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ASTRONOMY AND ASTROPHYSICS

Identification of a complete sample of northern ROSAT All-Sky Survey X-ray sources

VI. K to M-type stars south of Taurus-Auriga

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Abstract. We present first results of a spectroscopic study of lithium absorption lines in late-type stars at high galactic latitude. The investigated stars were identified previously as optical counterparts of ROSAT All-Sky Survey sources. They are contained in a complete X-ray count-rate limited representive subsample of the RASS which was completely optically identified by our group. No selection criteria other than requiring RASS count rates larger than 0.03 cts s^{-1} were applied. The stars are located at galactic latitudes $|b^{II}|$ between 28° and 45° in an area $\sim 20°$ south of the Taurus-Auriga star forming region. In the sample of 35 stars with spectral types between K0 and M5 we found 9 stars with significant Li Iλ6708 absorption lines, 8 K stars and 1 M0 star. No lithium was found in stars with spectral types later than M0. The Li I equivalent widths (corrected for the contribution of Fe I) are between ~150 mÅ and ~400 mÅ. The lithium strength of these stars is consistent with ages on the order of 10-30 Myr. These stars are still in a pre-main sequence evolutionary stage, and belong to the weak-line Tauri stars.

Key words: surveys – stars: formation – stars: late-type – stars: pre-main sequence – X-rays: stars

1. Introduction

The stellar component of the soft X-ray sky at high and low galactic latitude is dominated by young active coronal emitters, typically with ages of $\lesssim 1$ Gyr. At $|b^{II}| \leq 20°$, $\sim 85\%$ of all ROSAT All Sky Survey (RASS) sources were found by Motch et al. (1997) to be active coronae. At high galactic latitude, i.e. at $|b^{II}| \gtrsim 20°$, an extensive study of a count-rate limited sample of RASS sources carried out by our group yielded a significantly smaller fraction of $\sim 12\%$ to $\sim 65\%$ stellar X-ray emitters, depending on the location in the sky, of which many if not most are likely to be active coronae. A detailed description of this work comprising 674 RASS sources contained in six study areas has been given by Zickgraf et al. (1997, hereafter Paper II). The complete catalogue of identifications is published in Appenzeller et al. (1998, hereafter Paper III).

Using the absorption feature of the lithium resonance doublet at λ6708Å as age indicator, the study of high galactic latitude samples ($|b| \geq 20°$) of F to K type stars from the EINSTEIN Extended Medium Sensitivity Survey (EMSS), e.g. by Favata et al. (1993), had shown that a large fraction of these X-ray active stars are in fact relatively young, i.e. comparable to the Pleiades, and hence considerably younger than 1 Gyr. Some of them, surprisingly, are even pre-main sequence (PMS) objects, i.e. younger than the Pleiades. The sky areas investigated by us for the optical identification programme (cf. Paper II) are also at $|b| \gtrsim 20°$, away from known star forming regions (SFRs). In an intermediate resolution spectroscopic follow-up investigation of F to early K type stars from our RASS sample we detected relatively strong Li I absorption lines in a considerable fraction (≈10%) of the investigated stars. This indicates that similar to the EMSS sample studied by Favata et al., also our ROSAT sample appears to contain very young, possibly PMS objects (Ziegler 1993, PaperII) despite its location at high $|b^{II}|$.

The existence of PMS objects far from the galactic plane becomes even more important for the understanding of star formation, if recent results on the spatial distribution of weak-line T Tauri stars (WTTS) are considered. Various studies demonstrated that this class of PMS stars extends far beyond the limits of the star forming molecular clouds. Examples are provided by the Chamaeleon SFR (Alcalá et al. 1995, Covino et al. 1997), the Lupus SFR (Wichmann et al. 1996, 1997, Krautter et al. 1997), and an area south of the Taurus-Auriga SFR (Neuhäuser et al. 1995, 1997, Magazzú et al. 1997).

One of our study areas, which is designated area I in Paper II overlaps with the region studied in the above mentioned investigations by Neuhäuser et al. (1995, 1997), and Magazzú et al. (1997). Their search for PMS stars in this region of the

Send offprint requests to: F.-J. Zickgraf sky which is located at a rather large distance from the actual star forming molecular cloud resulted in the detection of numerous previously unknown PMS stars. Based on these results we may expect to find PMS stars also in our RASS sample in area I. For their study the mentioned authors used a selection method developed by Sterzik et al. (1995). It is based on certain assumptions about the X-ray characteristics of PMS stars. The selection was applied in order to increase the detection probability of PMS stars. The sample created in this way contained predominantly spectral types early G to mid K (e.g. Magazzú et al. 1997) mainly due to the optical brightness limit of their sample. In contrast to these studies, however, we did not pre-select RASS sources for our optical identification programme by applying any X-ray selection criteria or optical brightness limits, with the exception of the requirement that the RASS count rate was larger than the completeness limit of 0.03 cts s^{-1} (cf. Paper II). Our sample is therefore unbiased with respect to X-ray properties.

In order to study the age distribution of the late-type coronal emitters in our high galactic latitude RASS sample we started an observing programme for the investigation of the Li I absorption line. In this paper we present first results for study area I, i.e. a region of the sky in which PMS stars have already been found. Further results of this ongoing investigation on the remaining five study areas will be given in a forthcoming paper. In Sect. 2 the sample is presented. The observations are described in Sect. 3. The results given in Sect. 4 are discussed in Sect. 5. Conclusions are finally given in Sect. 6.

2. The observed sample

Study area I is located about 20° south of the Taurus-Auriga SFR and about just as far to the west of the Orion SFR. The $12° \times 12°$ area is centred on $R.A.(2000.0) \approx 3^{\rm h}40^{\rm m}$ and $DEC(2000.0) \approx +3°$. The galactic latitude is between $-28°$ and $-45°$. The location of our study area and of the region investigated by Magazzu et al. (1997) is depicted in Fig 1. 65 of the 100 RASS sources in this area were identified as stellar X-ray emitters (cf. Paper III), including 37 RASS positions with K and M type stars. The remaining 28 stellar counterparts were identified with stars having spectral types earlier than K0. In two RASS error circles two stars were found which both could contribute to the observed X-ray flux. They are counted individually here (cf. Table 1). Of the 21 K stars 18 are K0-K6 stars, of which 6 are listed as Ke stars in Paper III, and 3 are dK7e-9e stars. Eighteen stars have spectral types later than K9 all of which are dMe stars.

The relevant data of all 39 stars are summarized in Table 1. Spectral types and X-ray fluxes were taken from Paper III. Visual magnitudes are either from the Hubble *Guide Star Catalogue* (GSC) (Lasker et al. 1988) or from Paper III for stars fainter than the limit of the GSC. The GSC magnitudes were colour transformed using the colour coefficients given by Russell et al. (1990) and the $B - V$ colours of main sequence stars for the corresponding spectral type. The ratio of X-ray to optical flux, $f_{\rm x}/f_V$, was calculated with the formula given by Stocke et al. (1991). We obtained low resolution spectra ($\Delta\lambda \approx 3-4$Å) for 37 stars with spectral types K0 and later at 35 RASS source positions. The two RASS sources not observed are RXJ0330.7+0305 and RXJ0336.7+0035. The first object has been observed by Magazzú et al. (1997) who found no Li I absorption in both components of a spectroscopic binary, RXJ0330.7+0306N (K5e) and RXJ0330.7+0306S (K7). The second object is the RS CVn star V 711 Tau.

