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The Nature of the lithium rich giants

Mixing episodes on the RGB and early-AGB

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Abstract. We present a critical analysis of the nature of the so-called Li-rich RGB stars. For a majority of the stars, we have used Hipparcos parallaxes to determine masses and evolutionary states by comparing their position on the Hertzsprung-Russell diagram with theoretical evolutionary tracks. Among the twenty Li-rich giants whose location on the HR diagram we were able to determine precisely, five appear to be Li-rich because they have not completed the standard first dredge-up dilution, and three have abundances compatible with the maximum allowed by standard dilution. Thus, these should be re-classified as Li-normal. For the remaining stars, the high Li abundance must be a result of fresh synthesis of this fragile element.

We identify two distinct episodes of Li production which occur in advanced evolutionary phases depending upon the mass of the star. Low-mass RGB stars, which later undergo the helium flash, produce Li at the phase referred to as the bump in the luminosity function. At this evolutionary phase, the outwardly-moving hydrogen shell burns through the mean molecular weight discontinuity created by the first dredge-up. Any extra-mixing process can now easily connect the ^{3}He-rich envelope material to the outer regions of the hydrogen-burning shell, enabling Li production by the Cameron & Fowler (1971) process. While very high Li abundances are then reached, this Li-rich phase is extremely short lived because once the mixing extends deep enough to lower the carbon isotopic ratio below the standard dilution value, the freshly synthesized Li is quickly destroyed.

In intermediate-mass stars, the mean molecular weight gradient due to the first dredge-up is not erased until after the star has begun to burn helium in its core. The Li-rich phase in these stars occurs when the convective envelope deepens at the base of the AGB, permitting extra-mixing to play an effective role. Li production ceases when a strong mean molecular weight gradient is built up between the deepening convective envelope and the shell of nuclear burning that surrounds the inert CO core. This episode is also very short lived. Low-mass stars may undergo additional mixing at this phase.

The compiled data provide constraints on the time scales for extra mixing and some insight on processes suggested in the literature. However, our results do not suggest any specific trigger mechanism. Since the Li-rich phases are extremely short, enrichment of the Li content of the ISM as a result of these episodes is negligible.

Key words: hydrodynamics – turbulence – stars: abundances – stars: interiors – stars: AGB and post-AGB – stars: rotation

1. The so-called Li-rich RGB stars

During the first dredge-up, the lithium abundance at the surface of a red giant star decreases due to dilution of the external convective stellar layers with the lithium-free region in the interior. Depending on the stellar mass and metallicity, the surface lithium abundance decreases with respect to its value at the end of the main sequence by a factor that varies between $\sim$ 30 and 60. The post dredge-up lithium abundance also depends on the surface depletion of this fragile element during the pre-main sequence and main sequence phases; in Population I stars this is known to be important at masses lower than $\sim$ 1.2 $M_{\odot}$ and in stars originating from the Li dip (see volume edited by Crane 1994 for reviews). Starting from the present interstellar medium abundance of log N(Li)$\simeq$3.3 (where log N(Li) = log[n(Li)/n(H)]+12), one thus expects a post-dilution value lower than about 1.8 to 1.5 for Pop I stars and, indeed, most G-K giants fall below this upper limit (Lambert et al. 1980, Brown et al. 1989, Mallik 1999).

However, about 1% of G-K giants show unexpectedly strong lithium lines (Wallerstein & Sneden 1982, Brown et al. 1989, Gratton & D'Antona 1989, Pilachowski et al. 1990, Pallavicini et al. 1990, Fekel & Balachandran 1993). Some of these Li-rich giants have abundances that are even higher than the present interstellar medium value (de la Reza & da Silva 1995, Balachandran et al. 2000). Various suggestions have been made to explain the Li-rich giant phenomenon. Some are related to external processes, like the contamination of the external layers of the giant by the debris of nova ejecta or by the engulfing of a planet (Alexander 1967, Brown et al. 1989, Gratton & D'Antona 1989, Siess & Livio 1999). Other ex-

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planations explore internal processes, like the preservation of the initial lithium content or fresh lithium production (Fekel & Balachandran 1993, de la Reza et al. 1996, Castilho et al. 1999, Sackmann & Boothroyd 1999).

The other notable disagreement betwen the prediction of abundances in first ascent giants and observations is the carbon isotopic ratio. It has been observed that the carbon isotopic ratio in evolved stars of open clusters with turnoff masses lower than about 2.2M$_\odot$ (Gilroy 1989, Gilroy & Brown 1991) and in field giants at various metallicities (Sneden et al. 1986, Shetrone et al. 1993, Pilachowski et al. 1997, Charbonnel et al. 1998, Carretta et al. 1998, Gratton et al. 2000) is lower than the value predicted by the standard theory. Observations reveal that the carbon isotopic ratio does not decrease below the standard model predictions until the mean molecular weight gradient produced by the first dredge up is erased by the outwardly-burning hydrogen shell. This evolutionary phase is referred to as the bump in the luminosity function on the HR diagram and corresponds to a temporary decrease in the luminosity and a small increase in the effective temperature of the star when the chemical discontinuity is removed. It has therefore been surmised that a non-standard mixing process, previously inhibited by the mean molecular weight barrier, begins to act at this phase and results in “extra mixing” of the convective zone material with regions hot enough to convert ^{12}C to ^{13}C (Sweigart & Mengel 1979; Charbonnel 1994, 1995; Charbonnel et al. 1998).

The nature of the mechanism which produces the drop of the ^{12}C/^{13}C ratio remains uncertain, though rotation-induced mixing is a probable candidate. We do know that (i) the extra-mixing is inhibited by molecular weight gradients because, as our previous discussion showed, it has not been observed to occur before the star enters the bump, (ii) it occurs in $\sim 96\%$ of the low-mass stars (Charbonnel & Do Nascimento 1998) and (iii) it destroys part of the ^{3}He produced on the main sequence (as suggested first by Rood et al. 1984; see also Charbonnel 1995, Hogan 1995 and Sackmann & Boothroyd 1999). It may be responsible for other chemical anomalies. For instance, a significant decrease in the surface lithium abundance is seen in Population II giants which are at the red-giant bump (Pilachowski et al. 1993, Charbonnel 1995, Gratton et al. 2000). The continuous decline of the carbon abundance along the RGB, and the presence in the atmosphere of material processed by the ONeNa-cycle (see Kraft 1994 and Da Costa 1998 for reviews) seen in globular cluster giants may also result from a manifestation of the extra-mixing process (see Weiss et al. 2000 and references therein).

