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Lithium abundance in a volume-limited sample of nearby main sequence G and K stars*

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Abstract. We present observations of the Li I 6707.8 Å line in a volume limited sample of main sequence stars of spectral types ranging from late F down to M0, selected from the Gliese catalog of nearby stars, discussing the behavior of lithium abundance along the main sequence. An unexpected result from our survey is that a low but measurable abundance of surface lithium ($-0.5 < N(\mathrm{Li}) < -1.0$) is found to be a common feature in the cooler dwarfs in our sample. Possible explanations for the widespread presence of lithium in very cool dwarfs are discussed, with emphasis on the possibility of lithium being produced in stellar flares. We also discuss the feasibility of using kinematic age indicators for studying the lithium-age relationship, and show that surface lithium is found to be essentially uncorrelated with kinematic age indicators for the dwarfs in our sample.

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

1. Introduction

The study of lithium in late-type stars in the last decade or so has produced a flurry of new results. Each new set of observations has appeared to produce new, often puzzling results, which have often challenged the current "wisdom" on light element depletion.

Most of the recent high resolution, high signal to noise observations have been made on samples selected on the basis of some peculiarity, or of some defining characteristic, as for example age-homogeneous sample of stars from young open clusters (notably the Pleiades, Hyades, α Per and Praesepe clusters, see Soderblom et al. 1993), active binaries samples (Randich et al. 1993), tidally locked binaries samples or samples selected on the basis of their high X-ray activity (Favata et al. 1995a). Most of the dwarf Pop I stellar samples in which lithium has been studied have thus so far been relatively young, and, due to the magnitude limitation imposed by the distance of open clusters, have usually not extended much toward the red side of the main sequence.

Observations of representative samples of normal disk population stars have been notably lacking. Much of the knowledge about the behavior of lithium in field stars is based on observations made with now obsolete detector technologies, which, given the relatively low sensitivity, did not observe redder and therefore fainter stars, such as for example the work of Duncan (1981). A notable exception is the recent work of Pasquini et al. (1994), who have observed a sample of nearby stars with spectral type G0V–G5V using essentially the same instrument as the one used in the present work.

Some older works have looked at more limited samples of stars with modern instruments, such as for example the work of Pallavicini et al. (1987), which used the same telescope/spectrograph combination as the present work (with a Reticon detector) to observe a small sample (27) of nearby stars from late F to early K. However, given the size of the sample, and the unclear selection criteria, it is difficult to evaluate how representative of the general solar neighborhood population are the results.

We have therefore performed a survey of lithium in nearby dwarfs with spectral types ranging from late F down to late K. The aim of the survey has been twofold: on one hand we have observed a representative, volume limited sample of stars, aiming at studying the behavior of lithium in normal, disk population late-type dwarfs. On the other hand we have also observed a second sample of red dwarfs which have been observed in the X-rays with the *Einstein* observatory; the aim of this second sample has been to study (eventual) lithium-activity correlations, as well as to study the behavior of different age indicators for late-type stars. The results for the volume limited sample is described in the present paper, while the results for the X-ray selected sample are described in a companion paper (Favata et al. 1996, hereafter Paper II).

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* Based on observations obtained at the ESO La Silla observatory.

The present paper is structured as follows: Sect. 2 describes in detail the sample selection criteria, the observations, and their reduction and analysis, Sect. 3 discusses the general behavior of lithium across the color range surveyed, while Sect. 4 discusses the widespread presence of a weak lithium feature in the spectrum of the later type stars in our sample.

2. Sample selection, observations and data analysis

The observed sample discussed in the present paper has been selected from the Gliese catalog of nearby stars (Gliese 1969; Gliese & Jahreiss 1979); it consists of 100 objects with color index ($B-V$) ranging between 0.5 and 0.8 (i.e. late F and G dwarfs) plus 100 objects with $0.8 \leq B-V \leq 1.4$ (i.e. K dwarfs). The objects in the sample have been selected at random among all the Gliese stars falling in the above color range. This volume limited sample has been selected with no limitation in sky coverage, and it is uniformly distributed in the whole sky, with 96 objects in the northern hemisphere and 104 objects in the southern hemisphere. As the survey has been done from the southern hemisphere, we observed only the fraction of the sample accessible to our instrument, without compromising the unbiasedness of the sample. In total 94 objects have been observed, i.e. most of accessible sample. The observed sample, given the absence of selection biases, should be representative of the disk population typical of the solar neighborhood, and it is listed in full in Table 1.

All the observations used in the course of the present work have been conducted using the CAT 1.4 m telescope at the ESO La Silla observatory, with the Coudé Echelle Spectrometer (CES) using either the short camera with the RCA CCD (ESO #9), yielding an effective resolution of about 50 000, or the long camera, yielding an effective resolution of about 100 000. With a few exceptions due to uncooperative weather, the objects were exposed to a signal-to-noise ratio of at least 80 per pixel, with most object having a signal to noise ratio of more than 100 per pixel. The observations presented here were obtained in November 1993 and in February and August 1994.

The individual exposures were centered on the Li I 6707.8 Å feature, and covered about 40 Å. Standard data reduction (bias subtraction, flat-fielding, spectrum extraction and wavelength calibration) was performed using the facilities provided within the IRAF software package. Given the sensitivity of the RCA CCD to fringing in red light, we have flat-fielded the frames using both the internal flat-fielding lamp and a fast rotating bright B star (one per night). No difference in the reduced spectra using the two flat field methods is visible at the S/N level of our data.

The equivalent width of the Li I 6707.8 Å line has been measured for each spectrum, by fitting a gaussian to the line, using the procedure available in the *splot* task of the IRAF package. Continuum determination has been done both by eye and by using the line plus continuum fitting feature of the *splot* task, both approaches giving consistent results. In most cases, given the low rotational velocity of the sample stars, the Li I 6707.8 Å line was not blended with the nearby Fe I 6707.4 Å line, and therefore its equivalent width could be easily measured. In a few cases (2 in in the present sample, namely GJ 198 and GJ 23A) the two lines were irretrievably blended, and therefore the blend was measured, and the equivalent width of the Fe I line typical for the color of the star was subtracted. To compute the equivalent width of the Fe I line the calibration of Favata et al. (1993) relative to solar metallicity stars was used.

