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Lithium in ROSAT-discovered candidate members in the Alpha Persei cluster*

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Abstract. We present lithium observations of 23 X-ray selected candidate members of α Per, which are part of a larger sample of stars identified through two ROSAT surveys of the cluster. Our observations on one hand allowed us to confirm membership for 18 of the candidates, thus suggesting that a high percentage of the whole X-ray selected candidates are probably cluster members. On the other hand, we had the possibility to significantly enlarge the Li database for this cluster.

The distribution of Li abundances for stars in our sample (or 'new' members) is in good agreement with that for previously known (or 'old') members, although 'new' members in the 5000 – 4700 $T_{\rm eff}$ interval stay on the upper envelope of the Li vs. $T_{\rm eff}$ diagram. The comparison of the merged 'new' + 'old' sample with the younger IC 2602 and IC 4665 clusters and with the older Pleiades confirms that stars more massive than the Sun do not undergo any PMS Li destruction, whereas some depletion occurs during the early phases on the ZAMS. We readdressed the issue of the star-to-star scatter and Li–rotation connection for both α Per and the Pleiades; as several previous studies have pointed out, fast rotators, as a group, show higher lithium than slow rotators. At the same time, however, fast rotators exhibit a much narrower dispersion than slow rotators. We demonstrate that this dicothomy is unlikely due to projection effects and suggest that the reason for it could reside in the PMS rotational history and, in particular, in the presence (absence) of a circumstellar disk.

As to very cool stars ($T_{\rm eff} < 4500$ K), we find that α Per members do not seem to have higher lithium than the Pleiades. This result, however, must be confirmed with a larger sample of α Per stars before any conclusion can be drawn.

Key words: stars: abundances – stars: late-type – X-rays: stars – open clusters and association: individual: α Persei

1. Introduction

Considerable efforts have been devoted in the past 10 to 15 years, on both observational and theoretical grounds, to understand pre-main sequence and early-main sequence evolution of lithium. Surveys of lithium have been carried out for Classical and Weak lined T Tauri stars (e.g., Basri et al. 1991, Magazzù et al. 1992; Martín et al. 1994), as well as for late-type members of young open clusters (e.g., Balachandran et al. 1988, 1996; Soderblom et al. 1993; García López et al. 1994; Jones et al. 1996; Russell 1996; Zapatero Osorio et al. 1996; Martín & Montes 1997; Randich et al. 1997; Martín 1998). At the same time several theoretical models have been developed in order to explain Li observations (e.g., Pinsonneault et al. 1990; D' Antona & Mazzitelli 1994; Martín & Claret 1996; Ushomirsky et al. 1998).

The observations have shown that pre-main sequence (PMS) lithium depletion is negligible for stars with masses larger than $\sim 1\ M_{\odot}$; stars more massive than the Sun in the youngest clusters have indeed the same lithium content as T Tauri stars. On the other hand, stars with masses lower than $\sim 0.7\ M_{\odot}$ are strongly lithium depleted even at an age of 30 Myr, when they are still in the latest phases of approach to the main sequence, indicating that PMS depletion is very effective between a few Myr and a few tens of Myr. Theoretical models have not been able so far to reproduce the observed lithium patterns, predicting more depletion than observed for both solar-type and later-type stars. Most challenging for the models is the dispersion in lithium abundances which is seen in all young clusters (Pleiades at 70–100 Myr, α Persei at 50 Myr, IC 2602 at 30 Myr, IC 4665 at 35 Myr) for stars with masses lower than $\sim 0.9\ M_{\odot}$. Such a dispersion indicates that standard models (i.e., those taking into account only convection as a mixing process) are not able to explain the data, since they predict the same depletion for stars with similar mass, age, and metallicity. Pleiades, α Persei, and IC 4665 data indicate that there is a dependence of Li abundance on rotation. Such a link is not a one-to-one correlation, but the most rapid rotators are generally the most Li-rich. On the theoretical side, rotation is indeed regarded as the the most likely cause for the

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dispersion among 0.9-0.7 $M_\odot$ stars, although present theoretical models (i.e., those taking into account rotation and transport of angular momentum in the stellar interior) are not fully able to reproduce the observational results. The Li–rotation relationship breaks down for stars cooler than $\sim 0.7 M_\odot$ (García López et al. 1994; Jones et al. 1996), which was interpreted as due to the fact that, whereas warmer stars with thin convective zones are sensible to whatever additional (rotation related) mixing process, for cooler stars the convection zone is deep enough to reach the layers where Li is burned, independently on rotation[1].

As mentioned above, α Per is one of the clusters which were surveyed for lithium. The most extensive study was carried out by Balachandran et al. (1988) who presented the results for 46 a F-, G-, and K-type members of the cluster. As for the Pleiades, albeit on a much smaller sample, a dispersion in log n(Li) (where log n(Li)=log (Li/H)+12) was observed and a correlation between surface lithium abundance and projected rotational velocity was found to hold. In addition, about 30 % of the stars appeared to have a very low lithium; in a n(Li) vs. $T_{\rm eff}$ diagram these stars were located not only below the slightly older Pleiades, but also below the much older Hyades. Such a result represented for a few years a major puzzle in the understanding of Li depletion; Balachandran et al. (1996, BLS hereafter) re-analyzed the spectra of 39 of the 46 stars in their 1988 paper (the remaining 7 were identified as most likely non members), deriving new abundances which are now within the same range as those of the other stars in the cluster.

Additional lithium data for α Per were presented by García López et al. (1994) and Zapatero Osorio et al. (1996), who observed several very low mass stars in the cluster. They did not detect the lithium line in any of them, indicating a strong depletion.

We present here lithium abundances for 23 X-ray selected candidate members of α Per for which we obtained 1 Å resolution spectra covering the Li I λ 6708 Å line and Hα. Our aim is twofold: on one hand, we want to use lithium for the hotter stars (and Hα for the cooler ones) as an additional indicator for membership. On the other hand, the present sample, which includes stars in the $\sim$ 5500–3900 K effective temperature range, gives the possibility to significantly enlarge the original sample of BLS. In particular, our sample provides a better coverage of the 4500 – 4000 K range where only two stars were available from the previous survey. Moreover, since we observed very active, X-ray selected objects, we can investigate whether the distribution of their Li abundances statistically differs from that of the BLS sample (which may as well include active stars, but which was not selected on the basis of activity); this will allow us to further study the relationship between lithium, activity, and rotation.

In the following sections we will describe the sample in more detail (Sect. 2.1), present the observations and data analysis (Sects. 2.2 and 2.3), show our results and compare them with both previous results for α Per and for other young clusters (Sect. 3). A discussion of our results is given in Sect. 4, and the conclusions are drawn in Sect. 5.