3. Observations

The stars of the sample described above were observed during three observing campaigns, Sep. 20-23, 1996, Jan. 31 - Feb. 3, 1997, and Jan. 2-7, 1998, at the 2.2m telescope of the Calar Alto observatory, Spain. For the observations the focal reducer camera *CAFOS* was attached to the telescope. In 1996 and 1997 the instrument was equipped with a LORAL-80 2048×2048 pixel CCD chip with a pixel size of 15μm. In 1998 a SITe1d 2048×2048 pixel CCD chip with 24μm pixel size was used. Spectra of the wavelength range 4800-7450 Å were obtained (grism green-100) with a linear dispersion of 1.3 Å$\rm px^{-1}$ and 2.1 Å$\rm px^{-1}$ with the LORAL and the SITe1d CCD chip, respectively. With the Loral chip the measured spectral resolution achieved with a 0.7″ slit was 3.2 Å ($FWHM$). The SITe1d chip and a 1″ slit yielded a spectral resolution of 4.2Å. Wavelength calibration was obtained using He and HgRb lamps yielding an internal accuracy of 0.1 px, i.e. $\sigma_\lambda \approx 0.15$ to 0.2 Å, depending on the CCD chip used. For flat-field correction spectra of the dome illuminated with a halogen lamp were recorded. The data were reduced with the standard ESO-MIDAS imaging processing software package. The signal-to-noise ratio (S/N) of the spectra at 6700Å is typically 80 to 120. According to Cayrel (1988) this yields an approximate uncertainty of the equivalent widths of $\sigma_W \approx 1.5\sqrt{Fd}\ (S/N)^{-1} \approx 25-60$ mÅ, with F being the $FWHM$ (3.2 Å and 4.2 Å, respectively) and pixel size d (1.3 Å and 2.1 Å, respectively).

4. Results

The Hα eqivalent widths measured from our spectra clearly indicate that no classical T Tauri stars (CTTS) are present in our sample. The emission-line equivalent widths are all smaller than $|W| \approx 10$ Å, whereas CTTS typically show Hα emission lines stronger than this limit. The Hα emission line strengths are more indicative of WTTS. In nine cases we found even Hα absorption lines.

In order to identify Li I absorption features, the wavelength of the absorption line of Ca I λ6718Å and of possible absorption features around 6708Å were determined. If this difference deviated less than ±0.6 Å i.e. less than $3\sigma_\lambda$, from the difference of the laboratory wavelengths, the absorption feature at 6708 Å was considered to be at least partly due to Li I. We found nine cases with an absorption feature which we ascribed to Li I. All stars with Li I absorption have spectral types earlier than M1. The spectra normalized the estimated continuum are displayed in Fig. 2. They were shifted to the rest wavelength frame us-

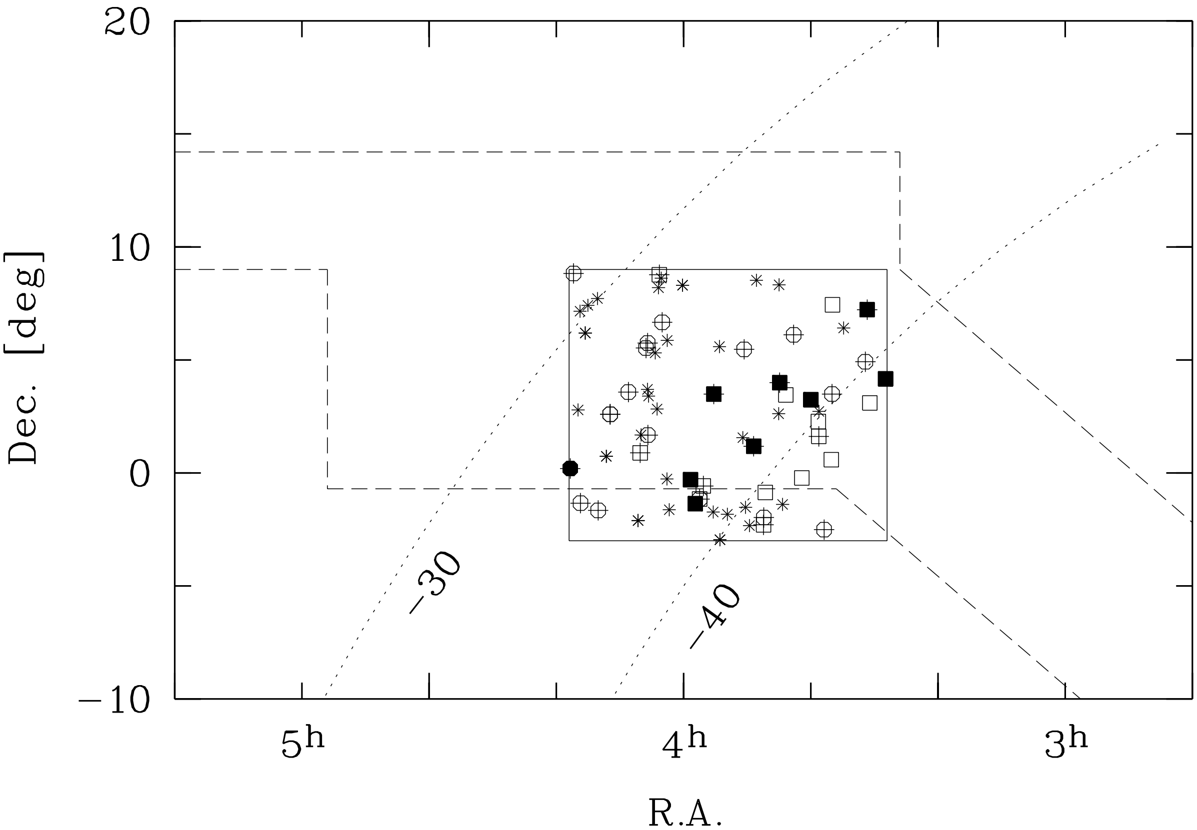

Fig. 1. The area studied by us is enclosed by the solid line rectangle. The larger area studied by Magazzù et al. (1997) is marked by the dashed line. M and K0-K9 stars are plotted as circles and squares, respectively. Filled symboles are plotted for stars with Li I absorption lines. Ke and Me stars are additionally marked with a cross. The $*$ symbols denote the locations of stellar X-ray emitters identified in the study area with spectral types earlier than K0. Galactic latitudes $b^{II} = -30°$ and $-40°$ are indicated by the dotted lines.

ing the emission line of Hα if present or Ca I$\lambda 6718$ otherwise. The wavelength region around Li Iλ6708Å of the same stars is plotted in an expanded scale in Fig. 4.

