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Optical high-resolution spectroscopy of ROSAT detected late-type stars south of the Taurus molecular clouds*

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Abstract. We study 111 late-type stars found with optical follow-up observations of ROSAT All-Sky Survey sources south of the Taurus molecular clouds. Some 30 of them have been claimed to be weak-line T Tauri stars, low-mass pre-main sequence (PMS) stars, based mainly on the presence of strong lithium 6708Å absorption in intermediate-resolution ($\sim$ 1Å) spectra. We obtained single-order echelle spectra at blue wavelengths for 106 of these stars, in order to measure their radial and rotational velocities, and investigate their angular momentum evolution and kinematic membership to the Taurus clouds. In addition, we obtained echelle spectra with high ($\sim$ 0.25Å) resolution for seven stars to measure precisely the lithium equivalent width W_λ(Li). We find that $\sim$ 1Å resolution is sufficient in order not to overestimate W_λ(Li), e.g. due to blending. Of our 111 stars, 19 are located on the λ Ori cloud, nine of which are K-type stars with lithium in excess of the zero-age-main-sequence (ZAMS) level, i.e. are PMS stars. At least 40 of the remaining 92 off-cloud stars display detectable lithium, 24 of which are lithium-excess stars, i.e. show lithium at least as strong as IC 2602 stars with the same spectral types. Of those 24 stars, nine (25% of the off-cloud stars with detectable lithium) are PMS stars isolated from cloud material; all have spectral type K, and three of them are spectroscopic binaries. 15 off-cloud stars have spectral type G and lithium comparable to IC 2602 stars, i.e. may have already arrived on the ZAMS just like G-type IC 2602 stars. However, all these 24 off-cloud lithium-excess stars are probably not older than IC 2602 ($\sim 3 \cdot 10^7$ yrs). We discuss possible sites and modes of origin of the isolated PMS stars south of Taurus.

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

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* Table 1 is also available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html, Table 2 only at CDS.

1. Introduction

Historically, low-mass pre-main sequence (PMS) stars, known as T Tauri stars (TTS), have been found closely associated with molecular clouds, where they have formed. Almost all TTS discovered prior to X-ray observations display strong $H\alpha$ and infrared (IR) excess emission. Objects with this signature are known as classical TTS (cTTS). They evolve along the Hayashi track, are often surrounded by circumstellar disks, and have ages ranging from $\sim 10^5$ to several times 10^6 yrs. Herbig (1978) suggested that if star formation has been on-going for at least as long as the sound-crossing time of the cloud complex, there should be large numbers of low-mass stars having evolved from cTTS to older, less active stars called 'post-TTS', approaching the zero-age-main-sequence (ZAMS).

With the launch of the *Einstein Observatory* (EO) X-ray mission, TTS with strong coronal X-ray emission but weak $H\alpha$ emission were discovered (e.g., Feigelson & Kriss 1981, Montmerle et al. 1983, Walter et al. 1988), which became known as weak-line TTS (wTTS). They show W_λ $(H\alpha)$ $\leq$ 10Å and no near-IR excess emission. The conventional dividing line between cTTS and wTTS at W_λ $(H\alpha)$ = 10Å is somewhat arbitrary, since the $H\alpha$ flux depends on the spectral type and can be highly variable. Furthermore, using only the equivalent width of $H\alpha$ is not necessarily the best way to discriminate between TTS with and without active disks. It is generally assumed that accretion of material in wTTS is coming or has come to a halt, resulting in weak $H\alpha$ emission. Hence, according to the evolutionary picture of low-mass star formation (e.g. Shu et al. 1987), wTTS should be older than cTTS. However, since wTTS populate all parts of the low-mass PMS tracks (both the convective Hayashi tracks and the radiative tracks), the wTTS population is not identical with the post-TTS population. There are no cTTS on radiative tracks, and it is not clear whether each and every wTTS has been born as a cTTS.

A late-type star is often identified as being truly young from the presence of strong lithium 6708Å absorption, although this may not be sufficient. In order for it to be PMS, a star must show more lithium than ZAMS stars of the same spectral type.