In this paper we draw a connection between the Li enhancement and the carbon isotopic ratio decline in red-giants and provide evidence for the hypothesis outlined in §2. For the first time it is shown that two phases of mixing occur in Population I stars depending upon the mass of the star; mixing occurs at the luminosity bump for low-mass stars and in the early-AGB phase before the completion of the second dredge-up in both low and intermediate-mass stars. Both lead to short-lived Li-rich phases. We discuss the similarities between the two events.

2. The hypothesis

We suggest that the Li-rich RGB stars are formed mainly as a precursor to the deeper mixing process which produces anomalously low carbon isotopic ratios.

In low-mass stars (i.e., stars which ascend the RGB with a degenerate He core), the fresh synthesis of lithium occurs at the start of the red giant luminosity bump phase when the outwardly moving hydrogen-burning shell burns through the mean molecular weight discontinuity. With the help of an extra-mixing process, the ^{3}He-rich envelope[1] can now be connected to the hotter inner region in the vicinity of the hydrogen-burning shell. Li production proceeds via the Cameron & Fowler (1971) mechanism in which ^{3}He is burned to create ^{7}Be via ^{3}He$(\alpha,\gamma)^7$Be. The ^{7}Be quickly decays into ^{7}Li via ^{7}Be(e$^-$,ν)^{7}Li. For the freshly synthesized ^{7}Li to survive, the ^{7}Be must be transported rapidly to cooler regions before the decay occurs. Depending on the mixing efficiency, which may vary from star to star, the ^{7}Li may or may not reach the stellar surface. In either case, once mixing extends deep enough to convert additional ^{12}C into ^{13}C (as is observed to occur in low-mass giants) the surface material is exposed to temperatures higher than ^{7}Li can withstand and the freshly synthesized ^{7}Li is steadily destroyed. Therefore the Li-rich phase is fleeting; a star will not retain its peak Li abundance once the ^{12}C/^{13}C ratio dips below the standard value.

The evolutionary sequence of an intermediate-mass star differs in one key aspect, and this leads to Li production at a different epoch of its life. Evolution up the RGB is rapid for intermediate-mass stars, and helium burning in the non-degenerate core has already begun before the hydrogen-burning shell burns through the mean molecular weight discontinuity caused by the first dredge-up. Therefore no extra mixing is facilitated on the short RGB phase of these stars, as is confirmed from the observations of the carbon isotopic ratio which agree with standard model predictions (Charbonnel 1994). When the mean molecular weight gradient is finally erased, the star is burning He in its core which is surrounded by the hydrogen-burning shell, the convective envelope is very shallow, and distant (both in terms of mass and radius) from the burning regions, so that extra-mixing may not be effective. However, once the core He-burning is exhausted and the star ascends the early-AGB, the convective envelope deepens in response to the contracting, slightly degenerate CO core with the helium- and hydrogen-burning shells at its outer edge. We suggest that it is at this phase that an extra-mixing process may be most effective in bridging the small gap between the base of the convective zone and the H burning shell, producing ^{7}Li via the Cameron & Fowler (1971) process. When the convective envelope reaches the external part of the hydrogen burning shell, a strong gradient of molecular weight will again inhibit the extra-mixing. We thus expect this phase to be very short and localized on the HR dia-

[1] During the first dredge-up, the deepening convective envelope is enriched in ^{3}He when it engulfs the ^{3}He peak built up while the star was on the main sequence. In the standard models, ^{3}He survives in the star until it is injected into the ISM by stellar winds and planetary nebulae ejection

gram. Note that the base of the convective zone of a low-mass star also comes into close proximity to the hydrogen-burning shell at this evolutionary phase, and therefore these stars have a second opportunity to become Li-rich if extra-mixing occurs.

In stars with initial mass higher than about $4M_\odot$ the hydrogen- burning shell is extinguished by the deepening convective envelope and significant changes in the surface abundance are seen when the H-He discontinuity is penetrated: the second dredge-up. Accordingly, we do not expect to see ^{7}Li-rich stars in the early-AGB phase at masses greater than about 4 $M_\odot$. However, we recall that it is in stars between $4M_\odot$ and $8M_\odot$ that hot-bottom burning leading to ^{7}Li production has been both observed and shown to be theoretically feasible at a later evolutionary phase (Smith & Lambert 1989, Smith & Lambert 1990, Plez et al. 1993, Smith et al. 1995, Sackmann & Boothroyd 1992, Forestini & Charbonnel 1997).

While some clues suggest that the deep mixing may be related to rotation, the physical description of the process is far from complete, and observational evidence is inconclusive up to now. We endorse no specific mechanism in this study. We have no clues on whether the trigger for the extra-mixing is the same in the low- and intermediate-mass stars. Rather, our hypothesis is based on a theoretical understanding of the structure of the red-giant star, on the results of the ^{12}C/^{13}C ratio studies referenced above and on our own analysis of the properties of Li-rich giants. The novel aspect of our study is that we are able to substantiate our claim with a critical analysis of Li-rich giant data from the literature. In particular, we have used Hipparcos parallaxes to determine the mass and evolutionary status of these objects to show that the highest Li abundances are indeed reached at the red-giant bump for low-mass stars and the early-AGB phase for intermediate-mass stars. The present analysis brings to light the first observational evidence for the production of Li in the latter group of stars.

3. Observational data

The main properties of the Li-rich giants are gathered in Table 1. The lower limit LogN(Li)>1.4 was chosen to classify a star as being abnormally lithium rich[2], though, as we will explain shortly, not all such stars are truly abnormal.

The parallaxes and associated errors are taken from the Hipparcos catalogue (Perryman et al. 1997) and stellar luminosities are derived from these. Of the 28 stars in the sample, five have no Hipparcos data. However HDE 233517 has a rotational period of 47.9 d measured from low-amplitude light variability presumably caused by spots (Balachandran et al. 2000). Combined with a rotational velocity estimated from spectral line broadening of $v\sin i = 17.6\,\mathrm{km^{-1}}$ Balachandran et al. (2000) estimate a lower limit to the luminosity of 100 $L_\odot$.

