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The relationship between lithium and activity in disk population main sequence G and K stars*

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Abstract. We present determinations of the lithium abundance (through observations of the Li I 6707.8 Å line) in a sample of main sequence stars with spectral types ranging from late F down to M0, selected from the sample of nearby stars which have been observed with the *Einstein* observatory. We show that lithium abundance is correlated with X-ray luminosity for the cooler stars in our sample ($4700 > T_{\rm eff} > 4000$), while no correlation is present for the hotter stars. However, the correlation is almost completely driven by a very small number of high lithium, high X-ray luminosity (and thus plausibly very young) cool dwarfs present in the sample. A number of high lithium K dwarfs are present in the survey, and their characteristics and likely age are discussed in detail.

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

1. Introduction

In the classical view of the evolution of solar-type stars both lithium and activity are expected to decay with stellar age, and are in fact observed to do so in open clusters, although the current observational data for open clusters are mostly limited to spectral types earlier than $\approx$ K2V. Although the functional form and the details of the decay laws are currently the subject of much debate, and classical, non-rotating models cannot explain the observed lithium abundance in solar-type stars, all currently proposed models do in one way or another account for age evolution of both quantities, and therefore a correlation can be expected between lithium and activity. Observations of open clusters, as well as of X-ray selected samples of stars, have produced a large number of results, regarding the presence (or lack) of correlations between lithium, activity and rotation, which are often difficult to reconcile with each other. Lithium is observed to be correlated both with activity and with rotation in solar type stars from the Pleiades cluster (Soderblom et al. 1993a), while in an X-ray selected sample (which is therefore strongly biased toward very high activity levels), the lithium–rotation correlation still holds in K dwarfs, while no lithium–activity correlation is present (Favata et al. 1995). Older results on field G dwarfs observed with the *Einstein* X-ray observatory (Maggio et al. 1987) also point to a correlation between activity level and lithium-derived age. Most of the more recent results are based on the observation of somewhat specially selected samples, while the older results of Maggio et al. (1987), while based on a somewhat less biased sample of stars (although not a truly unbiased one), could not make use of modern lithium determinations based on high resolution, high signal to noise spectroscopy. Cluster observations, given the magnitude limitations of most high resolution spectrographs, have not extended much toward the red side of the main sequence, and no work is available so far on the eventual lithium–activity correlation in normal field K dwarfs.

To study the relationship between lithium and activity in normal solar type dwarfs, as well as the effectiveness of lithium and kinematics as activity indicators, we have therefore performed a survey of lithium in a sample of nearby dwarfs with spectral types ranging from late F down to late K, selected from the sample of stars which have been observed with the *Einstein* X-ray observatory. This study has been carried on in parallel with a study of lithium in a purely volume limited sample of G and K dwarfs, which provides, in the present context, the reference frame for the behavior of normal stars. The results on the volume limited sample are described in Favata et al. (1996), hereafter Paper I.

The rest of the present paper is structured as follows: Sect. 2 and 3 describe in detail the sample selection criteria, the observations, their reduction and analysis, Sect. 4 discusses the correlations between lithium, activity and kinematics, while individual interesting objects are discussed in Appendix A.

2. The observed sample

The stars observed in the present work have been selected from the sample of stars present in Gliese catalog of nearby

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* Based on observations collected at the ESO La Silla observatory

stars which have also been observed by the *Einstein* observatory. Most of them have been used previously to determine the X-ray luminosity functions of solar neighborhood stars. They are in particular selected from the sample of late F and G main sequence stars of Maggio et al. (1987) and from the complete sample of all K stars observed, either in pointed mode or serendipitously, with the *Einstein* X-ray observatory (Barbera et al. 1993). The color range for the late F and G sample is $0.5 \leq B-V \leq 0.8$, while for the K stars it is $0.8 \leq B-V \leq 1.4$.

The parent sample (which is the total sample of G and K-type Gliese stars observed by the *Einstein* observatory) from which objects have been selected for the present work consists of 62 late F and G dwarfs and 88 K-type dwarfs, for a total of 150 objects. Of these, 62 in total have been observed in the course of the present work, selected exclusively on the basis of visibility at the time of observation (and therefore not imposing any further bias on the sample). For reference, the Gliese catalog contains 369 G stars and 779 K stars. The parent sample is not distributed uniformly in the sky, with 103 objects in the northern hemisphere and only 47 objects in the southern one. This is a reflection of its biases, and it is most likely due to the larger number of pointed *Einstein* targets in the northern hemisphere, which is in turn due to the higher density of "interesting" (i.e. well known) targets in the northern hemisphere at the time of the *Einstein* observations.

Obviously a truly unbiased sample, i.e. a volume limited sample containing X-ray measurements (detections or upper limits) for all the stars in the sample, would have provided a better starting point for the present investigation. However, *Einstein* X-ray luminosities were the only ones generally available at the time the observations presented here were made, and X-ray data on large volume limited samples of G and K dwarfs (for example from the ROSAT All Sky Survey program) were still not generally available at the time of the observations. X-ray selected samples, while interesting in their own right (see Favata et al. 1995) are strongly biased toward the more active sources, and completely miss the information on the less active stars, which is mostly "hidden" in the X-ray upper limits.