While cTTS cluster on dark clouds, wTTS are distributed over the complete extensions of a star forming region (SFR). Most TTS in a SFR typically share the same radial velocity and proper motion, so that membership of a TTS to a particular T association can be investigated using kinematic data. The Taurus SFR is one of the nearest ($\sim$ 140 pc, Elias 1978, Kenyon et al. 1994a) and best-studied regions with on-going low-mass star formation. TTS are occasionally also found to be isolated from molecular clouds, as in the case of TW Hya and HD 98800 (Rucinski & Krautter 1983, Gregorio-Hetem et al. 1992).

Prior to the ROSAT mission, $\sim$ 60 wTTS were known in Taurus, half of which were discovered by EO (c.f. Herbig & Bell 1988 and Neuhäuser et al. 1995b – henceforth N95b – for lists of TTS known prior to ROSAT). From EO observations, Walter et al. (1988) concluded that there should be as many as $\sim 10^3$ wTTS in the Taurus clouds.

Among the advantages of the ROSAT All-Sky Survey (RASS) is the complete sky coverage with a flux limit sufficient to detect most TTS in nearby SFRs (e.g. N95b). See Trümper (1983) for details on the X-ray satellite ROSAT and its instruments. A total of $\sim$ 70 lithium-rich stars – claimed to be wTTS - have been discovered among RASS sources in the central parts of the Taurus T association (Wichmann et al. 1996, henceforth W96). A few additional TTS were discovered with optical follow-up observations of sources found in deep ROSAT pointed observations in Taurus (Strom & Strom 1994, Carkner et al. 1996, and W96). Most X-ray discovered TTS are wTTS located on or very close to molecular clouds.

It is possible to pre-select TTS candidates by using X-ray hardness ratios (Neuhäuser et al. 1995a), and for sources with a nearby optical counterpart in the HST Guide Star Catalog (GSC), the pre-selection can be improved by incorporating the X-ray to optical flux ratios as well as the V magnitude (Sterzik et al. 1995). This procedure has been used in the survey for TTS south of Taurus by Neuhäuser et al. (1995c, henceforth N95c) and Magazzù et al. (1997, henceforth M97).

The latter study presents lithium results for over 100 ROSAT sources, and reports finding several dozen new wTTS in the area. Our main goal here is to present follow-up high-resolution spectroscopic observations of essentially the same sample, to investigate the nature of these stars in more detail, as well as their age and kinematics. We present the first large body of radial and rotational velocities for a sample of ROSAT discovered PMS stars.

Our paper is organized as follows: First, we define our sample (Sect. 2); then, we present radial and rotational velocities (Sect. 3) and compare W_λ(Li) obtained with our new high-resolution CASPEC spectra with previously published spectra taken at lower resolution. Next, we compare W_λ(Li) of our stars with those of young ZAMS stars in order to estimate their approximate ages relative to these clusters (Sect. 4); the radial and rotational velocities of our new stars are compared with bona-fide TTS in central Taurus. We discuss binarity in our sample in Sect. 5. Finally, we discuss the three-dimensional space motion as well as possible modes and sites of origin of these objects (Sect. 6), and then summarize our results (Sect. 7).

2. Definition of our sample

Our study area covers several hundred square degrees south of the Taurus clouds (c.f. Fig. 3 in N95c and Fig. 1 in M97), and our sample is defined as follows:

- N95c and M97 performed optical follow-up observations of 115 RASS sources, almost all of them selected as TTS candidates following Sterzik et al. (1995). They also included a few rejected sources as a small control sample (c.f. Fig. 2 in M97).
- N95c and M97 obtained broad-band low and/or medium-resolution spectra for 131 potential optical counterparts to these 115 RASS sources, also with spatially uniform distribution, in order to identify new stars with TTS-like spectra among them. Stars with a detected lithium 6708Å absorption line, i.e. with W_λ(Li) at least as large as the lower detection limit in their medium-resolution spectra, namely W_λ(Li) $\sim$ 0.1Å, are referred to as *lithium-rich* throughout this paper.
- Preliminary results were presented by N95c, who reported 15 stars with weak $H\alpha$ emission and lithium absorption as new wTTS.
- M97 completed this survey, and identified 30 new PMS stars (called 'certain PMS' in M97) with strong lithium, and 23 additional stars with somewhat weaker lithium ('PMS?' in M97); the M97 sample includes the N95c sample. While N95c identified wTTS solely on the basis of whether or not lithium is detected, M97 accepted as certain PMS stars only those stars that show lithium stronger than Pleiads of the same spectral type.
- To the 53 lithium-rich stars found by M97 (30 'certain PMS' and 23 'PMS?' stars), we add two 'wTTS' found by Alcalá et al. 1996 (henceforth A96) in our study area. We also add one star (RXJ0237.3-0527, c.f. remark 5 in Table 1), in which N95c found lithium, but which was not classified as 'PMS' (nor as 'PMS?') by M97. This gives a total of 56 lithium-rich stars south of Taurus (Table 1). Of these stars, 32 have previously been claimed to be PMS stars (N95c, A96, M97).
- For 51 out of these 56 lithium-rich stars we performed echelle spectroscopy (in the blue wavelength range) to measure radial and rotational velocities. Additionally, we performed single-order echelle spectroscopy for 55 stars where M97 did not detect lithium (Table 2).

