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ORIGIN OF LITHIUM ENRICHMENT IN K GIANTS

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ABSTRACT

In this Letter, we report on a low-resolution spectroscopic survey for Li-rich K giants among 2000 low-mass ($M \leqslant 3\ M_{\odot}$) giants spanning the luminosity range from below to above the luminosity of the clump. Fifteen new Li-rich giants including four super Li-rich K giants ($\log \epsilon(\mathrm{Li}) \geqslant 3.2$) were discovered. A significant finding is that there is a concentration of Li-rich K giants at the luminosity of the clump or red horizontal branch. This new finding is partly a consequence of the fact that our low-resolution survey is the first large survey to include giants well below and above the red giant branch (RGB) bump and clump locations in the H-R diagram. Origin of the lithium enrichment may be plausibly attributed to the conversion of ^{3}He via ^{7}Be to ^{7}Li by the Cameron–Fowler mechanism but the location for the onset of the conversion is uncertain. Two possible opportunities to effect this conversion are discussed: the bump in the first ascent of the RGB and the He-core flash at the tip of the RGB. The finite luminosity spread of the Li-rich giants serves to reject the idea that Li enhancement is, in general, a consequence of a giant swallowing a large planet.

Key words: stars: abundances – stars: atmospheres – stars: evolution – stars: late-type – stars: low-mass

Online-only material: color figure

1. INTRODUCTION

Lithium is readily destroyed within a main-sequence star and may survive only in a very thin surface layer provided that mixing between this layer and the interior does not occur. Surviving surface Li is greatly diluted as a star evolves to become a red giant because an extensive convective envelope develops. Standard stellar evolutionary models predict Li dilution by a factor of about 60 for low-mass solar-metallicity stars (Iben 1967a, 1967b). Thus, a star of approximately solar metallicity with an initial (say, meteoritic) Li abundance of $\log \epsilon(\mathrm{Li}) \simeq 3.2$ is predicted to have an Li abundance of 1.5 on the red giant branch (RGB). In general, observations of Li abundances in K giants confirm these predictions in the sense that the predicted Li abundance is the upper limit to observed Li abundances except for extremely rare cases exhibiting a higher Li abundance. For many RGB stars, Li is less than the predicted (Brown et al. 1989; Mallik 1999), and this is likely due to a combination of enhanced destruction of Li by mixing within a giant's main-sequence progenitor and continued destruction of Li in a giant.

This comfortable picture of destruction and dilution was demonstrated to be incomplete by the serendipitous discovery of an unusually large amount of Li in a K giant (Wallerstein & Sneden 1982). Since then a few more Li-rich K giants of solar metallicity have been discovered including examples with Li abundances at or even exceeding the expected maximum Li abundance of main-sequence stars. The first systematic search for Li-rich K giants (Brown et al. 1989) demonstrated the rarity of Li-rich giants, just about 1%, in the solar neighborhood.

In this Letter, we present results from a large survey of K giants designed to find additional Li-rich examples, locate their appearance in the H-R diagram, and so provide essential material for testing hypotheses about Li-enrichment. For example, Li production may be associated with the bump in the luminosity function for stars on the RGB as suggested from observations by Charbonnel & Balachandran (2000). Depending on mass and composition the bump occurs on RGB between luminosities, $\log(L/L_{\odot}) = 1.5$–2.2, and this has been predicted (Iben 1968) as a region where evolution of a giant is slowed down, creating a bump in the luminosity function of stars along the RGB. Internally, the bump is associated with the H-burning shell crossing over of H-discontinuity. Additionally or alternatively, the He-core flash may be the trigger for Li production and the creation of Li-rich red clump (horizontal branch) stars. Discrimination between bump and clump is possible because the two groups appear in somewhat different places in the H-R diagram. Our 2000 giants provide a reference sample comfortably spanning the luminosity of the clump and the bump. Also, the survey designed to test the suggestion of planet engulfment scenario by including giants from the base of RGB all the way to well above the clump/bump luminosities. With Brown et al.'s survey, a total of 2644 giants covering a wide range of luminosities and effective temperatures represent a potent database in which to search for clues to the origin of the Li enrichment in K giants.