2. Sample, observations and analysis

2.1. New α Per candidate members

As we mentioned in the Introduction, our sample stars are new candidate members of the cluster selected by means of X-ray observations. More specifically, two X-ray surveys of the cluster carried out with ROSAT PSPC (Randich et al. 1996; Prosser et al. 1996) revealed the presence of several sources, above a sensitivity threshold of about $\log L_X$ = 28.8-29 erg/sec, which did not have an optical counterpart among cataloged stars (both cluster members and non members). These sources were considered as possible new, previously unknown, cluster members. Follow-up optical observations of these candidates were carried out by Prosser & Randich (1997; PR hereafter) and Prosser et al. (1997; PRS hereafter): BVI CCD observations covered all new candidates, and $\sim$ 2 Å spectra at Hα and/or Echelle spectroscopy were obtained for part of them. The optical observations permitted to drop from the sample stars which were certainly non members, as indicated by photometry and/or radial velocities, as well as to select a sub-sample of most likely members, i.e., objects with photometry consistent with the color-magnitude diagram for previously known members and with radial velocity in agreement with cluster membership. These stars were given a "Y" membership flag. For part of the candidates, however, no spectra were obtained or the uncertainties on radial velocities were too large to allow any definitive classification, or the disagreement in radial velocity could be possibly explained by binarity. Some of these stars were given a membership flag indicating uncertain membership ("Y?" or "?"), whereas other ones were still denoted as "Y" members; we stress that all of them are to be considered as uncertain members and additional observations are needed to ascertain their membership. Our sample includes 23 of the new candidates; 10 of them are most likely members, while the remaining 13 are uncertain members. The stars are listed in Table 1. The names (APX#) and the information given in Table 1 were retrieved from PR and PRS. Specifically, we list in columns 2, 3, and 4 photometry for our sample stars, in column 5 projected rotational velocities as measured from Echelle spectra, and in column 6 the ratios of X-ray to bolometric luminosity; the membership flags are given in column 7. We completed the membership flag given by PR and PRS with an additional flag indicating cases where only photometry is available or stars with somewhat discrepant radial velocity. Two objects, APX3 and APX164 correspond to the previously known members AP101 and HE936, respectively; these two stars come from the lists of cluster members by Heckmann et

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[1] An alternative explanation for the star-to-star scatter has been given by Russell (1996). He suggested that the observed dispersion does not correspond to a real dispersion in abundances, since the Li I λ 6708 Å resonance line is not a good tracer of the real Li abundance. Being formed high in the star atmosphere, it could be affected e.g., by chromospheric emission, and thus the spread could be significantly reduced when using the subordinate line at λ 6104 Å. Martín (1998), however, showed that Russell systematically overestimated the 6104 Å line's equivalent width (EW).

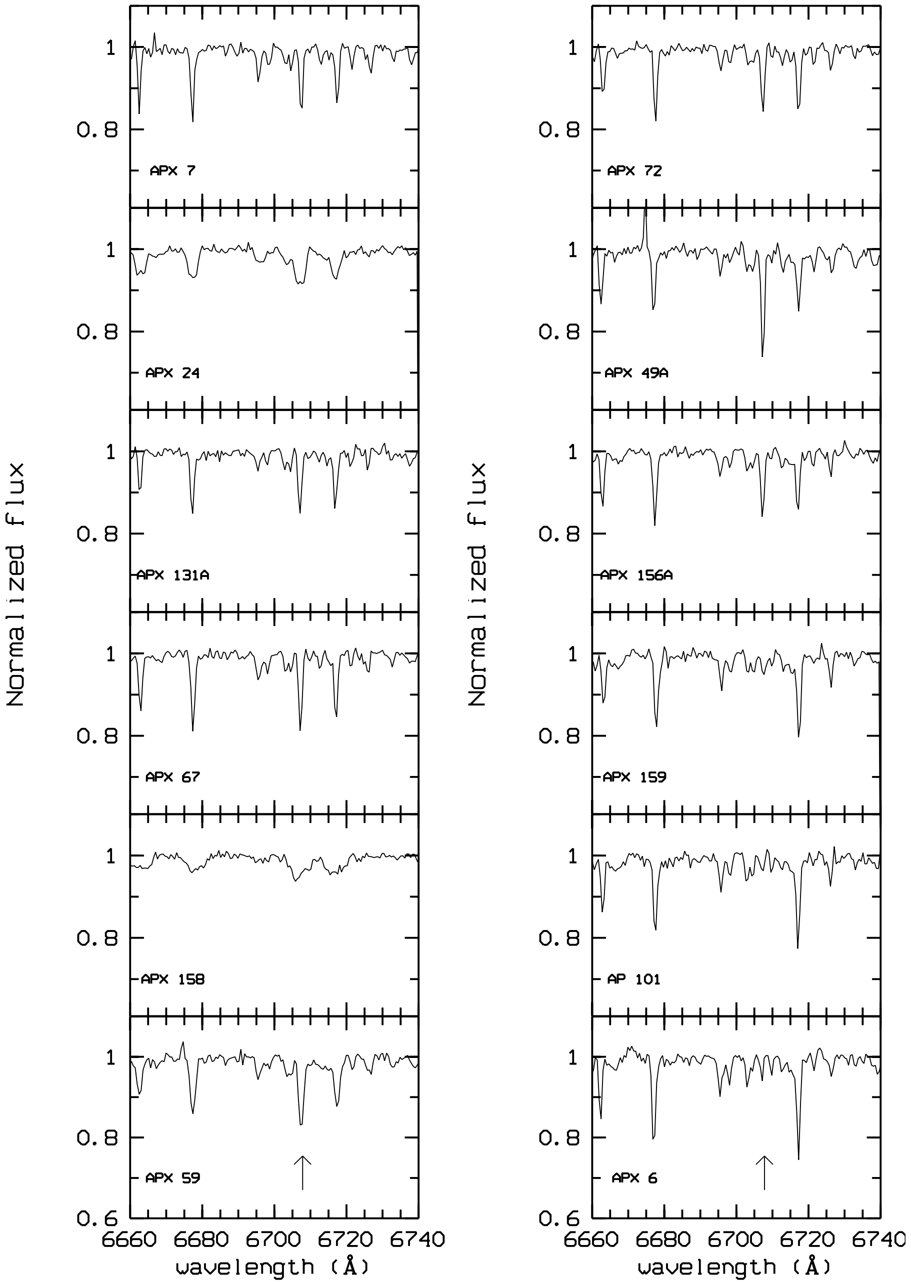

Fig. 1. Spectra of 12 stars in the observed sample. The position of the Li I line is indicated in the two bottom spectra.

al. (1956) and Prosser (1992), but they were not originally identified as the source of X-ray emission by Randich et al. (1996) and Prosser et al. (1996) due to the fact that the X-ray – optical distance was somewhat larger than the chosen cut-off. They were then recovered by PR and PRS and associated with APX3 and APX164.

2.2. Observations

The observations were carried out at the Observatorio del Roque de los Muchachos on La Palma, using the Intermediate Dispersion Spectrograph (IDS) at the Cassegrain focus of the 2.5m Isaac Newton Telescope (INT) on Nov. 30 – Dec. 4, 1996. We used the 235 mm camera, AgRed collimator, the H1800V grating, and a TEK 1024 × 1024 ($24\mu m$) CCD detector. With a $460\mu m$ wide slit ($\sim$ 2.5 arc sec on the sky), which projected onto 2 pixels, we achieved a resolution of $\sim$ 1Å. Data reduction, including bias subtraction, flat-fielding, extraction of one-dimensional spectra, and wavelength calibration, was carried out using MIDAS. Examples of the spectra are given in Fig. 1.

