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Lithium abundance and mass

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Abstract. Observations of cool giants have shown that there exists a large range in their lithium abundances even for apparently similar stars. The depletions are large in a majority of them, far in excess of the predictions of the standard stellar evolution models. In order to explore whether the large spread in Li abundances observed in giants can be interpreted in terms of mass, moderately high resolution CCD spectra of the Li I line at 6707.8 Å have been obtained in 65 subgiants, giants and supergiants and the lithium abundances derived. Their absolute magnitudes have been estimated from the Hipparcos data. Absolute magnitudes have also been determined for another 802 stars whose lithium abundances are already known from the available literature. All these stars have been plotted on the HR diagram and compared with the theoretical evolutionary tracks of Bressan et al. (1993) with initial masses ranging from 1 $M_{\odot}$ to 9 $M_{\odot}$ for a chemical composition typical of the solar neighbourhood: X=0.70, Y=0.28, Z=0.02. The stars of low mass of this sample, ($<2M_{\odot}$), span a wide range in evolution (unmixed warm subgiants and mixed giants) and therefore, show a correspondingly wide range of Li abundances, perhaps reminiscent of the large range in abundances observed on the main sequence. The spread is further augmented by the effects of increasing dilution and mixing as the stars evolve to the right and up the red giant branch. Higher mass stars show a different behaviour. Many of the giants of masses between 2.5 and 4.0 $M_{\odot}$ observed in the present study have Li abundances close to what is predicted by the standard stellar models. On the other hand, there are several high mass giants ($>$2.5 $M_{\odot}$) cooler than T_{eff} = 5000 K with Li abundances as low as those of low mass stars of similar effective temperature. There must be parameters other than mass and evolutionary status, as implied by the standard evolution model of a star, that control its Li abundance.

Key words: stars: abundances – stars: late-type

1. Introduction

Lithium survives only in the outer 2–3% of the stellar mass of a main sequence (hereafter MS) star where the temperature is lower than 2.5×10^6 K, below which lithium burns through the reaction ^{7}Li(p,α)^{4}He. As the star evolves to the red giant phase, the convective envelope gradually deepens and dilutes this Li-preservation zone with the Li-depleted material from below. The observed lithium abundance in such a star depends upon the surface lithium retained in its MS progenitor and the mass fraction incorporated into the convective envelope of the red giant. Stellar model calculations (Iben 1965, 1967a,b) predict that the surface dilution of Li varies from about a factor of 28 in a $1M_{\odot}$ star to 60 in a $5M_{\odot}$ star. The maximum Li abundance observed in red giants should therefore represent that of MS progenitors which have retained all of their initial Li abundance of log N(Li)=3.3. Any depletion of surface Li during the pre MS or MS phases will of course result in a smaller red giant abundance. Past observations of cool giants have shown a large range in lithium abundances, as large as 3 to 4 orders of magnitude (Lambert, Dominy & Sivertsen 1980, Luck & Lambert 1982, Brown et al. 1989, Randich et al. 1993, 1994; Mallik 1998). Although there are a handful of Li-rich giants, most of them have severe depletions, far in excess of Iben's calculations. In order to understand the reasons for the low Li content in giants, it is worth recapitulating briefly the behaviour of Li in MS stars since the Li abundance in a red giant is dependent upon the Li abundance of the progenitor MS star.

Past observations of the MS stars have strongly suggested that there is some destruction of lithium on the MS and that this destruction, at odds with the prediction of the standard model, is a function of mass and age (Herbig 1965, Herbig & Wolff 1966, Zappala 1972). A definite trend of decreasing abundance with decreasing mass is seen on the main sequence for spectral types later than F2. During a reanalysis of the stars with normal metallicity and a narrow range of T_{eff} and of mass from Duncan's (1981) sample of field F5-G5 dwarfs, Spite & Spite (1982) find that the repartition of the ages is not significantly different in the Li-rich and the Li-poor groups of stars. Statistically, the Li-rich stars are not any younger than the Li-poor stars, suggesting that there is no direct relation between lithium abundance and age on the MS, and that other mechanisms possibly are at play. Pasquini et al. (1994) also reiterate from their study that Li is not a good tracer of age for the solar type stars. There are several stars with high Li content but apparently old age. Li depletion on the MS is not explained by the standard model and is generally supposed to be due to one or the other of the processes like diffusion, slow mixing, rotational mixing, enhancing the effect of the classical convection but these additional processes are not expected to be identical in all stars, and therefore it is normal to find different Li in MS stars of the same age and mass. It is only in the mean that Li is lower in older stars. The MS Li depletion is also amply evidenced by the comparative study of the Pleiades and Hyades clusters (Duncan & Jones 1983, Soderblom et al. 1993, Thorburn et al. 1993). There exists a large scatter at a given spectral type in a cluster, in particular, in the Pleiades. This scatter is hard to explain if we believe all stars of the cluster are formed roughly at the same time. The persistence of this scatter suggests Li depletion is not dictated by age and mass alone. In the old open cluster M 67 stars of the same mass do not all have the same Li abundance. The basic finding is that the standard stellar model does not adequately account for the observed lithium abundances in MS stars. It does not predict MS depletion of Li in any except the coolest dwarfs ($T_{eff} < 4000$ K) because the bottom of the convection zone remains cooler than the lithium-burning temperature in the hotter stars. Yet, in stellar clusters, lithium abundances are observed to decrease in stars from spectral types earlier than F5 to later types, suggesting that the convective mixing is aided by non-standard mixing processes. Low mass giants (<2.0 $M_{\odot}$) are, therefore, expected to have statistically smaller surface abundances than their maximum predicted value of log N(Li)$\sim$1.8. This will be even more true of the stars located in the domain of the 'Boesgaard-Tripicco dip' (Balachandran 1995b). Since MS stars of spectral type earlier than F2 appear to retain their initial Li abundance, higher mass giants (2–5 $M_{\odot}$) are expected to have Li abundances near their maximum predicted value of log N(Li)=1.5$\pm$0.3.

Lambert, Dominy & Sivertsen (1980) in their study of Li in 50 G and K giants found really low abundances: $-1.0 \leq$ log N(Li) $\leq$ +1.0. The same is revealed in the study of 644 giants by Brown et al. (1989); bulk of them have $-1.5 \leq$ log N(Li) $\leq$ +1.0. Only 10 stars among them were found to be Li-rich with log N(Li) close to +2.0 and higher. Severe Li depletions were also observed in 31 giants and supergiants by Luck & Lambert (1982): $-0.89 \leq$ log N(Li) $\leq$ +0.84. Pallavicini et al. (1992), Fekel & Balachandran (1993), Randich et al. (1993, 1994) and Mallik (1998) have observed a fairly large number of chromospherically active and 'normal' giants to investigate whether chromospheric activity plays an important role in determining the lithium abundance. They find significant amounts of Li (*i.e.*, in excess of log N(Li)=1.0–1.5) only in a fraction of the stars surveyed. Activity seems neither a necessary nor a sufficient condition for Li excess in these cool evolved stars. A large range in Li abundances is observed in these stars too, over 2 to 4 orders of magnitude. Bulk of them are heavily depleted. One needs to explain on the one hand, a small fraction of giants that are Li-rich (log N(Li) $\geq$ 1.0) and on the other hand, the rest of them that have severe Li depletions. Randich et al. (1993, 1994) have found no obvious dependence on activity parameters nor on rotation. They contend that cool giants with a larger amount of lithium have evolved from the more massive progenitors and that the range of abundances has its origins in the MS stage itself. A detailed analysis by Luck & Lambert (1982) of G, K and M giants and supergiants also bear out the conclusion that the Li abundance in these stars is primarily controlled by the stellar mass.

The Hipparcos Catalogue (ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200) has made available accurately determined parallaxes and therefore, absolute magnitudes for a large number of stars and it is now possible to estimate their masses on an evolutionary diagram. With this in mind, the observation and analysis of a sample of 65 subgiants, giants and supergiants have been undertaken in order to investigate the relation between mass and the Li abundance. The discussion of the data has been enlarged by taking advantage of the information on lithium abundances of another 802 subgiants, giants and supergiants available in the literature (Lèbre et al. 1999, Balachandran 1990, Luck 1977, Pallavicini et al. 1987, Lambert, Dominy & Sivertsen 1980 and Brown et al. 1989). We thus present a study of a total of 867 stars to explore the connection between Li abundance and mass. Although the sample is not homogeneous, its largeness has helped establish statistically significant trends. The observations and the data reduction of the sample observed presently are described in Sect. 2, followed by analysis and the results in Sect. 3. Sect. 4 gives the interpretation and the discussion of the results. Sect. 5 contains the conclusions.

