Astron. Astrophys. 338, 623–636 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Chromospheric activity in cool stars and the lithium abundance

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Received 18 November 1997 / Accepted 28 May 1998

Abstract. A detailed analysis of the Ca II triplet lines $\lambda\lambda$8498, 8542, 8662 in 146 cool stars of all luminosities spanning a large range in metallicity has revealed that stars with similar temperature, luminosity and metallicity have different Ca II central depths due to different degrees of their chromospheric activity. Based on this idea, 14 stars in the sample have been identified as chromospherically more active than their counterparts with similar values of atmospheric parameters. In order to explore the interdependence between chromospheric activity, age and lithium abundance, CCD echelle spectra of the Li I line at 6707.8 Å have been obtained at a spectral resolution of 0.35 Å in these 14 active stars, 18 relatively inactive stars and another 17 stars randomly selected from the above sample. The analysis shows that although a few of the active stars are Li-rich, there does not exist a one-to-one correlation between Li abundance and chromospheric activity. There is almost an equal number of inactive stars which are Li rich. Otherwise, lithium depletions are large and there is a large spread in Li abundances in both active and inactive stars especially among giants and supergiants. For most of them, the abundance log N(Li) lies roughly between -0.3 to +0.7. A similar large range in Li abundances is found for giants not selected on the basis of chromospheric activity. The above observations suggest there are parameters besides the activity related ones controlling the lithium abundance in these stars.

Key words: stars: abundances – stars: activity – stars: chromospheres – stars: late type

1. Introduction

The emission components of the Ca II H and K($\lambda\lambda$3968, 3934) lines have long been known to be important indicators of the presence of chromospheres in late F, G, K and M stars (see Linsky 1980, Cassinelli & MacGregor 1986). The infrared triplet lines of Ca II at $\lambda\lambda$ 8498, 8542, 8662 although not as widely used as the H & K lines, are more easily observed in cool stars and are an alternative activity tracer. They do not show any emission of chromospheric origin within their absorption profiles even at high enough spectral resolution except in the very luminous stars of class 0–Ia (Anderson 1974, Linsky et al. 1979, Mallik 1994, 1997). However, Linsky et al. (1979) found in their study of 49 stars of spectral types F9–K3 that stars having the same effective temperature and luminosity have different central depths; the shallower lines indicating a more active chromosphere. Observations of the Ca II triplet lines λ8498 and λ8542 in a sample of F, G and K dwarfs randomly selected from the 'Catalogue of Nearby Stars' of Gliese (1969) by Cayrel de Strobel (1992) also showed that the central depths of the Ca II triplet lines are a potential probe of chromospheric activity in stars. More recently, a detailed survey of the Ca II triplet lines in 146 stars sampled from the Bright Star Catalogue (Hoffleit 1982) and the [Fe/H] catalogue (Cayrel de Strobel et al. 1992) spanning all luminosity types, spectral types from F7 to M4 and metallicity [Fe/H] from -3.0 to +1.1 was undertaken to explore the sensitivity of the Ca II triplet strengths to luminosity, metallicity and temperature (Mallik 1997). A careful inspection of the spectra of the stars, when grouped together according to the same luminosity, metallicity and spectral type, revealed that stars within a given group have central residual intensities (CRIs) of the Ca II triplet lines higher than in their counterparts suggesting higher chromospheric activity in them. 14 stars were thus found to be more chromospherically active than stars of similar luminosity, metallicity and temperature.

Based on the assumption that chromospheric activity is tightly correlated to the age of a dwarf (i.e. the more active stars are younger), Cayrel de Strobel (1992) used the central depths of the Ca II triplet lines as a parameter for ranking the age of the observed disk stars and showed in particular HD 17925 to be very young. Cayrel de Strobel & Cayrel (1989) also detected a very strong lithium line in HD 17925 (K2 V). On the other hand, stars with lesser chromospheric activity (deeper line cores) did not show lithium, implying lithium is already totally depleted in these older stars. Chromospheric activity and lithium abundance would thus seem linked to each other through the age of a star. However, it is well known that the cool evolved RS CVn binaries are chromospherically active, so the phenomenon of chromospheric activity is not necessarily connected to the youth of a star. Also the lithium content of a star is not solely determined by its age. There are several other factors that control the lithium abundance. Extensive studies of the chromospher-

Send offprint requests to: S.V. Mallik ically active RS CVn type binaries and several other normal giants by Pallavicini et al. (1992), Randich et al. (1993, 1994) and Fekel & Balachandran (1993) have shown that several of these are Li-rich, in excess of the predictions of stellar model calculations (Iben 1967). However, a significant Li excess is not a general property of all active stars. Due to the various destruction, dilution and production mechanisms affecting the surface Li abundance of a star, an accounting of its abundance in terms of chromospheric activity alone is difficult to assess. Fekel & Balachandran (1993) in their study of chromospherically active single giants argue that the ^{12}C/^{13}C ratio of 7–25 in these stars reaffirms that mixing has indeed taken place. It would appear, therefore, that either Li is newly produced or is protected from destruction of its initial content. These authors have explored the possibility of Li being synthesised in these giants. Actually, the manufacture of Li via ^{7}Be synthesis (Cameron-Fowler mechanism) has been predicted and observed in the AGB phase (Sackmann & Boothroyd 1995, Smith & Plez 1995) but is not predicted for the first red giant phase because the temperature required to synthesise ^{7}Be is about a factor of 10 higher than that expected at the base of the convective envelope of these stars. Even if there is a feasible mechanism of bringing freshly synthesised Li to the surface in the first ascent giants, whether such a mechanism is aided by the phenomenon of chromospheric activity remains a problem, for if it were so, one would expect all active stars to be Li-rich. This is not the case although Fekel & Balachandran (1993) find that if one isolates the chromospherically active single giants, then the proportion of the Li-rich stars is significantly larger. Pallavicini et al. (1992) and Randich et al. (1993, 1994) in their detailed survey of both northern and southern RS CVn binaries and some chromospherically active single giants find significant amounts of Li 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.

Randich et al. (1993,1994) discuss several mechanisms by which Li could be enhanced or modified, the first among them is a suggestion originally by Pallavicini et al. (1987, 1993) that the Li line may appear enhanced as a consequence of the presence of large cool spots. The second possibility is that Li is produced in the surface layers of these stars by spallation reactions that occur during powerful flares. Both these are ruled out by them on the grounds that there are several active stars with only a weak Li line; Li abundance is not directly related to activity by a cause-and-effect relationship. The third possibility of modifying the Li abundance is through rotationally induced mixing and the fourth is the one suggested by Fekel & Balachandran (1993) where enhancement of Li in moderately rapidly rotating chromospherically active single giants is a consequence of the transfer of both angular momentum and simultaneous dredge-up of freshly synthesized Li. The last two interpretations are also ruled out by Randich et al. because of the poor correlation between Li abundance and rotation. They have found no obvious dependence of Li abundance on activity parameters. Randich et al. (1993) instead suggest that cool giants with an appreciable amount of Li have evolved from sufficiently massive progenitors with very shallow or absent outer convection zones – the likely progenitors are stars with main sequence masses greater than $1.5 M_\odot$. Since lithium abundance results from both Li destruction on the MS and dilution during post MS evolution, according to them, a variety of different situations have occurred for the different stars in their sample.

With the idea of further exploring the connection between chromospheric activity, age and lithium abundance, we have in our present study observed the Li I line at λ6707.8 Å in the 14 stars identified to be chromospherically active and their counterparts and in several other stars chosen in an unbiased fashion from the sample of 146 stars initially observed for the Ca II triplet study. Li abundances have been derived to investigate how closely these depend upon age, mass and other parameters that might influence the lithium content. Sect. 2 details the observations and data reduction. The analysis and results are described in Sect. 3. Sect. 4 gives the interpretation and discussion of these results. Conclusions are given in Sect. 5.

2. Observations and data reduction

From a detailed examination of the observed sample of Ca II triplet spectra, we have picked out stars that are chromospherically more active than stars of similar luminosity, metallicity and temperature. The Li I line at 6707.8 Å has been observed in these 14 stars and in their less active counterparts. The data are listed in Table 1. Earlier studies of Ca II lines by Wilson & Bappu (1957) and Wilson (1976) led to the assignment of a certain chromospheric activity index I_k based on the eye estimate of the Ca II K emission intensity of each star. 9 out of our 14 stars are in common with Wilson's list. Except for χ^1 Ori they all have $I_k \geq 3$ as seen in Column 11 of Table 1. And they all have I_k consistently higher than their counterparts except in the case of the δ Vir-η Gem pair where the values are comparable. This further vindicates the premise that the Ca II triplet lines are a good diagnostic of chromospheric activity. It must be emphasized here that stars of the same spectral type and roughly the same metallicity were paired and the ones of higher central depth than their counterparts are deemed relatively more active. Some of the counterparts are by no means inactive in the absolute sense, as one can judge by the value of their activity index, e.g., η Gem, α Tau, η Per, ϵ Gem, ζ Gem. However, the less active one in each pair will often be referred to as inactive or quiet in our subsequent discussion for the sake of a convenient expression. Strassmeier et al. (1993) in their catalogue of chromospherically active binary stars have classified the stars based on the Ca II H and K emission estimates. For consistency they have defined intensity relations between the different scales due to Hearnshaw (1979), Wilson (1976) and other classifications. For example, strong emission in their catalogue is equivalent to Wilson's I_k = 5; moderate emission refers to I_k = 4 and 3 and weak emission to $I_k \leq 2$. The chromospherically active stars in the catalogue encompass the entire range from I_k = 2 to I_k = 5. The activity index I_k of the active stars of the present study compares well with those of Strassmeier et al. (1993). Table 2 contains the data for another 17 stars (mostly giants) chosen at random from the rest of the sample of the Ca II triplet survey.