Effective temperatures are typically taken from the same source as the Li abundance. In cases where there are multiple estimates, either the mean or the more reliable estimate is chosen. Temperature errors listed are those cited by the authors. No attempt has been made to evaluate them; they are typically in the range of 100 to 200 K. Metallicities are taken from the Cayrel de Strobel et al. (1997) or Taylor (1999) compilations when available. Otherwise they are usually taken from the same source as the Li abundance. For multiple listings, the values are typically in good agreement. Most objects have a metallicity close to solar. About a third of the objects have carbon isotopic ratio measurements. Errors are given when listed by the authors. Rotational velocities and information about binarity is taken primarily from the CORAVEL compilation of De Medeiros et al. (1996) and De Medeiros & Mayor (1999). The source for the effective temperature, the metallicity, Li abundance, carbon isotopic ratio and rotational velocity are listed alongside the values in Table 1. As for temperature and metallicity, the error in the estimate of the Li abundance is that cited by the authors.

Accurate luminosities and temperatures allow placement of the stars on the HR diagram. Masses were then derived from the Geneva-Toulouse evolutionary tracks (see §4.1). Solar metallicity tracks were used for all stars except HD 33798, HD 39853 and HDE 233517. For these, mass estimates were interpolated from solar and [Fe/H]=-0.5 tracks for the metallicity of the star. Errors on the masses reflect errors in luminosity and temperature.

Towards the end of this study, four more Li-rich giants were identified by Strassmeier et al. (2000): HD 6665, HD 109703, HD 203136, and HD 217352. All have Hipparcos parallaxes, but other than the Strassmeier et al. (2000) study, there is no published information on these stars. Strassmeier et al. (2000) used Tycho B-V colors (Perryman et al. 1997) to derive temperatures and non-LTE curves of growth from Pavlenko & Magazzu (1996) to derive Li abundances. Because the reddening is unknown, the temperatures of these stars are uncertain. Strassmeier (private communication) suggested that the canonical reddening of 0.1 mag per 100 pc may be adopted. Under such an assumption, the listed temperatures of the 4 stars may be too cool by as much as 300 K to 700 K. The uncertain temperatures result in uncertain Li abundances. We have therefore not derived the masses of these stars and we have not included them in Fig. 1. However these stars are discussed briefly in the subsequent sections, though we caution that the interpretation is uncertain. A thorough spectroscopic analysis of these stars would be valuable.

The four stars without parallax measurements: HD 19745, HD 25893, HD 95799 and HD 203251 are not discussed further.

4. Evolutionary behaviour of lithium on the HR diagram

4.1. The Hertzsprung-Russell diagram

To determine the mass and the evolutionary status of the Li-rich giants, we have computed new stellar tracks with the Geneva-Toulouse evolutionary code with up-to-date input physics (same as in Charbonnel & Talon 1999), but with no diffusion or rotationally induced mixing. The tracks range in mass from 1.0 to 5.0 $M_\odot$ and in [Fe/H] from 0.0 and -0.5. The models were computed from the pre-main sequence up to the helium flash for the low-mass stars and up to the early-AGB for the intermediate-

[2] This corresponds to the value usually used in the literature

Table 1. Properties of the Li-rich field giants

HD number	Status	π [a] (mas)	$\sigma(\pi)$ (mas)	V	$T_{\rm eff}$ (K)	$\log(L/L_\odot)$ [b]	$M/M_\odot$ [c]	[Fe/H]	log N(Li)	$^{12}C/^{13}C$	$v\sin i$ (km s^{-1})
787	$\sharp$	5.33	0.87	5.29	4181±50(4)	2.79	4.0±0.5	+0.03(6)	1.80±0.3(5)	15(7)	1.9(9)
6665	$\otimes$	3.53	1.01	8.56	4500:(17)	1.65	..	..	2.92:(17)	..	10(17)
9746	$\star$	7.77	0.82	6.2	4400±100(5)	1.92	1.9±0.3	−0.06(18)	3.75±0.16(1)	28±4(5)	8.7(9)
19745	..	..	..	9.11	4990±100(8)	..	..	..	4.08±0.1(8)	15(7)	1.0(10)
21018	$\ominus$	2.92	0.95	6.37	5136±200(2)	2.52	4.7±0.7	..	3.35±0.4(2)	..	..
25893	..	48.59	1.17	7.13	5300±200(11)	-0.1	very low	−0.10(11)	1.65±0.2(11)	..	5.1(9)
30834	$\sharp$	5.81	0.82	4.79	4200±100(5)	2.85	4.5±0.3	−0.05(6)	1.80±0.3(5)	13(3)	2.7(9)
31993	$\ominus$	4.2	1.09	7.48	4500±200(11)	1.93	2.2±0.6	+0.10(11)	1.40±0.2(11)	..	31.1(11)
33798	$\ominus$	8.94	1.35	6.91	4500±200(11)	1.40	1.1±0.5	−0.30(11)	1.50±0.2(11)	..	29(12)
39853	$\sharp$	4.37	0.72	5.62	3900±100(14)	2.81	1.5±0.3	−0.46(14)	2.80±0.2(14)	7(7)	3.1(9)
40827	$\ominus$	6.92	0.74	6.32	4575±100(5)	1.92	2.5±0.3	+0.05(18)	1.60±0.3(5)	..	1.8(9)
95799	..	..	..	7.99	4800±200(16)	..	..	−0.11(16)	3.22±0.2(16)	10±7(16)	..
108471	$\ominus$	4.54	0.90	6.36	4970±100(5)	2.20	4.0±0.3	−0.01(18)	2.00±0.3(5)	25±7(5)	4.1(9)
109703	$\otimes$	2.82	1.08	8.70	4825:(17)	1.59	..	..	2.82:(17)	..	35.2(17)
112127	$\star$	8.09	0.85	6.91	4340±100(5)	1.57	1.1±0.2	+0.09(6)	2.70±0.3(5)	22±7(19)	1.6(9)
116292	$\ominus$	10.20	0.73	5.36	4870±100(5)	1.92	3.2±0.2	−0.15(18)	1.50±0.3(5)	..	..
120602	$\ominus$	8.09	0.81	6.00	5000±100(5)	1.83	3.2±0.2	−0.08(18)	1.90±0.3(5)	16(3)	5(11)
121710	$\sharp$	5.03	0.78	5.02	4100±100(5)	2.88	3.5±0.5	−0.27(6)	1.50±0.3(5)	..	1.3(9)
126868	$\ominus$	24.15	1.0	4.81	5500±100(5)	1.27	2.1±0.1	−0.07(18)	2.40±0.2(5)	..	14.4(9)
146850	$\sharp$	3.77	0.85	5.97	4200±200(13,15)	2.76	4.0±0.9	+0.00(20)	2.00±0.2(20)	..	14.4(9)
148293	$\star$	11.09	0.47	5.26	4640±100(5)	1.93	2.7±0.4	+0.08(6)	2.00±0.3(5)	16(3)	1.2(9)
183492	$\star$	11.38	0.73	5.57	4700±100(5)	1.75	2.5±0.3	−0.08(6)	2.00±0.3(5)	9(3)	1.0(9)
203136	$\otimes$	4.35	0.69	7.83	4983:(17)	1.64	..	..	2.23:(17)	5.4(17)	
203251	..	..	..	8.03	4500±200(11)	..	..	−0.30(11)	1.40±0.2(11)	..	44.8(9)
205349	$\ominus$	2.17	0.61	6.27	4480±100(5)	3.25	> 5	..	1.90±0.3(5)	..	..
217352	$\otimes$	5.11	1	7.28	4569:(17)	1.83	..	..	2.64:(17)	35.3(17)	
219025	$\star$	3.25	0.81	7.67	4570±200(13,15)	2.07	2.9±0.5	−0.10(15)	3.00±0.2(15)	..	25(13)
233517	$\star$	..	..	8.41	4475±70(1)	2.0[d]	1.7±0.2	−0.37(1)	4.22±0.11(1)	..	17.6(1)