3. High-resolution spectroscopy

3.1. Single-order echelle spectra in the blue

For 104 of the 131 optical counterparts studied in M97 (plus two wTTS found by A96 in our study area), we obtained high-resolution echelle spectra at blue wavelengths with the purpose of determining radial velocities (RV), and also projected rotational velocities $v \cdot \sin i$.

We used nearly identical echelle spectrographs on the 1.5 m Wyeth reflector at the Oak Ridge Observatory (Massachusetts, USA), the 1.5 m reflector at the Whipple Observatory (Mt. Hopkins, Arizona, USA), and the Multiple Mirror Telescope (MMT). The instrument configuration and reduction techniques are essentially the same as described by N95c: our single-order echelle spectra cover a 45Å region centered at 5187Å, and the resolving power is $\lambda/\Delta\lambda \simeq 3 \cdot 10^4$. Radial velocities are derived by cross-correlation using the XCSAO task (Kurtz et al. 1992) under IRAF[1], with templates selected from an extensive grid of synthetic spectra based on model atmospheres by Kurucz (1992a, 1992b). The typical uncertainty in RV for sharp-lined stars in a single observation is 0.5 $km\ s^{-1}$.

In order to guard against the presence of spectroscopic binaries (SBs), which could significantly affect the measured velocity (especially if the orbital period is short) we obtained at least two observations for all but five of our objects, and continued to monitor the short-period systems more frequently.

In addition to the radial velocities, we interpolated between our templates seeking the best match with the observed spectra, to derive $v \cdot \sin i$ and also effective temperatures T_{eff} from our multiple observations. Estimated errors are 100 to 150 K for the temperatures, and 3 $km\ s^{-1}$ for $v \cdot \sin i \ \leq\ 80\ km\ s^{-1}$, and somewhat larger errors of 5 to 10 $km\ s^{-1}$ for more rapidly rotating objects. For the extremely rapid rotators ($v \cdot \sin i \geq 140\ km\ s^{-1}$) we cannot derive T_{eff} because of the low contrast of the lines; similarly, for the double-lined binaries, the presence of the secondary complicates the analysis, and we have therefore not estimated T_{eff} or $v \cdot \sin i$. Results are listed in Tables 1 and 2, described below.

3.2. CASPEC echelle spectra in the red

Stars in young clusters such as IC 2602 (age $\sim 3 \cdot 10^7$ yrs) and the Pleiades ($\sim 10^8$ yrs) show characteristics rather similar to wTTS as far as our pre-selection criteria are concerned (X-ray hardness ratios, X-ray to optical flux ratios, and optical magnitudes), and are thus not easily distinguished. Active ZAMS stars are also known to exhibit weak $H\alpha$ emission or absorption (as do the wTTS) and lithium 6708 Å absorption, our primary identification criteria. In addition, the equivalent width of the lithium 6708Å absorption line can be overestimated if the spectral resolution is insufficient to distinguish nearby lines (Basri et al. 1991). The measurement of W_λ(Li) can also be inaccurate due to veiling, although this is not usually a problem in X-ray discovered stars, which typically show neither evidence of accretion nor veiling.

For most of the stars in our sample, however, spectra have already been obtained at a relatively high resolution of 0.7 to 1.5Å (M97), which is sufficient to distinguish the lithium line from other nearby lines. Hence, we do not expect the measures of W_λ(Li) to be significantly overestimated in our sample. Nevertheless, we obtained new spectra with much higher resolution still ($\sim$ 0.25Å), to check this hypothesis and to establish which resolution is sufficient for a reliable determination.