2.3. Abundance analysis

To estimate the effective temperatures for our α Persei stars we used two $T_{\rm eff}$ –color calibrations based on $V-I_C$ (Bessell 1979; also employed by Randich et al. 1997 in their study of IC 2602) and $B-V$ (Alonso et al. 1996), respectively. $V-I$ colors in the Kron system were translated into the Cousins ones

Table 1. The observed sample

name	V	B$-$V	V$-$I$_{\rm K}$	$v$sin$i$ (km/sec)	log $L_X/L_{\rm bol}$	Prosser et al. membership
APX1	12.57	0.92	0.81	13	–3.32	Y
APX3 (AP101)	13.89	1.25	1.24	...	–2.94	Y[a]
APX6	13.15	1.29	1.34	20	–3.28	Y
APX7	11.94	0.81	0.67	11	–3.64	Y
APX14	12.97	0.98	0.91	12	–3.55	Y[b]
APX24	12.07	0.82	0.75	55:	–3.08	Y[a]
APX27A	12.58	0.92	0.87	50:	–2.88	Y?[a]
APX28	11.91	0.86	0.91	...	–3.20	Y?[a]
APX35B	14.00	1.51	1.47	12	–3.91	Y?[b]
APX43A	13.26	1.06	1.05	14	–2.94	Y
APX49A	12.75	0.99	0.98	21	–3.36	Y
APX50	13.28	1.09	1.09	$<$10	–3.31	Y?[b]
APX59	12.70	0.96	0.88	38:	–3.16	Y
APX61	11.89	0.81	0.70	26	–3.24	Y?
APX67	11.62	0.89	0.80	12	–3.41	Y?
APX72	12.96	0.95	0.94	16	–3.58	Y?[b]
APX120A	13.94	1.30	1.38	19	–2.84	Y
APX131A	12.19	0.89	0.80	14	–3.58	Y
APX156A	12.92	1.00	1.00	15	–3.30	Y
APX158	12.38	0.89	0.92	170:	–3.38	Y[a]
APX159	13.80	1.16	1.24	25	–3.01	Y
APX164 (HE936)	11.40	0.61	0.54	...	–3.77	?
APX198	12.21	0.92	0.81	13	–3.86	Y[b]

a): based only on photometry
b): $v_{\rm rad}$ more than 3 km/s off from the cluster mean

following the relation provided by Bessell & Weis (1987). A mean reddening $E(B-V)=0.08\pm0.02$ (Mitchell 1960) was adopted to be consistent with the value used by Balachandran et al. (1988) and García López et al. (1994), and the reddening relationship $E(V-I_C)=1.60\times E(B-V)$ (Rieke & Lebofski 1985) was used to correct the V$-$I$_C$ colors. Effective temperatures derived from B$-$V using the calibration provided by Alonso et al. are consistent (with a maximum difference of 65 K) with those derived from the $T_{\rm eff}-$(B$-$V) relation used by Randich et al. (1997). On the other hand, temperatures based on the $T_{\rm eff}$ (V$-$I$_C$) calibration are in most cases lower than those coming from B$-$V (showing a mean difference of 91 ± 134 K). García López et al. (1994) investigated the possible correlation between the dispersion in $T_{\rm eff}$ (related to the three calibrations used by them for late-type stars in the Pleiades) and $v$sin$i$, which would indicate systematic effects of rotation on the effective temperatures obtained from different indices. They did not find any clear correlation between the two parameters, concluding that such systematic effects were probably not present. A similar test, plotting $T_{\rm eff}$ (B$-$V)–$T_{\rm eff}$ (V$-$I$_C$) against $v$sin$i$ and $\log L_X$, was carried out for our α Per stars indicating also no systematic effects of activity or rotation on the derived effective temperatures. Mean $T_{\rm eff}$ values for our stars are listed in Table 2, with errors including the differences between both calibrations and the uncertainty adopted for the reddening. Lithium abundances were derived, both in LTE and NLTE, using equivalent widths and the curves of growth (COG) of Pavlenko et al. (1995), which were computed for solar metallicity and surface gravity $\log g=4.5$. At our resolution the Li I resonance doublet at λ 6708 Å is blended with lines of other atomic and molecular species. The Fe I λ 6707.44 Å line is the main contributor in late-type stars, followed by the V I λ 6708.07 Å line which becomes important for stars cooler than ~ 4500 K. Lambert et al. (1993) provide a list of atomic and CN lines which reproduces well the high-resolution spectra of Ba giants, and these lines are blended with the Li ones in our spectra. Since the COG of Pavlenko et al. consider only the Li doublet, we used the line data (species, wavelengths, excitation potentials and transition probabilities) listed by Lambert et al. to compute synthetic equivalent widths which were employed to correct the measured ones. The iron abundance used was log n(Fe)$=7.51$ and the abundances of the other elements were scaled using [X/H]$=-0.05$ (Boesgaard & Friel 1990).

Soderblom et al. (1993) used an analytical relation between B$-$V and equivalent widths measured in spectra of a sample of old, inactive field stars (warmer than ~ 4500 K) to correct their Li measurements in late-type stars of the Pleiades. Corrections derived from their relation are in very good agreement with our

Table 2. Li equivalent widths and abundances

name	$T_{\rm eff}$ (K)	$\Delta T_{\rm eff}$ (K)	Li I+other EW(mÅ)	ΔEW (mÅ)	other EW(mÅ)	Li I EW(mÅ)	log n(Li) LTE	log n(Li) NLTE	Δ logn(Li)	Hα	membership flag
APX1	5091	59	199	5	13	186	2.43	2.46	0.11	abs.	Y
APX3	4275	45	69	10	19	50	0.52	0.68	0.17	emis.	Y
APX6	4171	60	57	5	19	38	0.26	0.40	0.14	emis.	Y
APX7	5479	100	182	8	13	169	2.75	2.74	0.15	abs.	Y
APX14	4890	57	39	13	15	24	0.58	1.11	0.28	abs.	N
APX24	5329	74	286	10	13	273	3.23	3.07	0.13	abs.	Y
APX27A	5009	87	233	10	14	219	2.52	2.54	0.13	emis.	Y
APX28	5057	200	66	8	14	52	1.55	1.68	0.26	abs.	N
APX35B	3914	92	22	5	16	6	-0.92	-0.81	0.27	abs.	N
APX43A	4634	93	187	5	17	170	1.74	1.86	0.14	emis.	Y
APX49A	4795	107	297	13	16	281	2.61	2.54	0.20	fil.	Y
APX50	4561	95	93	5	17	76	1.10	1.27	0.17	abs.	Y
APX59	4957	67	285	19	14	271	2.78	2.70	0.19	emis.	Y
APX61	5427	68	231	7	13	218	2.98	2.91	0.11	abs.	Y
APX67	5148	59	231	9	13	218	2.67	2.66	0.11	abs.	Y
APX72	4893	114	196	5	15	181	2.15	2.23	0.18	abs.	Y
APX120A	4139	70	46	5	19	27	0.04	0.21	0.17	emis.	Y
APX131A	5148	59	190	5	13	177	2.44	2.48	0.10	abs.	Y
APX156A	4760	115	190	12	16	174	1.94	2.03	0.21	abs.	Y
APX158	5001	170	281	12	14	267	2.81	2.73	0.22	abs.	Y
APX159	4369	123	64	13	18	46	0.59	0.76	0.29	emis.	Y
APX164	6066	92	63	5	7	56	2.51	2.55	0.16	abs.	N
APX198	5091	59	25	5	13	12	0.85	1.00	0.23	abs.	N

synthetic ones for stars hotter than ~ 4500 K. At their resolution the Fe I λ 6707.44 Å line should not be blended with the V I λ 6708.07 Å line (included in our synthesis), but this line becomes important only for cooler objects.

Columns 4, 5, 6, and 7 of Table 2 list the observed equivalent widths of the Li blend, the measurement errors, the equivalent widths estimated for the lines considered in the Lambert et al.'s list, and the corrected Li EWs ($\rm EW_0$ hereafter), respectively. Lithium abundances, in LTE and NLTE, and the uncertainties in the latter, are listed in columns 8, 9, and 10. These errors were estimated taking into account the error associated with the uncertainty in measuring the equivalent width, the error in $T_{\rm eff}$, and 0.05 dex to consider the uncertainties in $\log g$ and microturbulence. Finally, in the last two columns we indicate whether Hα is seen in emission or absorption, and the revised membership flag inferred on the basis of our data, as explained in the next section.