This Letter is restricted to discussing the location of the Li-rich stars in the H-R diagram. Full details of the survey will be provided in a subsequent publication.

2. SAMPLE SELECTION AND OBSERVATIONS

K giants with accurate astrometry (parallaxes and proper motions) were chosen from the *Hipparcos* catalog (Perryman et al. 1997; van Leeuwen 2007) to span the luminosity bump on the RGB. Stars were selected according to their $(B - V)$ color such that stars were confined to the mass range of 0.8–3.0 $M_{\odot}$. Filters were applied to select nearby ($d \leqslant 150$ pc) bright ($m_V \leqslant 8$) stars within the declination range of $-60^{\circ} \geqslant \delta \leqslant 80^{\circ}$. These criteria resulted in a total of 2000 K giants. All of which were observed at low spectral resolution ($R = \lambda/\delta\lambda \leqslant 3500$) at one of three telescopes: the 2 m Himalayan *Chandra* Telescope with the faint object spectrograph camera at the Indian Astronomical Observatory, Hanle; the 1 m Zeiss

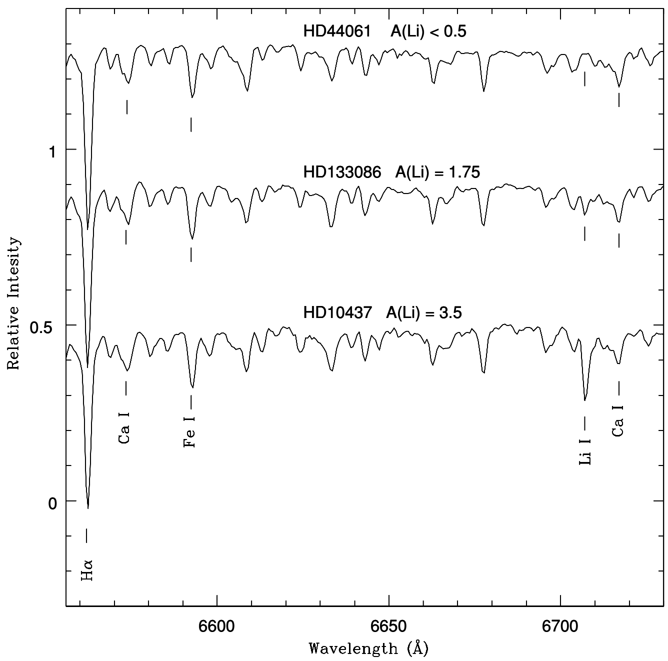

Figure 1. Sample low-resolution spectra of three K giants. The Li line at 6707 Å and Ca at 6717 Å which are used in the calibration are shown.

telescope fitted with the universal astro-grating spectrograph; and the 2.34 m Vainu Bappu Telescope (VBT) fitted with the optometrics medium-resolution spectrograph at the Bappu Observatory (VBO), Kavalur.

Sample low-resolution spectra showing Li and Ca features are shown in Figure 1. The K giants with a moderate to strong Li doublet at 6707.7 Å were identified and pursued at high-resolution ($R = 60{,}000$) spectroscopy with the 2.34 m VBT equipped with the echelle spectrograph (Rao et al. 2005) and/or with the 2.7 m Harlan J. Smith telescope with Robert G. Tull coudé echelle spectrometer (Tull et al. 1995) at the McDonald Observatory. The raw data were processed under standard tasks in the IRAF package.[3]

The parameters luminosity and effective temperature are obtained in identical fashion for the stars in our and Brown et al.'s survey. Luminosities are obtained using parallaxes from the *Hipparcos* catalog and the magnitudes (m_V) taken from the SIMBAD database. Effective temperatures ($T_{\rm eff}$) are derived using the $(B-V)$ color and the calibration given in Alonso et al. (1999). Since sample stars are nearby, the effects of interstellar extinction are not taken into account. However, we note that by neglecting reddening we would have underestimated $T_{\rm eff}$ by about 50–100 K considering canonical reddening of about $E(B-V) \approx 0.03$–0.05 for giants of distances of 100–200 pc. Neglecting reddening will not affect the $T_{\rm eff}$ of Li-rich K giants because these temperatures were derived using iron lines in the high-resolution spectra. The temperatures derived from high-resolution spectra are in good agreement (within ±100 K) with the values derived for the same stars using the $(B-V)$ color and the Alonso et al. (1999) calibration.