The sample discussed here has some overlap with the volume limited sample of Paper I; this is a consequence of the independence of the two samples, i.e. some of the objects in the X-ray selected sample happen to fall by chance in the volume limited sample. The number of objects which fall in both samples is 13 (and they were of course observed only once). The total sample is listed in Table 1.

3. Observations

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 in November 1993 and in February and August 1994, 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. The data reduction and analysis procedure used has been described in detail in Paper I, and will not be repeated here. We will only remark that $R-I$ colors from the large survey of Bessel (1990) (except for GJ 233, for which the $R-I$ color has been taken from Cutispoto 1991, and for GJ 9185, for which $R-I$ was taken from Eggen 1971, as they were not observed by Bessel 1990) have been used to determine $T_{\rm eff}$, as the $R-I$ versus $T_{\rm eff}$ calibration is basically unaffected by metallicity or reddening effects (Buser & Kurucz 1992). For the few stars (11 out of 62) which had no $R-I$ color available in Bessel (1990), $b-y$ colors were obtained for 9 of them from various sources in the literature (the $b-y$ index also provides a good degree of independence from metallicity effects, see Olsen 1984). The two remaining stars (GJ 201 and GJ 9400A) only have $B-V$ colors available from the literature, and therefore their $T_{\rm eff}$ determination is correspondingly more uncertain than for the rest of the sample.

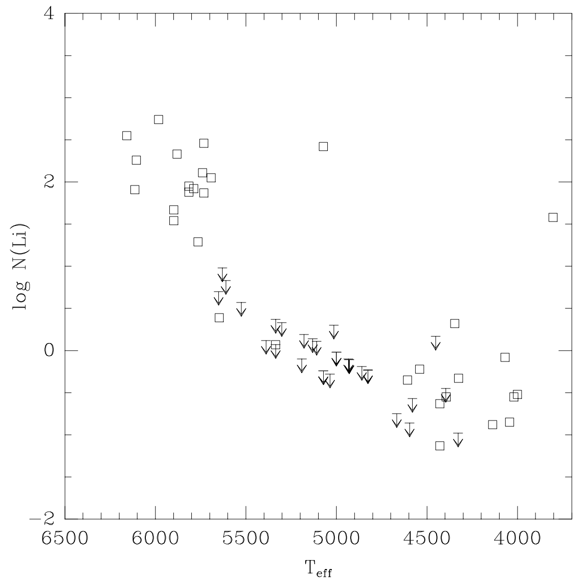

Fig. 1. Lithium abundance versus effective temperature for all the stars in our sample. Down-pointing arrows indicate upper limits to the lithium abundance due to the lack of detection of the Li I 6707.8 Å line.

The uncertainty on the derived lithium abundance derives mainly from the uncertainty on the measured equivalent width, which we estimate, by comparison with existing measurements (for example Pasquni et al. 1994), to be $\approx 10\%$ (increasing for the stars with the smaller W(Li)), and the uncertainty induced by the uncertainty in the $T_{\rm eff}$. For the stars with good $R-I$ measurements, assuming a photometric error on the color of ≈ 0.01 mag (typical of good photoelectric measurements) this induces an uncertainty in $T_{\rm eff}$ of ≈ 70 K for a cool dwarf, which translates to a resulting uncertainty in the lithium abundance of $\approx$ 0.07 dex. When combined with the uncertainty on the equivalent width, we estimate a total resulting uncertainty of ≈ 0.08 dex. For some of the sources with more uncertain photometry (specially the ones with $B-V$ colors only) the resulting uncertainty can be twice as large.

Table 1. The observed sample. For each star the Gliese (GJ) number is given, as well as the HD number (where applicable). Spectral types and colors are taken from the literature (see main text for references). The W(Li) values are from our observations, and the N(Li) values are the corresponding computed abundances. X-ray luminosities are given as the logarithm of the luminosity in erg/s. 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 I, while a "Y" indicates the stars which are considered kinematically young.