Given that randomly selected stars in the solar neighborhood are expected to show a range of metallicities with [M/H] ranging from about -0.4 dex up to about $+0.2$ dex, it is necessary to consider the influence of metallicity effects in the determination of the effective temperature. In particular, the $B-V$ color index is rather sensitive to metallicity effects, with the $T_{\rm eff}$ calibration varying by about 200 K at $B-V=1$ in the metallicity range of interest here (see Fig. 17a of Buser & Kurucz 1992). We have therefore used, wherever available, the $R-I$ color index, which is effectively insensitive to metallicity effects in the range $-2.0 <$ [M/H] $< +0.5$, as shown again by Buser & Kurucz (1992). An additional advantage of using the $R-I$ color index is its being essentially insensitive to interstellar reddening; however, as all of our stars are nearby, this is not expected to be a problem. We have used the effective temperature versus color calibration of Bessel (1979), which presents a coherent calibration for several color indices, including $B-V$, $R-I$ and $b-y$. We were able to get a self-consistent set of measurements as the same author (Bessel 1990) has also performed a photometric survey of nearby southern late type dwarfs, so that for 68 stars in our sample we used $R-I$ values obtained with the same instrument and from the same author as the $T_{\rm eff}$ calibration. We estimate the error on the $T_{\rm eff}$ induced by observational errors in the photometry to be about 75 K, corresponding to an uncertainty in $R-I$ of 0.05 mag. Note that a few of the stars which do not have $R-I$ colors available from Bessel (1979) had $R-I$ data available from other sources (namely Carney 1980, Fuhrmann et al. 1994, Jacobsen 1970 and Weis 1991) which are indicated in Table 1.

Of the remaining stars, 14 had $b-y$ measurements available in the literature from various sources. Although not as insensitive to the metallicity as the $R-I$ index, $b-y$ still shows very little sensitivity to variations in [M/H]. As shown by Olsen (1984), the inclusion of a metallicity term in the temperature-color relationship for disk G and K dwarfs changes the temperature dispersion from 0.011 dex to 0.009 dex, i.e. a small change equivalent to an error in $b-y$ of only 0.004 mag. We have therefore, to maintain a self-consistent temperature calibration, used the $T_{\rm eff}$ vs. $b-y$ calibration of Bessel (1979), which does not include metallicity effects, rather than more modern ones as, for example, the one of Olsen (1984). We estimate an error on $T_{\rm eff}$ comparable to the one obtained using $R-I$ indices.

Finally, for the few (13) remaining stars for which no other photometric indices where available, we used the available $B-V$ data, again from miscellaneous sources. Because of the metallicity dependence discussed above, we estimate the $T_{\rm eff}$ error to be significantly larger for these stars, i.e. about 180 K, due the combined effect of errors on the color measurements and [M/H] effects. Finally, for one star (GJ 9037) for which

Table 1. The observed sample. For each star the Gliese (GJ) number is given, as well as the HD number (when available). Spectral types and colors are taken from the literature. Only the color used to determine the $T_{\rm eff}$ (see text) is listed. The W(Li) values are from our observations, and the N(Li) values are the corresponding computed abundances. In the comments field objects which have been observed at R = 100 000 are indicated. A "B" in the comments field indicates objects which are in common with the sample discussed in Paper II, while a Y indicates that the object is kinematically young. Also indicated are objects for which the color information comes from sources other than Bessel (1979).

GJ	HD	Sp.	Color	W(Li) (mÅ)	$T_{\rm eff}$ K	N(Li)	Comments
9029A	4597	G0?	$B-V=0.54$	27	6122	2.29	
904	222368	F7V	$R-I=0.291$	26	6105	2.26	B; Y
496A	113415	F8V	$R-I=0.292$	61	6096	2.66	
9002A	142	G1IV	$b-y=0.358$	51	6013	2.49	Y
504	115383	G0V	$R-I=0.305$	83	5983	2.74	B
127A	20010	F8IV	$R-I=0.310$	13	5940	1.80	
198	34721	G0V	$R-I=0.310$	33	5940	2.23	
312	73524	G4IV	$R-I=0.310$	49	5940	2.41	Y
243	48938	G2V	$R-I=0.315$	35	5898	2.21	
23A	3196	F8V	$R-I=0.316$	54	5890	2.41	Y
9209A	44120	G3V	$b-y=0.379$	47	5880	2.33	B
9287A	78643	G1V	$B-V=0.60$	46	5877	2.32	
77	11112	G4V	$R-I=0.318$	58	5873	2.44	Y
404	94444	F8IV	$R-I=0.320$	31	5856	2.12	Y
598	141004	G0V	$R-I=0.325$	20	5815	1.88	B; Y
871A	214953	G1V	$R-I=0.328$	63	5790	2.40	
9730	202628	G5V	$R-I=0.330$	41	5773	2.17	R = 100 000; Y
9802	216435	G3IV	$b-y=0.397$	70	5770	2.44	Y
559A	128620	G2V	$R-I=0.331$	6	5765	1.29	B
9819	219709	G2V	$b-y=0.399$	<3	5758	<0.98	Y
327	76151	G3V	$R-I=0.335$	23	5732	1.87	B; Y
691	160691	G5V	$R-I=0.335$	<2	5732	<0.77	R = 100 000; Y
9252	67458	G4V	$R-I=0.335$	29	5732	1.98	
19	2151	G2IV	$R-I=0.339$	72	5700	2.39	
9409A	108799	F8V	$R-I=0.339$	90	5700	2.53	
9208A	43587	G0V	$R-I=0.340$	23	5692	1.83	
9317	88218	F9V	$R-I=0.340$	52	5692	2.21	
9273	73350	G0?	$b-y=0.412$	42	5681	2.10	
9037	6434	G3IV	–	<2	5671	<0.71	$T_{\rm eff}$ from Fuhrmann et al. (1994)
9075B	13612B	G4V	$b-y=0.414$	26	5670	1.87	Y
9378A	103432	G6V	$b-y=0.417$	5	5653	1.10	Y
135	20619	G2V	$R-I=0.345$	17	5651	1.65	
9396	106116	G4V	$R-I=0.345$	<2	5651	<0.70	
9774	210918	G5V	$R-I=0.345$	<2	5651	<0.70	
9092A	16619	G4V	$b-y=0.418$	1	5647	0.39	B; Y
744	177565	G5IV	$R-I=0.350$	<1	5611	<0.35	R = 100 000
9223A	53705	G3VSB	$R-I=0.335$	<3	5571	<0.79	
9450	117939	G4V	$R-I=0.360$	<2	5532	<0.57	$R-I$ from Carney (1980)
9769	210277	G9V	$R-I=0.360$	4	5532	0.88	
746	178428	G5V	$b-y=0.440$	<2	5526	<0.57	R = 100 000
9790	213941	G5V	$R-I=0.362$	<2	5516	<0.56	
9463	121849	G5V	$R-I=0.368$	<2	5468	<0.51	
869	214759	G8V	$R-I=0.370$	<3	5453	<0.48	
9220B	NA	G4V	$B-V=0.72$	38	5438	1.81	Y
9223B	53706	K0V	$b-y=0.465$	<3	5399	<0.61	
530	120690	G5V	$R-I=0.382$	6	5359	0.88	
9269	72769	G5V	$B-V=0.75$	<1	5354	<0.10	
580A	135204	G8V	$R-I=0.385$	3	5336	0.55	
9177	33811	G5	$B-V=0.77$	<2	5302	<0.33	B
9792A	214615	K0V	$R-I=0.390$	<2	5297	<0.33	Y
9350	NA	K1?	$B-V=0.78$	<2	5276	<0.30	
113.0	17382	K1	$b-y=0.490$	<5	5272	<0.70	Y
315.0	73667	K1	$b-y=0.495$	<2	5245	<0.27	
9019	3795	G3V	$R-I=0.400$	<2	5221	<0.24	R = 100 000
559B	128621	K0	$R-I=0.404$	<1	5191	<-0.10	B
9045B	7438	G9V	$R-I=0.405$	<3	5184	<0.38	
309	72673	K0V	$R-I=0.410$	<2	5146	<0.16	
56.3A	7895	K1	$R-I=0.412$	<2	5131	<0.14	B
9249.0A	66509	K2V	$B-V=0.85$	<2	5092	<0.10	
9395.0	106092	K0	$R-I=0.420$	<2	5072	<-0.07	$R-I$ from Weis (1991)
491A	112758	K0V	$R-I=0.425$	<4	5036	<0.33	
120.1B	NA	NA	$B-V=0.87$	<2	5032	<-0.02	
505.0A	115404	K2	$b-y=0.532$	<3	5021	<-0.18	
53.1A	NA	K4	$R-I=0.430$	<1	5000	<-0.32	
9245	64606	G8V	$R-I=0.430$	<3	5000	<0.16	

