of super Li-rich K giants at the bump and also the relatively high values of carbon isotopic ratios (Charbonnel & Balachandran 2000). As K giants evolve away from the bump Li starts decreasing with the decreasing  $^{12}\text{C}/^{13}\text{C}$  ratio. A totally different approach was suggested from the computations by Denissenkov & Herwig (2004). An enhanced extra mixing triggered by spinning up of the K giants with the external angular momentum can produce the required mixing coefficients. The source of the external angular momentum could be either the synchronization of K giant's spin with the orbital motion of a close binary or the engulfment of a massive planet. This mechanism will enhance K giant's angular momentum by 10-fold, and explains the high rotation velocity observed in some of the Li-rich K giants. But, as stated earlier, it fails to explain the presence of all the six super Li-rich at the bump and the absence of super Li-rich stars anywhere along the RGB path. In all of these models, a Li peak was achieved when the  $^{12}\text{C}/^{13}\text{C}$  ratios are around 15–28 which are in general agreement with the five of the six super Li-rich stars shown in Table 2.

The exception being the results of HD 77361 presented in this paper. It is the only bump K giant that has a very low  $^{12}\text{C}/^{13}\text{C}$  ratio and still continuous to have peak Li abundance. This result may put further constraints on the RGB models. The peak Li abundance ( $\log \epsilon(\text{Li}) = 3.82$  dex) on the surface and the lowest  $^{12}\text{C}/^{13}\text{C} = 4.3$  of HD 77361 suggest whether the removal of the  $\mu$ -barrier and hence the free deep mixing is essential for Li enhancement. To understand the exact mechanism that is responsible for the observed Li enhancements on the K giants, it is worthwhile to make a systematic survey of low-mass ( $M \leq 2.5 M_{\odot}$ ) K giants all the way from the start of first dredge-up to the tip of the RGB.

We are grateful to David Lambert for obtaining the high-quality spectrum for HD 77361. We also thank the VBO observatory staff for their help during the observations.



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