Table 1. Chromospherically active and inactive stars: stellar parameters and lithium abundances

Star Identification HR	Name	Spectral type	B−V	$T_{eff}(^oK)$ from (B−V)	$T_{eff}(^oK)$ from Catalogues	log g	[Fe/H]	ξ_t ($kmsec^{-1}$)	v sin i ($kmsec^{-1}$)	I_k	Li+FeI (mÅ)	Fe I (mÅ)	Li I (mÅ)	*log N(Li)	[Fe/H] present analysis
2269		K3 Ib	1.61	3950	3294	1.13	−0.07	10.0			145	31	114	0.46	+0.03
9103	3 Cet	K3 Ib	1.63	3700	4235	0.80	−0.20	4.5	<15		77	38	$\leq$39	$\leq$0.48	−0.03
2269		K3 Ib	1.61	3950	3294	1.13	−0.07	10.0			145	31	114	0.46	+0.03
834	η Per	K3 Ib	1.69	3500	4307	1.0	−0.15	2.5	35	4	72	43	$\leq$29	≤ -0.12	+0.09
8796	56 Peg	G8 Ib	1.36	4250	5100	1.2	−0.15	2.8	<15	4	71	20	51	0.62	−0.20
8465	ζ Cep	K1.5 Ib	1.57	3900	4500	0.75	+0.22	3.0	<15	3	82	56	26	−0.15	+0.28
8796	56 Peg	G8 Ib	1.36	4250	5100	1.2	−0.15	2.8	<15	4	71	20	51	0.62	−0.20
2473	ϵ Gem	G8 Ib	1.40	4150	4582	0.8	−0.05	2.9	<15	4	85	50	35	0.44	+0.20
6536	β Dra	G2 Ib-II	0.98	4925	5250	1.60	+0.14	1.9	10	3	26	18	8	0.70	+0.06
2650	ζ Gem	G0 Ib	0.79	5450	5727	1.9	+0.33	3.0	25		30	10	20	1.59	+0.16
4910	δ Vir	M3 III	1.58	3700	3652	1.3	−0.09	2.3		4	180	20	$\leq$160	$\leq$0.95	−0.16
2216	η Gem	M3 III	1.6	3600	3600	1.5		3.0		5	86	28	$\leq$58	$\leq$0.17	+0.04
2574	θ CMa	K4 III	1.45	4000	4000	1.8	−0.37	1.7	<20	3	43	21	22	−0.32	−0.16
1457	α Tau	K5 III	1.54	3850	3875	0.55	−0.16	1.9	<15	3	77	40	37	0.02	−0.10
4232	ν Hya	K2 III	1.25	4250	4330	2.32	−0.30	2.1	<15	3	31	18	13	−0.09	−0.24
2040	β Col	K2 III	1.16	4450	4582	2.8	+0.13	1.8		2	105	34	71	1.04	+0.28
2973	σ Gem	K1 III	1.12	4500	4541	2.4	−0.30	1.7	25		56	21	35	0.66	−0.02
2990	β Gem	K0 IIIb	1.00	4750	4865	2.75	−0.04	1.5	<15	1	38	22	16	0.71	−0.01
8961	λ And	G8 III	1.08	4550	4600	3.11	−0.56	2.0	<20	5	25	10	15	+0.28	−0.43
1907	ϕ^2 Ori	K0 III	0.95	4900	4750	2.46	−0.53	1.7		2	24	8	16	0.74	−0.50
3482	ϵ Hya	G5 III	0.68	5700	5300	3.02	−0.14	2.0	15		39	9	30	1.74	−0.11
3323	o UMa	G5 III	0.80	5300	5220	2.67	−0.21	0.8	15	1	26	14	12	1.13	+0.06
5409	ϕ Vir	G2 IV	0.70	5600	5478	3.9	+0.00	2.0	10	3	122	7	115	2.60	−0.02
6623	μ Her	G5 IV	0.76	5450	5520	3.7	+0.04	2.6	10	0	38	12	26	1.68	+0.11
5409	ϕ Vir	G2 IV	0.70	5600	5478	3.9	+0.00	2.0	10	3	122	7	115	2.60	−0.02
6212	ζ Her	G0 IV	0.65	5750	5825	3.8	+0.05	0.85	10	0	14	7	$\leq$7	$\leq$1.05	+0.15
1084	ϵ Eri	K2 V	0.88	5000	5180	4.75	−0.09	1.9	<15	4	12	9	3	0.25	+0.06
1325	o^2 Eri	K1 V	0.82	5200	5091	4.31	−0.34	2.4		2	48	8	40	1.32	−0.25
509	τ Cet	G8 V	0.72	5500	5305	4.32	−0.66	1.1	$\leq$15		19	8	11	1.22	−0.38
1008	82 Eri	G8 V	0.71	5550	5498	4.25	−0.48	0.8			14	6	$\leq$8	$\leq$1.09	
2047	χ^1 Ori	G0 V	0.59	5950	5953	4.46	−0.03	1.3	10	2	106	9	97	2.93	+0.11
4983	β Com	G0 V	0.57	6025	6029	4.38	+0.03	1.8	10	1	73	6	67	2.61	+0.07
2047	χ^1 Ori	G0 V	0.59	5950	5953	4.46	−0.03	1.3	10	2	106	9	97	2.93	+0.11
4540	β Vir	F9 V	0.55	6100	6176	4.14	+0.13	1.8	10	0	51	6	45	2.38	+0.12
5317		F7 V	0.48	6350	6417	4.04	−0.02	1.9	25		44	6	38	2.53	+0.08
7776	β Cap	F8 V	0.79	5350	6146	4.0	+0.62	1.7	65		36	22	14	1.37	+0.52

* Based on the standard scale log N(H) = 12.0

The Li I line was also observed in them. These stars were picked without any reference to their activity index. It does not imply they are all necessarily quiet. In fact 7 of them have $I_k \geq 3$. These constitute our unbiased sample.

Columns 3 and 4 of Tables 1 and 2 give the spectral type and B−V of the star. Columns 6, 7 and 8 list respectively T_{eff}, log g and [Fe/H], taken from the Catalogue of Cayrel de Strobel et al. (1997). The catalogue often gives more than one set of values of the above parameters for a given star, based on different studies done of that star. Care was taken to choose the values derived from the best quality data, i.e., data obtained at high resolution and/or in red/near infrared and the ones based on fine analysis/spectrum synthesis. T_{eff} given in Column 6 has been determined using different methods/calibrations for different stars. For a really meaningful comparison of lithium abundances, it is very important to use a uniform temperature scale. We, therefore, rederived the T_{eff}'s using the calibration T_{eff}-(B−V) of Schmidt-Kaler (1982) and Bohm-Vitense (1981) separately for dwarfs, giants and supergiants. These are tabulated in Column 5. The agreement with the T_{eff}'s from the [Fe/H] catalogue is excellent for dwarfs and giants except for β Cap and HR 3664. The values are much more discrepant in the case of supergiants. In the case of HR 3664, T_{eff} from (B−V) seems more realistic for its spectral type, whereas just the opposite holds true for β Cap. The microturbulent velocity ξ_t tabulated in Column 9 has been taken from the individual sources for each star listed at the end of the [Fe/H] Catalogue (1997). The projected rotational velocity, v sin i, listed in Column 10 is adopted from the Revised Catalogue of Stellar Rotational Velocities of Uesugi & Fukuda (1982). These values do not differ much from those listed in the Bright Star Catalogue.

Each pair in Table 1 have very similar values of T_{eff}, log g, ξ_t and [Fe/H]. The only glaring case is that of the HR 5317-β Cap pair. At the time of analysis when stars of similar types were being grouped, the 1997 [Fe/H] catalogue was not available; the 1992 catalogue was made use of where the latest value of [Fe/H]