2. Observations and Data reduction

For the current observations, 38 stars were chosen out of the sample of 49 stars observed earlier by Mallik (1998). Another 27 subgiants and giants were sampled from the Bright Star Catalogue (Hoffleit 1982) and the [Fe/H] Catalogue of Cayrel de Strobel et al. (1997), 17 of which form a part of another lithium program. Table 1 lists the relevant stellar parameters for the 65 program stars. The Hipparcos Catalogue contains very accurate astrometric data giving absolute trigonometric parallaxes for stars with a precision of around a milliarcsecond and accurate broad-band photometric data giving apparent visual magnitudes with a precision typically around 0.002 magnitude. From these data the absolute visual magnitudes for all the above stars have been estimated and converted into luminosities using the bolometric corrections from Flower (1996). These are tabulated in Column 8. The error in log L/$L_{\odot}$ obtained above is within $\pm$ 0.08. Since the distances for a large majority of stars are within 100 pc, the reddening corrections are deemed inconsequential and hence are not taken into account. Columns 6 and 7 list the apparent visual magnitude and the parallax (in milliarcseconds) respectively. Columns 3 and 4 give the spectral type and B$-$V of the star, obtained from the Bright Star Catalogue and the [Fe/H] Catalogue. Column 5 lists T_{eff} derived from the T_{eff}-(B$-$V) calibration of Flower (1996). These values are remarkably close (within $\pm$ 50 K) to the T_{eff} values obtained from the calibrations of Schmidt-Kaler (1982) and Bohm-Vitense (1981). Log g and [Fe/H] listed in Columns 9 and 10 respectively have been taken from the [Fe/H] Catalogue of Cayrel de Strobel et al. (1997) and the microturbulent velocity ξ_t in Column 11 from

Table 1. Stellar parameters and lithium abundances

HR	Name	Spectral type	B−V	T_{eff}(K)	m_v	parallax (mas)	log L/$L_\odot$	log g	[Fe/H]	ξ_t ($km sec^{-1}$)	Li I (mÅ)	log N(Li)
834	η Per	K3 Ib	1.69	3493	3.77	2.45	4.544	1.00	−0.15	2.5	≤29	≤ −0.12
1023	-	G5 III	0.86	5136	6.37	2.92	2.517	2.30	-	-	210	2.93
1030	o Tau	G6 III	0.89	5068	3.61	15.42	2.191	2.75	−0.15	2.6	6	0.50
1411	θ^1 Tau	K0 IIIb	0.99	4862	3.84	20.66	1.893	3.17	+0.04	2.0	21	0.81
1457	α Tau	K5 III	1.54	3906	0.87	50.09	2.709	0.55	−0.16	1.9	37	0.02
1464	ν^2 Eri	G8 IIIa	0.98	4883	3.81	15.62	2.145	2.92	−0.09	2.2	15	0.66
1580	o^2 Ori	K2 III	1.15	4569	4.06	19.26	1.980	2.56	−0.26	2.1	16	0.30
1784	29 Ori	G8 III	0.96	4922	4.13	18.71	1.848	2.24	−0.19	1.8	13	0.62
1829	β Lep	G5 II	0.82	5231	2.81	20.49	2.232	2.10	+0.05	3.2	6	0.86
1907	ϕ^2 Ori	K0 III	0.95	4943	4.09	28.10	1.509	2.46	−0.53	1.7	16	0.74
2035	δ Lep	G8 III-IV	0.99	4862	3.76	29.05	1.656	2.95	−0.75	1.9	13	0.61
2040	β Col	K2 III	1.16	4553	3.12	37.94	1.748	2.80	+0.13	1.8	71	1.04
2134	1 Gem	G7 III	0.87	5114	4.16	21.64	1.668	3.18	−0.01	2.0	25	1.14
2216	η Gem	M3 III	1.6	3773	3.31	9.34	3.427	1.50	-	3.0	≤58	≤0.17
2269	-	K3 Ib	1.61	3748	5.67	5.95	2.565	1.13	−0.07	10.0	114	0.46
2286	μ Gem	M3 IIIab	1.64	3664	2.87	14.07	3.440	1.00	+0.11	1.9	≤126	≤0.75
2473	ϵ Gem	G8 Ib	1.40	4209	3.06	3.61	3.928	0.80	−0.05	2.9	35	0.44
2574	θ CMa	K4 III	1.45	4070	4.08	12.94	2.493	1.80	−0.37	1.7	22	−0.32
2580	o^1 CMa	K2 Iab	1.73	3339	3.89	1.65	5.345	0.00	−0.11	3.5	≤155	≤0.93
2646	σ CMa	K7 Iab	1.73	3339	3.49	2.68	5.085	1.00	+0.00	3.0	≤133	≤0.75
2650	ζ Gem	G0 Ib	0.79	5307	4.01	2.79	3.465	1.90	+0.33	3.0	20	1.59
2927	25 Mon	F6 III	0.47	6409	5.14	16.11	1.431	3.21	+0.44	2.5	7	1.76
2973	σ CMa	K1 III	1.12	4622	4.23	26.68	1.596	2.40	−0.30	1.7	35	0.66
2985	κ Gem	G8 IIIa	0.93	4984	3.57	22.73	1.893	2.90	−0.16	3.8	22	1.08
2990	β Gem	K0 IIIb	1.00	4843	1.16	96.74	1.639	2.75	−0.04	1.5	21	0.83
3323	o UMa	G5 III	0.80	5282	3.35	17.76	2.137	2.67	−0.21	0.8	14	1.20
3477	-	G5 III	0.87	5114	4.05	14.27	2.058	2.50	−0.03	1.5	12	1.14
3482	ϵ Hya	G5 III	0.68	5620	3.38	24.13	1.823	3.02	−0.14	2.0	30	1.74
3518	γ Pyx	K3 III	1.27	4366	4.02	15.63	2.250	2.35	−0.11	2.1	54	0.60
3616	σ^2 UMa	F6 IV	0.49	6324	4.80	48.87	0.602	4.00	+0.02	-	6	1.67
3664	-	G6 III	0.86	5136	5.98	7.17	1.893	2.20	−0.85	1.9	≤12	≤1.16
3775	θ UMa	F6 IV	0.43	6587	3.17	74.15	0.886	4.09	−0.20	2.1	100	3.32
4069	μ UMa	M2 IIIab	1.59	3797	3.06	13.11	3.131	1.35	+0.00	2.1	≤124	≤0.70
4232	ν Hya	K2 III	1.25	4399	3.11	23.54	2.238	2.32	−0.30	2.1	13	−0.09
4310	χ Leo	F2 III-IV	0.33	7063	4.62	34.54	0.964	-	-	-	25	2.77
4382	δ Crt	K0 III	1.12	4622	3.56	16.75	2.268	2.59	−0.48	2.2	2	−0.61
4450	ξ Hya	G7 III	0.94	4963	3.54	25.23	1.813	2.93	−0.04	2.1	34	1.27
4608	o Vir	G8 IIIa	0.97	4902	4.12	19.08	1.845	2.34	−0.33	2.0	28	1.23
4786	β Crv	G5 II	0.89	5068	2.65	23.34	2.215	2.20	+0.27	3.2	26	1.18
4910	δ Vir	M3 III	1.58	3821	3.39	16.11	2.819	1.30	−0.09	2.3	≤160	≤0.95
4932	ϵ Vir	G8 IIIb	0.94	4963	2.85	31.90	1.885	2.70	+0.10	2.0	12	0.81
5017	20 CVn	F3 III	0.30	7216	4.72	11.39	1.886	3.00	+0.18	0.9	6	2.35
5176	-	K2 III	1.35	4234	5.46	7.18	2.414	1.10	−0.80	1.8	≤3	≤ −1.00
5185	τ Boo	F6 IV	0.48	6366	4.50	64.12	0.488	4.30	+0.00	1.0	8	1.93
5235	η Boo	G0 IV	0.58	5964	2.68	88.17	0.954	3.83	+0.19	2.2	15	1.85
5338	ι Vir	F7 IV	0.50	6282	4.07	46.74	0.937	3.94	−0.11	2.1	5	1.58
5409	ϕ Vir	G2 IV	0.70	5559	4.81	24.15	1.259	3.90	+0.00	2.0	89	2.39
5744	ι Dra	K2 III	1.16	4553	3.29	31.92	1.848	2.74	+0.03	1.5	19	0.37
5889	δ Crb	G3.5 III	0.80	5282	4.59	19.71	1.550	3.15	−0.32	2.1	20	1.36
5908	θ Lib	G8.5 IIIb	1.02	4806	4.13	20.02	1.832	2.99	−0.31	1.6	11	0.52
5986	θ Dra	F8 IV	0.52	6198	4.01	47.79	0.942	4.13	+0.20	1.7	4	1.49
6212	ζ Her	G0 IV	0.65	5717	2.81	92.63	0.874	3.80	+0.05	0.9	≤7	≤1.05
6536	β Dra	G2 Ib-II	0.98	5016	2.79	9.02	3.008	1.60	+0.14	1.9	8	0.70
6569	λ Ara	F3 IV	0.40	6725	4.76	45.72	0.666	4.15	−0.27	2.3	20	2.53
6623	μ Her	G5 IV	0.76	5386	3.42	119.05	0.437	3.70	+0.04	2.6	8	1.13
6703	ξ Her	G8 III	0.94	4963	3.70	24.12	1.789	2.92	−0.10	2.0	45	1.41