GJ numb.	HD	Sp.	Color	W(Li) (mÅ)	$T_{\rm eff}$	N(Li)	log $L_{\rm X}$ (erg/s)	Comments
364	84117	F9IV	$R-I$ = 0.285	45	6158	2.55	27.04	Y
449	102870	F9V	$R-I$ = 0.29	12	6113	1.91	<28.32	
904	222368	F7V	$R-I$ = 0.291	26	6105	2.26	<27.98	B, Y
504	115383	G0V	$R-I$ = 0.305	83	5983	2.74	<29.00	B
17	1581	F9V	$R-I$ = 0.315	35	5898	1.54	27.26	
147	22484	F9V	$R-I$ = 0.315	47	5898	1.67	27.51	
9209A	44120	G3V	$b-y$ = 0.379	47	5880	2.33	27.90	B
598	141004	G0V	$R-I$ = 0.325	20	5815	1.88	<27.50	B, Y
291AB	64096	F9V+G4V	$R-I$ = 0.325	23	5815	1.95	<27.56	
9073A	13043	G2V	$b-y$ = 0.394	23	5788	1.92	28.58	
559A	128620	G2V	$R-I$ = 0.331	6	5765	1.29	<26.99	B
9032	5294	G5IV	$b-y$ = 0.402	38	5740	2.11	<28.26	
9012	1835	G3V	$R-I$ = 0.335	76	5732	2.46	<28.68	Y
327	76151	G3V	$R-I$ = 0.335	23	5732	1.87	<28.22	B, Y
137	20630	G5V	$R-I$ = 0.34	37	5692	2.05	<28.75	Y
780	190248	G6-8IV	$R-I$ = 0.345	<2	5651	<0.70	27.27	R = 100 000
9092A	16619	G4V	$b-y$ = 0.418	1	5647	0.39	28.09	B, Y
9085	16141	G5IV	$b-y$ = 0.421	<4	5630	<0.98	27.95	
547	126053	G1V	$R-I$ = 0.35	<3	5611	<0.83	27.70	
746	178428	G5V	$b-y$ = 0.440	<2	5526	<0.57	27.91	R = 100 000
9158	28946	K1	$b-y$ = 0.467	<1	5389	<0.12	<27.54	
9357	98281	G8V	$R-I$ = 0.385	<2	5336	<0.37	28.58	
71	10700	G8V	$R-I$ = 0.385	<1	5336	<0.07	26.78	
139	20794	G5V	$R-I$ = 0.385	1	5336	0.07	27.03	
9177	33811	G5	$B-V$ = 0.77	<2	5302	<0.33	28.67	B
559B	128621	K0	$R-I$ = 0.404	<1	5191	<-0.10	27.08	B
27	3651	K0	$b-y$ = 0.507	<2	5179	<0.19	<27.50	
56.3A	7895	K1	$R-I$ = 0.412	<2	5131	<0.14	27.46	B
217.2	39194	K0	$R-I$ = 0.415	<2	5109	<0.11	<28.11	
86	13445	K0	$R-I$ = 0.42	<1	5072	<-0.24	27.72	
166A	26965	K1	$R-I$ = 0.420	<1	5072	<-0.24	27.58	
117	17925	K0	$R-I$ = 0.42	187	5072	2.42	28.60	Y
785	192310	K0	$R-I$ = 0.425	<1	5036	<-0.28	<27.36	R = 100 000
384A	88746	G8V	$R-I$ = 0.428	<4	5014	<0.30	<27.80	Y
9185	37656	K5V	$R-I$ = 0.43	<2	5000	<-0.02	<28.69	$R-I$ from Eggen (1971), Y
340.2	80367	K0	$R-I$ = 0.430	<2	5000	<-0.02	<28.07	
9087	16287	K0	$b-y$ = 0.544	<2	4934	<-0.1	28.53	
66B	10361	K0V	$R-I$ = 0.44	<2	4929	<-0.11	27.18	
66A	10360	K2	$R-I$ = 0.44	<2	4929	<-0.11	27.21	
144	22049	K2	$R-I$ = 0.44	<2	4929	<-0.11	28.21	Y
33	4628	K2	$R-I$ = 0.45	<2	4860	<-0.19	<27.17	
702A	165341	K0	$R-I$ = 0.455	<2	4826	<-0.23	27.96	R = 100 000
319.1A	74385	K0	$R-I$ = 0.455	<2	4826	<-0.23	<28.80	
783A	191408	K3	$R-I$ = 0.48	<1	4667	<-0.75	<26.99	R = 100 000
183	32147	K3	$R-I$ = 0.490	3	4608	-0.35	27.31	B, R = 100 000
349	82106	K3	$R-I$ = 0.492	<1	4596	<-0.86	28.07	Y
105A	16160	K3	$R-I$ = 0.495	<2	4580	<-0.57	27.05	
862	213042	K5	$R-I$ = 0.502	5	4541	-0.22	<28.08	
233	45088	K3V	$R-I$ = 0.52	<16	4452	<0.17	29.08	$R-I$ from Cutispoto (1991)
845	209100	K5	$R-I$ = 0.525	3	4429	-0.63	27.27	
250A	50281	K6V	$R-I$ = 0.525	1	4429	-1.13	27.68	B
453	103932	K5	$R-I$ = 0.545	<2	4396	<-0.45	27.51	
157A	24916	K5V	$R-I$ = 0.533	4	4394	-0.55	28.01	Y
879	216803	K5V	$R-I$ = 0.545	30	4346	0.32	28.06	R = 100 000, Y
435	101581	K5	$R-I$ = 0.550	<2	4328	<-0.98	<27.63	Y
201	35171	K5V	$B-V$ = 1.09	8	4326	-0.33	28.02	Y
9400A	NA	K8V	$B-V$ = 1.22	4	4137	-0.88	<28.00	
517	118100	K5V	$R-I$ = 0.668	25	4068	-0.08	29.54	Y
428A	99279	K7	$R-I$ = 0.690	5	4044	-0.85	<28.00	B, Y
830	204587	M0	$R-I$ = 0.717	10	4020	-0.55	<28.08	
142	21531	K7	$R-I$ = 0.74	11	4000	-0.52	28.17	
182	NA	M1V	$R-I$ = 0.934	280	3803	1.58	29.60	Y