To compare our measurements with previous surveys of α Per, we have re-analyzed part of the data provided by BLS (only those stars with $V-I$ measurements available were considered) using the same procedure as for our stars. We took into account that the equivalent widths listed by BLS were already corrected for the contribution of the Fe I line and that the V I line is probably not blended with the Li doublet in their spectra. Hence, the corrections applied (in the range 1 to 4 mÅ) are negligible in most cases. Table 3 lists the effective temperatures estimated by us and by BLS (columns 2 and 3), the EWs from their paper as well as after the correction applied by us (columns 4 and 5), and the LTE and NLTE lithium abundances derived by us together with their LTE abundances (columns 6, 7, and 8, respectively).

To complete the sample we also consider the three α Per stars observed by García López et al. (1994; GL hereafter), which were analyzed in a very similar way and provide only upper limits to Li abundances. We will not consider, however, the additional stars studied by Zapatero Osorio et al. (1996), because they are much cooler and we have not tested yet the line list at those $T_{\rm eff}$, and also because they are only upper limits which do not provide further information.

3. Results

3.1. Cluster membership

In Fig. 2 lithium $\rm EW_0$s are plotted as a function of $B-V$ both for our sample stars (filled squares) and for those from BLS and GL (open circles). The figure shows a good agreement between the two datasets for all but four of the new cluster candidates which lie considerably below the distribution of previously known members. The four stars are HE 936, APX 14, APX 28, and APX 198. HE 936 was originally selected as a candidate member on the basis of proper motion (Heckmann et al. 1956).

Table 3. Balachandran et al.'s (1996) sample (BLS)

name	$T_{\rm eff}^{\rm our}$ (K)	$T_{\rm eff}^{\rm BLS}$ (K)	Li I+other EW (mÅ)	Li I EW (mÅ)	log n(Li)$^{\rm our}$ LTE	log n(Li)$^{\rm our}$ NLTE	log n(Li)$^{\rm BLS}$ LTE
AP 19	5470	5570	120	117	2.45	2.50	2.75
AP 28	4727	4850	66	62	1.21	1.38	1.58
AP 32	6342	6350	99	98	3.02	2.99	3.30
AP 33	4836	4870	109	105	1.66	1.80	1.94
AP 37	4977	5080	77	73	1.64	1.76	1.94
AP 38	5591	5660	187	185	2.93	2.89	3.24
AP 43	4840	5050	146	142	1.88	1.99	2.40
AP 51	6340	6390	73	72	2.86	2.85	3.10
AP 56	4801	4970	149	145	1.84	1.96	2.30
AP 65	4798	4850	58	54	1.23	1.40	1.50
AP 70	4886	4970	164	160	2.03	2.12	2.40
AP 72	4911	5000	102	98	1.71	1.85	2.01
AP 78	4775	4920	150	146	1.81	1.93	2.20
AP 79	6257	6230	107	106	2.98	2.94	3.19
AP 90	5923	5970	147	146	2.92	2.89	3.26
AP 91	4837	5160	254	250	2.47	2.46	3.20
AP 93	4873	5160	245	241	2.47	2.46	3.20
AP 97	5249	5330	192	188	2.61	2.62	2.89
AP 98	4912	4970	201	197	2.27	2.32	2.63
AP 100	4460	4650	95	91	1.07	1.25	1.60
AP 101	4272	4370	50	47	0.48	0.64	0.86
AP 106	4847	4950	139	135	1.85	1.96	2.09
AP 110	5087	5200	196	192	2.45	2.49	2.82
AP 112	4430	4650	<3	0	< -0.49	< -0.49	< 0.60
AP 114	4609	4770	110	106	1.35	1.52	1.86
AP 117	4913	5110	209	205	2.31	2.35	2.80
AP 118	5340	5510	215	211	2.84	2.80	3.30

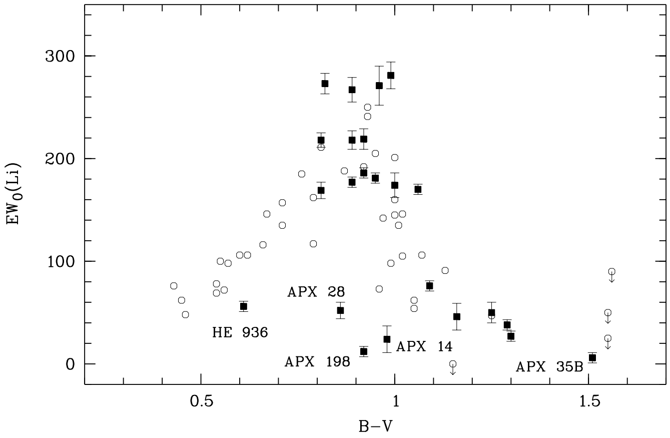

Fig. 2. Lithium equivalent widths corrected for the contribution of Fe and molecular lines (see text) are plotted as a function of B−V color for the 23 stars in the present sample (filled squares) and α Per members in BLS and GL samples (open circles). The five stars which are most likely non members are marked.

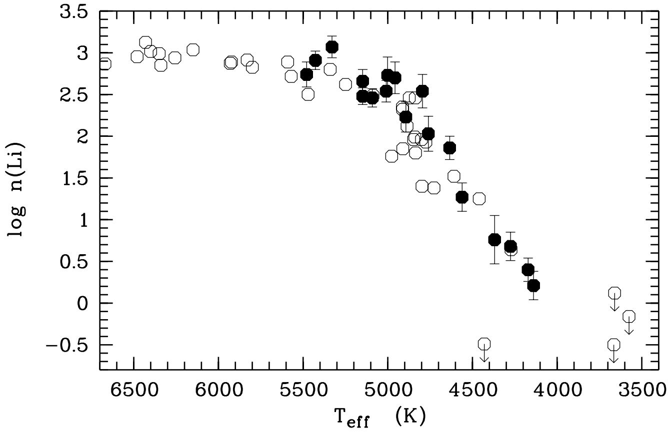

Fig. 3. NLTE Li abundance as a function of effective temperature for the 18 likely members in our sample and stars in BLS and GL samples (filled and open circles, respectively).

Photometry and radial velocity indicated that, on the contrary, it was most likely a non member (see PRS). The low lithium content which we find confirms that it is not a cluster member. As to the other three stars, two of them (APX 14 and APX 198) have radial velocities of −6 and +4 km/s (the average $v_{\rm rad}$ for α Per is −3 km/s), while the membership flag for APX 28 was based on photometry only (see Tab. 1). The low lithium content of these objects suggests that they are indeed field stars rather than α Per members. Finally, there is an additional object which we believe is a non member: it is APX 35B. For this star a radial velocity of -12 km/s was measured by PR. Given the very late spectral-type ($(V-I_K)_o$ = 1.37), the absence of lithium is not a definitive proof against membership; however, the fact that Hα is not seen in emission suggests that it is a non member, since known α Per members later than $(V-I_K)_o \sim 1.2$ show Hα in emission (e.g., Prosser 1992). To conclude, five out of the 23 targets (i.e., 22 %) appear to be non members. All of them are stars with v_{rad} off from the cluster mean or without v_{rad} measurements. On the contrary, our data confirm membership for all the candidates which were classified by PR and PRS as most likely members (Y) and for seven of the 12 (54 %) uncertain members. Additional observations are needed to ascertain membership for the candidates in PR and PRS samples not observed by us. If, as it is the case for the present sample, membership will be confirmed for $\sim$ 60 – 80 % of them, in the end a significant number of cluster members will have been identified through X–ray observations, with important consequences for the cluster optical luminosity function.