$\ominus$ undergoing standard Li dilution $\star$ at luminosity function bump $\sharp$ at early-AGB phase $\otimes$ uncertain T_{eff} and Li

[a] from Hipparcos catalogue [b] derived from Hipparcos data [c] derived from evolutionary tracks [d] computed from P_{rot} and $v\sin i$

(1) Balachandran et al. (2000) (2) Barrado y Navascues et al. (1998) (3) Berdyugina & Savanov (1994)
(4) Blackwell & Lynas-Gray (1998) (5) Brown et al. (1989) (6) Cayrel de Strobel et al. (1997)
(7) da Silva et al. (1995) (8) de la Reza & da Silva (1995) (9) de Medeiros & Mayor (1999)
(10) de Medeiros et al. (1996) (11) Fekel & Balachandran (1993) (12) Fekel & Marschall (1991)
(13) Fekel & Watson (1998) (14) Gratton & D'Antona (1989) (15) Jasniewicz et al. (1999)
(16) Luck (1994) (17) Strassmeier et al. (2000) (18) Taylor (1999)
(19) Wallerstein & Sneden (1982) (20) This paper

mass stars which ignite He in a non-degenerate core (Fig. 1). For clarity, we show only the advanced evolutionary phases for the [Fe/H]=0.0 tracks. The subgiant and RGB evolutionary tracks are shown by solid lines and the early-AGB phase for masses higher than 3 $M_\odot$ is shown by long dashed lines. On the HR diagram, two dashed lines show the beginning of Li dilution (warmer line) and the end of the first dredge-up (cooler line). Between these two, the dashed-dotted line shows the onset of the carbon isotopic ratio dilution. Because lithium burns at a very low temperature, the deepening convective envelope reaches the lithium-free region before it engulfs the ^{13}C peak built on the main sequence. Also shown in Fig. 1 is the RGB bump indicated by the shaded region. Only low-mass stars that have a highly degenerate He core on the RGB, and later undergo the He flash, evolve through this phase. In the intermediate-mass stars, helium burning in the core begins before the hydrogen-burning shell reaches the chemical discontinuity. Finally, a solid line connects the points (asterisks) where a molecular weight barrier starts to appear due to the second dredge-up on the early-AGB (long dashed lines).

In Fig. 1, all the Li-rich giants for which we are able to estimate luminosities are plotted with filled symbols. The four possible Li-rich giants from Strassmeier et al. (2000) are excluded because their temperatures and subsequently their Li abundances are uncertain. They are however discussed in the text. The open circles are data with -0.1$\leq$[Fe/H]$\leq$+0.1 from the large sample of giants studied by Brown et al. (1989). Luminosities for these stars are also based on Hipparcos parallaxes. In each case, the size of the symbol indicates the Li abundance of the star as indicated in the legend. Error bars on the Li-rich