The derived lithium abundances are plotted versus the effective temperature of the stars in Fig. 1. One evident characteristic of the X-ray selected sample is the presence of a large fraction of cool ($T_{\rm eff} \lesssim 5000$ K) objects with large surface lithium abundance (N(Li) $\gtrsim -0.5$). High lithium red dwarfs are completely absent in the volume limited sample (see Paper I), pointing at the bias toward younger (and therefore more active) stars being present in the parent sample of stars observed by the *Einstein* observatory.

4. The relationship between lithium, kinematics and activity

We have shown, in Paper I that, on the basis of current models for the kinematic evolution of galactic dynamics, kinematic criteria can be a useful tool for discriminating between young and old population for the purpose of studying observables (such as the lithium abundance) which are expected to decay with time, as long as the characteristic decay time of the observable is less than about 1 Gyr. We have therefore used kinematic criteria as a basis for testing for the presence of age evolution of the lithium abundance in the present context.

4.1. The G dwarfs

Pasquini et al. (1994) as well as our Paper I have shown lithium to be a poor age proxy for G dwarfs in the solar neighborhood, yet Maggio et al. (1987) find that, using lithium derived ages, "the clear correlation between the level of X-ray emission and the stellar age is a striking feature...". The lithium-based ages of Maggio et al. (1987) where derived using observed lithium abundances from the literature and the time scales for lithium depletion of Duncan (1981). To understand why Maggio et al. (1987) did find such a correlation, we have repeated their analysis, using our lithium data and the lithium-age calibration of Duncan (1981). The resulting "age-activity" plot is shown in Fig. 2, showing that the data are indeed highly scattered with no obvious strong correlation (although the X-ray luminosity upper limits at the left of the plot may be suggestive to the eye). A formal correlation analysis (see below) shows that both lithium-derived age and lithium abundance are uncorrelated with X-ray luminosity in this sample. While Maggio et al. (1987) did not test for a formal correlation (although they computed a power-law regression), their sample only had 6 points which were detections in both lithium and X-ray luminosity (as does ours); our Fig. 2 can be compared with Fig. 9c of Maggio et al. (1987).

We have also compared our effective temperatures and lithium equivalent widths and abundances for the 11 stars in common between our sample and the one of Duncan (1981), as shown in Fig. 3. While there is general good qualitative agreement between our data and Duncan's, the effective temperatures show a large spread (with over 100 K standard deviation in the differences), perhaps due to their using much older photometric data, while the equivalent widths of the Li I line show a strong systematic effect, with the equivalent width of the most intense lines being overestimated in Duncan's work by up to 50%. Given the very good agreement between our equivalent widths and the

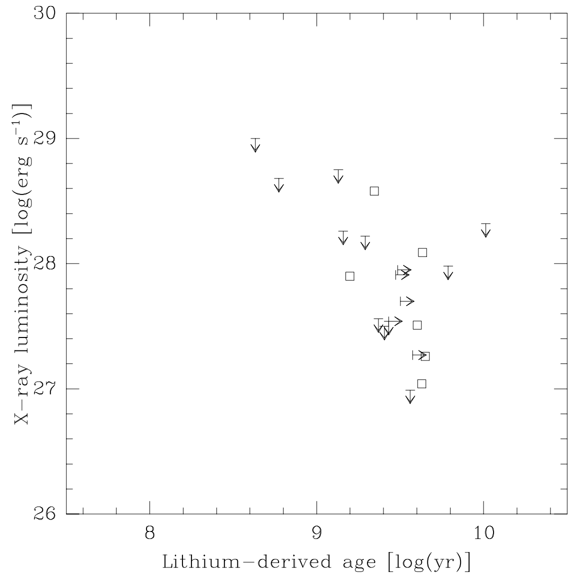

Fig. 2. X-ray luminosity versus "lithium computed" age, using the decay time scales of Duncan (1981) for the stars from our sample falling in the temperature range covered by the calibration of Duncan (1981).

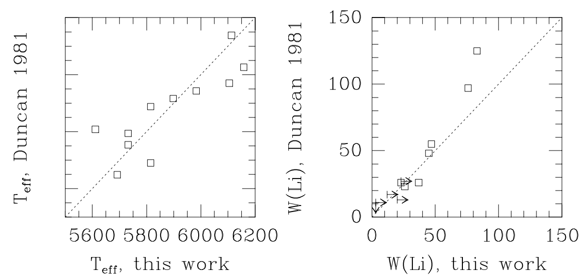

Fig. 3. The effective temperature (left panel) and the equivalent width of the Li I line (right panel) for the stars in common between our sample and the one of Duncan (1981), plotted against each other.

ones of Pasquini et al. (1994) (see Fig. 2 of Paper I), we are confident in considering our equivalent widths as more reliable. Given the complex instrumental setup of Duncan (1981), it is possible that the systematic shift for the stronger lines could be due to some instrumental effect. Such systematics will essentially make young stars appear much younger, thus effectively stretching the horizontal axis of Fig. 2, and reinforcing any visual impression about a possible correlation.