Table 1. (continued)

GJ	HD	Sp.	Color	W(Li) (mÅ)	$T_{\rm eff}$ K	N(Li)	Comments
150.0	23249	K0IV	$R-I=0.435$	29	4964	1.14	
613.0	144628	K3	$R-I=0.445$	<2	4894	<-0.15	
42.0	5133	K3	$R-I=0.460$	<2	4793	<-0.28	Y
368.1A	NA	K1	$R-I=0.465$	<2	4761	<-0.32	
86.1	NA	K2	$R-I=0.465$	4	4761	-0.01	Y
165.2	NA	K4	$R-I=0.470$	<2	4729	<-0.36	
18.0	2025	K3	$R-I=0.480$	2	4667	-0.45	
531.0	120780	K1	$R-I=0.480$	<2	4667	<-0.45	
429.0B	99492	K2	$R-I=0.482$	<2	4665	<-0.46	$R-I$ from Jacobsen (1970)
118.2A	18143	K2V	$B-V=0.98$	<2	4635	<-0.49	Y
183	32147	K3	$R-I=0.490$	3	4608	-0.35	B; R = 100 000
118.1A	NA	K3	$R-I=0.495$	<2	4580	<-0.57	
429.4	NA	K4	$R-I=0.495$	<2	4580	<-0.57	
610.0	144253	K2V	$R-I=0.518$	<4	4461	<-0.45	
250A	50281	K6V	$R-I=0.525$	1	4429	-1.13	B
293.2	NA	K4V	$R-I=0.530$	<3	4407	<-0.67	
456.1A	NA	K5	$R-I=0.540$	2	4366	-0.92	Y
149.0	NA	K4	$R-I=0.541$	<5	4362	<-0.50	
141.0	21197	K5	$R-I=0.555$	<2	4310	<-1.01	
868.0	214749	K5	$R-I=0.565$	5	4276	-0.62	Y
664.0	156026	K5	$R-I=0.580$	4	4232	-0.78	R = 100 000
1106.0	NA	K5	$B-V=1.19$	<3	4173	<-0.98	
1176.0	119291	K7	$B-V=1.19$	3	4173	-0.98	
140.1A	NA	K5	$R-I=0.620$	<1	4139	<-1.53	
428A	99279	K7	$R-I=0.690$	5	4044	-0.85	B; Y
9347.0	NA	K5	$R-I=0.695$	3	4039	-1.10	
1177.0A	120036	K5	$B-V=1.32$	10	4000	-0.57	
798.0	196877	K7	$R-I=0.748$	8	3993	-0.68	R = 100 000
1008.0	NA	K7	$B-V=1.33$	11	3983	-0.54	

no color information was available in the literature, we used an available $T_{\rm eff}$ determination based on excitation equilibrium available in the literature.

While it would certainly have been desirable, in principle, to derive effective temperatures directly from the spectra (from the excitation equilibrium), the limited spectral coverage of our CAT/CES spectra (only about 40 Å), makes this difficult. In particular, no Fe II lines are present in the spectra, and we have verified that using only the (plentiful) Fe I lines makes it very difficult to disentangle metallicity effects from effective temperature effects, specially for the cooler stars.

The lithium abundance was subsequently determined by fitting a bi-cubic spline to the curves of growth of Soderblom et al. (1993). Although our sample contains a large fraction of binaries, none of the star in the sample show a double lined spectral system (except for GJ 233 from Paper II, which we observed in a phase in which the Li I feature from the primary is irretrievably blended with other lines from the secondary, making the spectrum unusable for our purposes), and therefore no correction for the presence of the companion has been necessary. It is also worth noting that the effect of a spread in metallicity on the Li I curves of growth is (in the [M/H] range of interest here) essentially negligible.