Table 2. Unbiased sample of stars : stellar parameters and lithium abundances

Star Identification HR	Name	Spectral type	B−V	$T_{eff}(^oK)$ from (B−V)	$T_{eff}(^oK)$ from Catalogues	log g	[Fe/H]	ξ_t $(kmsec^{-1})$	v sin i $(kmsec^{-1})$	I_k	Li+FeI (mÅ)	Fe I (mÅ)	Li I (mÅ)	*log N(Li)	[Fe/H] present analysis
2646	σ CMa	K7 Iab	1.73	3200	3877	1.00	+0.00	3.0		5	201	68	≤133	≤0.75	+0.16
2580	o^1 CMa	K2 Iab	1.73	3200	4235	0.00	−0.11	3.5	<20	3	229	74	≤155	≤0.93	+0.25
2286	μ Gem	M3 IIIab	1.64	3450	3600	1.0	+0.11	1.9		5	154	28	≤126	≤0.75	+0.00
4069	μ UMa	M2 IIIab	1.59	3700	3847	1.35	+0.00	2.1		5	150	26	≤124	≤0.70	+0.00
6705	γ Dra	K5 III	1.52	3900	3930	1.55	−0.14	2.0	<15	3	68	27	41	0.00	−0.08
3518	γ Pyx	K3 III	1.27	4200	4270	2.35	−0.11	2.1		3	74	19	54	0.60	−0.04
1580	o^2 Ori	K2 III	1.15	4400	4440	2.56	−0.26	2.1	<15	3	38	22	16	0.30	−0.10
5744	ι Dra	K2 III	1.16	4400	4490	2.74	+0.03	1.5	<15	2	55	36	19	0.37	+0.33
5176		K2 III	1.35	4075	4032	1.1	−0.80	1.8			13	10	≤3	≤ −1.0	−0.73
5908	θ Lib	G8.5 IIIb	1.02	4700	4730	2.99	−0.31	1.6	<20	1	26	15	11	0.52	−0.08
4608	o Vir	G8 IIIa	0.97	4850	4825	2.34	−0.33	2.0	<20	1	38	10	28	1.23	−0.25
2985	κ Gem	G8 IIIa	0.93	4950	5000	2.90	−0.16	3.8	10	1	32	10	22	1.08	−0.20
4932	ϵ Vir	G8 IIIb	0.94	4950	4990	2.7	+0.10	2.0	<15	1	32	20	12	0.81	+0.15
2134	1 Gem	G7 III	0.87	5125	5100	3.18	−0.01	2.0			42	17	25	1.14	+0.05
3664		G6 III	0.86	5150	4165	2.2	−0.85	1.92		1	18	6	≤12	≤1.16	−0.35
458	υ And	F8 V	0.54	6125	6212	4.17	+0.09	1.3	10		53	7	46	2.41	+0.11
799	θ Per	F8 V	0.48	6350	6309	4.3	−0.02	1.3	10		69	5	64	2.84	+0.01

* Based on the standard scale log N(H) = 12.0

cited for HR 5317 was +1.01. The 1997 catalogue now cites it as −0.02. So the metallicity difference between the two stars is large. Later we shall see that Li abundance does not depend crucially upon [Fe/H]. Also, T_{eff} of 5350 K for β Cap obtained from (B−V) is much less than that given in the catalogue, the latter value in fact is very close to that of HR 5317.

The Li I observations of the 49 stars listed in Tables 1 and 2 were carried out at the 102 cm telescope at Vainu Bappu Observatory, Kavalur with the coude echelle spectrograph and a CCD detector (384×576) with a pixel size of 23μ square. The spectra were obtained with a 79 lmm^{-1} echelle grating blazed at 6746 Å in the 34th order, a 150 lmm^{-1} cross dispersion grating blazed at 8000 Å in the first order. This configuration with the slit width used gave a spectral resolution of ∼0.35 Å in the 33rd order where the Li I line lies. A Thorium-Argon hollow cathode lamp was used for line identification and a Xenon lamp was used as a flat field source. A number of 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.

The reduction procedure involved bias subtraction, flat field correction, extraction of the orders of the echelle spectrum, wavelength calibration and normalisation by fitting a continuum. The bias was subtracted from the raw spectrum, then the spectrum was divided by the flat field image accounting for the pixel to pixel sensitivity difference of the detector. The echelle orders ranging from 25 to 35 were extracted. The wavelength scale for the 33rd order of the spectrum where Li is observed was derived using the absorption lines in the stellar spectrum itself, ensuring that the lines are of photospheric origin (with $\chi \geq$ 2eV). The stellar features chosen in the neighbourhood of Li I are the Al I lines at $\lambda\lambda$6696.032, 6698.669; Si I at λ6721.844 and the Fe I lines at $\lambda\lambda$6677.997, 6703.576, 6705.105, 6713.044, 6713.745, 6715.386, 6716.252, 6725.364, 6726.673, 6733.153, 6737.978, 6750.164, 6752.716. Each observed spectrum was divided by an estimated continuum. The placement of the continuum in an M giant is a difficult task; the primary problem is the general overlying haze arising from myriads of TiO lines, as has been emphasized by Luck & Lambert (1982). We have 4 M giants in our program list, three of which, namely, δ Vir, η Gem and μ Gem have particularly messy spectra. Luck & Lambert (1982) have discussed how best to place the continuum on the spectra of M giants. We have followed their procedure and used their value of 'TiO depth' for δ Vir and μ Gem to place the continuum in these stars as accurately as possible.

The reduced spectra of a few sample pairs of active and inactive stars in the vicinity of Li I are displayed in Fig. 1. Fig. 2 shows spectra of a few stars of the unbiased sample. The spectral coverage is around 70 Å-80 Å although the figures here show trimmed spectra of 40 Å each. The spectra are centered around the λ6707.8 Å Li I line and include several Fe I lines that have already been mentioned. In most cases, the S/N ratios were between 40 and 60. The equivalent width (EQW) of the Li I feature at 6707.8 Å was measured for each star from the normalised spectra obtained as above. Repeated settings of the continuum and measurement of the EQW indicated that errors in the measurement were less than 6 mÅ. In the case of M giants these errors tended to be higher. Measurements of the EQWs from two spectra of the same star yield differences of about 5 mÅ. Column 12 of the Tables 1 and 2 lists the measured EQW of the Li I feature.

3. Analysis and results

The Li I feature is blended with an Fe I line at 6707.445 Å whose strength becomes comparable to the Li I EQW in supergiants. The TiO bands seriously affect the Li I spectrum only in M stars. However, the CN lines of the red system do affect the Li I EQW, ^{12}CN(5,1)R_1(64) being the major contaminant. There is also a V I feature but it is much weaker than the CN and TiO features.

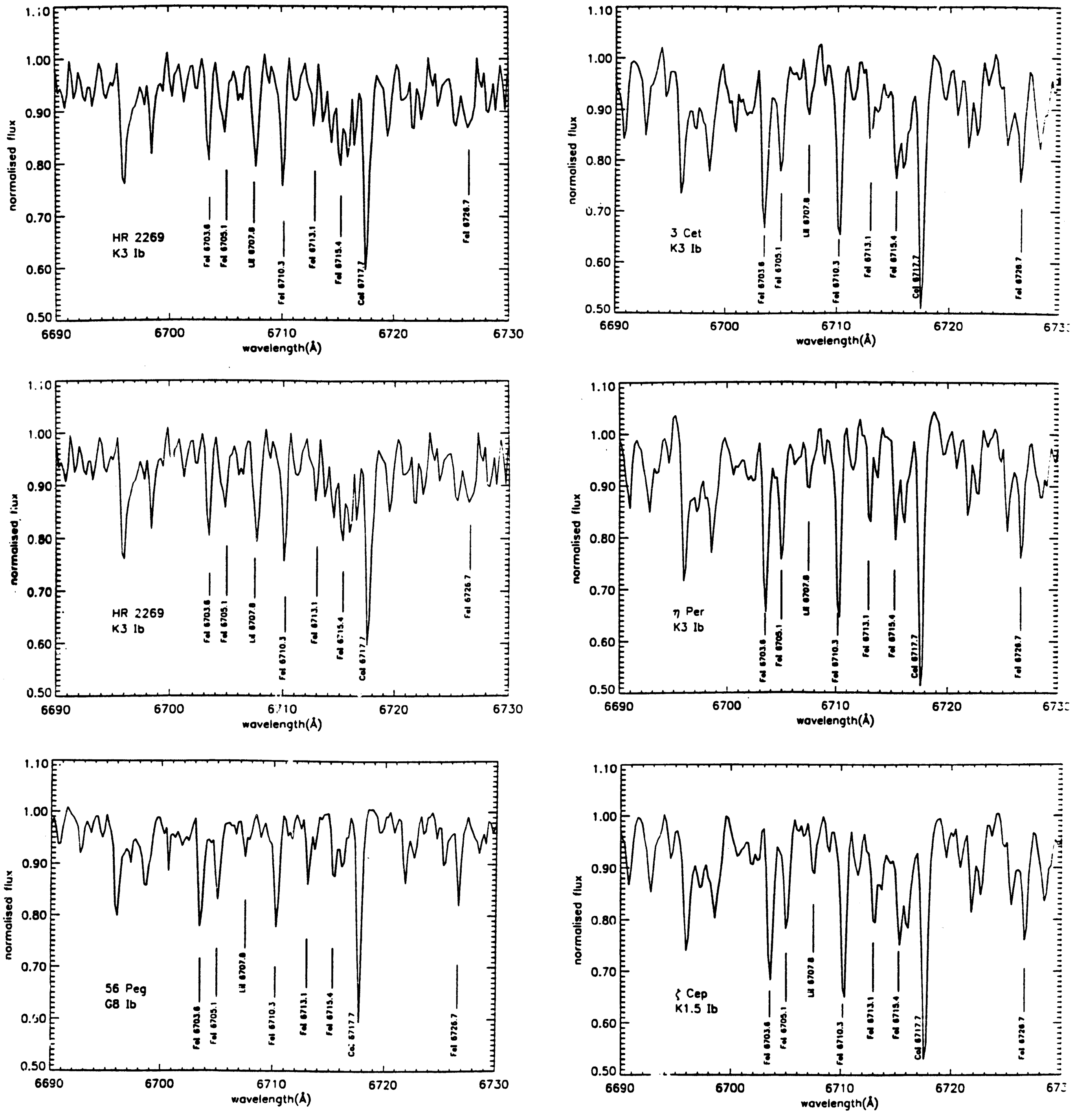

Fig. 1. The normalised Li I spectra in a few active and inactive stars. Note the strong Li I line in HR 2269