The equivalent widths of the absorption features at $\lambda 6708$ were measured by fitting Gaussian profiles and integrating the fitted profiles. The results are listed in Table 2. For those cases in which the wavelength shift was too large or in which no features stronger than $\sim$60 mÅ were present, which is the approximate detection limit, we list an equivalent width of $W_\lambda(\lambda 6708) \lesssim$ 60 mÅ.

Recently, Favata et al. (1997) compared high and low resolution spectra of late-type stars and found rather large uncertainties of the measured low-resolution Li I equivalent widths for several G-K stars. Likewise, Covino et al. (1997) compared high and low resolution Li I equivalent widths and derived ratios of $W(\mathrm{high}) - W(\mathrm{low})/W(\mathrm{high})$ of up to 2.5. This effect is to a large part due to the problem of separating the Li I line from other absorption lines near this wavelengths. Particularly for the G stars they can contribute a significant fraction of absorption to the absorption line profile observed with low resolution. Comparison of our spectra with higher resolution spectra of late-type stars in the Pleiades and in α Perseus obtained by García López et al. (1994) and in the Chamaeleon SFR displayed by Covino et al. show that the contribution of the lines of Fe I at $\lambda 6703, 6705, 6710,$ and 6713 Å is indeed important for early to mid K stars, decreasing in strength towards late K, and negligible for M stars. The latter confirms the conclusion of Favata et al. who found spectra of M stars with a resolution like that of our data adequate for the determination of lithium abundances.

In order to correct the observed equivalent widths of the detected absorption features at $\lambda 6708$ for the contribution of the Fe I lines we fitted multiple Gaussian line profiles to the observed spectra. An example is shown in Fig. 3. The observed line profile was fitted by the superposition of Gaussian profiles for Li I 6707.84Å and for Fe I lines with central wavelengths $\lambda = 6703, 6705, 6710, 6713$Å and fixed relative intensities. The Fe I line at 6707.44 Å was not taken into account because in K stars it is weak, $W_\lambda \lesssim 20$ mÅ (e.g. Pallavicini et al. 1987). The strength of the Fe I lines was adjusted relative to the Ca I 6717.69 Å line which was also included in the fit. The relative strengths were estimated from the spectra shown in Covino et al. (1997) and García López et al. (1994). With I_c being the central line depths measured in units of the continuum flux, ratios of $I_c(\mathrm{Fe\,I}\lambda 6703)/I_c(\mathrm{Ca\,I}\lambda 6718) \approx 0.3$ gave good fit results for the early to mid K stars. For the later spectral types the strength of Fe Iλ6703 was reduced to ≈ 0.15 to $0.2\times$ Ca I$\lambda 6718$ for late K and 0.05 to $0.1\times$ Ca I$\lambda 6718$ for M0. We finally estimated the

Table 1. Basic data of the sample of late-type X-ray emitters in study area I with spectral types K0 and later. Spectral type SP and X-ray flux $f_{\rm x}$ in the ROSAT band (0.1-2.4 keV) in 10^{-13} erg $\rm s^{-1}$ $\rm cm^{-2}$ were taken from Paper III; for the visual magnitude V see text. $\log(f_{\rm x}/f_V)$ was calculated from the relation given by Stocke et al. (1991).

Star	SP	V [mag]	$f_{\rm x}$	$\log(f_{\rm x}/f_V)$	Comments
RXJ0328.2+0409	K0	9.6	49.3	-2.09	SAO 111210
RXJ0330.7+0305	K1	11.0	4.9	-2.54	Magazzú et al. (1997): RXJ0330.7+0306N, K5e
RXJ0331.1+0713	K4(e)	10.9	16.4	-2.06	Paper III: K4e
RXJ0331.4+0455	M4e	13.5	5.0	-1.52	
RXJ0336.5+0726	K0	11.1	5.2	-2.47	
RXJ0336.6+0329	M5e	13.7	2.9	-1.66	
RXJ0336.7+0035	K1	5.7	837.9	-2.42	V 711 Tau, RS CVn
RXJ0337.9−0230	M1e		5.1		no photometry available, Paper III: M0
RXJ0338.7+0136	K5e	10.8	3.7	-2.75	
RXJ0338.8+0216	K4	8.8	13.8	-2.97	
RXJ0339.9+0314	K2	12.0	2.2	-2.48	
RXJ0341.4−0013	K3		9.6		no photometry available, close to HD22993 (A0 star)
RXJ0342.6+0606	M4e	16.8	6.2	-0.14	
RXJ0343.9+0327	K1	9.0	2.3	-3.67	
RXJ0344.8+0359	K1e	12.4	2.8	-2.23	cf. Neuhäuser et al. (1995)
RXJ0347.1−0052	K3	12.1	1.9	-2.50	
RXJ0347.3−0158	M3e	11.5	27.2	-1.61	
RXJ0347.4−0217	K7e		4.8		no photometry available
RXJ0348.9+0110	K3(e)	10.7	5.4	-2.62	
RXJ0350.4+0528	M3e	14.0	3.5	-1.50	
RXJ0355.2+0329	K3e	11.6	3.0	-2.53	
RXJ0356.8−0034	K4e	12.9	2.6	-2.06	
RXJ0357.4−0109A	M3e	11.5	26.1[1]	-1.16	GJ 157A
RXJ0357.4−0109B	K5	8.0	26.1[1]	-3.01	GJ 157B
RXJ0358.1−0121	K4e	11.8	2.4	-2.53	
RXJ0358.9−0017	K3e	11.4	1.9	-2.77	
RXJ0403.3+0639	M4e	15.6	2.7	-0.96	
RXJ0403.8+0846	K9e	12.6	4.4	-1.95	
RXJ0405.6+0140	M3e	15.6	3.1	-0.91	
RXJ0405.6+0544	M3e	12.8	9.6	-1.52	
RXJ0405.9+0531	M3e	15.5	2.7	-1.02	
RXJ0406.8+0053	K8e	12.6	2.9	-2.13	
RXJ0408.6+0334	M0e	11.9	6.0	-2.07	
RXJ0411.5+0235A	M2e		4.8[1]		no photometry available, SW star of close pair
RXJ0411.5+0235B	M2e		4.8[1]		no photometry available, NE star of close pair
RXJ0413.4−0139	M4e	13.9	5.6	-1.34	
RXJ0416.2−0120	M3e	16.0	2.3	-0.87	
RXJ0417.2+0849	M4e	14.2	7.4	-1.10	
RXJ0417.8+0011	M0e	12.0	5.7	-2.06	

[1] total X-ray flux of both components, A and B

total equivalent widths of the $\lambda 6708$ Å feature and the corrected Li I equivalent from the fitted Gaussian profiles. For the total equivalent width the Li I line and the Fe I lines at 6703, 6705, and 6710 Å were taken into account. The results are listed in Tab.2 in column $W_\lambda(\lambda 6708)$ and W_λ(Li I), respectively. The correction factors derived in this way are in very good agreement with the directly measured factors of Covino et al. (1997) for stars of similar spectral types. Test calculations with different Fe I line strengths and different continuum levels showed that equivalent widths smaller than ≈ 60 mÅ were not significant. In these cases we list an upper limit of 60 mÅ for the Li I equivalent width. The fit procedure was carried out for all stars with spectral types K0 to M0. For later types the inceasing strength of the molecular absorption bands does not allow a meaningful fit of the metal lines and was therefore not attempted. However, none of the objects later than M0 showed evidence for an absorption feature at $\lambda 6708$Å. For these stars we list an upper limit of 60 mÅ for both, $W_\lambda(\lambda 6708)$ and W_λ(Li I).