We have tested, using the Peto-Prentice test from the ASURV Rev. 1.2 Package LaValley et al. (1992), whether the lithium abundance distribution functions of kinematically young and old G dwarfs in the present sample are statistically different. The test was limited to stars with $T_{\rm eff} \geq 5600$ K, to avoid the influence of the preponderant upper limits to the lithium abundance for $T_{\rm eff} < 5600$ K. Stars were considered kinematically young or old according to whether their U and V space velocities fall in the "kinematically young region" defined by Eggen (1973). The result of the test is that the lithium abundance distribution of kinematically young and old G dwarfs are

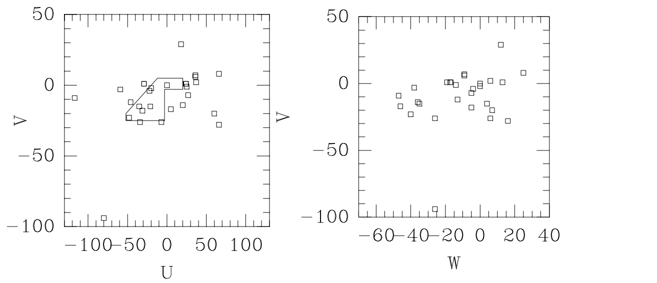

Fig. 4. The space motions of the G stars observed for the present work.

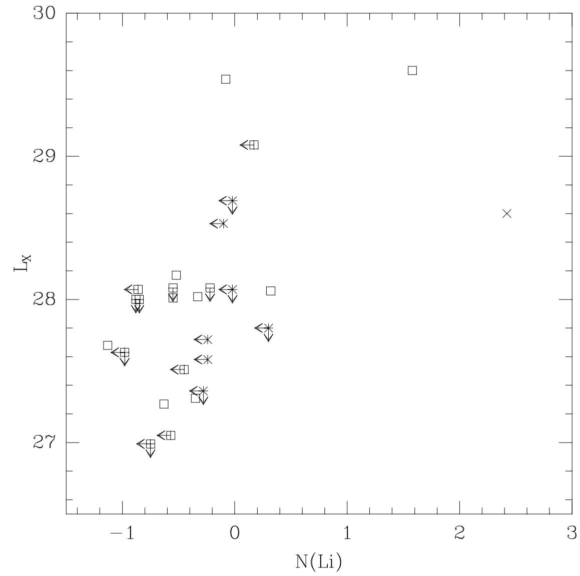

Fig. 5. The X-ray luminosity and lithium abundance of the K dwarfs observed in the present work. Square symbols represent stars with $T_{\rm eff} \leq 4700$ K, while crosses represent stars with $5100\,{\rm K} \geq T_{\rm eff} \geq 4700$ K. Symbols with arrows indicate upper limits.

found to be statistically identical, with the null hypothesis that the kinematically young and old subsamples are drawn from the same parent population being rejected only at the 62% confidence level. Given that X-ray luminosity is a relatively good age proxy for normal G dwarfs, this can be interpreted as saying that the lithium abundance distributions of young and old G dwarfs are quite similar, as discussed originally by Spite & Spite (1982) and, on the basis of modern data, by Pasquini et al. (1994) and in Paper I. However, the same lack of difference between the lithium distribution functions of kinematically young and old K dwarfs (see Sect. 4.2), together with the strong lithium–activity correlation found in the same sample, cautions us from making strong statements based on samples discriminated using kinematic properties alone.

To confirm the lack of apparent correlation between activity and lithium abundance in G dwarfs evident in Fig. 2 we have also tested for an eventual correlation between either X-ray luminosity or the $f_{\rm X}/f_v$ ratio and N(Li); such a correlation would be indicative of a similar relationship between age and activity on one hand and age and lithium abundance on the other. The result, obtained using the generalized Kendall's τ test from the ASURV package (which deals properly with upper limits), is that no correlation is present in our sample of G dwarfs between X-ray luminosity or $f_{\rm X}/f_v$ and surface lithium abundance at the 53% probability level.

We have also tested the lithium abundance distribution function of the G star sample discussed here against the lithium abundance distribution function of the volume limited sample of G stars of Paper I. They are statistically identical, again pointing to the fact that the enhanced activity of the present sample (due to the selection biases discussed in Sect. 2) has little if any influence on the lithium abundance.

The space velocity distribution of the G dwarfs, shown in Fig. 4, although perhaps showing to the eye a peculiar lack of stars with $|{\rm V}| \gtrsim 30$ km/s, is statistically very similar to the space velocity distribution of a randomly selected sample of disk stars, both in terms of the relative number of stars in the kinematically young region (9 out of 26) and in terms of the W velocity dispersion ($\sigma_{\rm W}$ = 17.8 km/s).