The contribution of CN is negligible in F, G and K dwarfs and subgiants but is enhanced in giants and supergiants. A detailed spectroscopic analysis of β Gem (K0 III) by Ruland et al. (1980) has shown that CN contributes less than 20% to the Li I EQW. In his study of abundances in G and K supergiants, Luck (1977) has discussed in detail the effect of CN blending in these stars. In the present work, we have not rigorously accounted for the presence of CN in the Li I feature. So the EQWs of the Li I cited here are upper limits in the sense that there is likely to be a small contribution to it from CN. Since it is a comparative study of pairs of stars with very similar T_{eff}, log g, ξ_t and [Fe/H], it does not drastically alter the conclusions of our present study. However, the absolute values of the abundances derived from the measured EQWs tend to be higher. In order to get an approximate idea of how much the lithium abundance is affected by CN contamination, the Li abundances were recomputed with

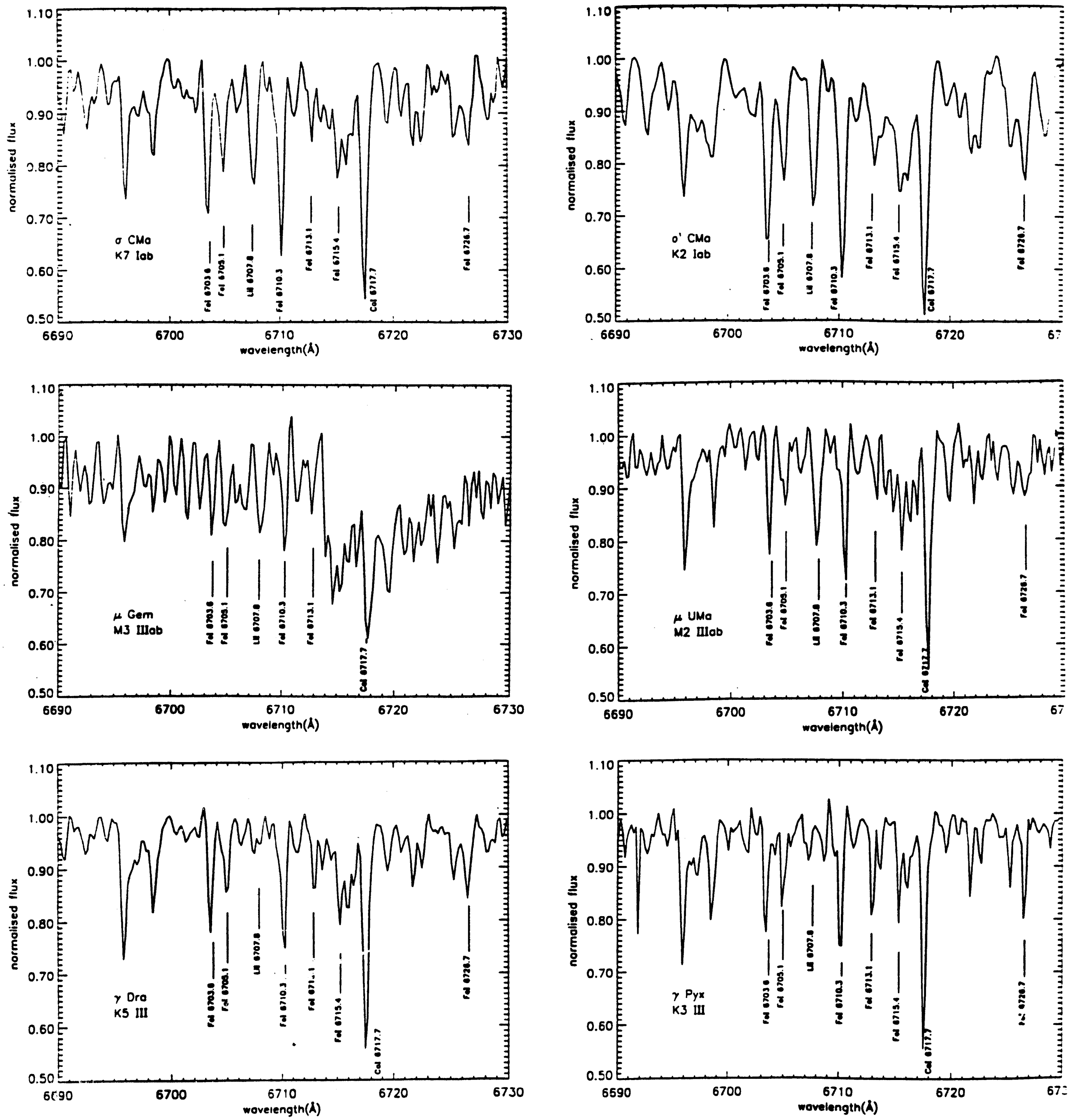

Fig. 2. The normalised Li I spectra in a few stars of the unbiased sample. The Li I line is specially strong in σ CMa, o^1 CMa, μ Gem and μ UMa.

the EQW reduced by 20%–30%. The log N(Li) values differ by 0.1 to 0.15 which as will be seen later is within the accuracy of the determination of the lithium abundances.

The contribution of the Fe I line to the Li I feature was estimated using LINES (the standard LTE line analysis code due to Sneden 1973) and the model atmospheres of Gustafsson et al. (1975) and Bell et al. (1976) with the grid generated by Luck (1992). The stellar atmosphere parameters such as T_{eff}, log g, [Fe/H] and ξ_t are already known for the program stars from fine analysis. Based on these parameters, an appropriate model was chosen for each star from the grid of model atmospheres. The spectra include 6 other Fe I lines at $\lambda\lambda$6705.105, 6713.044, 6715.386, 6726.673, 6733.153 and 6752.716 having the same lower excitation potential as the 6707.445 Å Fe I blend. The data for the Fe I lines considered and the Li I line under study are given in Table 3. For each of these lines, the LINES program

Table 3. Line data

Wavelength (Å)	Excitation potential(eV)	log gf
Fe I		
6705.105	4.61	−1.15
6707.445	4.61	−2.31
6713.044	4.61	−1.61
6715.386	4.61	−1.64
6726.673	4.61	−1.13
6733.153	4.64	−1.58
6752.716	4.64	−1.36
Li I		
6707.811	0.00	0.171

was used to calculate Fe abundance with the chosen model atmosphere and the observed EQW as the input. The EQW of the Fe I (6707.445 Å) blend in the Li feature was then estimated using LINES, the same model atmosphere and the Fe abundance determined above. The average of the EQWs thus obtained was adopted as the strength of the Fe I blend and subtracted from the measured EQW of the Li feature to yield the EQW of the Li I component alone. The differential Fe abundances derived using LINES above are listed in Column 16. It would be worthwhile comparing these with the [Fe/H] taken from the Catalogue of Cayrel de Strobel et al. (1997). Any difference would obviously be due to the use of different codes and model atmospheres. We note that the new abundances for most of the stars are well within ±0.2 of the old ones. It must be pointed out that the [Fe/H] values taken from the Catalogue refer to the most recent reference cited and where they differ by more than ±0.2 from the new values, there exists an older determination of [Fe/H] which matches with the new value. The only serious discrepancy is in the case of HR 3664; it would partly be attributed to poor signal-to-noise ratio of the HR 3664 spectra obtained in the present study. The EQWs of the Fe I blend and of the Li I component are tabulated in columns 13 and 14 in the Tables 1 and 2. Typically the Fe I blend has an EQW ranging between 5 mÅ to 50 mÅ for the stars studied. It is usually less than 10 mÅ for dwarfs and subgiants. For most of the giants it lies within the range 20–30 mÅ. For some of the supergiants, it is even higher than 50 mÅ. Since an incorrect estimate of the Fe I 6707.45 Å EQW reflects on an incorrect estimate of the Li abundance, it is worth exploring what parameters the former crucially depends on. We find that the largest error in [Fe/H] and Fe I 6706.45 Å EQW is caused by an uncertainty in the microturbulence. A higher microturbulence yields a lower EQW. For example, a difference of 0.5 kmsec^{-1} in ξ_t in the χ^1 Ori-β Com pair causes a difference of 3 mÅ in their Fe I EQWs. On the other hand, the Fe I EQWs are not so sensitive to T_{eff}. A change of as high as 300 K in T_{eff} effects a change in the EQW of only around 1 mÅ. That is why in spite of a difference of 250 K in T_{eff} between β Gem and σ Gem, similar EQWs are obtained for the two stars. One notes that β Cap, a F8 V star has a rather high Fe I EQW of 22 mÅ compared to 6–8 mÅ for other similar stars. This is principally due to its high metallicity ([Fe/H] = +0.62). The difference in metallicity also explains the low Fe I EQW in 56 Peg compared to that in its counterparts.