3. LITHIUM ABUNDANCES

Lithium abundances of the stars observed at low resolution were estimated from the strength of the Li I 6707.7 Å doublet relative to that of the Ca I line at 6717.6 Å. An empirical relation between the line-depth ratio of Li and Ca lines and the Li abundance was derived from known Li-rich K giants with Li abundances from high-resolution spectra. Fifteen K giants in our survey were estimated to be Li-rich on the basis of the low-resolution spectra. Accurate abundances for these stars were then obtained from high-resolution spectroscopic analysis (Table 1). Previously known Li-rich giants of which several were reobserved and reanalyzed are listed in Table 2. Our survey confirms the earlier survey (Brown et al. 1989) that the Li-rich K giants are rare.

Table 1
Derived Results of the New Li-rich K Giants

Star	$\log(L/L_\odot)$	$T_{\rm eff}$	$\log g$	[Fe/H]	$\log\epsilon$(Li) LTE	$\log\epsilon$(Li) NLTE	^{12}C/^{13}C
HD 8676	1.68	4860	2.95	0.02	3.86	3.55	5.0
HD 10437	1.77	4830	2.85	0.10	3.76	3.48	5.0
HD 12203	1.69	4870	2.65	−0.27	2.01	2.08	7.5
HD 37719	1.76	4650	2.40	0.09	2.70	2.71	...
HD 40168	2.10	4800	2.50	0.10	1.49	1.70	...
HD 51367	1.59	4650	2.55	0.20	2.58	2.60	8.5
HD 77361	1.66	4580	2.35	−0.02	3.96	3.80	4.3
HD 88476	1.87	5100	3.10	−0.10	2.12	2.21	9.0
HD 107484	1.78	4640	2.50	0.18	2.04	2.14	12.5
HD 118319	1.68	4700	2.20	−0.25	1.88	2.02	...
HD 133086	1.70	4940	2.98	0.02	2.03	2.14	7.0
HD 145457	1.61	4850	2.75	−0.08	2.49	2.49	10.0
HD 150902	1.83	4690	2.55	0.09	2.64	2.65	5.0
HD 167304	1.93	4860	2.95	0.18	2.95	2.85	7.5
HD 170527	1.69	4810	2.85	−0.10	3.31	3.12	...

Tables 1 and 2 give the atmospheric parameters ($T_{\rm eff}$, $\log g$, and [Fe/H]) derived from iron lines in the high-resolution spectra. A majority of the entries for Table 2 are taken from the papers reporting the Li abundances. The LTE and Non-LTE Li abundances are tabulated where the latter are based on the recipe given in Lind et al. (2009). In the tables, we also present ^{12}C/^{13}C values for the Li-rich K giants. The values of ^{12}C/^{13}C measurements are based on molecular lines in the 8003 Å region using a similar procedure to that described in Kumar & Reddy (2009). For a few giants carbon ratios could not be determined owing to their large rotation and as a result broad spectral features.

4. THE HERTZSPRUNG–RUSSELL DIAGRAM

Giants from our and Brown et al.'s surveys are shown on the H-R diagram in Figure 2 along with evolutionary tracks (Bertelli et al. 2008) computed for solar metallicity, [Fe/H] = 0.0, and stellar masses ranging from 0.8 $M_\odot$ to 3 $M_\odot$. All stars observed only at low resolution are assumed to have a solar metallicity. For Li-rich K giants actual metallicities measured from the high-resolution spectra are adopted and most are close to solar values. Errors derived from the quoted uncertainties in the parallaxes and in the derivation of temperatures for the Li-rich K giants are marked in Figure 2.