Table 1. (continued)

HR	Name	Spectral type	B−V	T_{eff}(K)	m_v	parallax (mas)	log L/$L_\odot$	log g	[Fe/H]	ξ_t ($km sec^{-1}$)	Li I (mÅ)	log N(Li)
6705	γ Dra	K5 III	1.52	3945	2.24	22.10	2.826	1.55	−0.14	2.0	41	0.00
7063	β Sct	G4 IIa	1.12	4622	4.22	4.73	3.104	0.94	−0.15	2.7	50	0.93
7479	α Sge	G1 II	0.78	5333	4.39	6.89	2.532	3.11	−0.15	3.1	10	1.24
7602	β Aql	G8 IV	0.86	5136	3.71	72.95	0.781	3.60	−0.30	1.8	4	0.63
7882	β Del	F5 IV	0.44	6541	3.64	33.49	1.391	3.50	+0.00	-	66	3.00
8465	ζ Cep	K1.5 Ib	1.57	3853	3.39	4.49	3.753	0.75	+0.22	3.0	26	−0.15
8796	56 Peg	G8 Ib	1.36	4280	4.76	6.07	2.756	1.20	−0.15	2.8	51	0.62
8961	λ And	G8 III	1.08	4694	3.81	38.74	1.426	3.11	−0.56	2.0	10	0.07
9103	3 Cet	K3 Ib	1.63	3689	4.99	2.03	3.953	0.80	−0.20	4.5	≤39	≤ 0.48

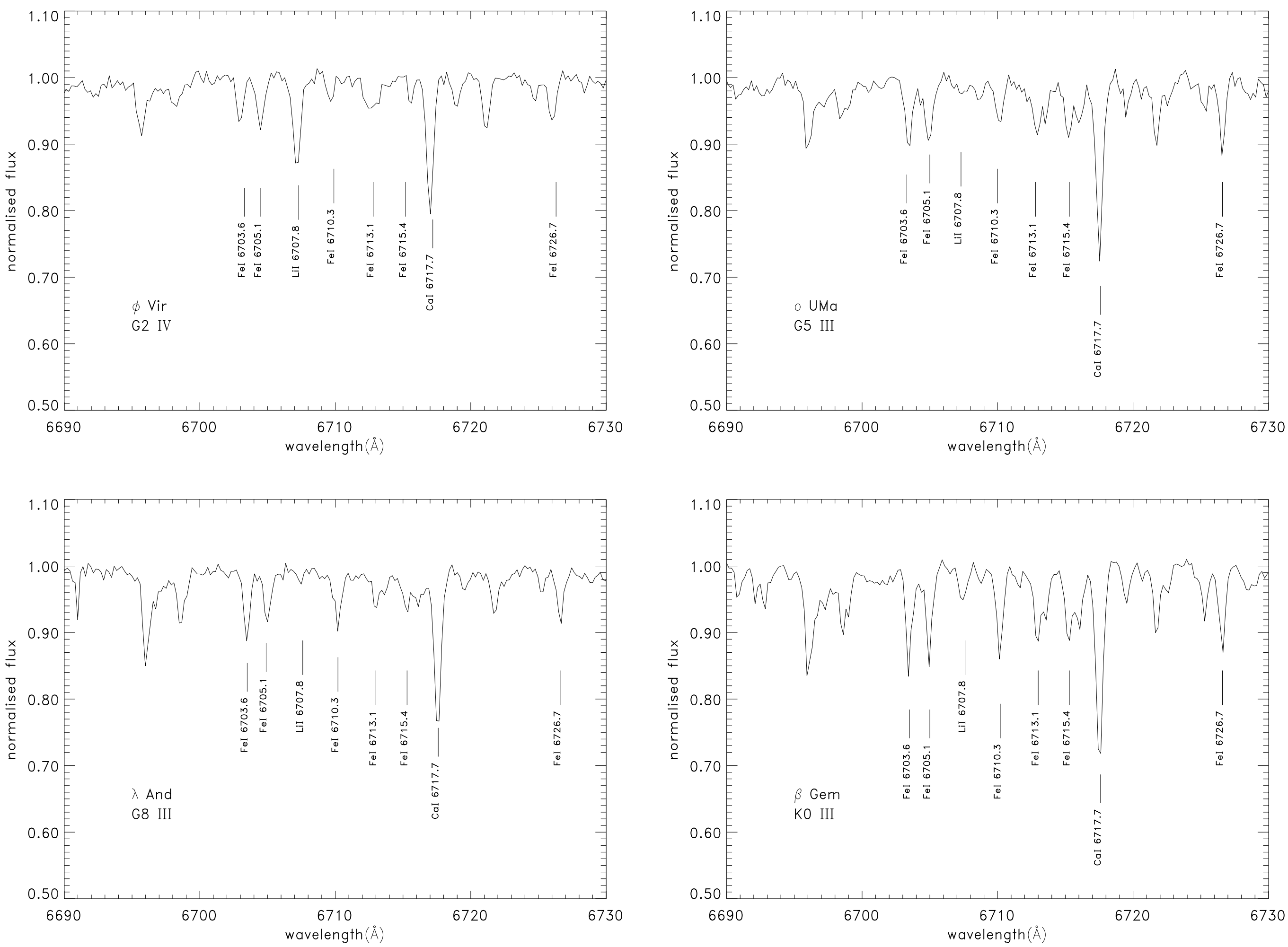

Fig. 1. A few normalised sample spectra in the neighbourhood of the Li I 6707.8 Å line. Note the strong Li line in ϕ Vir and very weak, nearly absent in o UMa and λ And

the individual sources for each star listed at the end of the same catalogue.

The CCD spectra in the region of the Li I line at 6707.8 Å have been obtained of the above stars using the coude echelle spectrograph at the 102 cm telescope at the Vainu Bappu Observatory. These spectra have a spectral resolution of ∼0.35 Å in the 33rd order where the Li I line lies, as also judged by the resolving power of the spectral lines of the Thorium-Argon hollow cathode lamp used for line identification. Xenon lamp was used as a flat source. Several bias, comparison and flat field frames were taken well spaced out in time in between the star frames. Data reduction was carried out with the IRAF software package following exactly the same procedure as described in Mallik (1998). The normalised spectra of 4 sample stars in the neighbourhood of the Li I line are displayed in Fig. 1. The spectral coverage in the 33rd order is around 70–80 Å although the figure here shows trimmed spectra of 40 Å each. The spectra are centered around the λ6707.8 Li I line and include several Fe I lines that were also used for the wavelength calibration. The equivalent width (EQW) of the Li I feature was measured for each star from the normalised spectra. Repeated placements of the continuum and the measurement of the EQW point to errors in the measurement less than 6 mÅ.

3. Analysis and results

The Li I feature is blended with an Fe I line at 6707.445 Å which has a weak contribution in subgiants but becomes fairly strong in supergiants. The contribution of the Fe I line to the Li I feature was estimated by exactly the same procedure as described in detail by Mallik (1998). The calculated EQWs of the Fe I line are typically 5 to 10 mÅ for subgiants and become as high as 50 mÅ for some of the supergiants. The corrected Li I EQWs range from around 5 mÅ to 100 mÅ spanning spectral types from F3 to M3. These are listed in Column 12 of Table 1. The abundance determinations of Li are based on the measurement of the EQW of the Li I line at 6707.8 Å. From the input EQW and the model atmospheres of Gustafsson et al. (1975) and Bell et al. (1976) with the grid generated by Luck (1992), lithium abundances were calculated using LINES (the standard LTE line analysis code due to Sneden 1973, the upgraded version). These are tabulated in Column 13 of Table 1. For a given measured EQW of Li I, the primary uncertainty in lithium abundance arises from its temperature sensitivity. A change in T_{eff} of 200 K changes the Li abundance by a substantial amount of up to 0.3. Accounting for uncertainties arising from T_{eff}, ξ_t and log g, the accuracy in the determination of log N(Li) is expected to be within $\pm$0.20 to $\pm$0.25 dex, given the error in the EQW measurement. Because of the lack of model atmospheres with $T_{eff} < 3750$ K, only the upper limits to the Li abundance could be given for several stars. Upper limits are also given for HR 5176, HR 3664 and 82 Eri either because of the low S/N of their spectra or the extreme weakness of the Li line.