The Li I EQWs range from around 5 mÅ to 100 mÅ for stars spanning all luminosities and covering a range of spectral types from F7 to M3. All abundance determinations of Li are based on the measurements of the EQW of the Li line at 6707.8 Å. It is a doublet split by fine structure consisting of two lines at 6707.761 Å and 6707.912 Å with gf values of 0.989 and 0.494 respectively (Andersen, Gustafsson & Lambert 1984). The blended feature is at 6707.811 Å with a gf value of 1.483. We assume in our calculation of Li abundances that the Li feature is a single line with this value of gf. Balachandran (1990) has done an exercise over a large range of EQWs to show that the error in treating the Li doublet as a single line is negligible for small EQWs; at EQWs higher than 100 mÅ it is close to 20 per cent. This result is independent of the effective temperature of the star and other model atmosphere parameters. There are 7 stars in the present study with Li EQW exceeding 100 mÅ. LINES was used to calculate Li abundances from the input equivalent widths and model atmospheres. These are tabulated in Column 15 of the Tables 1 and 2. In order to determine the accuracy of log N(Li), several runs of LINES have been made for a given change in a parameter, keeping other parameters of the model fixed. The lithium abundance is very insensitive to changes in gravity. A change of ±0.25 in the gravity changes the Li abundance by 0.01 to 0.03. It changes by an equal amount for a change of ±0.5 in ξ_t. The dependence on the metallicity of the model is even more negligible. A change in T_{eff} of 200 K however changes the Li abundance by a substantial amount of 0.22 to 0.30. An error in EQW of 5 mÅ leads to a larger change in log N(Li) for stars with lower Li I EQW $e.g.$, a change of 0.18 for EQW of 15 mÅ. The same error for a star with high Li I EQW of 115 mÅ yields a change in log N(Li) of only 0.05. So for a measured EQW of Li I, the calculated Li abundance depends almost exclusively on T_{eff} and on the choice of the model atmosphere (see Spite 1996 and Spite 1997). 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 ±0.2 to ±0.25, given the error in the EQW measurement. The value of Li abundance determined is critically dependent upon the choice of T_{eff}. The grid of model atmospheres of Gustafsson et al. (1975) and Bell et al. (1976) extends down to T_{eff} = 3750 K. Because of the non-availability of model atmospheres with $T_{eff} < 3750$ K, only the upper limits of lithium abundance could be given for several stars that have $T_{eff} <$ 3750 K. Actually for supergiants 3 Cet, η Per, σ CMa and o^1 CMa, the T_{eff} obtained from the [Fe/H] Catalogue are closer to 4000 K. Upper limits are also given for HR 5176, HR 3664, 82 Eri and ζ Her either because of the low S/N of their spectra or because of extreme weakness of the Li I line in them.

Lithium abundances have been determined in the past in several of the stars that are common with the present study. Four of the dwarfs and subgiants namely, β Vir, HR 5317, υ And and μ Her studied here have also been observed by Balachandran (1990) and Fekel & Balachandran (1993). The abundances agree rather well, the Δlog N(Li) = $\pm$0.2, which is within the accuracy of the present determinations. For τ Cet, our value is much higher than that obtained by Pallavicini et al. (1987). For η Per, ζ Cep, ϵ Gem, β Dra and o^1 CMa, the agreement is excellent with the previous studies of G and K supergiants (Luck 1977). The value for ζ Cep by Brown et al. (1989) is much larger. This is most likely due to the lower T_{eff} we have adopted from the (B$-$V) colour of this star. The Li abundance in σ CMa in the present study is quite a bit higher than that obtained by Luck & Lambert (1982). There are previous determinations of the Li abundance (Brown et al. 1989, Luck & Lambert 1982, Lambert, Dominy & Sivertson 1980, Fekel & Balachandran 1993) for 13 giants in common with the present study. For ν Hya, σ Gem, β Gem, λ And and θ Lib, the agreement is very good. There are large disagreements for cooler stars, the late K and M giants. Ours are consistently larger perhaps owing to not having accounted for the CN blending and in addition for the M giants also due to the difficulties with the placement of the continuum. The present values of several giants thus tend to be overestimates of the Li abundance.

It should be noted that the following discussion of the Li abundance of the active star relative to its inactive counterpart should be viewed keeping in mind the errors/uncertainties in the choice of T_{eff} in each case.

4. Interpretation and discussion

As a consequence of several ways in which Li can be destroyed and/or produced, the observed Li content of stars spans 6 orders of magnitude. Even the Tables 1 and 2 in the present study with a limited number of stars show that the Li abundance varies over 4 orders of magnitude. Fig. 3 displays the lithium abundance of the stars observed as a function of their effective temperature. Both the active and the inactive stars of each pair as also the stars not selected on the basis of their chromospheric activity are shown. It is a heterogeneous sample encompassing F and G dwarfs, K giants and supergiants and also M giants. It is clear from this figure that F and early G dwarfs have log N(Li) close to 3.0 and late G and K dwarfs are heavily depleted. Most of the G and K giants and supergiants seem to have undergone severe depletion resulting in log N(Li) $\leq$ 1.0. There are a few whose Li abundances exceed 1.0. The most striking result is the large range in Li abundance especially among giants (more than 2 orders of magnitude) and that it exists both for the active as well as the inactive stars. A similar range is also found in the sample not specifically selected on the basis of chromospheric activity. Since in dwarfs chromospheric activity is tightly related to age and it is not so in giants, the interpretation of observations in terms of the connection between lithium abundance and chromospheric activity is best done separately for dwarfs and giants.

4.1. Dwarfs

4 dwarf pairs (χ^1 Ori with 2 counterparts) are displayed in Table 1. Among these, 2 active stars namely, χ^1 Ori and HR 5317, have Li abundance significantly higher than their inactive counterparts β Vir and β Cap. On the other hand, ϵ Eri, the more active of the K dwarf pair, has a Li abundance over an order of magnitude less than o^2 Eri. In order to understand the existence of any link between chromospheric activity and Li abundance, it is worth analysing the observed abundances in the light of what is already known about lithium.

Old Population II stars are observed to have ^{7}Li abundances up to a maximum of log N(^{7}Li) $\sim$ 2 (Spite, Maillard & Spite 1984) and young, Population I stars up to a maximum of log N(^{7}Li) $\sim$ 3.1 (see, e.g., Duncan & Jones 1983; Boesgaard & Steigman 1985; Pilachowski, Booth & Hobbs 1987; Boesgaard, Budge & Ramsey 1988). Observations of ISM, T Tauri stars and other pre-main sequence stars, stars in young galactic clusters and analysis of abundances in meteorites (Boesgaard & Steigman 1985, Rebolo 1992) also provide evidence that stars are formed with a Li abundance $\sim$3.0, referred to as its cosmic abundance.

As a star evolves, Li is subject to destruction and dilution. At temperatures $\geq 2\times10^6$ K, Li is easily destroyed through the reaction ^{7}Li (p,α)^{4}He, so that on the main sequence itself, Li is depleted except in the very outer layers. The maximum Li abundance expected in a main sequence star is the initial value of log N(Li) $\approx$ 3.0. However, main sequence lithium burning is amply evidenced by the Sun and by dwarfs in the Hyades (Thorburn et al. 1993) in comparison with those of the Pleiades (Soderblom et al. 1993). These stars including the Sun are observed to be depleted considerably; the solar abundance is $\sim$ 1.0, down by 2 orders of magnitude. This is clearly borne out by our observations of MS stars. Fig. 3 shows that Li depletion is negligible in F and early G dwarfs; the abundance is close to the initial value of 3.0 except in β Cap. Depletion is severe in late G and K dwarfs (2 orders of magnitude and more). As it appears from its (B$-$V), β Cap is probably a late G/K0 star with a wrong spectral classification. Based on the fact that in dwarfs, chromospheric activity directly relates to age, it is not surprising that χ^1 Ori the more active star has much higher Li content than its respective inactive counterpart. On the other hand, ϵ Eri, is likely to have been on the MS a much longer time, and hence has a Li abundance lower than o^2 Eri. The above observations are explained by the fact that the destruction of Li is a function of both mass and age during pre-main sequence and main sequence evolution (Herbig 1965, Wallerstein, Herbig & Conti 1964, Zappala 1972 and Herbig & Wolff 1966). Fig. 4 shows the plot of log N(Li) vs. T_{eff} for the Pleiades dwarfs (Soderblom et al. 1993) and the Hyades dwarfs (Thorburn et al. 1993). On the same plot are also shown the small sample of dwarfs observed in the present study. It is to be noted that our sample of dwarfs falls more in line with Hyades than Pleiades suggesting some of them have spent long enough time on the main sequence. This phenomenon has been observed in Duncan's (1981) survey of field F5-G5 dwarfs also. Stars within a given cluster are close to the same age, so they would show the influence of differing masses. However, a large spread in Li abundances is observed at a given mass among late type stars in young clusters, e.g. Pleiades (Duncan & Jones 1983, Soderblom et al. 1993) and

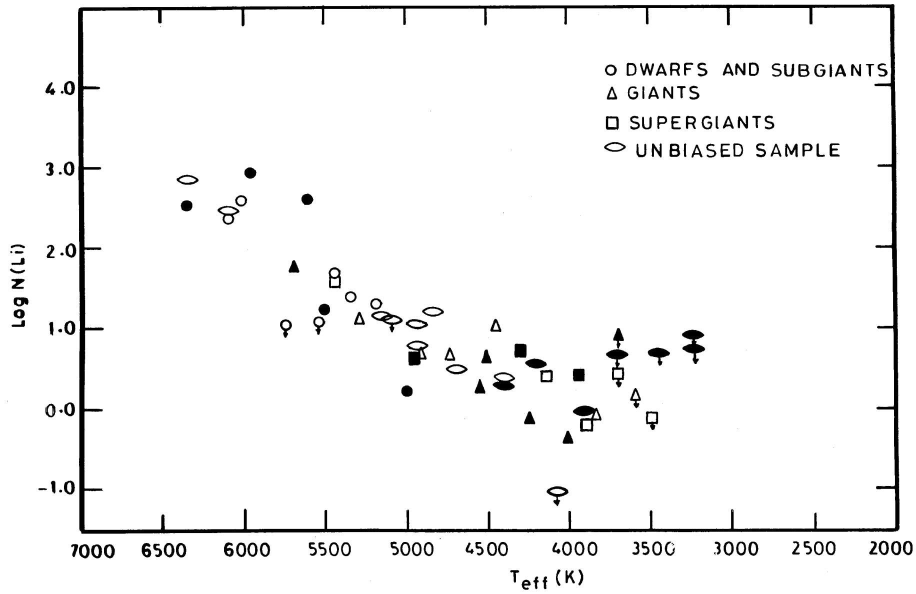

Fig. 3. Lithium abundance vs. effective temperature for the stars in Table 1 and Table 2.The symbols are described in the key. Filled symbols indicate the active stars and the open ones indicate inactive stars. Symbols with arrow pointing downward signify upper limits to Li abundance, also in the following figures.