All but a very few stars in the two samples have evolved beyond the base of the RGB (the red dashed line in Figure 2) and, therefore, their surface Li abundance has been greatly diluted. In panel (a) of Figure 2, there is the expected concentration of stars with luminosities of about log ≃ 1.7. This population in the H-R diagram in the main is red clump (horizontal branch) He-core burning stars that have evolved from the tip of the

[3] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 2
Atmospheric Parameters, Li Abundance, and Carbon Isotopic Ratios of the Known Li-rich Giants

Star	$\log(L/L_\odot)$	$T_{\rm eff}$	$\log g$	[Fe/H]	$\log\epsilon$(Li) LTE	$\log\epsilon$(Li) NLTE	^{12}C/^{13}C	Ref.
HD 787	2.65[a]	4181	1.5	0.07	1.80	1.99[a]	9	B00, Be94
HD 6665	1.37[a]	4700[a]	2.70[a]	0.20[a]	3.03[a]	2.93[a]	...	S00
HD 9746	2.02[a]	4425	2.30	−0.05	3.56[a]	3.44[a]	24	B00
HD 19745	1.90	4700	2.25	−0.05	3.70	3.40	16	R05
HD 21018[b]	2.58[a]	5150	1.96	0.15[a]	3.13[a]	3.06[a]	...	B98
HD 30834	2.81[a]	4200	1.5	−0.17	1.80	1.98[a]	13	B00, Be94
HD 39853	2.75[a]	3900	1.16	−0.30	2.80[a]	2.75[a]	6.0	G89
HD 40827	1.78[a]	4575	1.80	0.10	1.78[a]	2.05[a]	10[a]	B00
HD 63798	1.76[a]	5000	2.50	−0.10	1.86[a]	2.00[a]	8.0[a]	M06
HDE 233517	2.00	4475	2.25	−0.37	4.11[a]	3.95[a]	...	Ba00
HD 90633	1.55[a]	4600	2.30	0.02	1.98[a]	2.18[a]	7.0[a]	M06
HD 108471	1.86[a]	4970	2.80	−0.01	1.96[a]	2.10[a]	25	B00
HD 112127	1.44[a]	4340	2.10	0.09	3.01[a]	2.95[a]	19[a]	W82
HD 116292	1.82[a]	5050	3.00	−0.01	1.50	1.65	...	B00
PDS 365	1.85	4540	2.20	−0.09	3.30	3.13	12^{+8}_{-2}	D02
HD 120602	1.98[a]	5000	3.00	−0.08	1.95[a]	2.07[a]	16	B00
IRAS 13539−4153	1.60	4300	2.25	−0.13	4.10	3.90	20	R05
HD 148293	1.86[a]	4640	2.50	0.08	1.99[a]	2.16[a]	16	B00
IRAS 17596−3952	1.70	4600	2.50	0.10	2.20	2.30	...	R05
HD 183492	1.75[a]	4700	2.40	−0.08	2.00[a]	2.16[a]	9	B00
PDS 100	1.65	4500	2.50	0.14	2.50	2.40	9.0	R02
HD 194937	1.54[a]	4863	2.86	−0.01	3.41	3.18[a]	...	L07
HD 203136	1.75[a]	5100[a]	2.80[a]	0.05[a]	2.25[a]	2.34[a]	...	S00
HD 205349	2.82[a]	4480	0.6	0.03	1.90	2.25[a]	9	B00, Be94
HD 214995	1.54[a]	4740	2.56	0.00	3.16[a]	2.95[a]	13.0[a]	L07
HD 217352	1.77[a]	4570	2.53	...[c]	2.64	2.65[a]	...	S00
HD 219025	1.84[a]	4570	2.30	−0.10	3.00	2.93[a]	...	J99
G0928+73.2600	1.75	4885	2.65	−0.25	3.62	3.30	28	C10

Notes.
[a] From this work.
[b] Spectroscopic binary and weak G-band star.
[c] Could not be measured due to large $v \sin i$ ($\simeq$ 35 km s^{-1}).
References. Ba00: Balachandran et al. 2000; B98: Barrado y Navascues et al. 1998; Be94: Berdyugina & Savanov 1994; B00: Brown et al. 1989; C10: Carlberg et al. 2010; G89: Gratton & D'Antona 1989; D02: Drake et al. 2002; J99: Jasniewicz et al. 1999; L07: Luck & Heiter 2007; M06: Mishenina et al. 2006; R02: Reddy et al. 2002; R05: Reddy & Lambert 2005; S00: Strassmeier et al. 2000; W82: Wallerstein & Sneden 1982.