3. The behavior of Li with effective temperature

Fig. 1 shows the computed lithium abundances plotted versus the effective temperature for all the stars in the present sample. The qualitative behavior of N(Li) along the HR diagram in the solar neighborhood is strongly temperature dependent. Three "regions" can be distinguished, corresponding to the approximate ranges in temperature $6200 < T_{\rm eff} < 5500$ (corresponding approximately to F8V–G5V, with 40 objects in the present sample), $5500 < T_{\rm eff} < 4850$ (corresponding approximately to G5V–K2V, with 28 objects), $4850 < T_{\rm eff} < 4000$ (corresponding approximately to K2V–M0V, also with 27 objects).

The F8V–G5V region has been recently surveyed by Pasquini et al. (1994). Our volume limited sample has only 5 objects in common with their sample, out of a total of 39 objects in the same color range in our sample and a total of 42 objects in the Pasquini et al. (1994) sample, and therefore is an essentially independent one. As it is shown in Fig. 2, the agreement in the measured Li I equivalent width for the 5 objects in common between the sample discussed in the present paper plus the 7 objects in common between the sample discussed in Paper II and the Pasquini et al. (1994) sample is quite good, as is the resulting lithium abundance versus color relationship, which can be seen in their Fig. 3. We will not therefore much expand here on their conclusions about the behavior of lithium in this color range, as they are supported from our study and show no significant difference. In particular, the large spread of

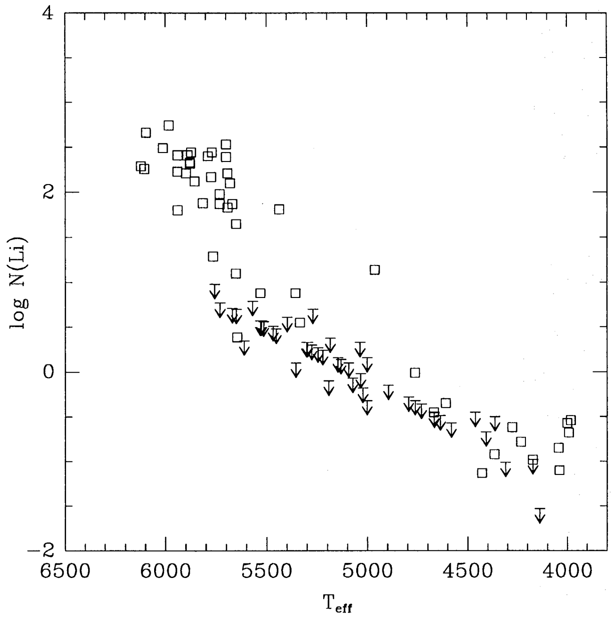

Fig. 1. Lithium abundance versus effective temperature for the stars in the sample. Down-pointing arrows indicate upper limits to the surface abundance due to the lack of detection of the Li I 6707.8 Å line

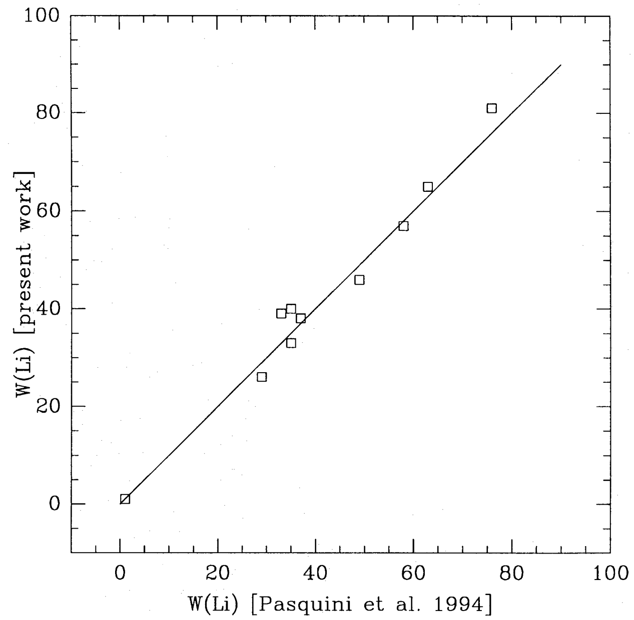

Fig. 2. Comparison between the Li I equivalent width measured in the present work and the values measured by Pasquini et al. (1994) for the 12 stars in common between their sample and the joint samples of this paper plus Paper II. The continuous line is the locus of the $x = y$ relationship

lithium abundances at any given color is evident from our data set. Also, by using kinematics as an age indicator, we find the same type of lithium rich old stars (which was already noticed by Spite & Spite 1982 and Pallavicini et al. 1987) discussed by Pasquini et al. (1994).

The second temperature range of interest here is the region comprised between $5500 < T_{\rm eff} < 4850$, i.e. main sequence stars with spectral types approximately comprised between G5V and K2V. In this color range, with the exceptions of one high lithium star (GJ 150, a well known object which we discuss in more detail later), only 3 of the 27 remaining objects observed show any detectable lithium line down to the mÅ level, and they are all at the hotter range of the $T_{\rm eff}$ interval. All of the objects in this color range in our samples rotate slowly, below the instrumental broadening limit, therefore allowing faint lines to be detected down to very weak equivalent widths. The slope visible in the N(Li) vs. $T_{\rm eff}$ plot is simply due to the temperature dependence of the curve of growth. In this temperature range therefore lithium appears to be quickly depleted, and basically undetectable down to quite low abundances in the largest majority of fields stars, as expected from current theoretical models.

The only high lithium K star in the sample, GJ 150, is a subgiant, one of the few evolved stars in the solar neighborhood. Its spectrum displays a well visible Li I line, implying a lithium abundance $N(\rm Li) = 1.14$. Given that the precise evolutionary status and mass of GJ 150 are not known, it is unclear whether it represents a case similar to β Hyi or whether it descends from a more massive and hotter (and therefore possibly lithium undepleted) progenitor. β Hyi is G2IV star often considered a very good "old sun" proxy. Although the estimated age for β Hyi is about 9.5 Gyr (i.e. about twice the solar age) its lithium abundance has been measured to be $N(\rm Li) = 2.4$ (Dravins et al. 1993), about an order of magnitude higher than the solar abundance. A simple model implying monotonic lithium depletion at the basis of the convective zone is clearly ruled out here, and several models, as discussed by Dravins et al. (1993) have been invoked to explain the "reappearance" of lithium in subgiants. GJ 150 does not however appear in any way peculiar, as lithium in sub-giants is a relatively common feature (Randich et al. 1995).