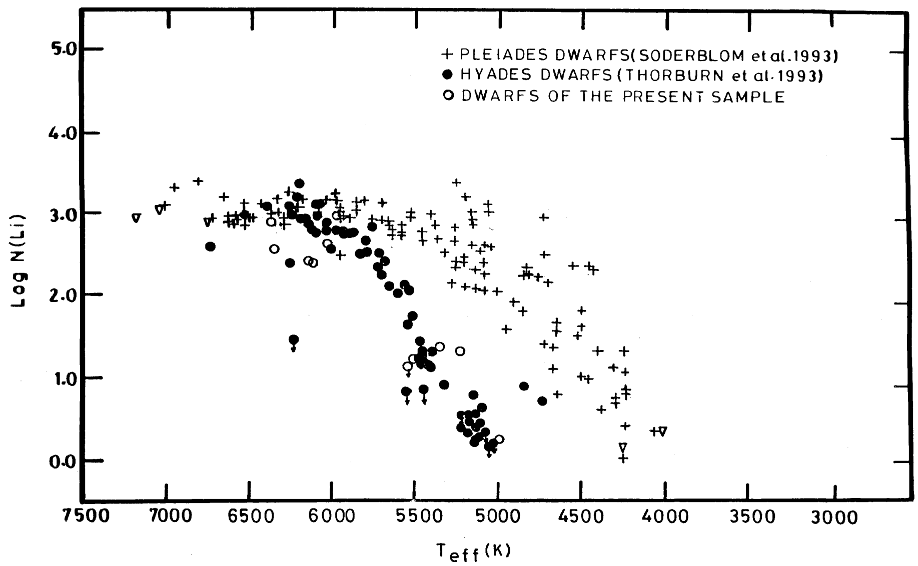

Fig. 4. Lithium abundance vs. effective temperature for the stars in the Pleiades (Soderblom et al. 1993) (pluses) and in the Hyades (Thorburn et al. 1993) (filled circles). Superimposed are the dwarfs of the present sample (open circles)

also among solar type stars in old clusters, e.g. M 67 (Pasquini et al. 1997). It is also worth noting that there are stars as old as the Sun that show much less Li depletion (Pallavicini et al. 1987). The persistence of the scatter suggests that Li depletion is not dictated by age and spectral type alone. Besides chromospheric activity, there are perhaps other variables that may influence the Li depletion.

4.2. Giants and supergiants

The situation is more complex in the case of evolved stars. Chromospheric activity and age do not have a one-to-one correlation. Also Li abundance depends not only upon age but on several other parameters. Among the subgiant, giant and supergiant pairs, only a fraction of chromospherically active stars have a Li excess (5 of them by sizeable amounts). On the other hand, an equal number of inactive stars is observed to have higher Li abundance than the active stars. It is worth noting that a considerably large range in Li abundance exists for giants for a given spectral type, e.g., for G5-K0 and for K1-K4 in Table 1 and for G5-G8 and K2-K5 in Table 2. Fig. 3 clearly exhibits this large range of over 2 orders of magnitude in lithium abundance in giants. During the post MS evolution, dilution becomes the dominant process for the change in surface Li abundances. Subgiants, since they are less evolved, may not show a Li depletion as large as in giants and supergiants. Our observations of subgiants ϕ Vir, μ Her, ζ Her confirm this. The more active star in the pair has log N(Li) closer to 3.0 whereas the counterpart has a much lower Li content.

As a star evolves up the giant branch, a deepening convective envelope dilutes the remaining Li from the MS and subgiant phases. Predicted Li dilution for the first dredge-up ranges from a factor of 60 for a 3 $M_{\odot}$ model to 28 for a 1 $M_{\odot}$ model (Iben 1967). These refer to a star at the tip of the red giant branch.

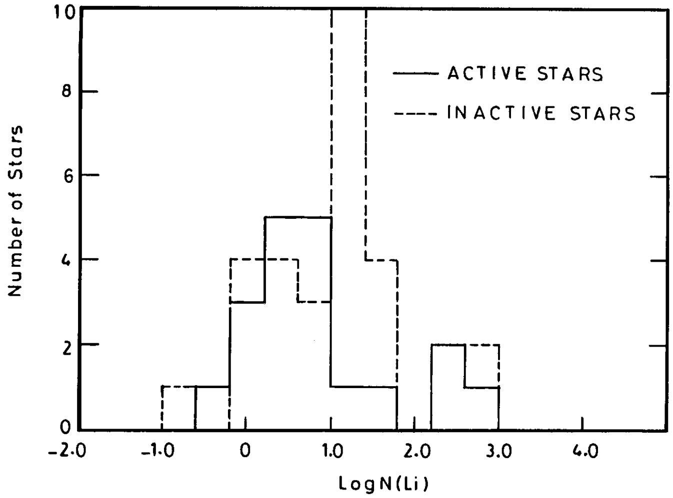

Fig. 5. Distribution of stars of the present sample vs. lithium abundance with a bin size of log N(Li) = 0.4 dex

Thus G, K and M giants and supergiants are expected to have log N(Li) down to the limit 1.5, the value reached if no MS depletion occurs. However, in reality giants and supergiants show much greater depletions – easily ranging from 2 to 4 orders of magnitudes with respect to the cosmic value. Lambert, Dominy & Sivertson (1980) in their study of Li in 50 G and K giants found really low abundances: $-1.0 \leq$ log N(Li) ≤ 1.0. The same is also revealed in the study of 644 giants by Brown et al. (1989): Bulk of the stars have lithium content log N(Li) $\leq$ 1.0. Only 10 stars were found to be Li rich. Incidentally one of our program stars ϕ Vir is among them with log N(Li) = +2.3, the value agreeing well with ours. Severe Li depletions were also observed in 31 giants and supergiants by Luck & Lambert (1982), $-0.89 \leq$ log N(Li) $\leq$ +0.84. In the present study, similar depletions are observed. There are also several stars in the sample that have Li content close to 1.0 and higher as Fig. 3 shows. The abundances are still moderate and do not exceed the value 1.5, the limit suggested by theoretical calculations, the exception being ζ Gem with log N(Li) as high as 1.59. Considering that the predicted upper limit of log N(Li) = 1.5 is rarely observed and that most of the stars have Li abundances far below this value (among the large sample of 644 giants of Brown et al., only 4% have log N(Li) $\geq$ 1.3 and another 4% between 1.2 and 1.3), the occurence of giants having log N(Li) above 0.5 and certainly above 1.0 is quite surprising. Although the large range in Li abundance could be due to the intrinsic heterogeneity of the sample, the Li abundances seen in many of the stars could also be due to other causes including chromospheric activity. It is worth investigating, therefore, whether chromospheric activity plays any role in controlling the Li abundance in giants.

Both active and inactive stars of Table 1 show a fairly large spread in their Li abundance (close to 2 orders of magnitude) with several of them in excess of log N(Li) $\geq$ 1.0. There is no apparent preference in active stars for higher lithium than the inactive stars. The stars of the unbiased sample (Table 2) consist of a mixture of active and inactive stars judging by their I_k value. They also show a similar spread in Li abundance, again several of them exceeding 1.0. This behaviour is better expressed in a histogram shown in Fig. 5 expressing the number of stars in bins of Li abundance of 0.4 dex. Here the active stars are denoted by the solid curve and the inactive ones by a dashed curve, the criteria being those with $I_k \geq 3$ are in the active category and those with $I_k < 3$ in the inactive category. We see that in the bin 1.0–1.8 inactive stars are many more. There is a suggestion of almost equal numbers of active and inactive stars in the other bins. Our data do not give any definite indication of a higher lithium abundance in active stars. However, it is very important to extend the sample to a much larger number of stars before we can make definite deductions.

It will be interesting to compare our sample with another large sample of cool giants not specifically selected on the basis of chromospheric activity to see if our stars are unique in any way. Fig. 6 displays our data which now include stars of both Tables 1 and 2 along with that of Brown et al. (1989) which consists of a heterogenous sample of 644 giants. Their numbers are large and the Li depletions are large but by and large similar trends are seen in the 2 samples. Our stars are clearly intermixed with those of Brown et al. The active stars of our sample are not particularly weighted towards higher lithium. In fact the ten really Li-rich giants of Brown et al. lie above the rest and the sheer number of their data gives a large scatter at each temperature. The inverted triangles denote upper limits to the lithium abundance. Stars to the right of T_{eff} = 3750 are 4 M giants and 4 supergiants observed by us. The supergiants stand apart from the rest also because their progenitors are perhaps massive stars which leave the main sequence with almost their original Li content. Whatever depletions are observed must be due to the dilution of Li caused by the gradual deepening of the convective envelope as the stars evolve off the main sequence.