4.2. The K dwarfs

The same statistical tests discussed above for the G dwarfs were also applied to the K dwarf sample. Two K dwarf samples were tested, i.e. the one cooler than 4700 K (it being the effective temperature at which Li I detections start to appear) and the complete K dwarf sample (i.e. all stars cooler than 5100 K). The tests show that the lithium abundance distribution of kinematically young and old K dwarfs in the sample of stars observed by the *Einstein* observatory cannot be distinguished at better than the 80% confidence level for either of the two samples described above. At the same time, lithium and X-ray luminosity are, in this sample of K dwarfs, correlated at the 98% level, both for the cooler subsample alone and for the complete sample of K dwarfs. The lithium–activity scatter plot is shown in Fig. 5.

However, the statistical significance of this correlation is strongly driven by the two very active, high lithium (and thus presumably young) objects present in the top right region of Fig. 5. If these objects are removed from the sample the statistical significance of the correlation between lithium and X-ray luminosity drops to 87% (from 98%), becoming statistically not significant.

The lithium–activity correlation present in K dwarfs is most likely a simple reflection of the age evolution of both quantities, rather than the result of some direct physical correlation. This correlation is however somewhat surprising in the light of the fact that the lithium abundance distribution functions of kinematically young and old stars from the same sample are statistically identical, while, as shown in Paper I, kinematic criteria would be expected to have a good discriminating power for observables which decay with fast ($\tau << 1$ Gyr) time scales. However, the actual time scale of lithium decay in the cooler dwarfs is not actually well determined observationally, as the observations of open clusters available in the literature do not extend beyond spectral type K2 or so (with the notable exception of the recent Keck data on the Pleiades, see Soderblom et al. 1995, which extend down to $T_{\rm eff} \approx 4200$ K). At the same time there is not, in the sample, a large enough number of young objects to constrain such a relationship. In fact the clustering of sources in the lower left corner of Fig. 5 is a reflection of the predominance of relatively old stars in a sample of disk stars. Stars as young as the Pleiades would occupy the upper right corner of the plot, while Hyades stars would cluster around N(Li) ≈ 0.2 and $\log L_{\rm X} = 28$ (a region of the plot which is well populated). The scarcity of objects in the region of the plot between the Hyades locus and the Pleiades locus is a reflection of the paucity of sufficiently young objects in a sample of disk population stars, even if biased toward younger ages by virtue of its X-ray selection biases. Therefore, the lack of stars in this region makes it difficult to constrain any possible correlation, and it makes the observed correlation fragile.

Kinematics was found in Paper I to be uncorrelated with lithium for a truly volume limited sample of stars. We concluded that, if a correlation was actually present, either the decay time of lithium in cool dwarfs was so long ($>$ 1 Gyr) that kinematic criteria were an ineffective way of studying the process, or that the decay time is so rapid (tens of Myr) that the the younger population (and thus with higher lithium abundance) is effectively absent in the truly volume limited sample, thus making the correlation impossible to detect. Some very young stars are clearly present in our sample, in a sense filling a gap in the volume limited sample of Paper I. Indeed their presence drives the lithium–activity correlation, indicating that an intrinsic lithium–age correlation is present, and with short time scales (although the present data are not sufficient for estimating the time scale itself). The presence of low levels of lithium in most of the cooler dwarfs, extensively discussed in Paper I, indicates that the process is likely to be more complicated. A likely scenario, in the light of the present data is that the "large" primordial lithium abundance undergoes a rapid depletion (moving the stars from the upper right toward the center-left of Fig. 5), until its abundance reaches levels comparable to the lithium which in Paper I was discussed as possibly produced by spallation in the stellar coronae. From then on the evolution of lithium changes because of the competing production and depletion process, thus creating a "bunching" of stars in the lower-left corner of the diagram.

A small number of high lithium K dwarfs are present in our sample (see Fig. 5), with lithium abundances and activity levels qualitatively similar to the ones of Pleiades-age clusters. On the basis of a constant stellar birth rate hypothesis, less than 1% of a volume limited sample of stars is expected to be younger than 100 Myr, and therefore the fact that at least 4 objects have lithium abundances compatible with their being 100 Myr or younger is a clear indication of the biases present in the parent sample, and in particular of the presence in the sample of several stars which were the target of *Einstein* observations precisely because of their high activity level and thus of their young age. No high lithium K dwarfs are present in the volume limited sample of Paper I.

Given the unclear status of lithium as an age indicator we have examined in detail the high lithium K dwarfs, i.e. the objects which are located above the upper envelope of the distribution of lithium abundance of a volume limited sample (see Paper I). The four objects satisfying this condition are GJ 117, GJ 879, GJ 517 and GJ 182, and their spectra are shown in Fig. 6. The available information on each of these objects is presented in Appendix A. In Fig. 1 there also is an object with a low $T_{\rm eff}$ and a large upper limit, in the middle of the high lithium objects. This object, GJ 233, is also discussed in Appendix A.