Our high-resolution lithium observations covered the wavelength range from $\lambda \simeq$ 5700 Å to $\lambda \simeq$ 7950 Å and were carried out at the European Southern Observatory (ESO) in July 1996, using the 3.6 m telescope in conjunction with the Cassegrain Echelle Spectrograph (CASPEC, c.f. Pasquini 1993 and references therein). The 31.6 lines mm^{-1} echelle grating was used together with the red cross-disperser (158 lines mm^{-1}) and the long camera (focal length = 560 mm, f/3). The above combination, together with ESO CCD #37 (TK1024AB, with 1124 $\times$ 1024 pixels^2 of 24 μ^2) and a slit aperture of 200 μm ($\sim 1.4''$ on the sky), resulted in a nominal resolving power of $R = 2.7 \cdot 10^4$. The slit height was set to $5''$, giving enough inter-order spacing to allow the subtraction of scattered light. The quality of our spectra varies from star to star, with typical S/N ratios from 40 to 80.

Data reduction was performed using the echelle reduction package available within the Munich Image Data Analysis System (MIDAS, version Nov95), with the addition of some specially developed procedures making use of the algorithms prescribed by Verschueren & Hensberge (1990) for background subtraction and optimal order extraction. The reduction included tracing of the echelle orders, fitting and subtraction of the background from all frames, fitting of the blaze function and normalization to the continuum, extraction of echelle orders, wavelength calibration using thorium calibration lamp exposures taken at the same telescope position of each individual science frame, and merging of the orders.

We observed all stars south of δ_{2000} = 0° for which either N95c or M97 found lithium, with the exception of the faintest one, RXJ0255.8-0750N ($V \sim$ 15.5). We also observed RXJ0251.8-0203, classified as dKe star. The resulting wavelength-calibrated CASPEC spectra for stars where we have detected lithium are shown in Fig. 1.

Two stars observed with CASPEC are apparently SB2. In the case of RXJ0255.8-0750S the two sets of lines are easily separable, but no strong lithium line(s) can be identified. M97 did not resolve the pair, and assigned a spectral type K7-M0 to the combined spectrum. Our echelle spectra confirm the binarity already noted in M97.

3.3. Results and comparison with other observations

In Table 1 we list all stars in our sample for which lithium was found either by M97 or in our CASPEC spectra, as well as two stars identified as wTTS by A96. We list T_{eff}, $v \cdot \sin i$, and RV from our single-order echelle spectra as well as spectral types from M97 (or A96) for comparison. Objects in this table are separated into several groups, which are described below. We also list the lithium abundance log N(Li), which we computed from the M97 medium-resolution or our high-resolution W_λ(Li) data and T_{eff} as given in Table 1, using NLTE curves of growth

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Table 1. High-resolution data for lithium-rich ROSAT source counterparts. Listed are all stars for which lithium was found either by M97 or in our CASPEC spectra, as well as two stars identified as wTTS by A96, also located in our study area. Listed are the designation (as in M97 and A96), number of single-order echelle spectra taken, effective temperatures, projected rotational velocities, mean heliocentric radial velocities with errors (see text), radial velocities in the local standard of rest, and remarks on variability in RV as found in our high-resolution spectra (colons indicate less reliable data). For comparison, we also list the results on spectral types of the stars (with 'e' for $H\alpha$ emission) as found by M97 (or A96) with low- and medium-resolution spectroscopy. Objects already reported as wTTS by N95c are marked by an additional '(N)'. In the last two columns, we list the (NLTE) lithium abundance (given on a scale where log $N(H) = 12$) and the lithium excess above the relevant Pleiades upper envelope. Lithium data given with a $*$ are from high resolution CASPEC red spectra; upper limits indicate stars where the M97 spectra suffer from either low S/N or low resolution.