RXJ0344.8+0359 had already been found by Neuhäuser et al. (1995) to show Li I absorption. They measured an equivalent width of W_λ(Li I) = 310 mÅ from a spectrum with a resolution of about 1 Å. This star was observed by us in order to check

Table 2. Results of the spectroscopic observations. The equivalent widths of Hα are given in Å (negative sign meaning emission). The equivalent widths of the absorption feature at the wavelength of λ6708Å and the resulting equivalent width of Li Iλ6708Å corrected for the contribution of Fe I lines are given in mÅ. In 20 cases a significant λ6708Å feature was found of which 9 require a contribution of Li Iλ6708Å stronger than 60 mÅ. Lithium abundances $\log N$(Li) were obtained from the curve-of-growth by Pavlenko et al. (1995) and Pavlenko & Magazzù (1996). $T_{\rm eff}$ (K) values are from de Jager & Nieuwenhuijzen (1987).

Star	SP	$T_{\rm eff}$	W_λ(Hα)	W_λ(6708Å)	W_λ(Li I)	$\log N$(Li)	Comments
RXJ0328.2+0409	K0	5150	+1.9	340	180	+2.6	
RXJ0331.1+0713	K4e	4540	−0.9	540	410	+2.9	
RXJ0331.4+0455	M4e	3288	−4.2	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.6$	
RXJ0336.5+0726	K0	5150	+1.5	245	$\lesssim 60$	$\lesssim +1.9$	
RXJ0336.6+0329	M5e	3170	−9.7	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.8$	
RXJ0337.9−0230	M1e	3664	−2.7	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.1$	
RXJ0338.7+0136	K5e	4405	−1.2	200	$\lesssim 60$	$\lesssim +1.0$	
RXJ0338.8+0216	K4	4540	+0.8	150	$\lesssim 60$	$\lesssim +1.2$	
RXJ0339.9+0314	K2	4833	+1.8	290	140	+2.0	
RXJ0341.4−0013	K3	4690	+1.3	300	$\lesssim 60$	$\lesssim +1.4$	
RXJ0342.6+0606	M4e	3288	−1.0	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.6$	
RXJ0343.9+0327	K1	4989	+1.9	270	$\lesssim 60$	$\lesssim +1.8$	
RXJ0344.8+0359	K1e	4989	−0.3	480	250	+2.7	(1)
RXJ0347.1−0052	K3	4690	+1.4	260	$\lesssim 60$	$\lesssim +1.4$	
RXJ0347.3−0158	M3e	3404	−3.2	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0347.4−0217	K7e	4150	−2.7	100	$\lesssim 60$	$\lesssim 0.7$	
RXJ0348.9+0110	K3(e)	4690	+0.2	480	250	+2.3	(2)
RXJ0350.4+0528	M3e	3404	−5.2	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0355.2+0329	K3e	4690	−2.5	530	350	+2.7	
RXJ0356.8−0034	K4e	4540	−0.2	330	$\lesssim 115$:	$\lesssim +1.5$	(3)
RXJ0357.4−0109A	M3e	3404	−2.2	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0357.4−0109B	K5	4405	+0.8	135	$\lesssim 60$	$\lesssim +1.0$	
RXJ0358.1−0121	K4e	4540	−0.7	510	310	+2.4	
RXJ0358.9−0017	K3e	4690	−1.2	530	265	+2.4	
RXJ0403.3+0639	M4e	3288	−4.8	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.6$	
RXJ0403.8+0846	K9e	3941	−1.4	120	$\lesssim 60$	$\lesssim +0.4$	
RXJ0405.6+0140	M3e	3404	−5.9	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0405.6+0544	M3e	3404	−9.5	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0405.9+0531	M3e	3404	−5.6	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0406.8+0053	K8e	4046	−2.1	80	$\lesssim 60$	$\lesssim +0.5$	
RXJ0408.6+0334	M0e	3837	−2.1	$\lesssim 60$	$\lesssim 60$	$\lesssim +0.2$	
RXJ0411.5+0235A	M2e	3524	−3.0	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.3$	
RXJ0411.5+0235B	M2e	3524	−2.1	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.3$	
RXJ0413.4−0139	M4e	3288	−9.0	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.6$	
RXJ0416.2−0120	M3e	3404	−5.8	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.4$	
RXJ0417.2+0849	M4e	3524	−8.2	$\lesssim 60$	$\lesssim 60$	$\lesssim -0.6$	
RXJ0417.8+0011	M0e	3837	−2.4	445	380	+1.7	

(1) Neuhäuser et al. (1995): W_λ(Li I) = 310 mÅ
(2) Hα partly filled-in by emission
(3) wide absorption feature at λ6708Å, possibly with contribution of Li Iλ6708Å

consistency of our results with similar studies. The corrected equivalent width of W_λ(Li I) = 250 mÅ is in good agreement with that reported by Neuhäuser et al. (1995).

5. Discussion

5.1. Age of the lithium-rich stars

Our observations showed that 9 of the 35 observed stars of area I exhibit significant Li I absorption lines. These stars exhibit Hα emission lines weaker than $\sim$ 10Å. In three cases Hα appears even in absorption.

The equivalent widths of the Li I absorption lines determined as described above are plotted in Fig. 5 as function of $T_{\rm eff}$. Included in this figure are the upper envelopes of the measured Li I equivalent widths for the Pleiades (age $\sim 80-100$ Myr) and IC 2602 (age ~ 30 Myr). These curves were adopted from Neuhäuser et al. (1997). For the Pleiades the upper and lower lines refer to rapid and slow rotating stars, respectively.