Stars cooler that $\approx$ 4400 K show a much more complex spectrum, and a small equivalent width (i.e. a few mÅ) feature at the wavelength of the Li I line appears to become common. Their behavior, together with the implications of the widespread presence of low lithium abundance in red dwarfs is discussed in detail in Sect. 4.

4. The Li I feature in later type stars

Our volume limited sample contains a large fraction (of the order of 50%) later type stars which show a low but detectable lithium abundance. Lithium is not expected to be common in the photosphere of late type stars, as, according to theoretical models, it should burn very quickly, with a substantial fraction disappearing already in the PMS phase. We were therefore surprised to observe a feature at the wavelength of the Li I 6707.8 Å line and several mÅ in equivalent width in many of the cooler stars in the sample. To better determine the observed line in the cooler stars we have observed some of these with the CAT/CES and the long camera, a configuration which doubles the resolu-

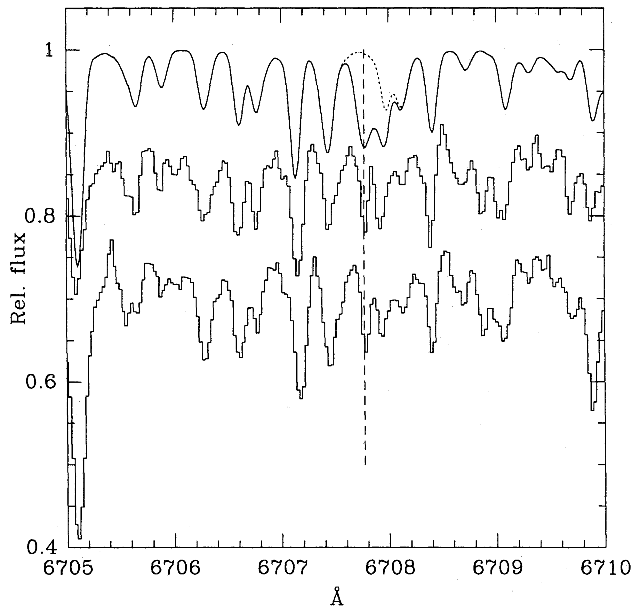

Fig. 3. A synthetic spectrum obtained with the model atmosphere, line lists and spectral synthesis code of Kurucz (1993) plotted together with the observed R = 100 000 spectra of GJ 142 and GJ 798. The dashed vertical line marks the position of the Li I 6707.8 Å feature. The synthetic spectrum is on top, computed for $N(\mathrm{Li}) = 0.0$ abundance (continuous line) and for a spectrum with no lithium (dashed line). The two observed spectra, plotted as histograms, are shifted for clarity by -0.15 and -0.30 for GJ 798 and GJ 142 respectively

tion of the short camera (i.e. to about 100 000). To study whether the observed feature could be due to a mis-identification with some other line (perhaps from molecular species, which are common in late-type star spectra) we have compared the resulting spectra, taken at a signal to noise ratio in excess of 150, with synthetic spectra based on the Kurucz (1993a) and Kurucz (1993b) models and codes. A segment of the synthetic spectrum (in the 6705–6710 Å range) for a $T_{\mathrm{eff}} = 4250$ K, $\log(g) = 4.5$, solar metallicity model is shown in Fig. 3, together with the two cooler observed spectra for which we have R = 100 000 observations[1]. No features which could be mistaken for lithium appear in the synthetic spectrum. The R = 100 000 observations for GJ 879, GJ 142 and GJ 798 and the analysis performed on them, together with a comparison with previous published work, are discussed in more detail in Favata et al. (1995b), to which the reader is referred for details. In particular, Favata et al. (1995b) show that the purported s element line used by Lambert et al. (1993) to explain the apparent detection of lithium in barium giants is very unlikely to be the explanation of the lithium feature in cool dwarfs.

The main conclusion of the work of Favata et al. (1995b) is that the feature visible in the spectrum of later type systems is either really lithium or it is observationally not distinguishable from it. Unfortunately, we have located no high-resolution, high S/N observations for single, slowly rotating later type dwarfs in the literature, and therefore have not been able to compare our results with previously published work. The possibility of the observed lithium feature in the cooler dwarfs being (partially) due to a line missing from the line lists we have used for producing the synthetic spectra is of course a real one. The resulting physical interpretation of the two above possibilities (a real lithium feature versus a feature mimicking it very closely) are obviously very different, and with very different consequences. Nevertheless, it is not possible, on the basis of the current data, to discriminate between them. Therefore, we will discuss in the following paragraphs, the implications of lithium being present in the cooler stars of our sample.

Classical stellar models predict that K dwarfs should deplete lithium faster than higher mass stars (i.e. F and G dwarfs), because of the deeper convection zone. Recent theoretical models of stellar evolution, as for example the rotating models of Pinsonneault et al. (1990) (hereafter PKD), confirm that the lower the stellar mass, the more rapidly should light elements be burned (although with much faster time scales than classical models), both during the PMS and during the main sequence phase, with a slow down in lithium depletion speed for the lowest masses (i.e. lower than $\approx 0.5\,M_{\odot}$, see Fig. 11 of PKD). For example, according to PKD models, a normal $0.6\,M_{\odot}$ star should have depleted its surface lithium by more than 4 dex by the time it reaches the Hyades age (i.e. down to $N(\mathrm{Li}) \approx -1$), and it should keep depleting it at a more or less exponential rate along its main sequence lifetime. Although the rate of depletion is likely to somewhat slow down when the star ages, because of the growing radiative core, these depletion rates are hard to reconcile with levels of lithium of up to $N(\mathrm{Li}) = -0.5$ which we observe being common in normal disk population red dwarfs. PKD models are computed for a solar metallicity element mix while lower metallicity stars should deplete lithium more slowly (Pinsonneault et al. 1992). However, the large fraction of low mass, lithium containing stars in our sample is not compatible with all of them being low metallicity objects. We have not measured the metallicity on our sample stars, however we will use the R = 100 000 spectra in a future paper to perform a complete spectral synthesis analysis and to measure the metallicity in these stars. Again, as no high resolution, high S/N observations of the Li I feature in red dwarfs appear to have been published so far, the predictions about the depletion of lithium in red dwarfs are so far basically untested.