The five most likely non members will be excluded from the following analysis. We also note that in the BLS sample as well there are a few stars with a Li EW considerably below the other cluster members. All these objects have been classified as certain members, although one of them (AP 37, $B-V$=0.96, $EW_0 = 73$ mÅ) has a radial velocity equal to 4.4 km/s (Stauffer et al. 1985) which is fairly off from the cluster mean[2]. Therefore, we will not discard them from the analysis; we caution however that our considerations and conclusions, in particular those concerning the dispersion in Li, might somewhat change should these objects turn out to be non members.

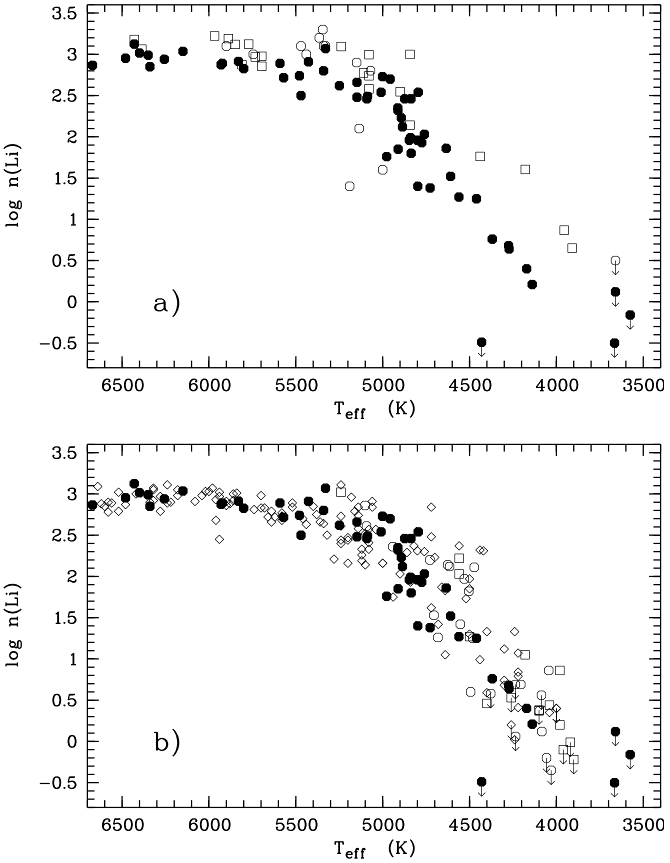

Fig. 4. (a) $\log$ n(Li) vs. T_{eff} for the merged (present + BLS and GL) α Per sample (filled circles) is compared with IC 2602 (open squares) and IC 4665 (open circles); **(b)** Same as panel **a**, but α Per is compared with the Pleiades. The different symbols for the Pleiades denote different lithium surveys of this cluster, namely, Soderblom et al. (1993, open diamonds), García López et al. (1994, open circles), and Jones et al. (1996, open squares).

3.2. Lithium abundances

3.2.1. Comparison with previous surveys in α Per

In Fig. 3 we plot NLTE lithium abundances vs. T_{eff} for our sample stars (filled circles) and for previously known members from BLS and GL (open circles). As explained in the previous section, part of the sample of BLS has been re-analyzed consistently with ours. Lithium abundances determined by us are systematically lower than those published by BLS (cf. Table 3). In most cases this is due to the fact that the temperatures which we derive for the stars in their sample are lower than the temperatures adopted by BLS, since we used a different color – T_{eff} calibration and, more important, we used an average of T_{eff} $(B-V)$ and T_{eff} $(V-I_C)$ while they used only one color. In a few instances, however, the differences in T_{eff} are not large enough to explain the differences in $\log$ n(Li). We note in particular AP 112: BLS list $T_{eff} = 4650$ K and $\log$ n(Li)< 0.60, whereas, assuming a temperature of 4430 K and a correction of 3 mÅ to their published EW, we derive $\log$ n(Li)< -0.49 both in LTE and NLTE. Using the same temperature as BLS and without correcting their EW, we would get $\log$ n(Li)< -0.02 in LTE and $\log$ n(Li)< 0.03 in NLTE which are still considerably below the value given by BLS.

Fig. 3 shows that, once dropped the five likely non members from our sample, abundances for ‘old’ and ‘new’ cluster members are consistent with each other. In other words, the abundances we find for the new candidates are within the same range of values as those of previously known members. New candidate members, however, tend to stay on the upper envelope of the lithium vs. T_{eff} distribution, in particular in the $\sim 4500 - 5000$ K interval, where they cluster around the maximum $\log$ n(Li) values, with some of the stars from the sample of BLS showing somewhat lower $\log$ n(Li). Given the selection criterium, our sample is biased towards X-ray active stars; if, as previous studies have pointed out, there is a link between lithium and rotation/activity for stars warmer than $\sim$ 4500 K, one would indeed expect that stars in our sample have, on average, a higher lithium abundance. We will further discuss this

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[2] The star is not classified as a binary nor as a variable; we also mention that BLS list for this star vsin $i < 10$ km/s, whereas the value given both by Stauffer et al. (1985) and Prosser (1992) is 29 km/s.

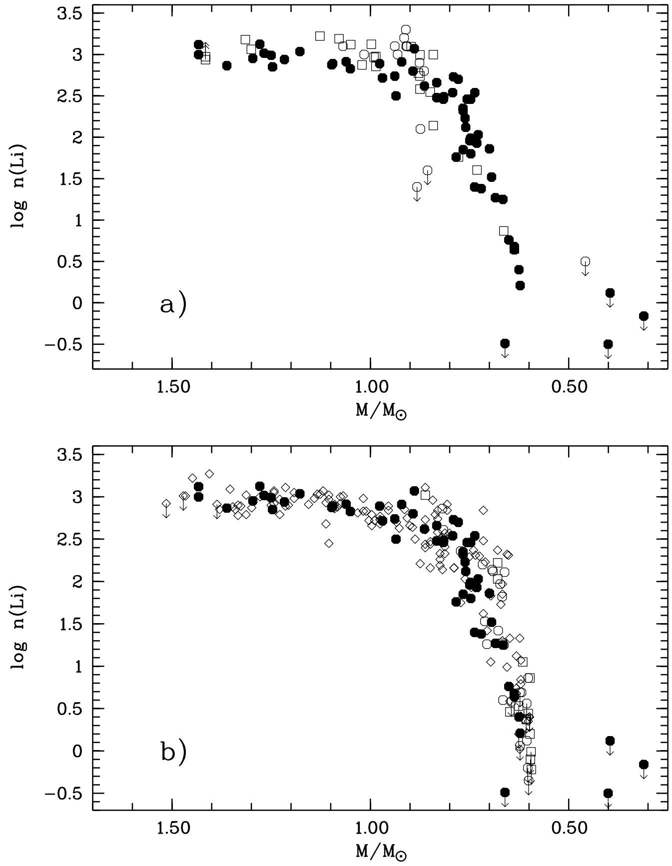

Fig. 5a and b. Same as Fig. 4, but log n(Li) is plotted as a function of $M/M_{\odot}$.