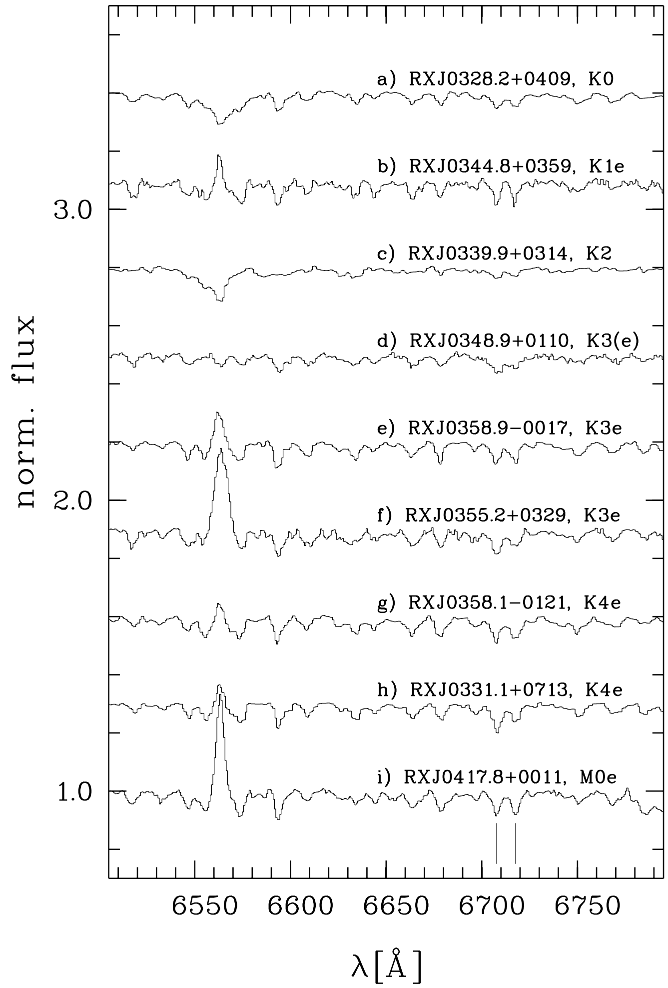

Fig. 2. Sections of the spectra between 6500 and 6800Å of the nine stars showing significant Li Iλ6708 absorption lines. The spectra have been rebinned to the rest wavelength frame and normalized to the continuum. The tick mark at the bottom of the figure indicate the wavelengths of Li Iλ6708 and Ca Iλ6718. The wavelength region around the Li I line is shown in more detail in Fig. 4.

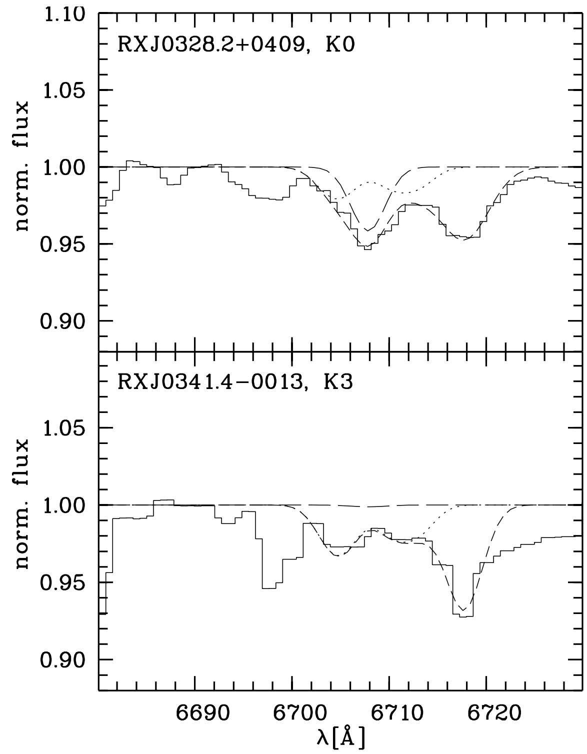

Fig. 3. Sections of the spectra of the lithium-rich K0 star RXJ0328.2+0409 and of a K3 star showing no lithium, RXJ0341.4−0013, around the line of Li Iλ6708. The observed spectra are plotted as solid lines. The different components of the multiple Gaussian fit discussed in the text are overplotted. The dotted line shows the contribution of the four Fe I lines to the total fit which is shown as the lower short-dashed line and which includes the lines of Li I, Fe I, and Ca I. The upper long-dashed line represents the resulting residual Li I absorption feature from which the corrected equivalent width of Li I was derived.

The equivalent widths of Li Iλ6708Å can be converted to lithium abundances by using e.g. the curves of growth published recently by Pavlenko et al. (1995) for $T_{\rm eff} < 3500$ K and Pavlenko & Magazzù (1996) for $T_{\rm eff} \geq 3500$ K. The $\log N$(Li) values given in Table 2 on a $\log N({\rm H}) = 12$ scale, were derived from the respective NLTE curves of growth for $\log g = 4.5$. For the conversion of spectral type to $T_{\rm eff}$ we applied the temperature scale of de Jager & Nieuwenhuijzen (1987) for luminosity class V using the corresponding values given in Table 6 of Martín et al. (1994). The estimated uncertainties of $T_{\rm eff}$ are on the order of $\Delta T_{\rm eff}$ ≈200 K. Taking this and an error of W_λ(Li I) of $\approx$ 60 mÅ into account the estimated uncertainty of $\log N$(Li) is on the order of 0.3 to 0.4 dex. We converted the Li equivalent widths for the stars in IC2602 observed by Randich et al. (1997) to Li abundances in the same way. They can therefore be directly compared with the results for area I.

With $\log N$(Li) $\approx 2-3$ the lithium abundances of the K stars in area I are close to the cosmic value of $\log N$(Li) = +3.2. The M type stars on the other hand definitely show much lower Li abundances. With cosmic lithium abundances these stars are expected to exhibit Li I absorption lines with equivalent widths of the order of 600 to 1200 mÅ for early to late M spectral type. Lines with this strength would be easily detectable in our low resolution spectra. We derived upper limits of $\log N$(Li) of $\lesssim 0$. The only M star exhibiting Li I absorption is the M0 star RXJ0417.8+0011. Its lithium abundance is ≈1.7. Taking the upper limits for $\log N$(Li) into account, it appears that the lithium depletion of the M stars is more than ≈3 dex, except for RXJ 0417.8+0011 for which the depletion is only 1.5 dex.

For the lithium-rich stars a trend for larger lithium equivalent widths with increasing strengths of Hα is indicated. However, no correlation of the lithium abundance with the strength of Hα seems to be present. Obviously, the correlation of the equivalent width of Hα with $T_{\rm eff}$ present in our data cancels the curve-of-growth dependence of the lithium abundance on $T_{\rm eff}$ and W_λ(Li I). Likewise, no correlation of N(Li I) with the X-ray flux appears to exist.