4. Interpretation and discussion

4.1. Lithium abundance and temperature

The observed Li abundances versus the effective temperatures for the sample of 65 stars studied here are depicted in Fig. 2. Subgiants, giants and supergiants are defined here as per the Bright Star Catalogue and the [Fe/H] Catalogue of Cayrel de Strobel et al. (1997). We shall see later from the positions of these stars and the stars of the other samples on the HR diagram based on Hipparcos parallaxes, that quite a few subgiants are actually main sequence stars and similarly several giants turn out to be subgiants or supergiants. The Li abundances span a range of four orders of magnitude. The gradual decline in the lithium abundance as a function of effective temperature is evidence of the increasing dilution due to the deepening of the convective envelope (Iben 1965, 1967a,b). The range observed at a given

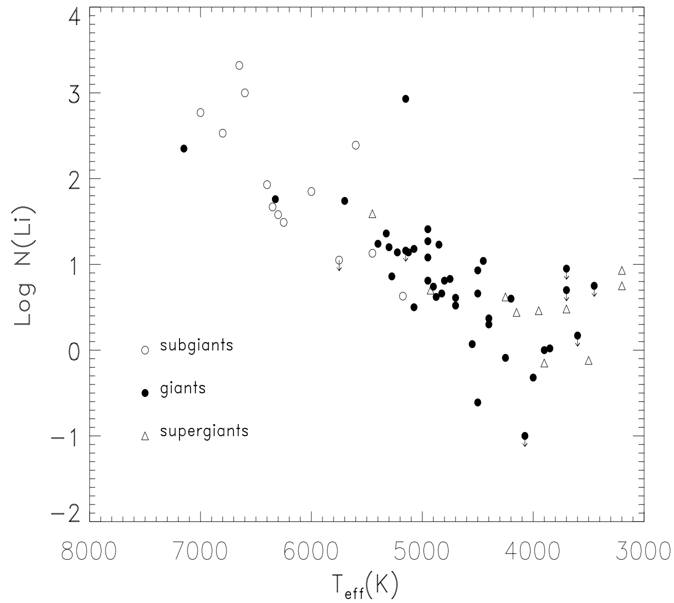

Fig. 2. Lithium abundance vs. effective temperature for stars of Table 1. The symbols described in the key are in accordance with spectral classification. Symbols with arrows pointing downward signify upper limits to the Li abundance

temperature is due to the range in masses and evolutionary ages. Mass loss on the MS and during the red giant phase may also add to the observed range in the Li content. In addition, the vestiges of the Li abundance-mass dependence prevalent in their MS progenitors may also have contributed to the observed spread. Several of the hotter (less evolved) subgiants have log N(Li) close to 3.0. Supergiants appear to be most heavily depleted and giants lie in between encompassing a larger range in Li abundances. As already noted, there are a few giants with log N(Li) close to 1.5 and higher, *i.e.*, in excess of the maximum predicted by the stellar model calculations. In particular, HR 1023, a G5 giant has log N(Li)=2.93, *i.e.*, a factor of 2.7 of the predicted value if the star had undergone standard giant branch mixing. The ‘cool bottom processing’ models of Boothroyd & Sackmann (1999) predict that Li could be synthesized in these giants, the same models also explaining the observations of the $^{12}C/^{13}C$ ratio in these same giants.

4.2. Lithium abundance and mass

Masses are difficult to determine for all stars. Taking into account the error in temperature, masses are particularly less accurate for giants and have to be inferred indirectly. The best way to test the dependence of Li abundance on mass is by plotting stars on the HR diagram with the theoretically calculated evolutionary tracks superposed. The Hipparcos Catalogue has now made available parallaxes to a high accuracy (about a milliarcsecond) and apparent visual magnitudes from an equally accurate photometric analysis of a large number of stars enabling an estimate of distances to an accuracy of better than 10 per cent. The resulting accuracy in log L/$L_\odot$ is better than 0.08. We have combined

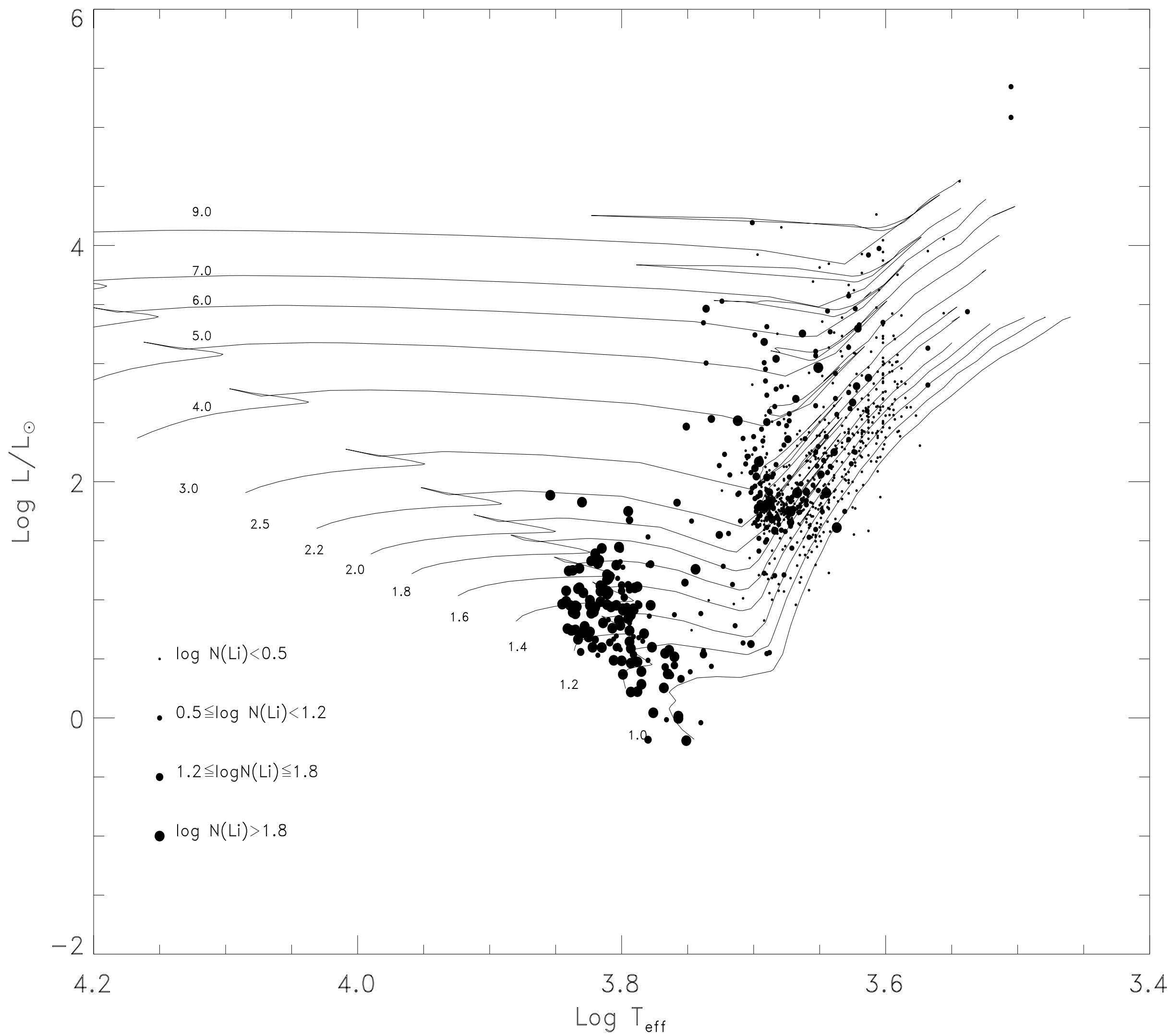

Fig. 3. HR diagram of the entire sample of stars for which absolute visual magnitudes are determined from the Hipparcos data. Symbols of increasing size denote increasing Li abundances. The bins chosen in log N(Li) are indicated in the key. Also shown are theoretical evolutionary tracks of Bressan et al. (1993) for stars of initial masses ranging from 1.0 to 9.0 $M_\odot$.