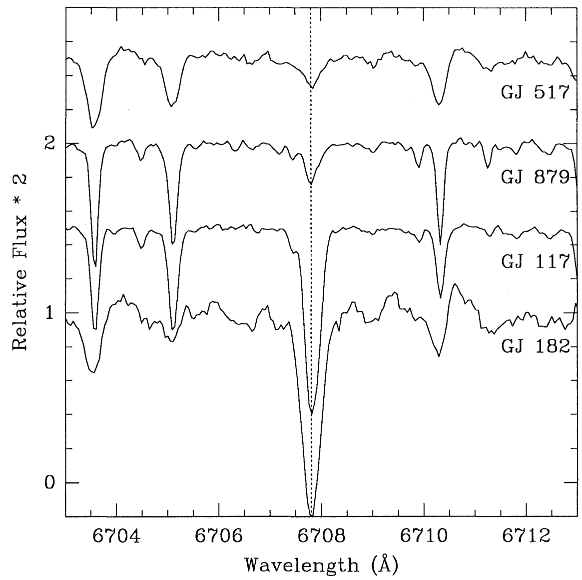

Fig. 6. The observed spectra of the late-type high lithium dwarfs. The spectra are shifted to rest wavelength frame and are vertically expanded by a factor of 2 for clarity. The vertical dashed line marks the wavelength of the Li I 6707.8 Å line.

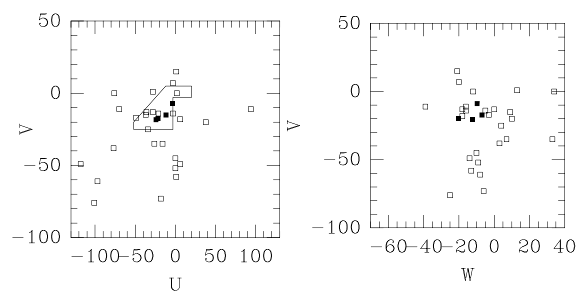

Fig. 7. The space motions of the K stars observed for the present work. The four high lithium objects discussed in the text are shown with filled symbols.

The space motions of the four high lithium K dwarfs (shown in Fig. 7 with filled symbols) are strongly clustered in the "young stars" area of the U–V plane, with very little if any spread in W, while the complete K sample shows a much broader distribution of space velocities, typical of disk population stars. Although the four high lithium objects definitely form too small a sample to allow statistically solid conclusions, the mean space velocities and their range of values are strongly suggestive of a kinematic group of very young stars. The mean space velocities of the group are (U, V, W) = (−18, −16, −17), with formal standard deviations $(\sigma_{\rm U}, \sigma_{\rm V}, \sigma_{\rm W})$ = (12, 6, 6). Given that the typical uncertainty of space velocities is about 5 km/s the four main sequence high lithium objects in our sample have coincident space motions within the observational error. The fact that the velocities all fall within the kinematic young region point at this group of objects having a characteristic age of less than $\approx$ 100 Myr (see Paper I), in agreement with their high lithium abundance being due simply to their being young.

If the young high lithium stars in our sample do indeed form a "moving group" and were therefore formed together, their very low velocity dispersion puts an additional strong constraint to their age. If one uses the approach of Wielen (1977) (which, as discussed in detail by Soderblom 1990 seems to be supported by the available observational evidence), this high level of velocity coherence implies an age of at most a few tens of Myr, i.e. an age comparable to the Pleiades. As discussed by Soderblom (1990) given the velocity perturbations, the procedure of tracing down present day space velocities to the likely time of birth of the star is unlikely to find the actual place of birth.

The relationship between lithium and age in late type dwarfs is still unclear, as age-homogeneous groups of stars from young open clusters show, specially for younger clusters (i.e. ages comparable to the Pleiades) a significant dispersion in lithium abundance. For example, Soderblom et al. (1995) show that stars in the Pleiades show a spread in W(Li) of about 1 dex at any given temperature between 5000 K and 4200 K. Nevertheless, a qualitative comparison between our group of high lithium stars and the Pleiades lithium–color relationship of Soderblom et al. (1995) shows that their lithium abundance is compatible with their being a few tens of Myr old. The four main sequence high lithium K dwarfs in our sample are all single, and show the high activity levels typical of young objects (three of them have been classified as BY Dra-type objects), with X-ray emission levels (with a formal mean of 28.95 dex, and a formal standard deviation of 0.75 dex) comparable to the levels observed in the Pleiades cluster (Micela et al. 1996).

Therefore all the available indicators (kinematics, activity, rotation, lithium) point toward the main sequence high lithium objects in our sample being young objects, a few tens of Myr in age, perhaps sharing, on the basis of the common proper motions, a common origin. It is tempting to associate the high lithium stars with a young moving stream (something like the Pleiades moving group), but we feel the current data, although strongly suggestive, will need to be supplemented by additional observations to support stronger conclusions. However, we see no need in the present context to invoke additional mechanisms, other than youth, to justify the presence of lithium in these stars.