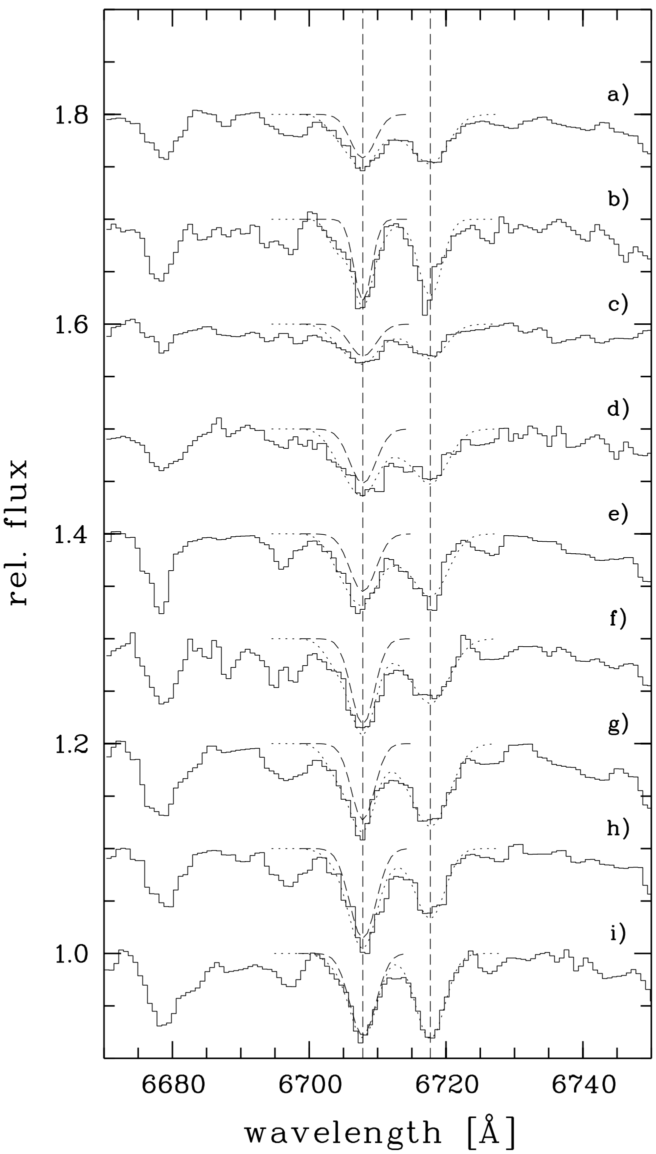

Fig. 4. Spectral region around Li Iλ6708Åof the stars a) to i) displayed in Fig. 2. The dashed vertical lines mark the positions of Li I$\lambda 6708$ and of Ca Iλ6718Å, respectively. Also shown are the total fit (dotted lines) and the fitted contributions of Li I$\lambda 6708$ Å (dashed lines).

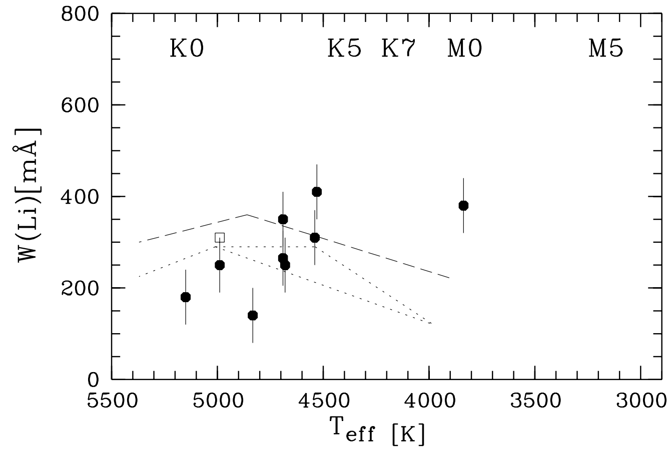

Fig. 5. Equivalent widths of Lithium versus $T_{\rm eff}$ for stars with sgnificant Li I absorption lines, i.e. $W({\rm Li\,I}) \gtrsim 60\,{\rm m}$Å. The open square is the Li I equivalent width of RXJ0344.8+0359 measured by Neuhäuser et al. (1995) from a higher resolution spectrum. The dotted lines represent the upper envelopes of the $T_{\rm eff} - \log N({\rm Li})$ relation for rapidly and slowly rotating stars, respectively, in the Pleiades. The dashed line correspondingly is the upper envelope for IC 2602.

In the upper panel of Fig. 6 the lithium abundances and the estimated upper limits, respectively, are plotted over the effective temperature. Also included are the lithium excess stars discovered by Neuhäuser et al. (1997) in the same sky area as studied by us. The trend of the $T_{\rm eff} - \log N({\rm Li})$ dependence suggests that significant depletion starts to occur around late K- early M, i.e. at temperatures $\lesssim 4000\,{\rm K}$. In the Pleiades and the α Perseus cluster significant Li depletion starts at mid K, i.e. at higher temperatures of $\sim\, 4500\,{\rm K}$ (García López et al. 1994) suggesting a younger age of the lithium rich stars in our sample than of the Pleiades and α Perseus stars. The lower panel of Fig. 6 shows that the Li abundances of IC 2602 and area I are comparable. The trend for the later-type K stars to exhibit lithium lines close to or stronger than the limits in the Pleiades and even in IC 2602 is also evident in Fig. 5, although for the early K stars an overlap with these clusters is present.

Model calculations show that in low-mass stars lithium is destroyed very fast. Recent results for evolutionary tracks of PMS stars by D'Antona & Mazzitelli (1994) demonstrated that at stellar masses around 0.2 to $0.8 M_{\odot}$, corresponding to spectral types of M5 to K0, respectively, lithium has disappeared at an age of $\approx\, 1 - 2\, 10^7$ yrs. Stars with higher masses, i.e. earlier spectral types than K0, on the other hand, preserve a large fraction of lithium even after 10^8 yrs when these stars have already reached the zero-age main sequence. In Fig. 6 we have included isochrones from D'Antona & Mazzitelli (1994) for Kurucz-Rogers & Iglesias opacities and MLT convection. Given the uncertainties of the location of the isochrones (cf. the discussion in D'Antona & Mazzitelli 1994) the absence of lithium in the later M-type stars and the presence of lithium in the K stars suggests an age of the lithium rich stars of $1 - 2\, 10^7$ yrs. The lithium-rich M0 star could be even younger than 10^7 yrs. Using Canuto & Mazzitelli (CM) convection models or Alexander opacties (cf. D'Antona & Mazzitelli 1994) would somewhat change the location of the isochrones, however, not affect our conclusions on the age of the stars. The comparison with IC 2602 (lower panel of Fig. 6) leads to a similar result, namley an age of less than or equal to $\sim\, 30\,{\rm Myr}$. In particular, the lithium-rich M star seems to be younger than IC 2602. In any case, the lithium-rich stars found in our sample appear to be significantly younger than 10^8 yrs, after which early K stars have reached the main sequence.