Table 1: High-resolution data for lithium-rich ROSAT source counterparts

Designation	no. obs.	T_{eff} $[K]$	$v \cdot \sin i$ $[km\ s^{-1}]$	RV_{hc} $[km\ s^{-1}]$	RV_{lsr} $[km\ s^{-1}]$	remark	results from M97	log N(Li)	δW_λ [Å]
K-type stars with lithium excess south of Taurus: $\leq 3 \cdot 10^7$ yrs old PMS stars									
RXJ0324.4+0231	2	4550	12	8.1 ± 0.2	-4.4		K5e (N)	2.5	0.12
RXJ0333.1+1036	3	4750	20	14.6 ± 0.9	3.3		K3e (N)	2.7	0.08
RXJ0344.8+0359	3	4900	27	16.0 ± 0.3	2.9		K3e (N)	2.9	0.06
RXJ0351.4+0953W	3	5000	7	14.0 ± 0.4	1.8		K1e	2.9	0.04
RXJ0407.2+0113S	2	5000	13	10.6 ± 0.1	-4.0		K3e	3.1	0.12
RXJ0434.3+0226	3	4950	7	24.8 ± 3.2	9.6	SB1	K4e	2.9	0.07
RXJ0444.7+0814	2	4600	17	15.0 ± 1.4	0.6		K3e (N)	2.3	0.04
RXJ0445.5+1207	2	4200	83	15.8 ± 1.0	2.3		K7	1.8	0.15
RXJ0450.0+0151	3	5000	67	20.7 ± 1.5	4.9		K3e	3.2	0.05
K-type stars located on λ Ori with lithium excess: $\leq 3 \cdot 10^7$ yrs old PMS stars									
RXJ0511.2+1031	3	4400	5	15.6 ± 0.2	1.1		K7e	3.6	0.50
RXJ0512.0+1020	13	5100	57	15.8 ± 0.5	1.3		K2e	3.4	0.11
RXJ0516.3+1148	2	4400	18	20.0 ± 0.6	5.7		K4e (N)	3.1	0.29
RXJ0518.6+0959	3	5200	37	21.6 ± 1.9	6.9		K2 (1)	3.6	0.14
RXJ0528.5+1219	2	5050	41	25.0 ± 1.9	10.7		K3e	3.1	0.05
RXJ0528.9+1046	8			28 ± 1	13	SB2	K3e	3.9	0.10
RXJ0529.3+1210	3	4300	18	-2.6 ± 5.8	-16.9	SB1	K7-M0e	2.4	0.21
RXJ0530.9+1015	4	4850	132	17.8 ± 3.7	3.0		K3 (1)	3.7	0.22
RXJ0531.8+1218	3	4700	24	21.8 ± 1.0	7.4		K4e (N)	3.1	0.11
F8- to G9-type stars with lithium excess: $\sim 3 \cdot 10^7$ yrs old ZAMS stars									
RXJ0312.8-0414NW	4	6150	33	7.8 ± 0.1	-5.2	(2)	G0	3.4 *	0.04 *
RXJ0312.8-0414SE	3	5400	11	8.7 ± 0.2	-4.3		G8	3.2 *	0.02 *
RXJ0338.3+1020	3	5500	16	13.2 ± 0.8	1.6		G9	3.2	0.01
RXJ0347.9+0616	4	6250	22	16.9 ± 0.5	4.1		G2	3.4	0.03
RXJ0348.5+0832	6	5600	127	22.4 ± 2.3	10.1		G7e	3.3	0.03
RXJ0354.1+0528	0						G8	3.2	0.01