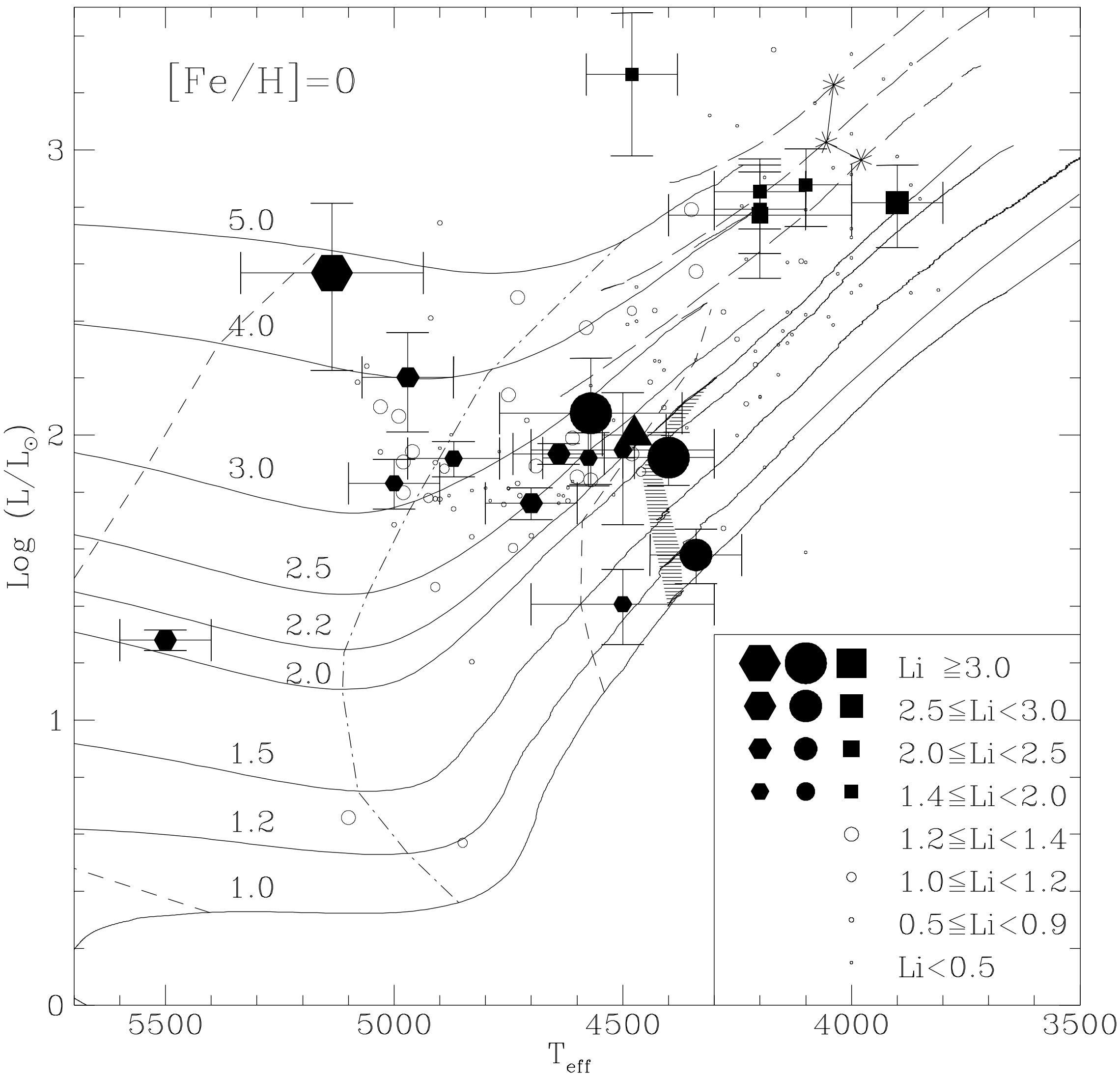

Fig. 1. The HR diagram for the Li-rich giants. Evolutionary tracks with [Fe/H]=0 are labelled by their masses. Two dashed lines delimit the first dredge-up; the warmer line corresponds to the start of Li dilution and the cooler line marks the deepest penetration of the convective zone. The dashed-dotted line indicates the start of the decrease in the carbon isotopic ratio due to dilution. The shaded region surrounds the location of the RGB bump. A solid line connects the points (asterisks) where a molecular weight barrier starts to appear due to the second dredge-up on the early-AGB. The filled symbols represent the so-called lithium rich stars which are grouped according to their evolutionary state as discussed in the text: hexagons indicate Li-normal stars undergoing first dredge-up dilution; circles and triangle (for HD 233517 whose luminosity was derived from P_{rot} and *v*sin*i*) show stars at the RGB bump; and squares indicate the early-AGB stars. The open circles are stars with Hipparcos parallaxes and -0.1≤[Fe/H]≤+0.1 from the Brown et al. (1989) survey. In all cases, the size of the symbol indicates the Li abundance of the star as shown in the legend. The error bars on luminosity are estimated from uncertainties in the Hipparcos parallax. Temperature uncertainties are taken from the literature (see Table 1).

giants show uncertainties in the luminosity and temperature estimates of these stars. Luminosity errors are based on parallax errors and temperature errors are as cited by the authors from whom the temperature estimate is taken (see Table 1).

At first glance, the Li-rich giants seem to be randomly distributed throughout the diagram. However, a more careful analysis leads us to divide the sample into three groups according to their evolutionary state. Each of these is now discussed separately.

4.2. Stars undergoing standard first dredge up dilution

The stars discussed in this section are indicated as filled hexagons in Fig. 1. Accurate parallax measurements which lead to luminosity and mass determinations show that the less evolved stars, HD 21018, HD 108471, HD 116292, HD 120602, HD 126868 and HD 205349 are not true Li-rich giants. With Li abundances larger than the upper limit of logN(Li)=1.4, the maximum theoretically allowed for low-mass giants which have completed the first dredge-up, these stars have been classified as Li-rich in the literature. However their position on the HR diagram shows them to be normal. HD 205349 with a mass greater than 5 $M_{\odot}$ is probably a supergiant crossing the Hertzsprung gap. HD 126868 and HD 21018, 2.1$M_{\odot}$ and 4.7 $M_{\odot}$ subgiants respectively, have only just begun their Li dilution phase. HD 21018 is a chromospherically active binary. It was discussed in some detail as being abnormally Li-rich by both Barrado y Navascues et al. (1998) and Mallik (1999). This is clearly not the case. At 4$M_{\odot}$, HD 108471 has begun but not completed its Li dilution. Standard models predict a dilution of roughly a factor of 7.5 for HD 108471. If it left the main sequence with its surface Li intact, its measured dilution is about a factor of 20. With a mass of 3.2$M_{\odot}$, both HD 116292 and HD 120602 are also currently undergoing the first dredge-up dilution. Rather surprisingly, the $^{12}C/^{13}C$ ratio of HD 120602 has been measured at 16 (Berdyugina & Savanov 1994). According to the standard models, this star should, at best, have only begun to dilute its $^{12}C/^{13}C$ ratio from the solar value of near 90. It should reach a $^{12}C/^{13}C$ ratio of near 25 to 30 at the base of the red giant branch when the standard dilution process has been completed. In the compilation of $^{12}C/^{13}C$ values, Charbonnel & Do Nascimento (1998) did not find any other stars like HD 120602. Its $^{12}C/^{13}C$ ratio requires closer scrutiny.

Despite their normal Li abundances, HD 108471, HD 120602 and HD 116729 appear to be unusual because a number of stars in their vicinity on the HR diagram show far smaller Li abundances (Fig. 1). We argue that this merely indicates that non-standard Li depletion has occurred in the other stars during the main sequence phase. While 3$M_{\odot}$ stars on the main sequence are not typically seen to be depleted in Li, observations have long suggested that the Li-preservation zones in these stars may not be as deep as predicted by the standard models, i.e., once the star evolves off the main sequence and its convective zone deepens, the Li abundance decreases far more rapidly than standard predictions (Charbonnel & Talon 1999 and references therein). Unlike these stars, HD 108471, HD 120602 and HD 116729 have Li-preservation zone depths that are in agreement with the predictions of the standard models.