our data of Li abundances of 65 stars with the already known Li abundance data of another 802 stars: 104 subgiants from Lèbre et al. (1998), 49 subgiants from Balachandran (1990), 38 giants from Lambert, Dominy & Sivertsen (1980), 12 supergiants from Luck (1977), 6 subgiants from Pallavicini et al. (1987) and 593 giants and supergiants from Brown et al. (1989). From the parallaxes and the apparent visual magnitudes given in the Hipparcos Catalogue, the luminosities have been obtained for all the above stars in exactly the same way as for the present sample using the T_{eff} - B.C. calibration of Flower (1996). Since most of these stars have distances less than 100 pc, the reddening effects are assumed negligible. Fig. 3 shows the positions of all the 867 stars on the HR diagram. The stars plotted are subgiants or giants or supergiants based on spectral classifications from several catalogues. However, based on the location on the HR diagram, it is found that a fraction of the subgiants turn out to be very close to the turn-off point or on the main sequence, especially for the lower masses. Similarly, several giants eventually turn out to be subgiants yet to reach the base of the red giant branch and a few of them are supergiants. Symbols of decreasing size indicate decreasing values of the Li abundance. The theoretical evolutionary tracks of Bressan et al. (1993) for masses ranging between 1.0 and 9.0 $M_\odot$ with Population I composition (X=0.70, Y=0.28 and Z=0.02) are also plotted. Two stars on top to the extreme right are supergiants perhaps more massive than 9.0 $M_\odot$. Tracks for masses higher than 9.0 $M_\odot$ are not shown, however. Although our sample is rather inhomogeneous, the principal features of the evolution of the Li abundance in the post main sequence phases of low- and intermediate-mass stars are quite apparent here. Most of the stars hotter than log T_{eff} = 3.78 (bluer than B $-$ V=0.56) are either on the main sequence or evolving off it. They are yet to enter the post main sequence depletion phase and their main sequence Li has been largely preserved. There is a paucity of stars in the range 3.78 $>$ log T_{eff}

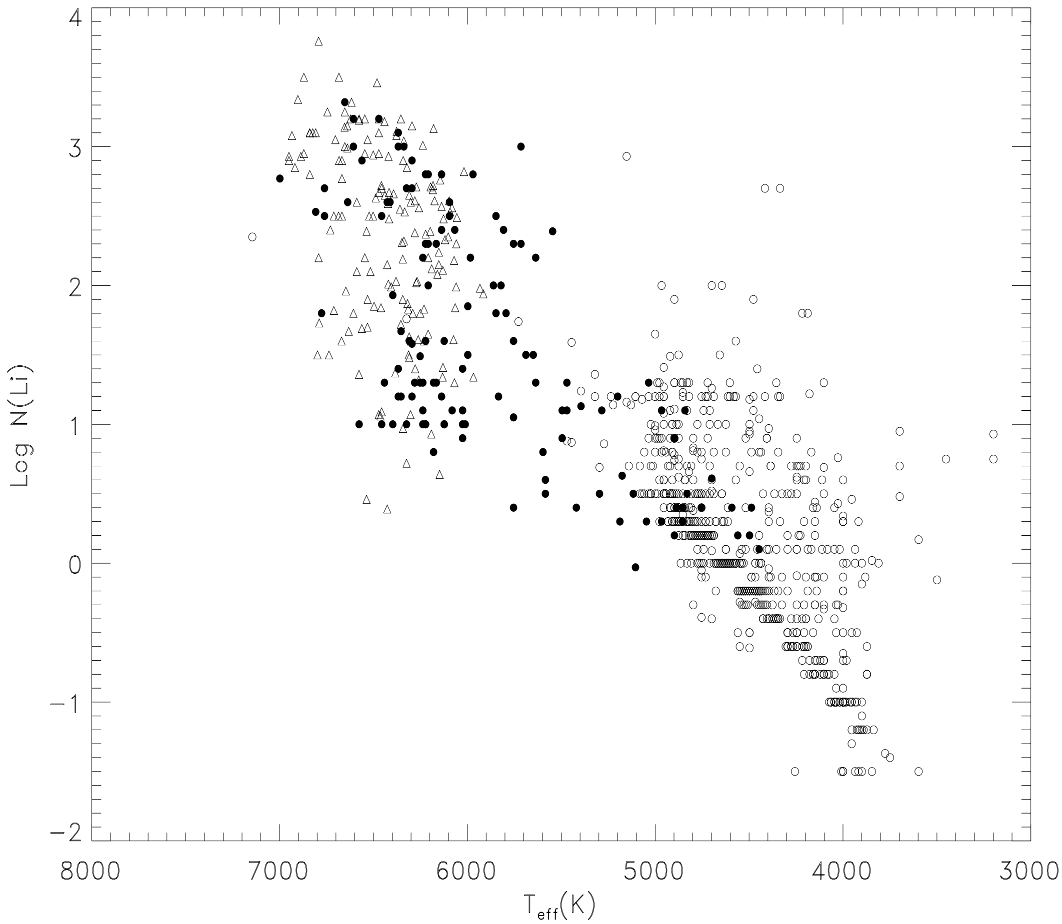

Fig. 4. log N(Li) vs. T_{eff} for all the stars plotted in Fig. 3. In addition, the remaining 140 stars of Balachandran's (1990) sample are shown denoted by triangles representing stars slightly evolved or evolving off the main sequence; filled symbols are the subgiants (our sample, Lèbre et al. 1999, Pallavicini et al. 1987, Balachandran 1990) and the unfilled symbols are the giants and the supergiants (our sample, Luck 1977, Lambert et al. 1980, Brown et al. 1989). The symbols are in accordance with spectral classification.

$>$ 3.70 (0.56 $<$ B$-$V $<$ 0.92) corresponding to the Hertzsprung gap. Depletion as a result of convective dilution is indicated in these stars. The range in abundance observed in these perhaps indicates a large range of it on the main sequence itself. The vast majority of the stars in the sample lie at log T_{eff} $<$ 3.70 and most of them are red giants. On an average Li appears to be severely depleted in these stars. In Fig. 4, we have plotted the Li abundance as a function of T_{eff} for all the stars shown in Fig. 3 plus the rest 140 stars of Balachandran's (1990) sample shown as triangles and defined as the stars just evolved or evolving off the main sequence. This plot permits us to follow the Li evolution as the star evolves along the subgiant branch and up the red giant branch. Following Spite & Spite (1982) and Pasquini et al. (1994), if we believe that MS stars with the same mass and age have different abundances, it is normal to find the corresponding Li spread in the subgiants, as proposed by Randich et al. (1999). Fig. 4 does indeed show that the subgiants exhibit a large spread of Li abundance. It requires a more detailed study of the progenitor sample in the same mass range to confirm whether this spread owes itself to the range of Li depletion obserevd in the MS stars. The trend of decreasing abundance with decreasing T_{eff} as a result of evolution to the right and up the giant branch is both expected theoretically and observed but the extreme low values of log N(Li) as seen in the sample cannot be explained. If one believed that convective dilution were the only reason for this remarkable decrease and used the standard model of stellar evolution (Iben 1967a) to calculate log N(Li) after the first dredge-up, starting from a main sequence value anywhere between 3.3 and 2.0, one would obtain on the giant branch values ranging between 1.8 and 0.22. However, the actual observed values are much lower and in some cases reach log N(Li) =$-$1.5 as seen in Fig. 4. Failure of the standard model in accounting for the Li abundance in red giants is obvious. There must be additional mixing and dilution of lithium taking place on the giant branch and perhaps even on the subgiant branch (see below).

Some more trends are apparent in Fig. 3. Stars of low mass ($< 2M_{\odot}$) span a large range of ages and they display a correspondingly large range in abundances. Among these, stars with the largest Li abundances are also the hottest, the main sequence and the near main sequence stars. Tracing their evolution on the displayed tracks, one notices the onset of dilution in the subgiant phase in or around log T_{eff} = 3.75. The deepening of the convective envelope in them has just begun and the subgiant dilution is very little. Further dilution continues and on the red giant branch (log $T_{eff} < 3.65$), very low abundances are reached. There are very few stars in the sample more massive than $2.0 M_{\odot}$ which are in the warm subgiant category. But a large number is present on the subgiant and the giant branches. High mass giants ($> 2 M_{\odot}$) show a somewhat different behaviour. There are several of them which have preserved their initial lithium to a greater or a lesser extent, which is understandable since in principle no MS depletion is expected in the massive stars (all being earlier than F2). However, there are a large number of giants that have rather low abundances, similar to what is observed in low mass giants, although the stars on the subgiant branch are Li-rich compared to the giants they evolve into. Iben's computations do predict that the dilution is higher in high mass giants. However, the abundances observed are much lower than the maximum theoretical expected value of log N(Li) = 1.5$-$1.8. The low lithium found in giants (both of low and high mass) is now generally attributed to the so-called extra-mixing or second mixing. Indeed, besides Li, there are other signatures of extra-mixing, e.g. the $^{12}C/^{13}C$ ratio. The post-dredge up $^{12}C/^{13}C$ ratios predicted in the framework of standard stellar theory are expected typically in the range 18–26 (Iben 1967, Dearborn et al. 1976). However, these ratios have been observed to be substantially lower in a large fraction of giants observed in open galactic cluster (Gilroy 1989, Gilroy & Brown 1991), as low as 10 in many of them. This gives a clue to the existence of additional mechanisms like extra-mixing. It is worth noting that the point where Li depletion reaches 0.5 is at higher luminosity for higher mass giants. The picture becomes clearer by considering separately subsamples with $T_{eff} < 5000$ K and > 5000 K (log $T_{eff} \sim$3.7).