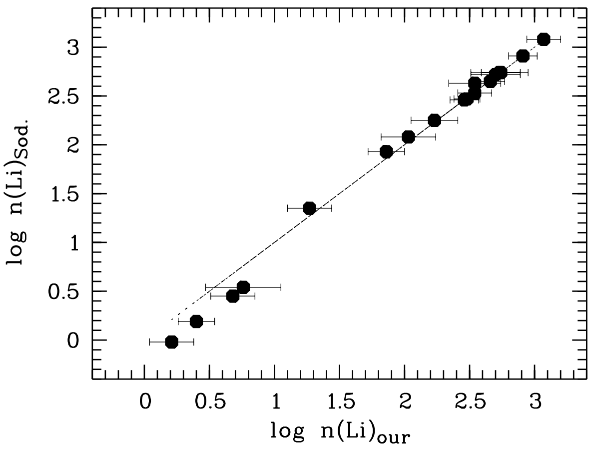

Fig. 6. log n(Li) determined through our analysis compared with log n(Li) which one would get by using the same analysis as Soderblom et al. (1993). In the figure only the 18 new most likely α Per members are considered.

point, and more in general the lithium –rotation – activity connection, in Sect. 4.2.

3.2.2. Comparison with other young clusters

In Fig. 4a log n(Li) vs. $T_{\rm eff}$ for the merged ‘old’ plus ‘new’ α Per sample (filled circles) is compared with IC 2602 (30 Myr, open squares) and IC 4665 (35 Myr, open circles), while in Fig. 4b the merged α Per sample is compared with the Pleiades. Figs. 5a and 5b are the same as Figs. 4, but log n(Li) is plotted as a function of $M/M_{\odot}$. Masses have been inferred from effective temperatures using D’ Antona & Mazzitelli (1994) isochrones[3]. Pleiades data have been taken from Soderblom et al. (1993, diamonds), García López et al. (1994, circles), and Jones et al. (1996, squares). García López et al. determined both $T_{\rm eff}$ and log n(Li) in the same fashion as we did and thus their dataset is consistent with ours. The same holds for IC 4665 data taken from Martín & Montes (1996). On the other hand, both Soderblom et al.’s and Jones et al.’s Pleiades samples and the IC 2602 sample from Randich et al. (1997) were analyzed in a different way: temperatures were inferred using only the B$-$V color and a different $T_{\rm eff}$ vs. B$-$V calibration; moreover, abundances were determined using Soderblom et al.’s (1993) COG and were afterwards corrected for NLTE effects using the prescription of Carlsson et al. (1994). We checked how the use of two different methods could affect our results by deriving log n(Li) for our sample stars with the method of Soderblom et al.’s and then comparing the results with those derived through our analysis. Incidentally, the use of Soderblom’s et al method also implies the determination of the 6707.441 Å feature using their analytical approximation. The comparison is shown in Fig. 6: the figure indicates that the differences between abundances derived with the two methods are within our estimated uncertainties and no systematic effect seems to be present, at least for the highest abundances. For log n(Li)$\leq$1, abundances inferred using Soderblom et al.’s analysis tend to be lower than those derived through our analysis, most likely since NLTE effects are not taken into account (Carlsson et al. code is not available for $T_{\rm eff} < 4500$ K). In these cases the difference is of the order of 0.2–0.3 dex for log n(Li)$_{\rm NLTE}-$log n(Li)$_{\rm LTE}$. We conclude that when looking at Figs. 4b and 5b one should consider that part of the Pleiades data points (i.e., those coming from Soderblom et al. and Jones et al.) and the IC 2602 data points cooler than 4500 K have actually a 0.2-0.3 dex higher log n(Li).

Figs. 4 and 5 show that *i)* $T_{\rm eff} \gtrsim 5300$ *K:* the distributions of α Per and the Pleiades are similar: the warmer stars in both clusters have log n(Li) between 2.9 and 3.1, i.e., close to the “cosmic” value for Pop. I stars (log n(Li)$\sim 3.1 - 3.2$); some depletion is seen below 6000–5800 K, but no major spread is visible. The IC clusters, instead, seem to be slightly more Li rich than α Per, although given the small size of both samples and the errors involved, we cannot say whether the difference is statistically significant or not; *ii)* $4500 < T_{\rm eff} \lesssim 5300$ *K:* in all the four clusters stars cooler than 5300-5200 K show a dispersion in log n(Li) , although the amplitude of the spread and the temperature at which it starts differ from cluster to cluster. We refer to Martín & Montes (1997) for the discussion of the

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[3] Their Model 1 has been used. We refer to Randich et al. (1997) for the discussion on how the use of different isochrones affects the results.

three IC 4665 stars which lie considerably below the other IC stars; *iii)* $T_{\rm eff} < 4500$ *K:* stars in the four clusters are strongly depleted; lithium steeply decreases with decreasing temperature until the so called "lithium chasm" (or "big lithium gap", see García López 1996; Basri 1998) starts: for $\rm T_{eff} \lesssim 4000$ K lithium is not detected in any of the four clusters and, on average, these clusters do not have more lithium than the Pleiades, contrary to what one would expect given the difference in age.

4. Discussion

4.1. $T_{\rm eff} > 5300$ *K*

Our results for warm stars are not new, but confirm previous findings (actually most stars above 5300 K come from BLS). Stars above 6000 K in the young clusters show no or little depletion, their Li content being similar to that of T Tauri stars. This indicates that depletion timescales for these objects are longer than at least 70–100 Myr. On the other hand, some Li destruction has occurred in both Alpha Per and Pleiades stars in the 5800 – 5300 K range, whereas in the IC clusters only a few stars above 5300 K (or 0.9 $M_\odot$) are depleted with respect to the cosmic value. This suggests that some Li destruction must occur on the ZAMS between 30 and 50 Myr.

4.2. The 4500-5300 K range: the rotation–lithium relation

In Fig. 7 we plot again $\log$ n(Li) vs. $\rm T_{eff}$ for α Per (upper panel) and the Pleiades (lower panel) in the 4500 – 5500 range. Objects with different $\rm v\sin\it i$ are represented with different symbols, but instead of considering a continuous distribution of velocities, as it is usually done, we subdivided the sample in objects with $\rm v\sin\it i$ above and below (filled and open symbols, respectively) a threshold velocity $\rm v_{thr}$. We choose $\rm v_{thr} = 15$ km/s. Crosses indicate known binaries (both photometric and spectroscopic) or radial velocity variables. AP37 was excluded from the α Per sample. The figure shows that stars with $\rm v\sin\it i \geq 15$ km/s in both clusters generally lie on the upper envelope of the diagram. This is a well known result as we have already mentioned. An additional feature appears in the figure: slow rotators are characterized by a much larger scatter than rapid rotators; most of the spread among fast rotators is removed by discarding known or possible binaries, whereas this is not the case for slow rotators. The dicothomy between slow and fast rotators is most evident for the Pleiades, in particular for stars between 5000 and 5300 K, for which about a factor of ten dispersion is seen among slow rotators, whereas virtually no spread is seen among the five slow rotators in α Per. We carried out a formal polynomial fit of the four (i.e., Pleiades 'fast' and 'slow'; α Per 'fast' and 'slow') log n(Li) vs. $\rm T_{eff}$ distributions considering stars below 5300 K, and excluding binaries; we obtained a formal r.m.s σ = 0.30 and 0.19 for the slow rotators in the Pleiades and α Per sample, respectively, and σ = 0.12 and 0.11 for the fast rotators, quantitatively confirming the above considerations.