It would also be worth comparing our sample with the sample of chromospherically active stars like that of Randich et al. (1993, 1994). Fig. 7 shows our data superimposed on that of Randich et al. which includes observations both of Northern and the Southern RS CVn binaries. Though our sample is not large enough, there is a definite indication of intermixing here also over the entire range of temperature. The symbols with arrows pointing downwards denote upper limits to the lithium abundance. Larger spread at each temperature exists in the sample of Randich et al. perhaps because of the larger numbers observed. Otherwise the same general trends are seen in the 2 samples, in particular, in the amount of depletion and the overall range of abundance. It is unlikely that there is a higher percentage of active/Li-rich stars in our sample relative to their sample. On these plots we have tried to locate the log N(Li) values from the literature of stars in common with the present sample which are notably different from those of ours. We find that there is no tangible change in the results; the general patterns like the range of Li abundance and the amount of depletion remain the same. Comparison of our data which is a combination of active and inactive stars with Brown et al.'s sample of 'normal' giants and with Randich et al.'s of RS CVn binaries and other chromospherically active giants suggests that both active and inactive

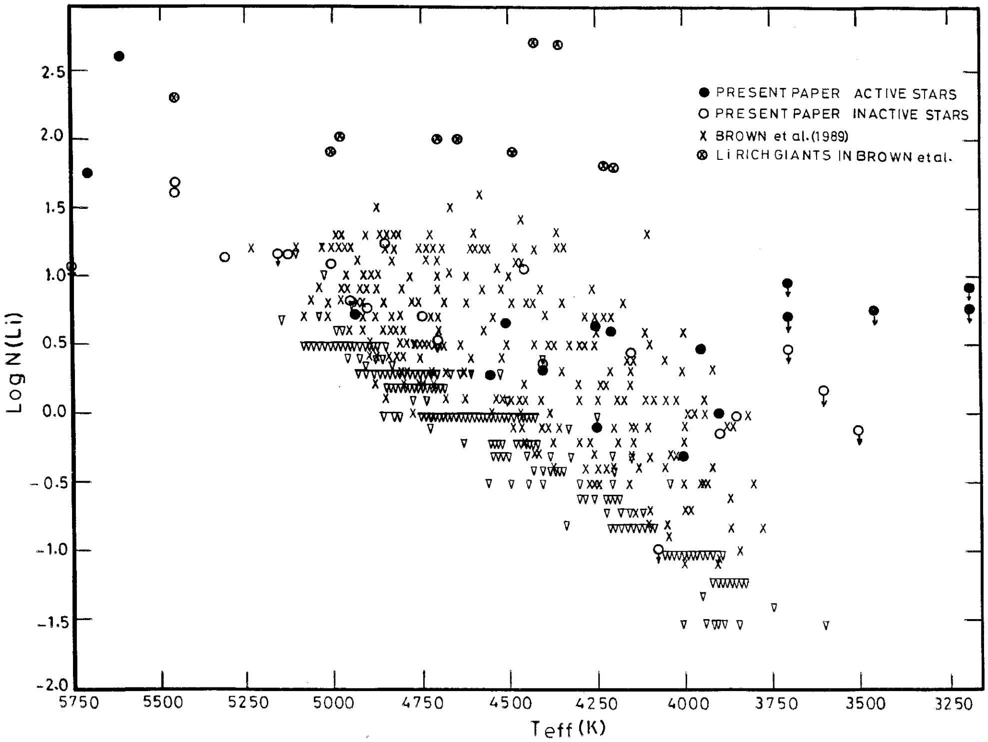

Fig. 6. Lithium abundance vs. effective temperature for the sample of Brown et al. (1989) (crosses). Encircled crosses denote the Li-rich giants in their sample. Inverted triangles indicate upper limits to Li abundance. Superimposed are the subgiants, giants and supergiants in our sample.

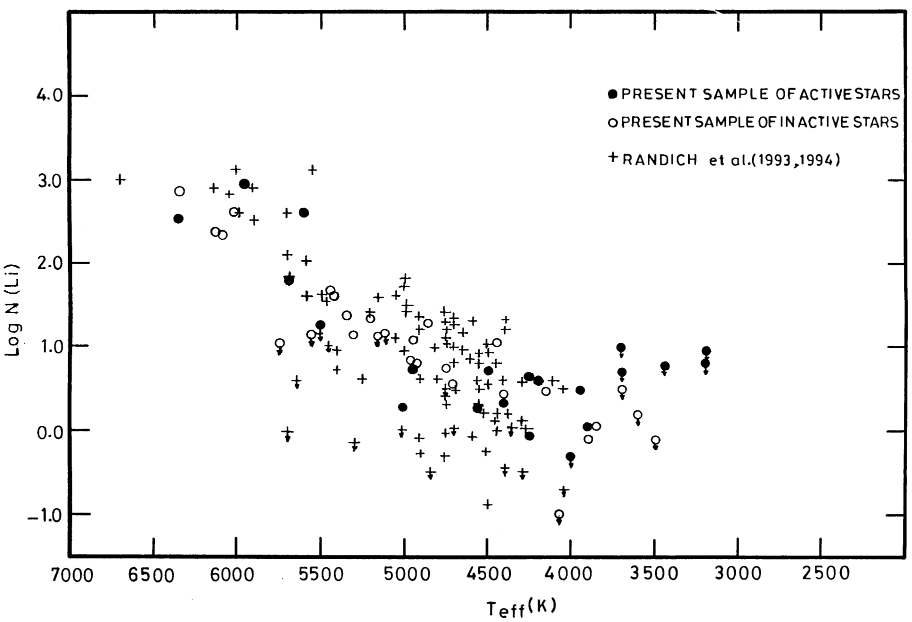

Fig. 7. Lithium abundance vs. effective temperature for the sample of Randich et al. (1993, 1994) (pluses). Also plotted are stars of our sample (circles)

stars are similarly spread in the lithium abundance over the observed temperature range and similar depletions are observed.

If lithium abundance had a direct relation to the phenomenon of chromospheric activity, then one would expect all active stars to have systematically higher Li abundance. This certainly is not the case.

4.3. Lithium and the other stellar parameters

In Fig. 8 log N(Li) is plotted against the projected rotational velocity *v sin i*, available for 34 stars of our sample. One notices that at any value of *v sin i*, log N(Li) shows a full range of values suggesting, in other words, there is no definite correlation between the lithium abundance and rotation. Although we have shown earlier that stars identified as chromospherically active using the Ca II triplet as the diagnostic also have the Ca II H & K emission index $I_k \geq 3$, it would be useful to see how the lithium abundance relates to I_k for all the stars with known I_k of the samples both of Tables 1 and 2. Fig. 9 displays such a correlation. This plot shows that larger Li does not go with higher I_k. In fact there are several stars with strong Ca II emission but

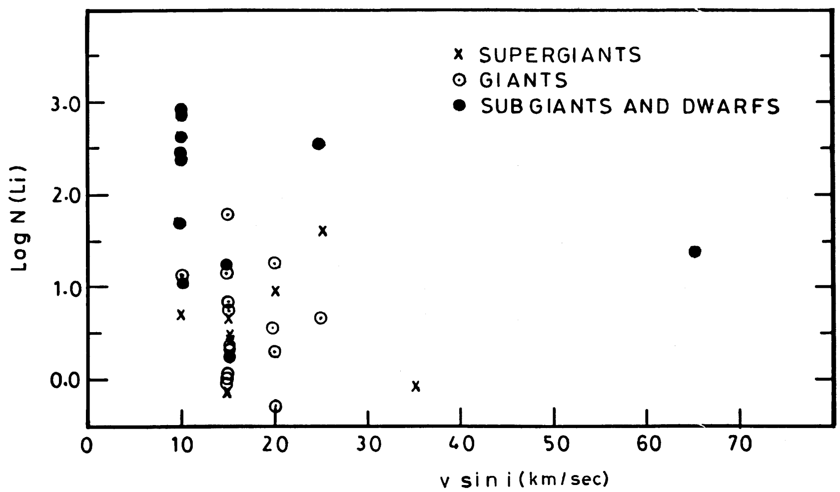

Fig. 8. Lithium abundance vs. *v sin i*. The symbols are described in the key

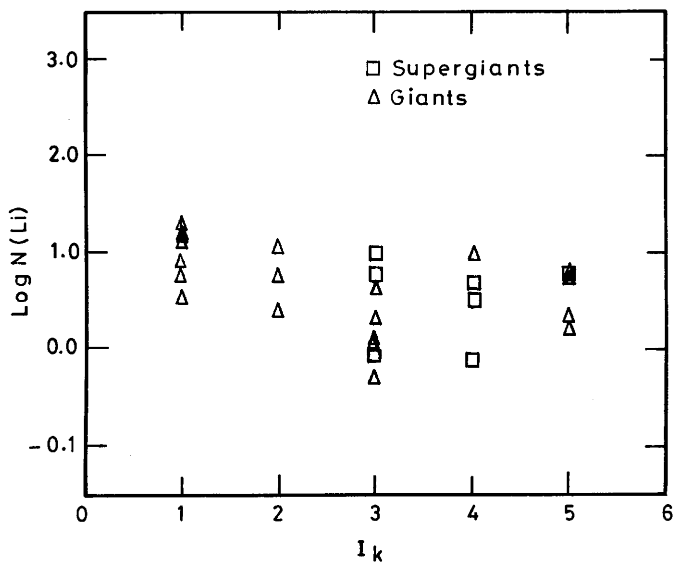

Fig. 9. Lithium abundance vs. Ca II K line emission index I_k. The symbols are described in the key.

no appreciable amount of Li and several stars with weak Ca II emission having significant Li. In general, for any given value of I_k, there exists a range of lithium abundances. As seen in Tables 1 and 2, the stars in our sample span a large range in Fe abundances: $-0.73 \leq$ [Fe/H] $\leq +0.52$ as inferred from the present analysis. In order to see if metallicity has any effect on Li abundances, we plot Li abundance vs. these values of [Fe/H] in Fig. 10 for all the stars. There is no obvious correlation between Li and Fe abundance. There is a faint suggestion of a mild increase of log N(Li) with higher [Fe/H] when dwarfs, giants and supergiants are each viewed separately as a group. A larger sample spanning a still larger range of metallicity would aid in making a definite conclusion. Of course the data would have to be corrected for log N(Li)-T_{eff} dependence also.