RGB: the thick black line in Figure 2 shows the predicted locations of clump stars. Extension of the $\log L/L_\odot \simeq 1.7$ concentration to cooler temperatures may include stars at the bump luminosity of the first ascent RGB stars (see red portions of the evolutionary tracks). Dominance of the H-R diagram by clump stars is expected because the lifetime of a clump star is typically one to two orders of magnitude longer than for a bump star. This argument is not strictly applicable to the Li-rich stars because their frequency is also dependent on the probabilities that clump and bump stars produce lithium.

Except for five luminous examples, the Li-rich stars are either at the luminosity of the clump or within the range of expected values for the bump, a range spanning the clump's luminosity. The five luminous exceptions must owe their Li richness to different phenomena than those accounting for the majority of the Li-rich stars. For example, HD 39853 (Gratton & D'Antona 1989) in Table 2 is an Li-rich K giant but with $\log L/L_\odot = 2.7$ is probably a post-clump early asymptotic giant branch (AGB) candidate where, as discussed by Charbonnel & Balachandran (2000), Li-production by the Cameron–Fowler mechanism has occurred by a variant of its operation in bump stars (see below). In contrast, the high luminosity warm ($T_{\rm eff}$ = 5150 K) Li-rich star HD 21018 is, as suggested by Charbonnel & Balachandran (2000), caught prior to dilution of lithium by the convective envelope, i.e., it is an Li-normal star exhibiting an Li abundance close to its initial abundance. We focus here on the Li-rich giants at bump and clump luminosities.

5. LITHIUM SYNTHESIS AT THE BUMP AND/OR CLUMP?

Since the Li-rich K giants are concentrated within a narrow luminosity range, one may suppose a significant event must be associated directly or indirectly with this range. One suspects that the significant event is either the bump on the first ascent of the RGB and/or associated with the red clump formed of He-core burning giants that have experienced the He-core flash at the tip of the RGB.

The observed luminosity range is crossed by first ascent RGB stars in which the H-burning shell passes into the region that previously was the maximum extent reached by the convective envelope. When the outward moving H-burning shell, as a result of increasing He-core mass, first encounters this region, a star reacts to the increased availability of H by lowering the surface luminosity. After a while, the giant continues its ascent of the RGB. This creates a kink on the evolutionary tracks for stars of