HD 203136 from Strassmeier et al. (2000) is in close proximity to HD 120602 on the HR diagram and has a comparable Li abundance within the errors. Standard models predict an abundance of log N(Li)=2.28, essentially identical with the measured abundance. HD 109703 from Strassmeier et al. (2000) has an unreddened T_{eff} of 4825 K which places it at a slightly more evolved phase than HD 203136. Its measured Li abundance of log N(Li)=2.82 is much larger than the standard model prediction of log N(Li)=1.75. Of the four stars from Strassmeier et al. (2000), HD 109703 is the most distance and it may have a reddening as large as E(B-V)=0.3. Such a large reddening would increase its temperature to 5500 K and the near-meteoritic Li abundance that would be derived from the increased temperature would be compatible with standard model predictions. However, given its Galactic latitude of b=+65.45°, it is unlikely that HD 109703 has such a large reddening and it remains an enigmatic star that requires further scrutiny.

Three stars in our sample show only marginal Li enhancement: HD 31993, HD 33798, and HD 40827. It remains questionable whether these should in fact be labelled as Li-rich. According to their positions on the HR diagram, these stars should have completed their Li dilution phase. Their Li abundances, close to the maximum allowed by the standard model, suggest that they have not undergone any significant depletion during the main sequence. Their masses are consistent with this conclusion; with masses of 2.2 and 2.5 $M_{\odot}$ respectively, HD 31993 and HD 40827 have evolved from the hot side of the Li dip and with a mass of 1.1 $M_{\odot}$ HD 33798 has evolved from the Li plateau region between the cool side of the dip and the G-dwarf Li decline where Li depletion is minimal. We suggest that these stars are not Li-rich, but having retained their initial Li abundance during their main sequence lifetimes, now exhibit standard post-dilution Li values.

4.3. Stars at the bump

The stars discussed in this section are shown as filled circles and a filled triangle in Fig. 1. Four stars with the highest Li abundances, HD 9746, HD 112127, HD 219025 and HD 233517, occupy a clump on the HR diagram coincident with the position of the red-giant bump. Of these HDE 233517 is the most Li-rich with a super-meteoritic Li abundance of log N(Li)=4.35 (Balachandran et al. 2000). Two pieces of observational evidence confirm that the large Li abundances in these stars is the result of fresh synthesis. First, beryllium depletion has been measured in two of the stars, HD 9746 and HD 112127 (Castilho et al. 1999) confirming that the second light element has undergone the expected dilution. Second, ^{6}Li is not detected in HD 9746 and HDE 233517; although this was not a direct measurement, Balachandran et al. (2000) found that consistent Li abundances are only measured from the resonance and excited lines of Li I when ^{7}Li alone is considered in the spectral synthesis. The absence of ^{6}Li also confirms that the observed Li is not entirely a remnant of the initial Li with which these stars were formed. The high Li abundances in these stars are consistent with our hypothesis that stars may undergo Li production at the red-giant bump via the Cameron & Fowler (1971) mechanism. Carbon isotopic ratios have been measured for two of these stars: HD 9746 and HD 112127. The standard $^{12}C/^{13}C$ ratios of 28 (Brown et al. 1989) and 22 (Wallerstein & Sneden 1982) respectively are also consisent with our hypothesis that Li-production precedes the extra-mixing phase which connects the convective envelope with the CN-burning region to produce the low, non-standard values of $^{12}C/^{13}C$ which are observed in 96% of the evolved giants (Charbonnel & Do Nascimento 1998). Three of the four stars have masses between 1.9 and 2.9 $M_{\odot}$ while HD 112127 has a lower mass of 1.1 $M_{\odot}$.

HD 148293 and HD 183492, are also in the region of the red-giant bump. These two stars have a Li abundance of log N(Li) = 2.0 and $^{12}C/^{13}C$ ratios of 16 and 9 respectively. Despite their perceived location to the left of the red-giant bump on the HR diagram, their low $^{12}C/^{13}C$ ratios suggest that they have evolved past the red-giant bump. We suggest two possible explanations. Either the temperatures of these stars are lower or the ^{12}C/^{13}C ratios are larger than estimated. Temperature errors are estimated at ±100 K by Brown et al. (1989). The stars are about 200 K from the theoretically estimated position of the red-giant bump. No error estimates are provided for the ^{12}C/^{13}C measurements. We are inclined to believe that the temperature shift required to place them at the red-giant bump is not unduly large given the general uncertainties in temperature measurement and the inhomogeneity in the sources from which the temperatures are gathered. With this caveat, we suggest that both stars are at the red-giant bump. According to the hypothesis we outlined in §2, and the measured ^{12}C/^{13}C ratios, HD 148293 and HD 183492 have completed the Li production phase and are currently undergoing "extra-mixing" leading to their lower ^{12}C/^{13}C ratios.

While the Li abundances of HD 148293 and HD 183492 are large, they are not as large as the four extremely Li-rich giants discussed above. According to our hypothesis, the Li production phase must be very short-lived. This is based on observations which indicate an abrupt change in the behavior of the carbon isotopic ratio shortly after the luminosity-function bump (see Charbonnel et al. 2000 for a recent review and references therein) Once the mixing process which connects the convective envelope to the CN-burning region sets in, the envelope material is exposed to a much higher temperature than Li can withstand, and a partial or complete destruction of the freshly synthesized is expected[3]. The current Li abundances of HD 148293 and HD 183492 therefore reflect a destruction of Li from their peak values which may have matched that of HDE 233517.

The position of HD 148293 and HD 183492 on the HR diagram, their Li abundance, and their ^{12}C/^{13}C ratios provide strong constraints on the timescale of the extra-mixing process. The abundance changes appear to be abrupt both in terms of luminosity and of time. Note that the time spent by the star at the bump corresponds to about 3% of the time along the ascent of the RGB (for a 1.5M$_\odot$ of solar metallicity, this corresponds to about 10 Myr). The mixing episode may last only a fraction of the time spent at the bump. Even if we assume that all stars go through the Li-rich phase, the swiftness of the phenomenon may explain the relative rareness of the Li-rich objects. Once the mixing process reaches the CN-burning regions, the low ^{12}C/^{13}C ratio remains to tell the tale of the mixing episode, while the fleeting Li-rich phase vanishes.

In the absence of significant reddening, the Strassmeier et al. (2000) stars HD 6665 and HD 217352 appear to be in close proximity to the luminosity bump and their high Li abundances are compatible with the other Li-rich giants seen in this region. These two stars warrant further spectroscopic study.