5.2. Comparison with galactic distribution models

An important question is whether we see an excess of young stars with respect to standard models for galactic stellar distribu-

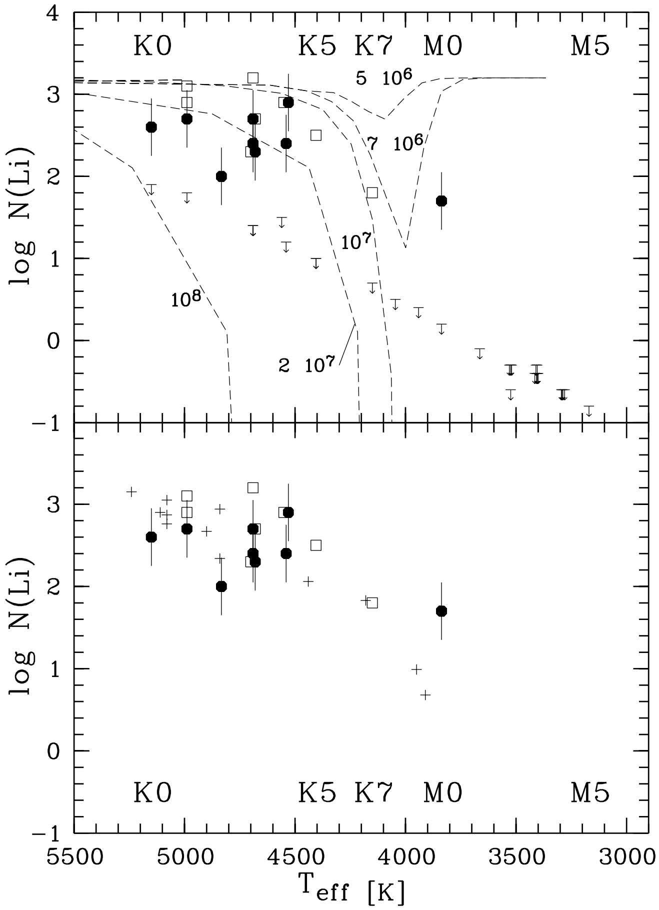

Fig. 6. Lithium abundances versus $T_{\rm eff}$. Filled circles and upper limits are from this work. Open squares are for stars from Neuhäuser et al. (1997) in the region around area I. The crosses in the lower panel represent the Li abundances for IC 2602. Some symbols were slightly shifted in temperature for reasons of graphic representation. The isochrones displayed in the upper panel are from D'Antona & Mazzitelli (1994) for $5\,10^6$, $7\,10^6$, 10^7, $2\,10^7$, and 10^8 yrs.

tion. Motch et al. (1997) compared the number counts of RASS sources in a low $|b|$ study area of the ROSAT galactic plane survey in the Cygnus region with a galactic distribution model by Guillout et al. (1996). The model takes three age groups into account, i.e. ages younger than 0.15 Gyr, 0.15 to 1 Gyr, and 1-10 Gyr. Motch et al. found a good agreement of the observed $\log N(>S) - \log S$ distribution with the model predictions for $|b| = 0°$. This shows that the model describes well the low $|b|$ stellar distribution.

We now consider the K-type stars and compare our high $|b|$ sample with the model by Guillout et al. for $b = 30°$ and $l = 180°$ which is the approximate location our study area I ($b^{II} = -28°$ to $-48°$, $l^{II} = 178°$ to $192°$). Our sample contains 20 RASS sources with counterparts of spectral types K0-K9 above the count-rate limit of 0.03 cts s^{-1}, excluding the RS CVn star V 711, but including the K-type component of RXJ0357.4−0109. With an area of 149 deg^2 the observed surface density of K stars thus is 0.134$\pm$0.030 deg^{-2}. Counting all age groups the model of Guillout et al. predicts 0.107 K stars per square degree for $b^{II} = 30°$. Taking a small decrease of $\approx 10\%$ of the surface density with b into account (cf. Table 4 in Guillout et al. 1996) we expect in area I ≈ 0.096 deg^{-2}.

In the youngest age bin, 0-0.15 Gyr, 0.060 stars per deg^2 are expected according to the model. We found 8 lithium rich K stars which belong to this age bin, and which comprise 40% of the total number of K stars. Their surface density thus is 0.054$\pm$0.019 deg^{-2}, and hence agrees with the expected number of 0.060 deg^{-2}. However, we must take into account that the lithium-rich K stars we identified are obviously significantly younger than 150 Myr, namely 10-30 Myr. If we adopt a mean age of 15 Myr for these stars as suggested by the isochrones in Fig. 6 and assume a constant star formation rate, we would expect only 10% of the predicted number of young stars in the 0-0.15 Gyr age bin with an age of 15 Myr, namely 0.006 deg^{-2}. This is equivalent to less than 1 K star in the entire sample of study area I in contrast to 8 K stars detected. With an age comparable to IC 2602 which is suggested as upper limit by Fig. 5 and the lower panel of Fig. 6, and assuming that all lithium-rich stars have about the same age, the expected number of K stars is about 2.

We thus find an excess of a factor of five to ten times more 15-30 Myr old K stars than predicted by the model of Guillout et al. (1996) for this spectral bin. The model predicts a probability of $p \approx 0.06$ (=0.006/0.096) for finding a star within the age bin 0-15 Myr. Hence, the probability $P(8)$ for detecting by chance 8 stars of this age bin in a sample of 20 is

$$P(8) = \binom{20}{8} p^8\,(1-p)^{12} = 1\,10^{-5}.$$

The observed number of 8 lithium-rich 15 Myr old K-type stars is therefore significantly different from the model prediction of less than 1 star in this age bin. Assuming an age of ~ 30 Myr, the predicted probability for finding a star in the age bin 0-30 Myr increases to $\sim\ 0.12$. This corresponds to $P(8) = 1.2\,10^{-3}$ which means that the observed number of 8 K stars also for this age is not in agreement with the model prediction.

Further evidence for the presence of an excess of young stars in area I comes from a comparison with study area VI (cf. Zickgraf et al. 1997) for which first preliminary results of a similar study as presented here for area I are available (the full results will be reported in a forthcoming paper). This area is located at a similar galactic latitude around $b^{II} \approx -40°$ and $l^{II} \approx 70°$. It contains a total of 12 X-ray active K stars in an area of 148 deg^2, i.e. 0.081$\pm$0.023 deg^{-2}. Although the observations in this area are not yet completed, it appears from preliminary results that the number of lithium-rich K stars is much smaller than in area I, suggesting an average age of $\gtrsim 100$ Myr. The total number of K stars observed thus probably represents at least the youngest age group of the model. Within the statistical uncertainties the observed surface density agrees well with the model predictions of Guillout et al. (1996) of 0.096 deg^{-2} (as above including a correction of 10% to account for the higher b). Hence, the model appears to predict the correct number of K stars for the considered galactic latitude of $|b| \approx 40°$ as well as for $|b| = 0°$(cf. Motch et al. 1997). This strengthens the conclusion of the presence of an excess of young stars in area I.

For the M0-M4 stars the model predicts also 0.094 deg^{-2} for all age groups taken together. The observed density is $0.11{\pm}0.03\,\mathrm{deg}^{-2}$ and hence close to the predicted value. However, if for the M stars the same age as for the K stars is assumed they would also display an excess in numbers. Unfortunately, our observations do not allow to draw a definite conclusion on the age of the M stars and hence on the proposed existence of an M star excess.