To summarize, the dependence of lithium on rotation emerging from Fig. 7 is somewhat different from what is currently thought: rapid rotators as a group do have more lithium than the slow rotators, but the star-to-star scatter is reduced with respect to slow rotators. Since a dispersion in $\rm v\sin\it i$ is observed among rapid rotators, this result implies that, above a given threshold velocity, the dependence on rotation is much weaker than for stars below the threshold[4]

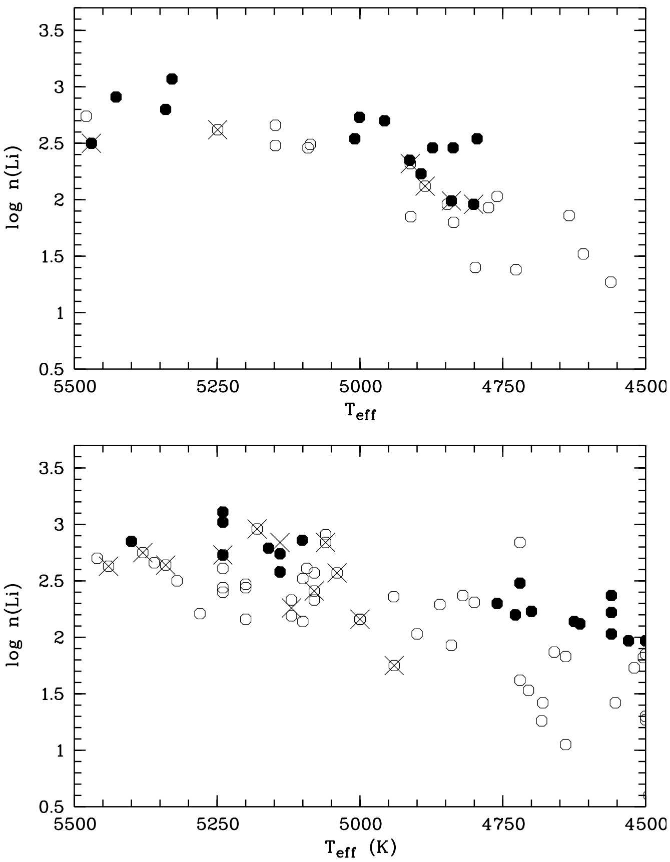

Fig. 7. log n(Li) vs. $\rm T_{eff}$ for α Per (upper panel) and Pleiades (lower panel) stars with $4500 \leq \rm T_{eff} \leq 5500$ K. Filled circles indicate stars with projected rotational velocity $\rm v\sin\it i \geq 15$ km/s, whereas open symbols denote stars with $\rm v\sin\it i < 15$ km/s. Known binaries or radial velocity variables are marked with crosses.

The first question one should ask is whether this is a real effect or whether the use of $\rm v\sin\it i$ is misleading, in the sense that the scatter among slow rotators is larger, since this group could actually include several rapid rotators seen at small $\sin i$. Fig. 8 is the same as Fig. 7, but instead of subdividing the sample on the basis of $\rm v\sin\it i$, we used the ratio of X-ray to bolometric luminosity $\rm \log L_X/L_{bol}$. As it has been shown by X-ray studies of young open clusters (e.g., Stauffer et al. 1994; Randich et al. 1996; Patten & Simon 1996; Randich 1998 and references therein), for stars with $\rm B{-}V \gtrsim 0.6 \log L_X/L_{bol}$ increases with increasing rotation until it reaches a saturation value, $\rm \log L_X/L_{bol} \sim$ constant $= -3$, above a critical velocity which depends on mass (Stauf-

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[4] The value of the threshold velocity is to be regarded as indicative; we made the same plot shown in Fig. 7 using 10 km/s as a threshold: the scatter among fast rotators slightly increases, but, most important, the dispersion among slow rotators does not disappear.

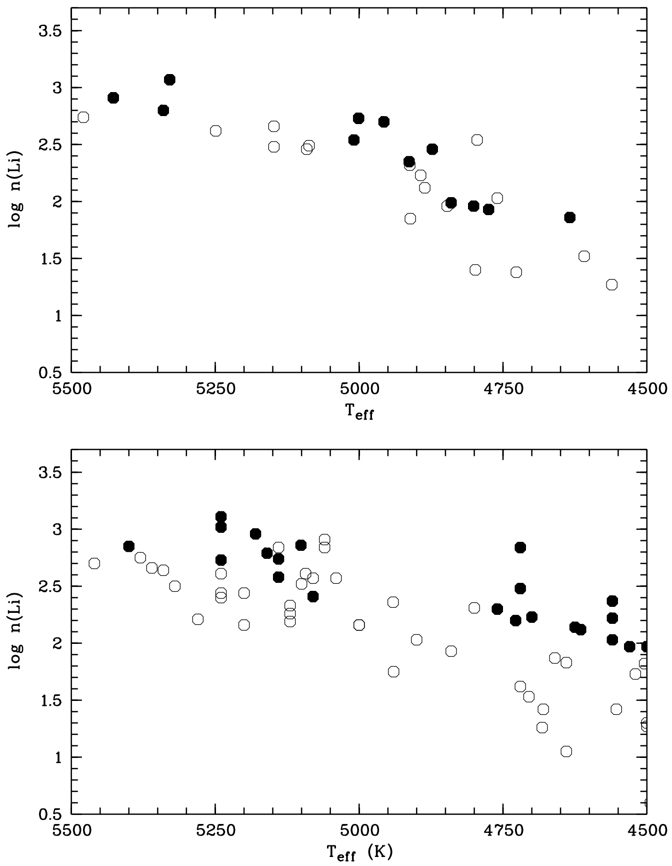

Fig. 8. Same as Fig. 7, but filled and open circles denote stars with $\log \mathrm{L_X/L_{bol}}$ above and below -3.2, respectively.

fer et al. 1997). The saturation velocity for stars in the range we are interested in is $\sim$ between 10 and 15 km/s, and thus objects with v > 15 km/s are expected to be saturated. Therefore, by sub-dividing our sample using a $\log \mathrm{L_X/L_{bol}}$ threshold instead of a velocity threshold we should be able to get rid of projection effects. We choose $\log \mathrm{L_X/L_{bol}} = -3.2$ as a threshold, in order to take into account the dispersion around the saturation plateau due to measurement uncertainties; $\log \mathrm{L_X/L_{bol}}$ values were available for most of α Per and Pleiades stars; they were taken from Prosser et al. (1996) for the known α Per members, from PR and PRS for the new candidates (see Table 1), and from Stauffer et al. (1994), or computed starting from $\mathrm{L_X}$ given by Micela et al. (1996) for the Pleiades.

Fig. 8 shows the same general pattern as Fig. 7: saturated stars (or rapid rotators) have a tighter $\log$ n(Li) vs. $\mathrm{T_{eff}}$ distribution than lower activity objects, reinforcing the conclusions from Fig. 7. Eventually only a few objects turned out to be fast rotators seen at low inclination angles.