[3] In Pop II giants, the decrease of the carbon isotopic ratio due to extra-mixing after the bump is clearly associated to a drop of the Li abundance (Pilachowski et al. 1993, Charbonnel 1995, Gratton et al. 2000)

The HR diagram provides another striking point which strengthens our hypothesis. A second clump of Li-rich giants is seen at a higher luminosity and we will discuss this in §4.4. With the exception of these stars there are no Li-rich giants detected at any evolutionary point between the bump and the tip of the RGB. Yet, for a 1.5M$_\odot$ star of solar metallicity for example, the duration required to cover the evolutionary phase between the bump and the tip of the RGB corresponds to about 20% of the giant's lifetime, i.e., about ten times longer than the duration spent on the bump. If the fresh Li produced at the bump was preserved in spite of the extra-mixing which decreases the carbon isotopic ratio, or if Li production was a continuous process all along the RGB (see §5.4), some Li-rich giants would surely have been detected between these two evolutionary points.

4.4. Stars on the early-AGB

A second clump of Li-rich giants is seen at higher luminosity (filled squares in Fig. 1). HD 787, HD 30834, HD 39853, HD 121710 and HD 146850 have relatively high masses (most between 3 and 4.5 M$_\odot$). As discussed earlier, these intermediate-mass stars do not undergo a bump phase on the RGB as their hydrogen-burning shell does not cross the chemical discontinuity created by the first dredge-up until core He burning has commenced. Since the convective envelope is very shallow during core He burning, extra-mixing may not be effective in altering the surface abundances at this stage. Once He in the core has been exhausted, the star begins its ascent of the AGB. The convective envelope deepens and the models show that in the stars at the Li-rich clump, it has not reached its maximum depth. Our hypothesis speculates that it is at this phase that an extra-mixing episode can most easily connect the ^{3}He-rich envelope with interior temperatures hot enough to fuel the Cameron & Fowler (1971) process, and this is precisely what the observations suggest occurs. However as soon as the convective envelope reaches regions which have been modified by nuclear processing, a new molecular weight barrier is established, and the extra-mixing episode should stop. We point to several observational aspects which are consistent with our hypothesis. First, Li-rich early-AGB stars have not been detected at higher luminosities where the molecular weight gradient would be re-established (above the asterisked points in Fig. 1). Second, although improved statistics would be valuable, we note that the Li abundances in these stars are lower than in the low mass RGB bump stars consistent with their smaller ^{3}He reservoir. Finally, the Li-rich early-AGB stars appear to be confined to masses $<$ 4.5 M$_\odot$; in stars of higher mass, the hydrogen-burning shell is extinguished by the deepening convective zone and therefore ^{7}Li production will not be predicted to occur according to our hypothesis.

Other surface abundance changes are expected to be induced by this event for the elements processed in the hydrogen-burning shell and these remain to be studied. In particular, the ^{12}C/^{13}C ratio may be modified. This value has been determined in three stars. In HD 787 and HD 30834 (which have masses of 4 and 4.5 M$_\odot$ respectively), the ^{12}C/^{13}C ratio is only marginally different from the values predicted by standard dredge-up for this mass range. This confirms that these stars did not undergo extra mixing on the RGB. On the other hand, HD 39853 has a significantly lower carbon isotopic ratio, and is also the most Li-rich object of this group. However at 1.5 $M_{\odot}$, it is also the only low-mass, relatively metal-poor ([Fe/H]=-0.46) star in this group and it must have gone through the RGB bump phase. Its low carbon isotopic ratio of 7 is in agreement with the values observed in low mass RGB stars with the same metallicity which have already gone through the bump (Charbonnel et al. 1998), and is certainly a signature of the first extra-mixing episode. We suggest that HD 39853 is actually a unique object in the sample since this star is undergoing Li production for the second time in its evolution.

4.5. Li-rich giants in open and globular clusters

Three Li-rich giants have recently been discovered in one open and two globular clusters, namely Berkeley 21 (Hill & Pasquini 1999), M3 (Kraft et al. 1999) and NGC 362 (Smith et al. 1999).

Berkeley 21 is a relatively metal-poor open cluster ([Fe/H]=-0.54) with an age of about 2.2 to 2.5 Gyr (Tosi et al. 1998) and a corresponding turnoff mass of about 1.4$M_{\odot}$. Hill & Pasquini (1999) observed three giants in Berkeley 21. All three are located in close proximity to each other on the HR diagram and only one was found to be Li-rich with a near-meteoritic Li abundance; the other two have Li upper limits of log N(Li) $<$ 0.5. The He-burning clump is evident on the color-magnitude diagram of Berkeley 21, and the observed giants are about 0.8 mag brighter than the clump (Tosi et al. 1998; Tosi, private communication). Theoretical models (Charbonnel et al. 1996) place the bump at about 0.5 mag above the red-giant clump. Therefore all 3 giants are consistent with being low-mass stars at or evolved slightly past the luminosity bump. The Li-rich star has a low carbon isotopic ratio (Hill, private communication). We suggest that this star is either on the RGB in which case it must have had a much higher peak Li abundance which has since been depleted, or it has evolved off the core-He burning clump and is undergoing a second Li-rich episode, similar to HD 39853.

The two Li-rich giants in the globular clusters M3 and NGC 362 are not as easily explained. The stars are bright, putting them either near the tip of the RGB or in the early-AGB phase. However, unlike the early-AGB stars discussed in §4.4, in these low-mass stars with very low metallicity the second dredge-up is particularly shallow. Therefore, mixing would have to be extremely efficient to bridge the gap between the base of the convective envelope and the hydrogen- burning shell. At this stage, we shall not attempt to compartmentalize the globular cluster stars with the two classes as that is not easily done yet. The discovery of additional Li-rich giants in globular clusters should provide further clues to the nature of these stars.

5. Li-enrichment mechanisms

Our study does not endorse any triggering mechanism for the extra-mixing. However, in the light of the data we have collected in this study we offer some insights into the various mechanisms suggested in the literature. We caution that in the final analysis, these enrichment mechanisms remain inconclusive.