5.3. The lithium-rich stars and the Gould Belt

Interestingly, area I is located close to the Gould Belt, a kpc-size expanding structure of gas and young stars that incorporates most of the nearby star forming regions, including Taurus-Auriga, Lupus and Orion (cf. Pöppel 1997). Several independent studies yield age estimates of 50-60 Myr which should be an upper limit for the young objects associated with the Gould Belt. A connection of WTTS with the Gould Belt has been recently found by Wichmann et al. (1997) for a region in Lupus and by Neuhäuser et al. (1997) for a region in Taurus-Auriga nearby to the region studied here. However, in both studies the selection of the X-ray sources was biased towards a PMS nature, because only X-ray sources with a high PMS probability (cf. e.g. Sterzik et al. 1995) were chosen for a detailed study. In this paper the selection of the X-ray sources was totally unbiased with respect to a PMS nature, since the identification is based on a complete flux-limited sample.

Guillout et al. (1998a) recently studied the large scale distribution of X-ray active stars and found a density enhancement which closely follows the Gould Belt. At galactic longitude $l = 185°$ the mid plane of the density enhancement is at $b \approx -25\,°$ and thus very close to area I. The possible connection of the lithium-rich stars in area I with the Gould Belt gives an estimate of 50-60 Myr for the age of the WTTS, i.e. the age of the Gould Belt. However, we would like to note that this would be an upper limit only; the WTTS could be considerably younger, since - as e.g. the very young star forming regions show - the Gould Belt did continuously form stars over the last 50-60 Myr. Whether the lithium-rich stars in area I are really members of the Gould Belt is, however, uncertain. In the direction to Taurus the Gould Belt is at distance of ~ 600 pc whereas the Taurus-Auriga star forming region is only at a distance of ~ 140 pc and therefore is not part of the Gould Belt. Note, that this is different in the case of the Lupus SFR which is at the distance of the Gould Belt.

Guillout et al. (1998b) suggest an alternative model for the Gould Belt, which they call the Gould Disk. In the direction of Taurus, the precise distance towards the inner disk rim is only loosely constraint from their data, but probably not much closer than 200-300 pc. They assume the young population found in the vicinity of Taurus-Auriga as foreground population which is not directly part of the Gould Disk. In order to obtain an estimate for the distance of the lithium-rich stars in our study area we used isochrones of D'Antona & Mazzitelli (1994) for determining the luminosity of the stars assuming ages of 10 and 30 Myr. For the M0 star we adopted a younger age of 5 and 10 Myr, respectively, in accordance with the observed lithium abundance. With bolometric corrections taken from Schmidt-Kaler (1982) for luminosity class V, we then calculated M_V, and using the visual magnitudes given in Table 1, obtained finally a distance range for the two adopted ages. The results are summarized in Table 3. The distances are distributed between about 60 pc and 300 pc. It therefore seems that the majority of the stars are at distances at least roughly in agreement with the distance of Taurus (~ 140 pc). Their minimum or maximum distances are within $\approx \pm 40$ pc around $d = 140$ pc. According to Neuhäuser et al. (1995) the star RXJ0344.8+0359 shows a radial velocity consistent with Taurus membership. Our estimate suggests that it is behind Taurus at a distance of $d \gtrsim 200$ pc, and thus may be located near the suggested inner rim of the Gould Disk. The M0 star RXJ0417.8+0011 probably is in the foreground of Taurus-Auriga. Note, that most of the M stars in our sample would be at about the distance of Taurus if an age of 5-10 Myr is assumed. Hence, most of the lithium-rich stars appear not be typical members of the large-scale structures formed by the Gould Belt or the Gould disk, but rather seem to represent a foreground population of very young, $\lesssim 30$ Myr old, stars which is possibly closely related to the Taurus-Auriga star forming region. However, keeping in mind the large uncertainties of the distances, a relation to the suggested Gould disk cannot be ruled out.

Table 3. Photometric distances of the lithium-rich stars estimated from D'Antona & Mazzitelli (1994) isochrones. The ranges for luminosities, absolute visual magnitudes, and distances are given for ages of 10 and 30 Myr, except for RXJ0417.8+0011 (spectral type M0), for which a younger age range of 5 to 10 Myr was assumed.

Star	$L[L_\odot]$	M_V	d[pc]
RXJ0328.2+0409	0.60-1.41	4.70-5.62	63-95
RXJ0331.1+0713	0.26-0.59	5.89-6.77	67-100
RXJ0339.9+0314	0.40-0.90	5.00-6.18	146-251
RXJ0344.8+0359	0.48-1.10	5.03-5.93	196-298
RXJ0348.9+0110	0.32-0.71	5.63-6.49	70-103
RXJ0355.2+0329	0.32-0.71	5.63-6.49	105-156
RXJ0358.1−0121	0.26-0.59	5.89-6.77	101-152
RXJ0358.9−0017	0.32-0.71	5.63-6.49	96-143
RXJ0417.8+0011	0.10-0.14	8.21-8.64	47-57

6. Conclusions

Our spectroscopic observation of significant Li I absorption lines in 9 of 35 K and M stars reveals the existence of very young, most likely PMS, stellar X-ray emitters in our RASS sample in study area I. This region is located $\sim 20°$ south of the Taurus-Auriga SFR. All but one of these stars have K spectral types. Eight out of the 20 K-type stars (not counting the RS Vn star V711 Tau) and one of the 18 M stars in the sample are lithium-rich. The measured strengths of the Hα emission lines of the lithium-rich stars suggest that they are WTTS. The estimated age of $\lesssim 3\,10^7$ yrs suggests that most of these stars belong to the older group of the WTTS, the post-T Tauri stars.

These stars, which were defined by Herbig (1978) represent the evolutionary stage between the CTTS as well as part of the WTTS, and the main sequence.

Contrary to Briceño et al. (1997) and Palla & Galli (1997) we find that the WTTS constitute a significant fraction of the young stellar population. Our results provide further evidence that the majority of the Li-rich stars found in the RASS are indeed younger than the foreground population of 100 Myr ZAMS stars predicted by the Briceño et al. (1997) model. A direct comparison with the results of Neuhäuser et al. (1997) and Magazzu et al. (1997) is difficult. Based on X-ray properties of known WTTS they pre-selected WTTS candidates from a sample of more than 1000 RASS sources as faint as the detection limit of the RASS. Our sample is limited to sources brighter than the completeness limit of 0.03 cts s^{-1} as discussed in Paper II (cf. also Guillout et al. 1998a) but otherwise complete. In the selected sample of 92 off-cloud sources Neuhäuser et al. (1997) classified $\sim 25\%$ as PMS stars younger than ~ 30Myr. In our complete count-rate limited sample we found an even larger fraction of PMS stars, $\approx 40\%$. This suggests that the number of wide-spread PMS stars detected in previous studies has even been underestimated rather than overestimated, and further strengthens the conclusion that they represent a significant fraction of the young X-ray active stellar component of the RASS.

The comparison of the surface densities of K stars with predictions of galactic distribution models and with another study area at the same galactic latitude strongly suggests that in area I an excess of young stars is present. It is not clear whether the lithium-rich stars are members of Taurus-Auriga, although there is evidence for this. High precision radial velocity measurements which are presently available only for RXJ0344.8+0359 would help to investigate this question for the new lithium-rich stars.

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