5. Summary

We have presented lithium abundance measurements for a sample of nearby dwarfs within a color range $0.5 \leq B - V \leq 1.4$ (spectral types ranging from F8 down to M0), selected from the sample of nearby stars observed with the *Einstein* observatory. While the G dwarf sample behaves, in terms of the lithium abundance identically to a volume limited sample (Paper I), the K dwarf sample contains a considerable fraction (4 out of 35) high lithium dwarfs, which are absent in a volume limited sample of comparable size. These objects have all the characteristics of young ($<$ 100 Myr) stars, which are most likely overrepresented in the sample of stars observed by the *Einstein* observatory, due to the biases present in the *Einstein* observational program. The low levels of lithium observed in many K dwarfs are very similar to the ones observed in a volume limited sample (Paper I).

Lithium and activity show a possible correlation for the cooler stars in our sample ($T_{\rm eff} \leq 4700$ K), while they appear uncorrelated for hotter stars. A lithium-activity correlation was found by Soderblom et al. (1993a) for late G and early K dwarfs in the Pleiades, but the correlation found in the present sample should be interpreted differently. While the correlation found in the Pleiades appears to be an intrinsic feature, as it is present in a coeval sample, and it is also linked to rotation (with very fast rotators having a higher activity and lithium abundance) the correlation of the present sample appears likely to be simply an age effect, with both lithium and activity decaying with age. No such correlation was found in a more heterogeneous sample selected purely on X-ray basis (and therefore strongly biased toward higher activity levels) by Favata et al. (1995). We see no contradiction between the two results, as the sample of Favata et al. (1995) was biased toward higher activity levels, and therefore toward younger ages, with low activity single dwarfs being absent. This, given the large scatter in the lithium–activity relation, will easily hide any correlation. Finally, we note that, combining the results of Paper I with the present sample, lithium still retains its status as an age indicator (albeit as a statistical one) for K-type dwarfs, with no evidence, in the large combined sample, of old high-lithium K dwarfs.

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Appendix A: notes on peculiar or interesting objects

In this appendix notes about objects which appear particularly interesting, including all the high lithium red dwarfs are collected.

- **GJ 201:** although its lithium abundance (N(Li) = -0.1) is marginally too low to be formally included in the group of high lithium K dwarfs discussed in Sec 4.2, it is still quite high for its spectral type (K5). The low space velocity (U, V, W = $-37, -15, -9$) is compatible with a young age, and the X-ray luminosity ($L_{\rm X}$ = 28.02) is also compatible with its being young. It is a single star (Duquennoy & Mayor 1991) with no signs of Hα emission (Young et al. 1989), although it is classified as dK5e in the Gliese catalog.

- **GJ 233:** a probable member of the UMa stream (Soderblom & Mayor 1993), it is a short period (P $\approx$ 7 d) synchronous binary (Edwards 1983), showing a high activity level (L_X = 29.0 dex), and it has therefore been classified as a BY Dra-type object. Soderblom et al. (1993b) report a measurement of the lithium abundance, giving an upper limit of 5 mÅ to the Li I line equivalent width, corresponding to an upper limit of 0.1 on N(Li). Our spectrum show two clearly distinct spectral systems, with a line due to Fe I of the secondary at the expected position of the Li I line of the primary, making the measurement of the Li I feature equivalent width impossible.
- **GJ 117:** a single K0V star showing no peculiarity except for the very deep Li I absorption feature comparable to a PMS object. Originally discussed by Cayrel de Stobel & Cayrel (1989), who consider it a run-away star formed in the Sco-Cen star forming region about 10 Myr ago (although Soderblom 1990 considers this conclusion difficult to substantiate). An active object, with L_X = 28.7 dex.
- **GJ 879:** a well known active star, with an unclear multiplicity status. Bopp & Fekel (1977) report it as a possible SB1 object, while Young et al. (1987) report it as a single object, considering the deviation from constant radial velocity as statistically non-significant. An active star (L_X = 28.1 dex), classified as a BY-Dra in the literature, it is considered to have the same proper motion as α PsA by Busko & Tores (1978), with an inferred age of 4×10^8 yr.
- **GJ 517:** a well known very active (L_X = 29.5 dex) BY Dra star. Classified as single in the literature, it is one of the very few dwarfs in our sample showing a rotational broadening of the spectral lines. The fast rotation, together with the high activity and the lack of a companion (which could justify both characteristics purely on the basis of tidal locking), point toward its being a young object. The measurable lithium abundance (N(Li) = -0.08) can therefore be justified on the basis of age.
- **GJ 182:** an M1 dwarf with a very deep Li I line (280 mÅ), which translates to an abundance of N(Li) = 2.8. Its deep Li I absorption feature was first noticed by Bopp (1974) on photographic spectra. No previous Li I equivalent width measurements are however available in the literature. A fast rotator for its spectral type (a value of $v\sin(i)$ = 8.7 km/s is reported by Vogt et al. 1983), it is considered a single object, and it is very active (L_X = 29.6). Classified as a BY Dra object in the literature.

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