5.1. Rotation

Rotation leading to meridional circulation, or differential rotation leading to turbulence have been regarded as the prime mechanisms for extra-mixing (Sweigart & Mengel 1979, Charbonnel 1995). Fekel & Balachandran (1993), for example, suggested that angular momentum may be dredged-up from the stellar interior along with ^{7}Li-rich material during the process in which a Li-rich giant is created. We looked for a possible correlation between Li enrichment and rapid rotation in the data. Of the stars near the RGB bump, HD 219025 and HD 233517 have large rotational velocities of 25 and 18 km s^{-1} respectively. However the Li-rich giants HD 9746 and HD 112127 have smaller rotational velocities of 8.7 and 1.2 km s^{-1} respectively and two stars which we claim have undergone only normal depletion, HD 31993 and HD 33798, also have large rotational velocities of 31 and 29 km s^{-1} respectively. Although there is no clear correlation between Li abundance and rotational velocity in the stars near the RGB bump, perhaps none is expected if Li enrichment and angular momentum dredge-up proceed at different timescales. For example, the dredge-up of angular momentum may not be hindered by the mean molecular weight gradient as the material mixing is. Without clear insight into the associated physical processes further conclusions may not be drawn.

5.2. Mass loss

In a series of papers, de la Reza and collaborators (de la Reza et al. 1996, de la Reza et al. 1997) have suggested that all low-mass stars go through one, possibly several, Li-enrichment episodes each of which is accompanied by a mass-loss event. This hypothesis was based on their finding that a majority of the Li-rich giants have far-infrared color excesses as measured from IRAS fluxes. The reader is referred to the original papers for further details. Although no triggering mechanism for the Li-enrichment process was suggested, the mass-loss scenario, if real, may provide leads for future investigations. In this context, we make the following observations. De la Reza et al. (1996) noted that several Li-rich giants had 60-25 micron excesses (see their Fig. 2). Among these are HD 108471 and HD 120602 which are undergoing standard first dredge-up and HD 31993 which has completed standard first dredge-up; these are not Li-rich. Of the early-AGB stars, HD 787 and HD 39853 and HD 121710 show no evidence of a dust shell, while HD 30834 and HD 146850 do. Fekel & Watson (1998) and Jasniewicz et al. (1999) independently obtained Li abundances in stars known to have far-infrared excesses and found none to be Li-rich. Although some Li-rich stars certainly have a far-infrared excess, and HDE 233517 is an example, there is no one-to-one correlation as hypothesized by de la Reza et al.

5.3. *Planet accretion*

Several studies (Alexander 1967, Brown et al. 1989 and most recently, and in most detail, Siess & Livio 1999) studied the accretion of a planet or a brown dwarf by an RGB star to produce a Li-rich giant. The reader is referred to these papers for details of the accretion process. There are several inconsistencies that make it unlikely that the observed Li-rich giants are made by this process. First, the accretion scenario encounters some problems in reproducing the very high log N(Li) values (i.e., ≥ 2.8), for which the authors have to invoke anyway an extra-mixing process (which could be triggered by the instabilities related to the accretion). Also, the accreted matter would result in a simultaneous enhancement of ^{6}Li, ^{7}Li and Be. Castilho et al. (1999) have shown that four Li-rich giants show no evidence of Be-enrichment. And Balachandran et al. (2000) have shown that the Li abundances derived from the resonance and excited Li I features in the Li-rich giants HDE 233517 and HD 9746 are matched only when ^{6}Li is not included in the synthesis, i.e., ^{6}Li is depleted in these stars. In addition to these chemical disagreements, planet accretion should be more easily achieved when the star is further up the RGB and has a larger radius, and the Li-enrichment at this phase should be larger as the convective zone is less deep. Yet, no Li-rich stars are seen between the RGB bump and the RGB tip. All of these factors combine to suggest that the accretion of a planet leading to the formation of a Li-rich giant may be very rare indeed.

5.4. *Deep circulation model*

There is little disagreement among the various studies, that if ^{7}Li is indeed manufactured in the Li-rich giants, it must occur by the Cameron & Fowler (1971) process. Sackmann & Boothroyd (1999) have recently suggested an ad-hoc two stream "conveyor-belt" circulation model, for circulating the ^{3}He-rich envelope of the red-giant to the H-shell burning temperatures to achieve ^{7}Be production. In their model, the depth of the extra-mixed region is related to a parametrized temperature difference up to the bottom of the hydrogen-burning shell. They demonstrate that certain assumptions, which depend critically on the mixing speeds and geometry of the ascending and descending streams, as well as the episodic nature of the mixing process, could lead to Li creation along the RGB with abundances in excess of log N(Li)=4. In particular, high Li enrichment was obtained when mixing was continuous along the RGB and this simultaneously led to a smooth decrease of surface ^{12}C/^{13}C ratio; the observed low values of surface ^{12}C/^{13}C are only reached at the tip of the RGB.

In contrast to their predictions that Li-rich giants would be produced all along the RGB, we have noted finding only a single clump at the luminosity bump phase of the low-mass stars and a second clump in the early-AGB phase of low and intermediate-mass stars. Furthermore, the predicted behavior of the ^{12}C/^{13}C ratio in the models differs from the observations, which show that the ^{12}C/^{13}C drops sharply just beyond the bump and then stays constant at a value that depends on the stellar mass and metallicity (see Charbonnel et al. 1998). Sackmann & Boothroyd's "evolving" models are thus not sustained by the observations. Rather, the observed behavior is better simulated by the single short lived mixing episode of Sackmann & Boothroyd (1999) under the assumption of a particularly fast stream. Of course, the driving force behind the stream remains a mystery.

6. Conclusions

On the basis of their position on the HR diagram, we are able to separate the so-called Li-rich giants into three different groups. The first group consists of normal stars which have only recently started lithium dilution, or have normal post-dilution lithium abundances, and are thus mis-labelled as Li-rich. The second group contains low-mass stars at the luminosity bump on the RGB. The third group contains low and intermediate-mass stars in the early-AGB phase. The second and third groups support our hypothesis that Li-rich stars are formed by an extra-mixing process which is effective when the convective zone is in close proximity to the hydrogen-burning shell and when the two regions are not separated by a strong gradient of molecular weight. Li production will be followed by a decrease in the ^{12}C/^{13}C ratio as the material mixes to deeper layers. When this occurs the freshly synthesized Li will be steadily destroyed. Other elements processed in the hydrogen-burning shell may be affected and this remains to be studied. As the Li production phase is short and these stars have only a moderate mass loss rate, they are not expected to contribute significantly to the Li enrichment of the ISM.

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