Fig. 5 displays on a more expanded scale for stars with $T_{eff} > 5000$ K. As stated before, a large concentration of points is seen around the lower mass tracks (M $\leq$ 2.0 $M_{\odot}$) and most of these stars are still to evolve to the red giant branch. One would notice that stars in the bins with log N(Li) $\leq$ 1.4 and 1.4 $<$ log N(Li) $\leq$ 2.0 are concentrated most in the mass range between 1.0–1.4 $M_{\odot}$ whereas in the mass range between 1.4 and 2.5 log N(Li) $>$ 2.0 predominates. There is thus a clear trend of higher Li abundance being associated with stars of higher mass while the less massive stars that have spent longer time on the MS with deeper convection zones have undergone more depletion. The more evolved stars in the diagram clustered to the left of a vertical cut at log T_{eff} = 3.70 have gone through significant post MS evolution and deeper mixing and are consistently lower in Li content independent of mass. Although there are a few stars among these (many belonging to the present sample of 65) with log N(Li) near 1.4, most of them (including o Tau and β Lep of the present sample) have Li abundances already much less than the canonical value of 1.5 $\pm$ 0.3. In a recent study of Population I subgiants with masses less than 2.0 $M_{\odot}$, Randich et al. (1999) find that a large number of stars that have completed the first dredge-up Li dilution but that have not yet evolved to the point where extra-mixing in the giant phase is thought to occur, have Li abundances considerably below the theoretical first dredge-up predictions. They attribute it to their progenitors having depleted Li on the main sequence. It is seen both in Figs. 3 and 5 that the Li spread is mostly apparent between the tracks of the masses 1.4 and 1.2 $M_{\odot}$, *i.e.* exactly for stars which were in the dip during their stay on MS. So that, in agreement with Balachandran (1995b), the present analysis shows the influence of the MS dip on the Li of the subgiants. However, the influence of a spread in the abundances of the progenitors, away from the dip, on the subgiant Li abundance is less clear. Most of the stars of the sample are more massive than the sun, so that the depletion on the MS as well as the spread is expected to be smaller or non-existent. A more systematic thorough study of the detailed data is being conducted to explore whether the subgiant spread is inherited from the progenitors and will be addressed to in a future paper. The more massive subgiants in Fig. 5 are also severely depleted and this is difficult to explain since these are evolved counterparts of main sequence stars of masses greater then 2.0–2.5 $M_{\odot}$ and hence have come from dwarfs earlier than A0. For these also Li is more diluted on the giant branch than predicted. It is fair to say that all studies to date indicate that the observed dilution on the subgiant branch is already rather great and this result is independent of stellar mass. The strong Li depletion found in these stars is often ascribed to non-standard mixing in the post main sequence evolutionary phases which may depend on parameters other than mass.

Fig. 6 presents a detailed view of the cooler stars with $T_{eff} < 5000$ K. It is evident from the figure that the lower mass giants ($< 2.0 M_{\odot}$) encompass a range of Li abundances. The scatter for a given mass is a consequence of the dilution effect - the stars more to the right on the red giant branch are evidently lower in their Li content. Considering the fact that standard convective dilution is essentially complete for the low mass stars at log L/$L_{\odot}$ = 1.5 (Charbonnel 1994), further dilution beyond this point is perhaps a result of extra mixing on the giant branch. The scatter near the base of the red giant branch for the various masses is perhaps reminiscent of the large range in abundances observed in their MS progenitors as has been pointed out by Balachandran (1995a) and more recently by Randich et al. (1999). The majority of the giants have much smaller Li abundances than the predicted maximum of 1.5. It is also striking that almost all giants with M $< 2.0 M_{\odot}$ are depleted, independent of mass and independent of the fact that they were in or out of the Boesgaard- Tripicco dip in their main sequence phase. Possibly, a very large dilution brings all low mass stars towards a low Li abundance, whatever was their MS Li abundance. Even if the MS progenitors of these have undergone Li depletion and Li is further reduced through standard convective dilution, one has to invoke extra mixing to explain such low abundances in these low mass giants.

A closer examination of Fig. 4 reveals that a very large fraction of stars cooler than log T_{eff} = 3.70 (*i.e.* around T_{eff} = 5000 K) have abundances below log N(Li) = 0.5 extending to values as low as log N(Li) = $-$ 1.5. There is a suggestion in the data that at around log T_{eff} = 3.70 a dip in the abundance occurs. In their study of the Population I subgiants, Randich et al. (1999) find evidence of the onset of an extra mixing for the

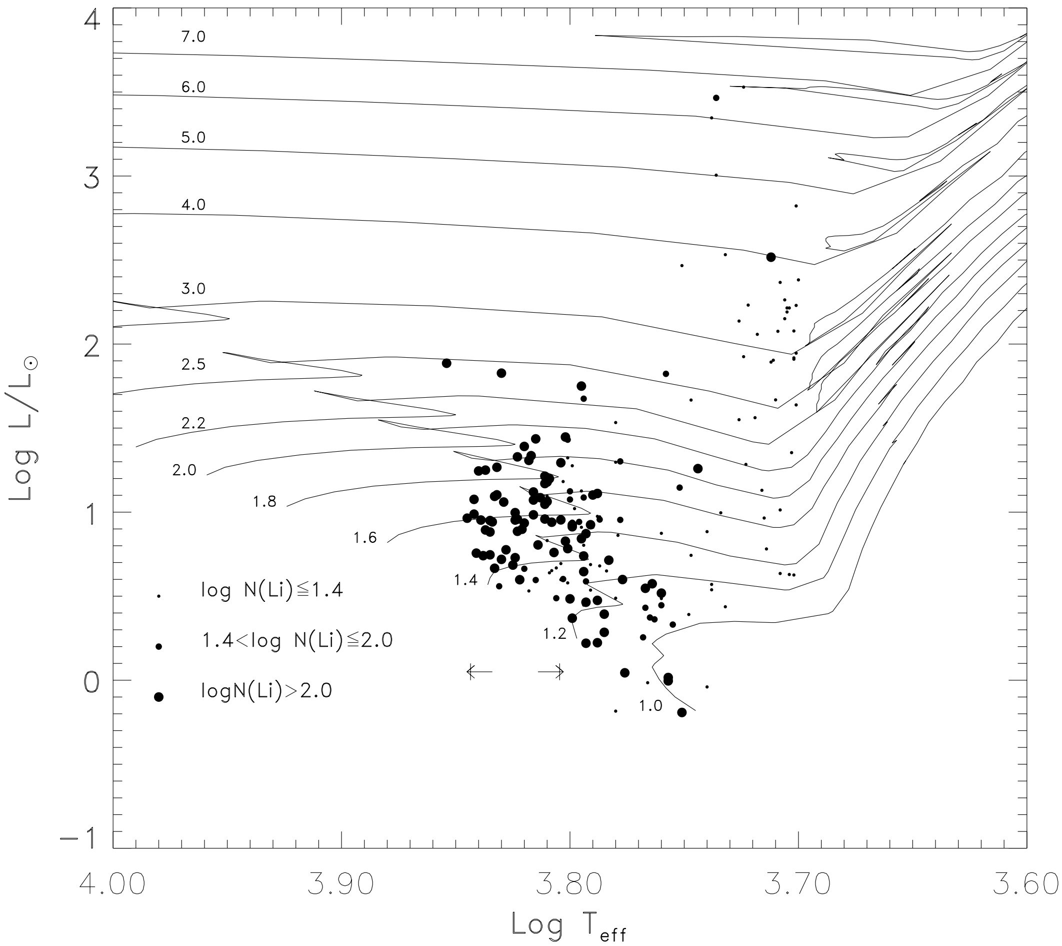

Fig. 5. The same as in Fig. 3 for stars with $T_{eff} > 5000$ K. The bins in log N(Li) are described in the key. The evolutionary tracks are exactly the same as in Fig. 3. The arrows indicate the T_{eff} limits of the Dip.

low mass stars at precisely this location which is due to a contact between the chemical discontinuity left in these stars by the convective envelope at its maximum extent with the hydrogen-burning shell that approaches it from below. The severe depletions observed in these stars are thus perhaps explained by this postulated process.