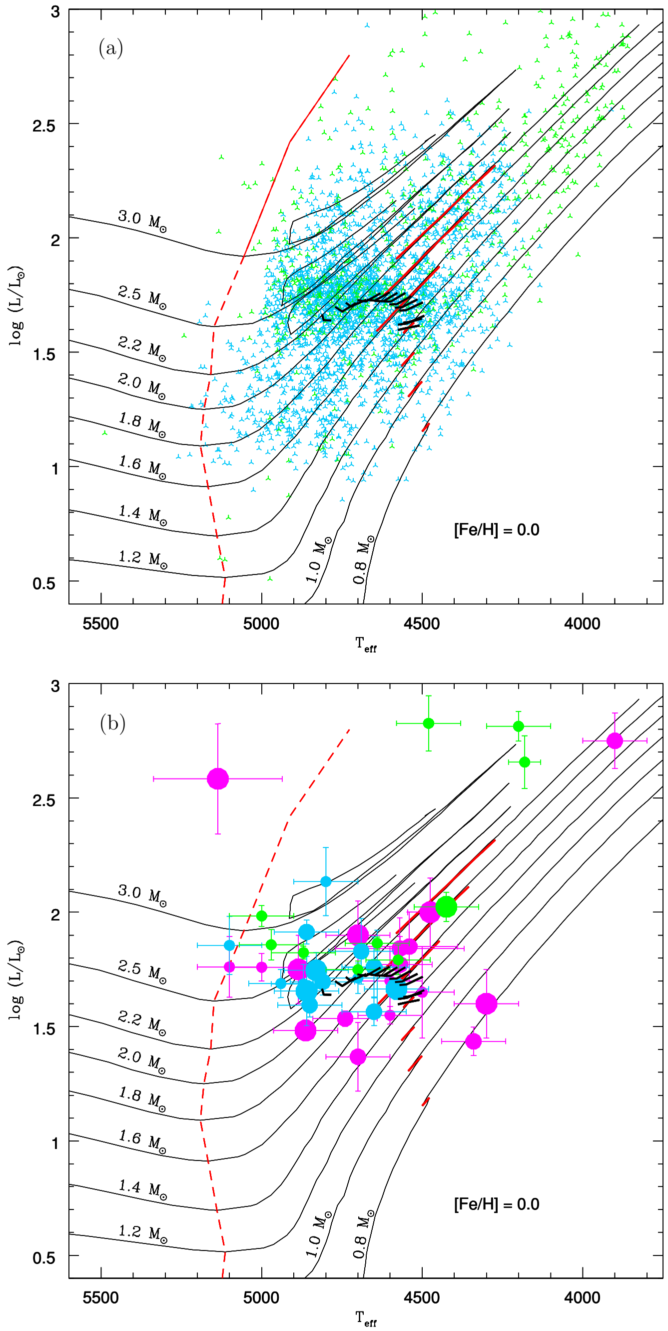

Figure 2. Stars from our (blue symbols) and Brown et al. (1989) (green symbols) survey are shown (panel (a)) along with evolutionary tracks computed by Bertelli et al. (2008). Li-rich K giants are shown in panel (b): blue filled circles denote new Li-rich giants found in this study, green symbols are Li-rich giants from Brown et al. (1989), and magenta symbols are other Li-rich giants taken from the literature. Symbol size indicates amount of Li. The base of the RGB is shown as a broken red line and red portion on each of the tracks represents the location of the luminosity bump which is predicted to be seen for masses $M \leqslant 2\ M_{\odot}$. The thick black lines represent the clump region for He-core burning stars of masses 0.8–2.5 $M_{\odot}$.

(A color version of this figure is available in the online journal.)

masses up to 2 $M_{\odot}$ (Iben 1968; Bertelli et al. 2008) and a bump in the luminosity function along the RGB. As shown in Figure 2, the kink on the evolutionary tracks (Bertelli et al. 2008) is visible only up to 2 $M_{\odot}$ for solar metallicity stars.

Internally, the kink is associated with an inversion in the run of mean molecular weight with distance from the stellar center. This inversion is linked to destruction of ^{3}He by the reaction ^{3}He(^{3}He, $2p$)^{4}He which lowers the mean molecular weight and the homogenization of the composition within the convective envelope. Eggleton et al. (2008) show that this inversion leads to "compulsory" mixing and changes to the surface abundances of C, N, and O isotopic abundances, i.e., the ^{12}C/^{13}C ratio is lowered relative to its value before the bump. Charbonnel & Lagarde (2010) recognize too that mixing occurs as a result of the molecular weight inversion but include the effects of rotationally induced mixing to drive the mixing. This mixing referred to as $\delta\mu$-mixing by Eggleton et al. (2008) or thermohaline mixing by Charbonnel & Lagarde (2010) is observationally confirmed by measurements of the ^{12}C/^{13}C ratio in giants along the RGB showing a decrease in the ratio at and above the luminosity of the bump.

As p-captures on ^{12}C create ^{13}C, the reservoir of primordial and main-sequence synthesized ^{3}He is depleted. It is this reservoir that is a potential source of ^{7}Li from the Cameron–Fowler (Cameron & Fowler 1971) mechanism (^{3}He(^{4}He, γ)^{7}Be(e^-, ν)^{7}Li) but in order for the ^{7}Li to enrich the stellar atmosphere it and its progenitor ^{7}Be must be swept quickly to temperatures too cool for proton captures to occur. Eggleton et al. (2008) calculations show that more than about 80% of the ^{3}He is destroyed in stars of masses less than about 1.5 $M_{\odot}$. This destruction seems unlikely to produce lithium because the mixing is too slow for the ^{7}Be and ^{7}Li to avoid destruction by protons (Lattanzio et al. 2008). However, the initial subsurface ^{3}He reservoir is such that only a minor fraction of the ^{3}He need to be converted with moderate efficiency to provide an Li-rich giant. It is anticipated that the lithium produced as the star crosses the bump's luminosity may be destroyed as the star with its convective envelope evolves to the tip of the RGB.