4.1. Li production in stellar flares?

Lithium generation through spallation processes in stellar flares has been considered in the past as a possibility to explain, for example, the high lithium abundances observed in active binaries (see Pallavicini et al. 1992), but it has not until now been considered a viable mechanism mostly because of energetics: the energy input required to generate the levels of lithium often observed in active binaries (up to $N(\mathrm{Li}) = 1.5$) exceeds the total energy output of the corona. However lithium production in flares could be a possible mechanism to explain the low lithium abundances of several of the red dwarfs in our sample,

[1] GJ 142 is an object from Paper II

where the abundances (and consequently the energy requirements) are much lower. If we assume a very simple model, in which the lithium destruction at the basis of the convection zone proceeds exponentially with time, and in which the lithium production in stellar flares is constant in time, the observed surface lithium abundance is the equilibrium value between the constant production and the exponential destruction processes, that is, $R_f = N_{\rm eq}/\tau$, where R_f is the lithium production rate in stellar flares, $N_{\rm eq}$ is the observed "equilibrium" lithium abundance and τ is the e-folding time for lithium depletion. Taking a value of ≈ 100 Myr for τ (from the observed lithium depletion in the Hyades), and an average $N_{\rm eq}$ of about -1.0 (in the usual logarithmic scale relative to a conventional H abundance of 12.0), the lithium production rate required to maintain the observed lithium abundance of -1.0 throughout the convection zone in a 0.6 $M_\odot$ dwarf (in which it constitutes $\approx 10\%$ of the total stellar mass) is $\approx 2 \times 10^{35}$ lithium atoms per year. As discussed by Ryter et al. (1970), the energy requirement for the production of a single lithium atom via spallation, assuming a E^{-3} particle spectrum, ranges from 1 to 10 erg of total emitted energy in the flare, implying that a coronal luminosity of $\approx 10^{27}$–10^{28} erg/sec will be needed to maintain an equilibrium surface abundance of N(Li) = -1.0. While these energy requirements are by no means negligible, they are not incompatible with the coronal energy output of typical stellar coronae for dK stars (Barbera et al. 1993; Schmitt et al. 1995). Also, longer time scales for lithium depletion (as suggested from the kinematics of the samples, see Sect. 5) would imply correspondingly lower energetic requirements. Note that the simple model sketched here does not imply that the lithium abundance of red stars should be constant; given that old cool dwarfs appear to show on average lower activity levels than young dwarfs of the same color (Barbera et al. 1993, although the matter is controverse, see also Fleming et al. 1995), on the reasonable assumption that the time scale for the age-activity relationship is longer than the time scale for lithium depletion, at each age (i.e. activity level) a "quasi-equilibrium" surface lithium abundance would be seen, which would depend on the activity level.

Lithium production from spallation reactions carries with itself two signatures which can help to define observational tests for this hypothesis. As discussed by Schramm et al. (1990), the ^{7}Li/^{6}Li isotopic ratio for the lithium produced by spallation is ≈ 2, while the ratio so far measured in stars or in the interstellar medium (hereafter ISM) is ^{7}Li/^{6}Li $\gtrsim 10$ (see the papers in Crane 1995 for a review of current results), although no direct measurements of the isotopic ratio in cool Pop I dwarfs are known to the authors. Lithium isotopic ratio measurements (requiring R $\geq 100\,000$ and S/N ≥ 400) in some of the red dwarfs showing N(Li) ≈ -1.0 would strongly constrain the possibility of lithium production by spallation in flares, at least by currently accepted mechanisms. The second signature of lithium production in flares is the production, at the same time, of Be and B, with well defined (as a function of the particle spectrum in the flare, see Walker et al. 1985) isotopic ratios. Given the difficulty in determining lithium isotopic ratios in these relatively faint stars, isotopic ratio determinations of beryllium and boron, whose spectral features are located in much less favorable spectra regions, are most likely to be outside the reach of current generation instruments. However, flare-related production should also alter the light element abundance ratios (and not only the isotope ratios). The Li/Be ratio could be determined for some of the stars from current ground based telescopes, providing one possible observational test. All of the stars are however too faint and red for HST-based boron measurements, at least with exposures of a few orbits, making a determination of the Li/B ratio very difficult.

If a strong age-activity correlation is present in the cool dwarfs, and if the observed lithium is actually (partially) produced in the corona, its abundance should show some level of correlation with stellar age. As discussed in Sect. 5 we do not find a correlation between the lithium abundance in the cooler dwarfs and their kinematic class. However, given the statistical nature and low sensitivity for phenomena with a decay time longer than 1 Gyr (as discussed in Sect. 5) of purely kinematic indicators, and the controverse state of the activity-age correlation for cool dwarfs, we do not regard this as conclusive evidence *against* the possibility of activity-related photospheric lithium production.

One final question raised by the possibility of lithium being produced in stellar flares in low mass stars is the impact of this lithium source on the evolution of the cosmic lithium abundance. Low mass stars have a long main sequence lifetime, therefore any potential contribution to the ISM lithium abundance due to high mass losses in the post-main sequence evolution should, for these stars, be negligible. Additionally, at the end of the main sequence lifetime the quasi-equilibrium surface lithium abundance is likely to be significantly lower than the values observed in current disk population stars, so that even if mass would be returned to the ISM the lithium content should be very low.