Although the present sample does not have giants and supergiants with Li abundance as high as log N(Li) = 1.5 and higher (except ζ Gem), it does show a large spread in Li abundances both among active and inactive giants. One does need 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 like in Brown et al. (1989). It must be recalled that theoretical calculations of Li dilution during post main sequence evolution show that a star that has suffered no Li depletion on main sequence should have a maximum Li abundance of $\sim$ 1.5. Randich et al. (1993, 1994) have suggested that the modest yet significant amount of Li (between 0.5 and 1.5) in cool stars ($T_{eff} \leq 5000$) thus could be due to the fact that these stars have undergone little depletion on the main sequence. In other words, cool giants with appreciable amount of Li have evolved from sufficiently massive stars with very thin or absent convective zones. As has been observed in previous studies of field dwarfs and the Pleiades and the Hyades dwarfs, Li depletion on MS is a strong function of mass. Large Li implies stars have evolved from progenitors with 1.4$\leq$M/$M_{\odot}$ $\leq$3.0 for which the convective mixing has been minimal. Where Li is low, it is presumed that Li has got depleted during MS lifetime and further decreased during post-MS evolution. The moderate amount of Li found in a fraction of the stars in the present sample (log N(Li)>0.5) could thus trace its origin to minimal convective mixing in the main sequence stage. On the other hand, since most other giants show log N(Li) much less than 1.5 this would imply that these stars have undergone MS depletion and therefore perhaps evolved from main sequence stars later than G dwarfs. Randich et al. contend that mass has to have a primary influence on the Li abundance of a giant and that the range of abundances has its origins in the MS stage itself. The spread in the MS lithium abundances due to the different masses is very likely to be reflected in the red giant abundances. This interpretation based on mass decouples the Li problem from the star's activity and explains in a natural way why significant Li is observed only for a fraction of the stars with no clear dependence on the level of activity. It also explains the range of Li abundance observed in these stars. It further explains why evolved stars with similar amounts of Li are observed in samples that are not selected on the basis of activity. The observed Li abundances are consistent with the theoretical upper limit pre-

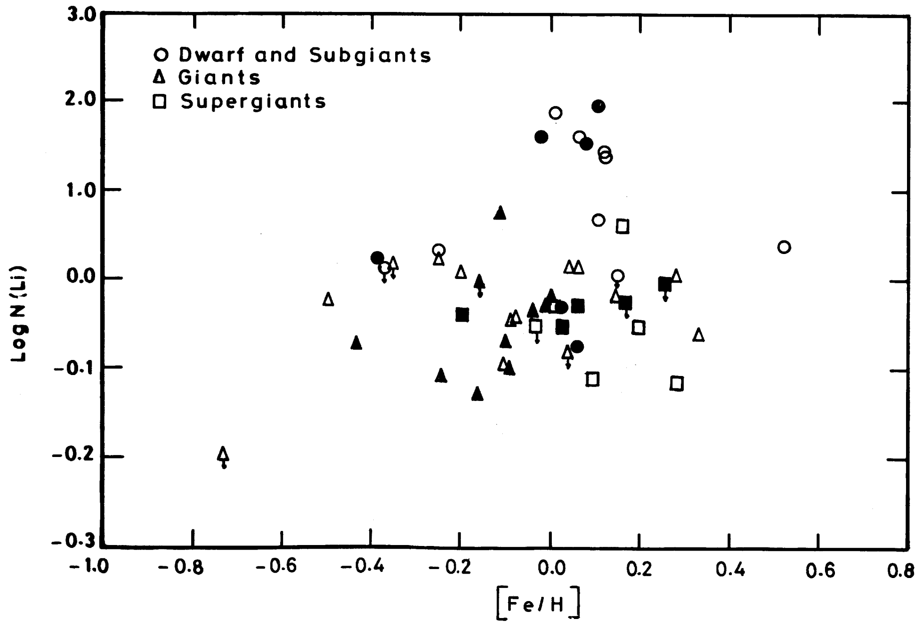

Fig. 10. Li abundance vs. Fe abundance for the stars of the present sample. Filled symbols are the active stars whereas the open ones inactive stars.

dicted for giants. In this framework the larger fraction of Li-rich stars in the sample of Randich et al. with respect to an unbiased sample of evolved stars could simply reflect the different mass distributions within the two samples.

At a given T_{eff}, a range of masses exist for giants and supergiants and masses are virtually unknown for most of the giants and supergiants. So there is no clear indication that at a given T_{eff} the cool giants with larger lithium abundance are also the more massive ones. Randich et al. (1994) have attempted to study possible correlations between Li abundance and stellar mass by comparing the position of stars in their sample in the HR diagram with theoretical evolutionary tracks. Lambert, Dominy & Sivertson (1980) and Luck & Lambert (1982) had earlier used the same technique and found that the Li abundance in G, K and M giants and supergiants is primarily controlled by the stellar mass. Randich et al. however have found a clear distinction between warmer stars (> 5000 K) and the cooler stars (< 5000 K). Among warmer stars there is a tendency of stars with larger Li to be also the more massive. However, for cooler stars this trend completely disappears: similar Li is found at virtually all masses. There are several high mass stars ($\sim 2-3M_{\odot}$) that have Li as low as those of low mass stars ($\sim 1M_{\odot}$) of similar T_{eff}. A similar result has been found for giants in general (Brown et al. 1989, Gilroy 1989, Pilachowski et al. 1990, Pilachowski & Sowell 1992). It suggests that Li depletion and dilution in evolved stars is much more complex than predicted by standard models. Lithium abundances among these stars is a consequence of the entire evolutionary history of the star and of the complex interplay of Li depletion, dilution and possibly production during MS and post-MS evolution. The present paper with a limited sample however has provided convincing evidence that lithium abundance has not much to do with chromospheric activity.

5. Conclusions

The detailed survey of the Ca II triplet lines in 146 stars of all luminosities ranging in spectral types from F7 to M4 and in metallicity from -3.0 to +1.1 has shown that the central depth of the Ca II lines is a good measure of chromospheric activity. The shallower the lines are in the spectrum of a star, the more active is its chromosphere. Based on this parameter, 14 stars were identified from the above sample to be chromospherically active. In order to explore the link between chromospheric activity, lithium abundance and age, the Li I line at 6707.8 Å has been studied in these 14 active stars, 18 relatively inactive stars and another 17 stars chosen at random from the sample of 146 stars. The lithium abundances derived show that:

1) The Li depletion is negligible in F and early G dwarfs except in β Cap. Log N(Li) for these stars is close to 3.0. On the other hand, depletion is severe in late G and K dwarfs. This is in conformity with the idea that the latter, being less massive have deeper convective envelopes, and hence show evidence of higher Li depletion.
2) G, K and M giants and supergiants are expected to have low Li abundances with log N(Li) up to a maximum of 1.5 because of the further deepening convective envelope and consequent mixing and dilution. The observations show that the depletion is even higher than predicted by the model calculations and that there is a large spread in the Li abundances. For most of the stars, log N(Li) lies between -0.3 and +0.7, much less than the theoretical limit of 1.5. It is equally true of active and inactive stars. Similar range is also observed for stars of the unbiased sample. However, a few stars in the present study have log N(Li) exceeding 1.0; in ζ Gem it is as high as 1.59.
3) Although a few chromospherically active stars are Li-rich, it appears there is little correlation between excess Li and chromospheric activity. A significant Li excess is not a general

property of chromospherically active giants.This amount of lithium is also found in a few normal inactive stars and the spread in Li abundances is also not dissimilar in inactive stars and in the sample of stars not specifically selected on the basis of activity.

4) The above observations fit rather well with the suggestion by Randich et al. (1993, 1994) that these stars have evolved from progenitors with different masses with differing depths of convection zones. This also holds true for the unbiased sample of stars and thus explains the similar amounts of Li and the spread of Li in them.

In this study we chose a sample of 49 stars from our Ca II triplet survey to explore the relationship between chromospheric activity and lithium abundance. We are working on an enlarged sample which includes all the subgiants, giants and supergiants of the triplet survey, besides several more observed independently. Effect of the Li abundance – mass relationship for these stars is best explored by plotting these stars on an HR diagram and superposing evolutionary tracks to obtain the masses. We hope to do this for several of these for which absolute magnitudes could be determined from the parallaxes available in the recently published Hipparcos Catalogue. We would thus like to investigate in our next paper whether stars at any given T_{eff} with higher Li are also the more massive ones.

Acknowledgements. I would like to thank Sunetra Giridhar for several discussions relating to the use of LINES code. I would also like to express my appreciation to D.L. Lambert and D.C.V. Mallik for kindly reading the manuscript and making numerous useful suggestions. I am grateful to the referee, S. Randich, for several critical comments which have helped in improving the paper.

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