We also note in Fig. 6 the distinct presence of several high mass stars ($> 2.5\, M_\odot$) with Li abundances as low as those of the lower mass stars of similar effective temperature. Quite the opposite was expected of them since high mass stars are supposed to have evolved from hotter progenitors that should have suffered no Li depletion during their residence on MS. Besides the dilution, characteristic of the giant phase, non-standard mixing is also strongly suspected in these stars. Gilroy's (1989) study of red giants in 20 open clusters with turn-off masses between 1.5 and 5.0 $M_\odot$ also reveals that these giants have Li abundances smaller than the predicted maximum value. As emphasised in the discussion on lithium in giants by Balachandran (1995a), either lithium is more diluted on the giant branch than predicted or the MS progenitors of these must have undergone Li depletion. The second hypothesis thus contradicts the assumption that the MS progenitors of these stars retain Li in the entire standard Li-preservation zone throughout their MS lives and merely dilute it during the red giant phase. Neither the low red giant abundances nor the observed spread within a cluster is predicted by the standard models. In both the hypotheses, a parameter in addition to mass must also affect the observed abundance distribution.

Contrary to the low-mass stars, there are, however, a fair number of higher mass stars with higher lithium content. This could be attributed to a better preservation of Li on the main sequence for these stars. Considering the MS depletion of Li to be a random phenomenon for the more massive stars (for want of any clue why such stars are depleted at all), one would then expect that only about half of them would have suffered depletion and their evolved counterparts then show lower Li on the giant branch than predicted by the standard model. Different Li thresholds in Fig. 6 have been tried in order to see if general inferences depend on the binning of the data. One finds that the general aspect of the data is preserved. It is worth noting in this figure that statistically speaking, there are many more stars with higher lithium content on the higher mass tracks and similarly, many more stars with lower lithium content on the lower mass tracks, thereby suggesting a link between the lithium abundance of a star and its mass. The giants (2–4 $M_\odot$) conglomerated be-

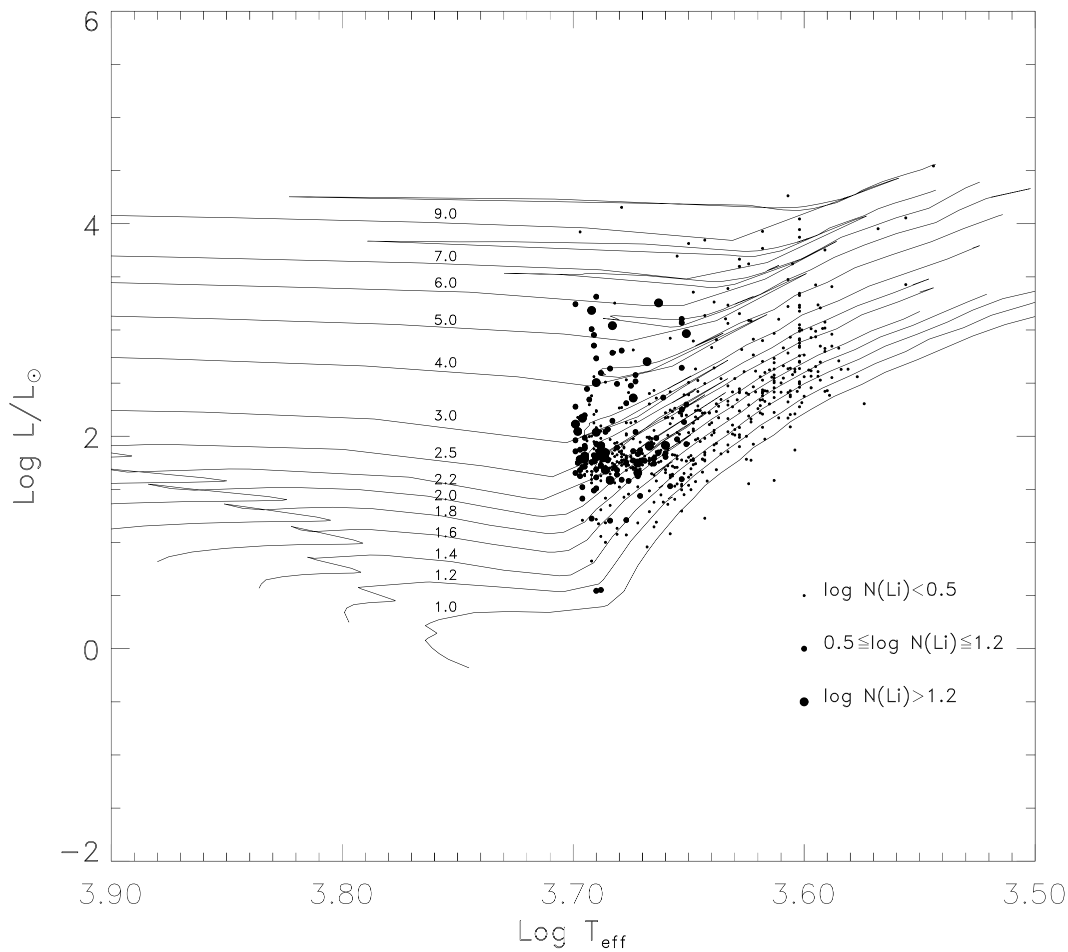

Fig. 6. The same as in Fig. 3 for stars with $T_{eff} \leq$ 5000 K superimposed on the same evolutionary tracks. The bins in log N(Li) are indicated in the key.

tween log T_{eff} = 3.70 and 3.65, for example, have definitely higher Li content than the less massive ones (1.2–1.4 $M_{\odot}$). Fig. 7 displays the same set of stars as in Fig. 6 except that the stars classified as supergiants are now denoted by open circles. As the Ib stars are massive and have MS progenitors of late B spectral type, all observed Li depletion presumably takes place only in the post main sequence phase. Conti & Wallerstein (1969) and Luck (1977) had found Li heavily depleted in F and G supergiants. Heavy depletion has also been observed in K supergiants (Luck 1994).

There are several uncertainties in the above comparison of stars with the evolutionary tracks. The evolutionary tracks for different masses become very close together at temperatures $\leq$ 5000 K. Although the Hipparcos survey gives distances and consequently luminosities of high accuracy (log L/$L_{\odot}$ to within $\pm$ 0.08), an observational error of $\pm$250 K on T_{eff} can easily move a red giant from a low to a high mass track or vice versa. Also, the theoretical tracks themselves depend strongly on metallicity. Fig. 8 shows evolutionary tracks of Bressan et al. (1993) with Z=0.02 and of Fagotto et al. (1994) with Z=0.05. The physical input to the models of both Bressan et al. and Fagotto et al. is exactly the same except the metallicity. The tracks are shown for initial masses 1.0, 1.6, 2.5, 4.0 and 7.0 $M_{\odot}$. The differences are non-negligible.

Besides errors arising from a given choice of T_{eff}, metallicity and to a smaller extent luminosity, there are several other effects which can complicate the interpretation of the data. For the more massive stars ($>$ 2.5 $M_{\odot}$), it is difficult to distinguish whether a star is on its first crossing to the red giant branch or is on the way back during a later evolutionary phase. Further, the effect of mass loss on the evolution for low and intermediate mass stars ($< 12 M_{\odot}$) has not been taken into account in the models of Bressan et al. (1993) and Fagotto et al. (1994). There have been speculations in the past whether mass loss on the MS and during the red giant phase is likely to contribute to the observed range in Li content. Luck (1977) has shown that mass loss on the MS and in the post MS phase before the onset of mixing can have serious consequences on the Li abundance if the mass loss rate is as high as $10^{-8} M_{\odot} yr^{-1}$, because such a substantial amount of mass loss can completely deprive the star of its outermost layers where Li resides. Such high mass loss rates are rarely observed. Considering the sensitivity of Li to mass loss, the time integrated mass loss in any phase of the star before the mixing begins has to be minimal. The low Li