Another possible mechanism for ISM lithium enrichment is through main sequence mass loss, i.e. stellar winds. Very few actual measurements of mass loss rates from low mass main sequence stars exist; mass loss rates as high as $10^{-10}\,M_\odot$/yr in M stars have been reported (Mullan et al. 1992) based on microwave measurements. If such high mass loss rates were actually common in M dwarfs, Mullan et al. (1992) predict that M dwarfs should return to the ISM up to 10 $M_\odot$/yr in the whole Galaxy. Assuming a mass for the disk of $6 \times 10^{10}\,M_\odot$ (Bahcall 1986) and a present day gas fraction of 0.2 (Rana 1991), M dwarfs would enrich the ISM in lithium by about ΔN(Li) = 10^{-10}/yr (again in the usual logarithmic scale) so that, even in the assumption of strong winds in M dwarfs, the total Li enrichment in the ISM after 10^{10} yr would be ΔN(Li) = 0, i.e. negligible in comparison with the measured initial Pop. I abundance of N(Li) ≈ 3.2. Therefore the production of lithium in flares in dwarf stars at the levels observed here would not have a measurable impact on the galactic light element evolution, or on the Li isotopic ratio in the ISM.

Low levels of lithium (independently from its being produced in stellar flares) could also be present in the atmosphere of earlier (i.e. G and early K) old stars; however, the strong dependence of the lithium ionization fraction on effective temperature would make low amounts of lithium effectively undetectable with any practically achievable resolution and S/N in the relatively hotter stars.

5. The relationship between lithium and kinematics

Space motions have long been used as a statistical age indicator for stars in the solar neighborhood, although the usefulness of kinematic class as an age indicator for late type (K and M) dwarfs has recently been questioned by Fleming et al. (1995), who fail to detect a statistically significant difference between the X-ray luminosity function of kinematically young and kinematically old red dwarfs using a volume limited sample of all K and M dwarfs within a 7 pc radius around the sun. Most stellar evolution models predict a lithium-age correlation, although perhaps only a statistical one (which however is not confirmed by most recent observational works); we have therefore tested if the N(Li) distribution functions of samples of stars sub-divided on the basis of kinematic class are statistically different. We have tested this, separately, for G dwarfs (i.e. with $6200 < T_{\rm eff} < 5500$) and for red dwarfs (i.e. $4850 < T_{\rm eff} < 4000$). For the intermediate temperature stars, given the preponderance of upper limits (rather than lithium line detections), the tests were not performed as they would not be meaningful. The stars in our sample were divided in kinematic young and old groups on the basis of their U and V space velocities, following the criterion of Eggen (1973).

To determine how effective the kinematic criteria which we are using in the present work can be for age discrimination we have computed the fraction of stars, as a function of age, which are expected to fall inside the "kinematically young" region (hereafter KYR) of Eggen (1973). The computation has been done under the assumption of constant stellar birth rate, assuming an age for the disk of 12 Gyr (Rana 1991), and assuming the Wielen (1977) age evolution model for the velocity dispersion. The results are only weakly dependent on the detailed shape of the stellar birth rate function or on the precise shape of the region used to discriminate young stars in the U–V plane. In particular, computations done using the revised region of Eggen (1989) yield very similar results.

Table 2 shows the result of our computation on the expected "discriminating power" of the Eggen (1973) kinematic criteria for distinguishing young and old disk population stars. The important point is that, while kinematic criteria are a good "necessary" condition for stellar youth, they are by no means "sufficient". For example, basically 100% of the stars younger than the Pleiades (10^8 yr) fall in the KYR, but by selecting at random stars in the KYR the probability of finding a Pleiades age (or younger stars) is only 4%. Even at a cut-off age of 2×10^9 yr, only 40% of the stars in the KYR are "young", with 60% being "old". Outside of the KYR, only 10% of the stars are younger than the cut-off age.

The effectiveness of the KYR criterion in selecting young and old stars therefore is a very steep function of the cut-off age. Also important in the present context is the usage of the KYR criterion to separate two sub-samples which are subsequently used to test whether some property shows some age evolution or not. In the present work we are using this criterion for testing for the age evolution of lithium abundance, which can be modelled as being exponentially decaying with time from some starting value. The age evolution in field stars of coronal and chromospheric activity, as well as of rotation, have often been modelled (at least qualitatively) with a similar law, and therefore the results of Table 3 can be also applied in these cases. We have computed the expected average value for a generic exponentially decaying quantity for various decay time constants. The effectiveness of KYR-based two sample tests depends strongly on the characteristic time scale(s) on which the given property

Table 2. The discriminating power of Eggen's kinematically young region for various cut-off ages. Column 1 shows the cut-off age being considered, column 2 is the fraction of stars younger than the cut-off age expected to fall in the kinematically young region and column 3 is the fraction of stars older than the cut-off age falling in the same region. Note that these are *relative* fractions, i.e. not rescaled by the absolute stellar densities. Column 4 gives the probability that a star selected at random in the kinematically young region is younger than the given cut-off age, while column 5 is the probability that a star selected at random outside the kinematically young region is younger than the given cut-off age

Cut-off age (τ)	% $t < \tau$	% $t > \tau$	P_y in	P_y out
5×10^7	1.00	0.23	0.02	0.00
10^8	0.98	0.22	0.04	0.00
2×10^8	0.92	0.22	0.07	0.00
5×10^8	0.80	0.21	0.14	0.01
10^9	0.68	0.19	0.25	0.03
2×10^9	0.55	0.17	0.40	0.10
5×10^9	0.37	0.13	0.68	0.34

Table 3. The average value of an exponentially decaying quantity, starting at a value of 1.0 at the star's birth, and decaying with the e-fold time given in column 1 (as the log of the time in years), is shown for a population sampled inside the kinematically young region (KYR) and outside the KYR

e-fold time (log yr)	avg. in KYR	avg. out KYR
6.30	4.43×10^{-4}	$\leq 10^{-6}$
6.70	1.53×10^{-3}	$\leq 10^{-6}$
7.00	3.37×10^{-3}	$\leq 10^{-6}$
7.30	7.06×10^{-3}	7.20×10^{-6}
7.70	1.73×10^{-2}	1.46×10^{-4}
8.00	3.34×10^{-2}	7.92×10^{-4}
8.30	6.16×10^{-2}	3.22×10^{-3}
8.70	1.30×10^{-1}	1.54×10^{-2}
9.00	2.16×10^{-1}	4.38×10^{-2}
9.30	3.40×10^{-1}	1.15×10^{-1}
9.70	5.55×10^{-1}	3.27×10^{-1}
10.00	7.15×10^{-1}	5.43×10^{-1}

evolves. The values shown in Table 3 are obviously "ideal case" values, as any measurement error (in either the decaying quantity or the kinematics) as well as any intrinsic spread in the decaying quantity, will smear out the distinction between the subsamples selected inside and outside the KYR. While phenomena decaying on time scales of up to 1 Gyr appear to be easily detected by testing the KYR selection method (with an expected average value inside the KYR ≈ 5 times larger than outside the KYR), already with a decay time of 2 Gyr the difference in average values is only a factor of ≈ 2, easily masked out by measurement errors and/or intrinsic spreads as well as by sampling errors due to small sample sizes.