This result provides a possible key to discern between different mechanisms which have been proposed to explain the dispersion in Li. Bouvier et al. (1997) modeled the early rotational evolution of solar-type and low mass stars assuming disk-locking; namely, the evolution of rotation during PMS and the final velocity on the ZAMS depend on the timescale for the dissipation of the circumstellar disk ($\tau_{\rm disk}$) (see also Krishnamurthi et al. 1997 and references therein). Stars with long-lived disks end up as slow rotators on the ZAMS, whereas stars which dissipate their disks at early phases reach the ZAMS as fast (or ultra-fast, depending on the initial period) rotators. In addition, Bouvier (1998) suggested that the assumption of solid body (SB) reproduces the distribution of rotational velocities of rapid rotators in young clusters, but differential internal rotation (DR) is needed in order to fit the distribution of the slow rotators. Slow rotators therefore undergo a strong loss of angular momentum during the PMS phase and then they do not loose any additional angular momentum later on the ZAMS. DR and lost of angular momentum during the PMS phase also imply that angular momentum transport, and thus mixing of material and Li burning, should take place. Since in Bouvier's model$\tau_{\rm disk}$ is a crucial parameter in determining the velocity on the ZAMS and the amount of angular momentum lost, one could hypothesize that the spread in lithium which is seen among slow rotators reflects a spread in $\tau_{\rm disk}$. If all slow rotators had a similar initial period ($\mathrm{P_0}$), at a given mass, both the velocity and n(Li) on the ZAMS would only depend on $\tau_{\rm disk}$ and a direct correlation between n(Li) and rotation would be expected. As a matter of fact, stars in a cluster are characterized by a distribution of initial periods: stars with different $\mathrm{P_0}$ and different $\tau_{\rm disk}$ may eventually reach the ZAMS with a similar rotation rate, but with different n(Li), introducing a scatter in the Li vs. rotation relationship. Martín (1998) has indeed shown that a Li–rotation period correlation does not hold for a small sub-sample of Alpha Per members in the 4920 – 4800 $\mathrm{T_{eff}}$ interval. This hypothesis is therefore difficult to assess, but it deserves farther investigation, in particular on theoretical grounds.

As to fast and moderate rotators, these stars have dissipated their circumstellar disk at early stages of their evolution and thus spin-up on their way to the MS. Bouvier (1998) and Krishnamurthi et al. (1997) suggest that these objects do not undergo dramatic losses of angular momentum until they reach the ZAMS. Therefore strong transport of angular momentum and differential lithium depletion due to different angular momentum loss should not occur in the PMS phase/early ZAMS phase. In the scenario which we have discussed above a major dispersion in lithium is not expected for these stars, as our results indeed show. As a final remark, we note that the $\tau_{\rm disk}$ scenario does not necessarily imply that the mechanism proposed by Martín & Claret, i.e., that very rapid rotation slows down lithium destruction, is not at work. Rapid rotators indeed lie above the distribution for slow rotators and different initial conditions for them could reflect in different amounts of lithium burning and the small spread that we see among rapid rotators. However, we do not think that this mechanism alone could explain the whole range of the spread since, as we have stressed above, the spread is much larger among slow rotators than among rapid rotators.

4.3. $T_{\rm eff} < 4500$ K

The high efficiency of Li destruction for cool stars in the PMS phase is also a well known result. Actually, as discussed by Martín & Montes (1997) and Martín (1998) it provides a way of dating cool dwarfs. A couple of features in Figs. 4 and 5 instead deserve a more detailed discussion. α Per members cooler than 4500 K seem to be characterized by a smaller dispersion in lithium than the Pleiades. This is most probably due to the small sample of cool stars for α Per (as well as for the IC clusters) and no conclusion can be drawn until a larger sample is studied.

Figs. 4 and 5 also show that $\log$ n(Li) vs. mass distribution for low mass Pleiades stars does not indicate a systematically lower lithium in the Pleiades. In order to check whether this is also due to low number statistics, we constructed a "Lithium distribution function" for the Pleiades in the $-0.21 \leq \log M/M_{\odot} \leq -0.19$ mass range carrying out a survival analysis using ASURV 1.2, which allows to take into account both detections and upper limits. Before doing this, we added 0.2 dex to both Soderblom et al.'s (1993) and Jones et al.'s (1996) abundances, in order to compensate for NLTE effects. We obtained a mean abundance $\log$ n(Li)=0.702 $\pm$ 0.112, whereas the 50th (median), 25th, and 75th percentiles are $\log$ n(Li)=0.677, 0.159, and 0.978, respectively. This means that if there were only five Pleiades stars in this mass range, i.e., the same as the number of α Per stars, one would roughly expect half of the objects to have $\log$ n(Li) larger than 0.677, with one of them with $\log$ n(Li)$\gtrsim$ 1. Only one object would have $\log$ n(Li) lower than $\sim$ 0.2. In the α Per sample there is only one star with $\log$ n(Li) larger than the median for the Pleiades (but no one with $\log$ n(Li) as large as 1.), two objects have abundances comparable to the median, and the last two are definitively below the median (one has an abundance comparable to the Pleiades 75th percentile). We therefore conclude that α Per stars in this sample are likely to be drawn from a population with a distribution in abundances similar to the Pleiades, if not even slightly more depleted.

The most straightforward explanation for this result would be that α Per is older than the Pleiades. However, while the absolute ages of both clusters might be wrong, indicators such as the level of rotation and activity, demonstrate that the relative ages are probably correct. The metallicities of the two clusters are comparable, with the Pleiades being slightly more metal rich than α Per, but within the error bars (e.g., Boesgaard 1989; Boesgaard & Friel 1990). If PMS lithium destruction at these masses occurs only through convective mixing (which however cannot explain the spread which is still seen among Pleiades low mass dwarfs), and if it is very sensitive to metallicity, this would be an additional argument, besides age, for α Per low mass stars being more Li rich than the Pleiades.

The simplest hypothesis would be that what we see now, not only in α Per , but also in the Pleiades is the result of PMS depletion only, and that any process of MS depletion is slow enough to not produce any significant depletion between the age of α Per and the Pleiades. Differences in the abundances of heavy elements, like oxygen, could also play a role in the lithium depletion (e.g., Swenson et al. 1994a,b). However, García López (1997, private communication) has carried out a preliminary analysis of the oxygen abundances in F- and G-type stars of both clusters, which indicates only a possible slight (< 0.1 dex, and within the error bars) oxygen overabundance in the Pleiades with respect to α Per.

5. Conclusions

ROSAT observations together with CCD photometry and low/medium resolution spectroscopy have permitted the identification of α Per candidate members which had not been selected through proper motion surveys. The observations presented in this paper allowed us to clean part of the sample rejecting likely non members; on the other hand, we confirmed membership for a high percentage of the candidates.

Our data also allowed us to enlarge the sample of α Per stars for which Li measurements are available, in particular among low mass stars. We re-analyzed part of the BLS sample and combined it with our one. The merged sample is still much smaller than that for the Pleiades; in addition, although we derived $\log$ n(Li) for the stars in BLS sample in the same way as we did for our sample, we used their published EWs, which could introduce some scatter/uncertainty in the results. Given this caveat, we can summarize our results as follows:

1. The comparison of α Per with the Pleiades and the IC 2602 and IC 4665 clusters confirms that stars warmer than $\sim$ 6000 K in the four clusters have essentially the same Li; whereas some depletion is seen at ~ 1 $M_{\odot}$ in the Pleiades and α Per , this is not the case for the two younger clusters, showing that some depletion occurs in stars of 1 $M_{\odot}$ or more massive than the Sun during the earliest phases on the ZAMS;

2. rapid rotators (defined as stars with v$\sin i > 15$ km/s) have on average less scatter in lithium than slow rotators (over the range 4500– 5300 K), besides having, as already known, typically more lithium than the slow rotators. Both facts (see Figs. 7 and 8) are quite evident for the Pleiades, but less evident for α Per. We qualitatively explain the difference in the behavior of slow and rapid rotators in terms of the difference of their early rotational histories and associate the spread among slow rotators with a spread in the disk dissipation timescales and/or initial rotation period;

3. the cooler stars ($T_{\rm eff} <$ 4500 K) in Alpha Per do not have more lithium than the (older) Pleiades and possibly have less scatter. Low number statistics may play a role here, and no definitive explanation for this effect can be offered at this stage. Besides a larger sample, additional data on metallicity and other heavy elements abundances are needed to clarify this issue.

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