The evidence from Figure 2 is that few of the Li-rich stars are aligned along the run of bump stars in the H-R diagram. Although the cooler Li-rich stars are likely to be bump stars, many Li-rich stars are too warm to be so identified. Thus, we suggest that Li-rich stars cannot be identified exclusively with the bump. Rather the co-location of the Li-rich stars in Figure 2 with the high concentration of observed (Li-normal) giants and the theoretical location of the clump suggest that they are clump stars. If Li produced at the bump on the RGB survives a star's evolution from the bump to the clump, such Li-rich stars from the survey may nonetheless appear predominantly as clump stars because the lifetime at the clump is similar to or longer than the time to evolve through the bump and to the clump via the tip of the RGB. Since Li, if produced at the bump on the RGB, may be destroyed by the time the star has evolved up the RGB to experience the He-core flash, the speculation is that the Cameron–Fowler mechanism may also operate at the He-core flash in at least some stars, i.e., in stars of $M < 2.25\ M_{\odot}$. Since Eggleton et al. (2008) predict survival of ^{3}He in stars with $M > 1.5\ M_{\odot}$, there seems in principal the possibility that the He-core flash may be the key to synthesis of lithium in stars in a narrow mass range centered at about 2 $M_{\odot}$ with the range's the upper limit set by the maximum mass for a He-core flash and the lower limit set by survival of sufficient ^{3}He following $\delta\mu$ or thermohaline mixing on the RGB. Evidently, the concentration of Li-rich stars at the clump implies that the synthesized Li is swiftly destroyed as a clump star evolves along the early reaches of the AGB. If all stars evolving through the He-core flash synthesize copious amounts of Li, they survive as an Li-rich giant for about 1% of their horizontal branch lifetime, i.e., about 2 Myr. (The four luminous Li-rich stars in Figure 2 have a mass in excess of those experiencing the He-core flash. Charbonnel & Balachandran (2000) suggest that these tap their ^{3}He to produce Li as the He-burning shell evolves outward.)

6. CONCLUSIONS

The principal novel result here is that the majority of Li-rich K giants have a luminosity and effective temperature combination suggesting that Li production may occur at the He-core flash in those stars. Although this speculation about the He-core flash has yet to be supported by calculations, the nuclear physics of Li production is surely that described by the Cameron–Fowler mechanism, i.e., conversion of ^{3}He to ^{7}Li by α-capture with ^{7}Be as a radioactive intermediary. An earlier suggestion that Li production, also by the Cameron–Fowler mechanism, occurs at the luminosity bump of the RGB (Charbonnel & Balachandran 2000) is not only required to account for cooler Li-rich stars, but may, if the Li produced at the bump survives evolution from there to the clump, account for some or all of the Li-rich clump stars.

Our discovery of that Li-rich giants are concentrated within a narrow luminosity range does not support a view that Li-rich giants result from the swallowing by the giant of a gaseous planet (Alexander 1967) or some other external origin.

It remains to confirm and interpret suggestions that Li-rich K giants may be unusual with respect to other K giants in exhibiting rapid rotation and/or an infrared excess (see, for example, Drake et al. 2002; Charbonnel & Balachandran 2000). There are certainly Li-rich giants with normal ^{12}C/^{13}C ratios (e.g., HD 108471 in Table 2), and/or rapidly rotating surfaces (e.g., HD 217352 with $v \sin i \simeq 35$ km s^{-1}; Strassmeier et al. 2000), and/or infrared excesses (e.g., PDS 365; Drake et al. 2002).

Perhaps, an area for observational scrutiny is a full determination of the C, N, and O elemental and isotopic abundances in order to search for discriminant between the candidate bump and clump Li-rich stars themselves and between these Li-rich stars and bump and clump stars exhibiting a normal Li abundance. Finally, a radial velocity study should be undertaken to see if the collection of Li-rich stars have the normal degree of binarity.

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