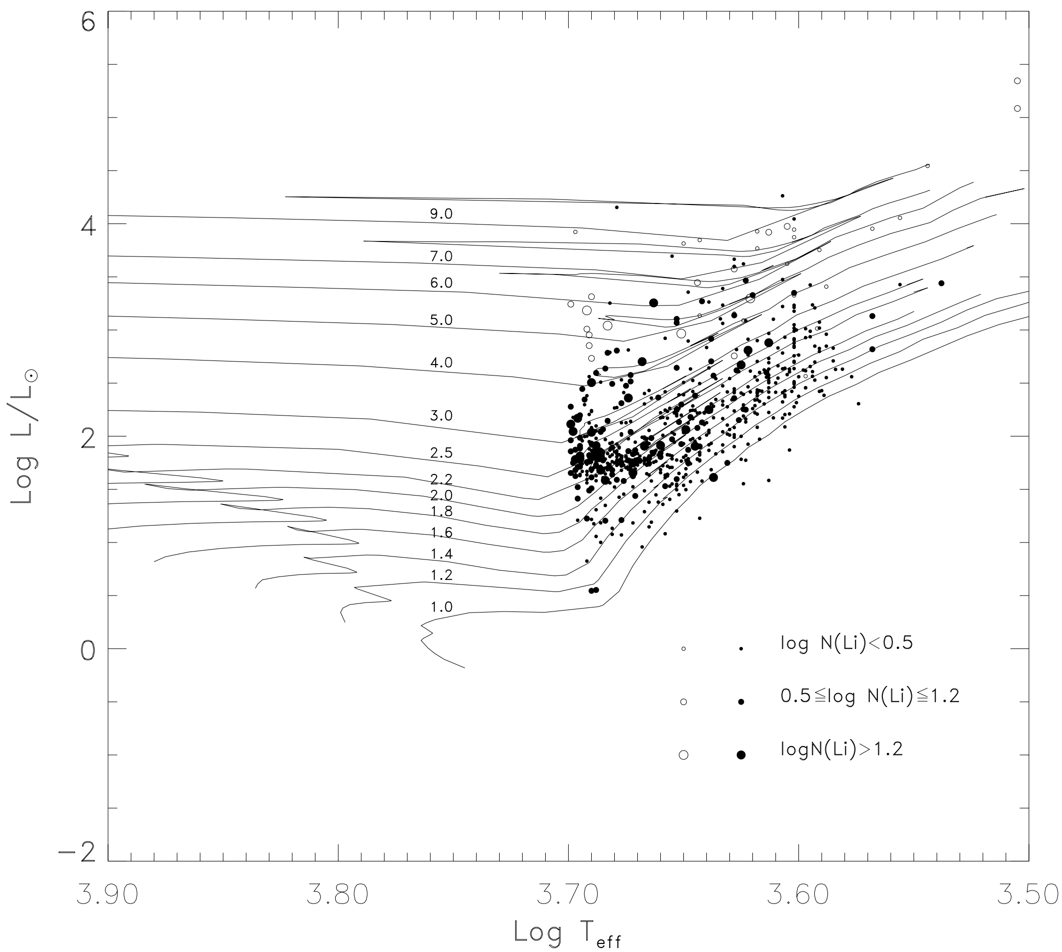

Fig. 7. The same as Fig. 6 showing stars with $T_{eff} \leq 5000$ K except that now the stars classified as supergiants (as per the catalogues) are highlighted by the open symbols. The log N(Li) bins are exactly the same as in Fig. 6.

abundance in evolved giants and supergiants may result from a combination of several factors, e.g. mass loss, extra mixing and so on. Since mass loss is higher in AGB stars and in supergiants, its effect on Li depletion should be greater in these categories of stars.

5. Conclusions

The lithium line at 6707.8 Å has been observed in a sample of 65 stars that are classified in the literature as subgiants, giants and supergiants spanning a spectral type range from F3 to M3, in order to analyse the relation between the lithium abundance and stellar mass. From the parallaxes and the magnitudes obtained of these stars from the Hipparcos survey, we have been able to determine their luminosities. Luminosities have also been obtained in the same manner for another 802 stars whose lithium abundances were already available in the published literature. The effective temperatures of all 867 stars have been obtained from the several published (B−V) - T_{eff} calibrations. All stars have been plotted on the theoretical HR diagram with evolutionary tracks of model masses 1.0 to 9.0 $M_\odot$ and solar composition superimposed. Due to the reliable determination of parallaxes in the Hipparcos survey, many of the hotter stars, particularly in the low mass category ($<$ 2.0 $M_\odot$), are located on or near the main sequence. We also find a fair number of stars of all masses evolving to the red giant branch. Many of these are located in the Hertzsprung gap. A very large number of stars are found on the red giant branch all the way up to a luminosity of log L/$L_\odot$ = 4.0 or higher. Our sample being rather heterogeneous, there may be some stars on the giant branch that are in the central helium burning or the AGB phase but we feel the vast majority are in the first red giant phase. A pattern of decreasing lithium abundance with decreasing temperature has been established for the entire sample. At any T_{eff} a large scatter is seen in Li abundance. In general, very large depletions are seen in the majority of them, much higher than predictions of the standard stellar evolutionary models. The problem is to try to find whether the extra-lowering is due to an extra-depletion in the MS phase, or to an extra mixing towards the end of the subgiant phase and in the giant phase, or to mass loss, probably inefficient in the MS phase, but not negligible in the giant phase or in massive (supergiant) stars. Certain trends of lithium abundance with respect to mass and temperature have provided some hints about the cause of the depletion.

Among the stars that are hotter than 5000 K:

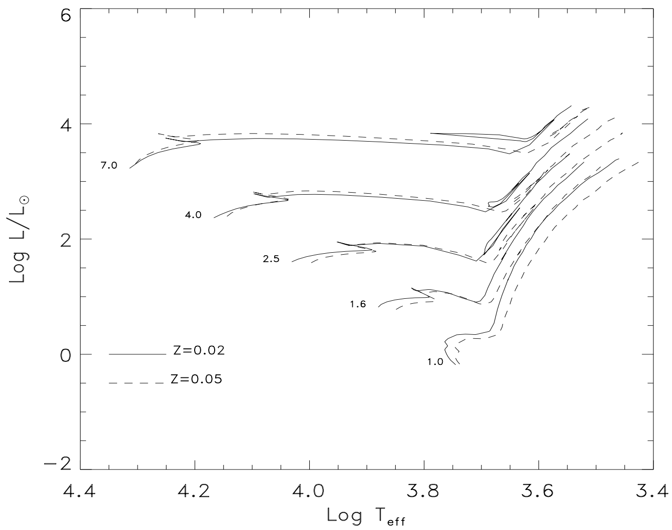

Fig. 8. Evolutionary tracks for two values of metallicity Z=0.02 and Z=0.05 from Bressan, Fagotto et al. (1993) and Fagotto, Bressan et al. (1994) respectively for initial masses 1.0, 1.6, 2.5, 4.0, 7.0 $M_{\odot}$.

1) We see a large number on or near the main sequence that are less massive than 2.0 $M_{\odot}$. A large scatter is present in their Li abundance. No appreciable convective mixing has occurred in these stars. These warmer subgiants near the turn-off retain, therefore, the Li abundance they had on the MS. There is a suggestion of stars with higher Li content to be the more massive ones in the group. This fits in with the idea that the less massive stars have a deeper convective zone which makes the Li depletion more efficient. Essentially, these subgiants reflect a spread in Li abundance that has already occurred in the MS phase itself, contradicting the standard model.
2) Close to the vertical cut at 5000 K, to the left are seen stars which have gone through significant post main sequence evolution and are thus consistently lower in their Li content with no obvious dependence on mass. Li depletion found in these stars is not explained by the standard convective dilution alone. Depletion on the MS, if occurring, seems only additional. Non-standard mixing or the so-called extra-mixing in the post MS phases, which may depend on parameters other than mass, has to be invoked. A fraction of the more massive stars in the group, however, has abundances close to what is predicted by the standard models.

Among the stars cooler than 5000 K:

3) We see in the low mass giants, a large scatter of Li abundances with most of the stars (with masses below 1.8 $M_{\odot}$) having very low Li. The origin of the range for a given mass is the dilution effect due to different mixings and most of the less depleted giants (between 2.0 and 3.0 $M_{\odot}$) are located, as expected, at the base of the giant branch; the more depleted ones being rather towards the tip of the branch. On the other hand, the spread of Li near the base of the red giant branch for the entire run of masses is traced to the large range in abundances present in the progenitors of different masses. Both the non-standard depletion in the MS phase observed for lower mass stars and the standard convective dilution are likely to cause depletion in the low mass giants but they are not sufficient enough to explain the unusually low abundances observed in them. It is imperative to invoke extra-mixing on RGB to explain the observed values.
4) Among the high mass giants, we note the distinct presence of several with Li abundance as low as that of the low mass stars ($\sim$ 1.2 $M_{\odot}$) at a similar evolutionary state. These stars have evolved from the much hotter, namely late B and A MS stars which are hardly expected to have suffered Li depletion on the MS. It is quite likely that even for these stars, there is extra-mixing on the RGB which besides the post MS dilution might be giving rise to such low abundance. Also, in these massive stars, mass loss may have played an important role in reducing Li abundances.

Despite several theoretical and observational uncertainties modifying the interpretation of the data, the analysis of the large sample above reveals a few well defined patterns of behaviour of lithium content in stars that relate to their mass and the stage of evolution. Lack of agreement with the prediction of standard mixing models, as evinced by the evolved giants with Li abundances lower than log N(Li) $<$ 1.0, points to some other processes (non-standard mixing on RGB, mass loss etc.) and parameters besides mass and the evolutionary status that control their lithium abundance.

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