5.1. Kinematics and lithium; correlation tests

All the tests discussed here were performed using the ASURV Rev. 1.2 package (LaValley et al. 1992), using the Peto-Prentice test which properly considers upper limits. For the yellow dwarfs the N(Li) distributions of kinematically young and old subsamples are statistically not distinguishable, with the null hypothesis that the kinematically young and old subsamples are drawn from the same parent population being rejected at the 80%. It is somewhat surprising not to find any correlation in our sample of G dwarfs, given that, in the work of Pasquini et al. (1994), systems which are classified as young on the basis of chromospheric activity display higher lithium abundance than older systems, although with a large scatter. The observed lack of correlation between lithium abundance and kinematic age in our sample could be due either to the intrinsic statistical nature of kinematic age itself or to a lack of intrinsic correlation. Unfortunately, the lack of available homogeneous chromospheric indicators for our G dwarf sample does not allow to discriminate between these two possibilities.

The same test applied to the red dwarf sample ($T_{\rm eff} < 4850$) shows that the lithium abundance distribution functions of kinematically young and kinematically old stars are also not distinguishable statistically, with the null hypothesis being rejected at the 77% level, indicating that kinematic class is not a statistical indicator of photospheric lithium abundance for red dwarfs. Given the large age dispersion present in each kinematic group, and the intrinsic statistic, rather than deterministic, nature of kinematic criteria it is still possible that an "intrinsic" lithium-age correlation could exist, with time scales longer than 1 Gyr, and which would therefore not be detected using kinematic age indicators. An alternative interpretation is that a correlation with a very rapid (i.e. a few Myr) decay scale exists, which is not visible in our sample because of the lack (due to their relative paucity) of sufficiently young stars in the sample.

The space velocity distribution of the K stars in our sample is shown in Fig. 4. From the relative fraction of stars falling in the kinematically young region (9 out of 32) a "characteristic age" of around 5 Gyr can be inferred, very close to the expected value of 50% of the disk age (12 Gyr) (confirming the unbiasedness of the volume limited sample). Also, the lack of high lithium main sequence objects is not surprising. Assuming, from the data on open clusters, that high lithium K stars have an age less

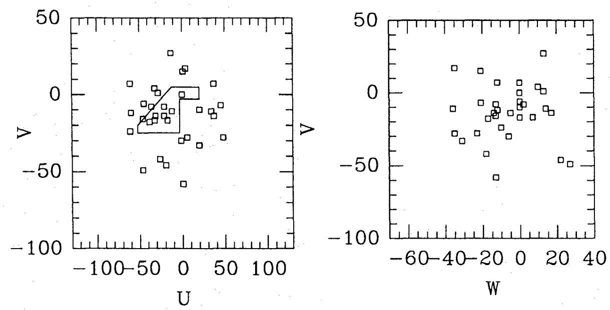

Fig. 4. The space motions of the K stars in our sample

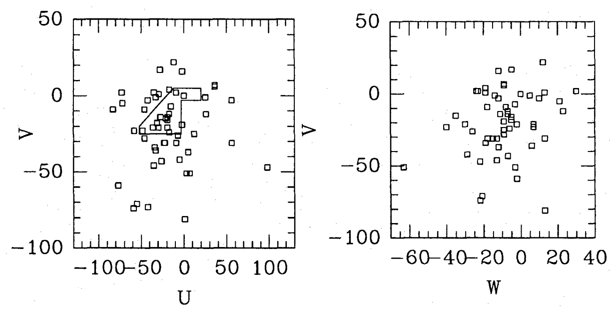

Fig. 5. The space motions of the G stars in our sample

than the age of the Pleiades (i.e. approx 100 Myr; the data in Paper II support the present assumption), less than 1% of the field K dwarfs are expected, in the hypothesis of a constant birth rate, to have a high surface lithium, i.e. less than 1 object in our sample of 32 objects.

The space velocity distribution of our G star sample, shown in Fig. 5, is very similar to the K star distribution, again with a characteristic age around 50% of the disk age.

6. Summary

We have presented lithium abundance measurements for a volume limited sample of nearby dwarfs with effective temperatures ranging from 6200 K down to 4000 K (spectral types ranging from F8V down to M0V). For the G dwarfs down to approx. G5V, we find a large spread of possible lithium abundances, ranging basically from the cosmic value down to (temperature dependent) detection limit. On the basis of kinematic age indicators, we confirm that lithium is not a good age proxy in this color range. For objects in the range $5500 < T_{\rm eff} < 4850$ (G5V–K2V) surface lithium always is, with very few exceptions, below the detection limit, while for the cooler stars in the sample ($4850 < T_{\rm eff} < 4000$, K2V–M0V) low ($N$(Li) $\lesssim 0.5$) surface lithium abundances seem to be relatively common.

The lack of correlation between the observed lithium abundance and kinematic age indicators for the cooler dwarfs indicates that, if there is any age-lithium correlation at all in the sample, the lithium decay process has a decay time scale longer than 1 Gyr. Alternatively, a lithium-age correlation could exist, with a very short decay time scale (a few Myr), which is not visible in our sample due to the lack of sufficiently young stars in our volume-limited sample.

We have discussed possible explanations for the unexpected widespread presence of lithium in the photospheres of cool dwarfs, and show that lithium production in stellar flares would be a possibly viable mechanism, in particular from the point of view of the energetics. It is worth remarking once more that not finding an alternative explanation for the observed feature at the wavelength of the Li I doublet in the cooler dwarfs is not equivalent to proving that the observed feature is actually due to lithium. The possibility of the feature being due (in part) to some other, yet to be identified, atomic or molecular line should be actively investigated, and we hope this paper will stimulate further work in this direction.

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