RXJ0354.3+0535	4	6250	46	10.9 ± 0.5	-2.3		G1 (N)	3.4	0.03
RXJ0357.3+1258	3	6250	71	12.7 ± 1.1	0.9		G0	3.6	0.10
RXJ0407.2+0113N	5	5650	29	10.2 ± 1.2	-4.3	SB1 ?	G4	3.0	0.02
RXJ0422.9+0141	2	6700	13	-66.8 ± 1.1	-81.8	(3)	F8	3.2	0.05
RXJ0427.4+1039	2	6250	38	9.5 ± 0.5	-3.8		G0e (4)	3.5	0.09
RXJ0427.5+0616	7	5700	26	19.7 ± 0.6	5.5		G4	3.2	0.06
BD+08 742	6	5200	12	18.4 ± 0.5	4.3		G7	2.7	0.03
RXJ0445.2+0729	2	6300	83	19.0 ± 0.8	4.4		G0	3.6	0.10
RXJ0511.9+1112	3	5600	13	22.4 ± 0.4	8.1		G4	3.2	0.06
Lithium upper limits due to low S/N or low-resolution spectra									
BD+07 582B	2	5200	14	14.1 ± 0.2	1.2		K2e	?	$\leq$ 0.14
RXJ0333.0+0354	3	4250	9	16.4 ± 0.4	3.8		K7-M0e (N)	?	$\leq$ 0.05
RXJ0347.2+0933SW	0						K4e	?	$\leq$ 0.11
RXJ0255.8-0750N	0						M5e	?	?
RXJ0347.2+0933NE	2	4650	18	12.2 ± 0.2	0.1		G9	?	-
BD+11 533	4	6000	21	10.3 ± 0.2	-1.4		G2	?	-
BD+07 582	2	5300	15	14.6 ± 0.1	1.8		K0	?	-
Stars with lithium, but without lithium excess: $\sim 10^8$ yrs old ZAMS stars									
RXJ0219.7-1026	7	5000	30	-0.9 ± 13.7	-11.8	SB1	K4e (N)	2.1 *	- *
HD 15526	1	5500	17	13.2 ± 0.9	1.5		G8	2.9 *	- *
RXJ0237.3-0527	3	4500	11	27.7 ± 0.3	16.5		K5e (5) (N)	1.4 *	- *
RXJ0329.1+0118	5	6100	62	11.8 ± 0.9	-1.1		G0 (N)	3.0	-
RXJ0339.6+0624	4	5000	10:	46.2 ± 3.1	33.8	SB1 or 2	G9e (N)	2.1	-
RXJ0343.6+1039	28			-43.3 ± 0.1	-55.0	SB2 orbit	K0	2.3	-
RXJ0351.8+0413	0						G6 (6)	2.1	-
RXJ0358.1+0932	2	4750	28	14.9 ± 0.1	2.3		K3e (N)	2.2	-
RXJ0404.4+0519	2	5250	36	22.0 ± 0.9	8.3		K0e	2.9	-
HD 286556	3	6100	6	-23.0 ± 0.8	-35.5	SB1 ?	F9	2.8	-
RXJ0410.6+0608	3	4750	6	-0.7 ± 12.3	-14.5	SB1	K4e	1.8	-
RXJ0423.5+0955	3	4750	81	13.5 ± 1.9	0.1		K4e	2.5	-
HD 286753	2	6200	63	21.2 ± 2.2	8.2		F9	2.7	-
RXJ0426.4+0957E	0						G2	3.1	-
RXJ0442.9+0400	7	5250	10	19.3 ± 2.2	4.1	SB1	K0	2.8	-
RXJ0444.4+0725	3	4750	20	-5.0 ± 20.2	-19.5	SB1	K5e	1.8	-

Remarks: (1) Spectral type given by A96, who identified these stars as wTTS. (2) SB as found in our CASPEC spectrum; components NW and SE are separated by 14″ (M97). (3) SB as found by M97, who found lithium in both components; data given here are for the primary, which is much brighter. (4) We have revised W_λ(Li) down to 0.25Å from the value given in M97, which apparently was too large due to an incorrect assumption on the continuum level. (5) Classified as a wTTS by N95c, but as a dKe star by M97; we detect lithium in our CASPEC spectrum but not in excess of the Pleiades level, and conclude that this star is a K5 ZAMS star. (6) M97 detected lithium, but did not classify this star as 'PMS' or 'PMS?'.

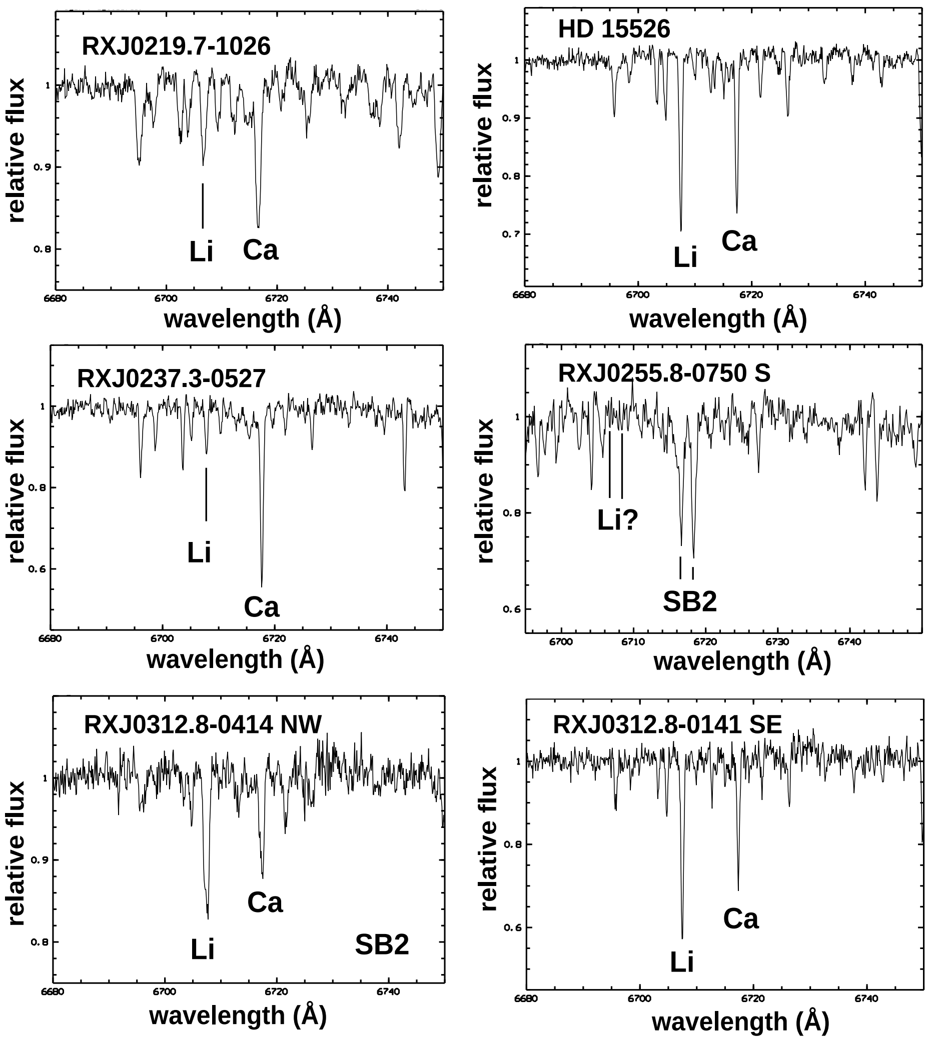

Fig. 1. High-resolution CASPEC spectra. Plotted are relative flux versus wavelength (from about 6700 Å to 6750 Å) for stars where lithium has been detected.

for gravity log g = 4.5 from Pavlenko & Magazzù (1996), who estimate their internal error to be less than 15%. Including also our uncertainties in T_{eff} and W_{λ}(Li), we expect the error of individual log N(Li) values to be less than $\sim$ 25%. In the last column we add a 'lithium excess above the ZAMS level' explained below (Sect. 4.3).

For stars with constant RV, the value listed in the velocity columns is the weighted average of all measurements; for single- or double-lined SBs (abbreviated SB1 and SB2, respectively) where we have solved for an orbit (as indicated in the remarks; Torres et al., in preparation) the center-of-mass velocity is given; for SB2 with unknown orbits, the value listed is the mean of all primary and secondary velocities combined, which should give roughly the center-of-mass velocity if the masses of the components are not too different. We converted heliocentric radial velocities to the local standard of rest by correcting for the solar motion towards the solar apex: α = 271° and δ = 30° for B1900.0 (Allen 1973).

In Table 2 we list the same parameters for stars where no lithium was found.

For most of our stars, two independent estimates of the stellar effective temperature T_{eff} are available. On the one hand, we have obtained new values by matching our echelle spectra in the blue with synthetic templates through cross-correlation, with errors of $\pm$100 to 150 K. Also available are the spectral types reported by M97 (or A96), obtained by comparison of their broad-band low- and/or medium-resolution spectra with standard stars. These are good to two or three sub-types (i.e. $\pm$250 to 300 K). We have converted these spectral types to T_{eff} using the calibration by Bessell (1979, 1991).

The agreement between the two sets of temperatures is seen in Fig. 2, where the scatter about the line, $\sim$ 200 K, is consistent with the systematic uncertainties and errors in the original measurements. As expected, the agreement is somewhat better for stars with low-resolution spectra (resolution 2.5Å) compared to stars with medium-resolution spectra (resolution $\sim$ 1Å), since the spectral range of the low-resolution spectra is larger so that more reliable spectral types can be assigned.

The results of our CASPEC lithium observations, obtained with a resolution of $\sim$ 0.25Å, are compared in Table 3 with other

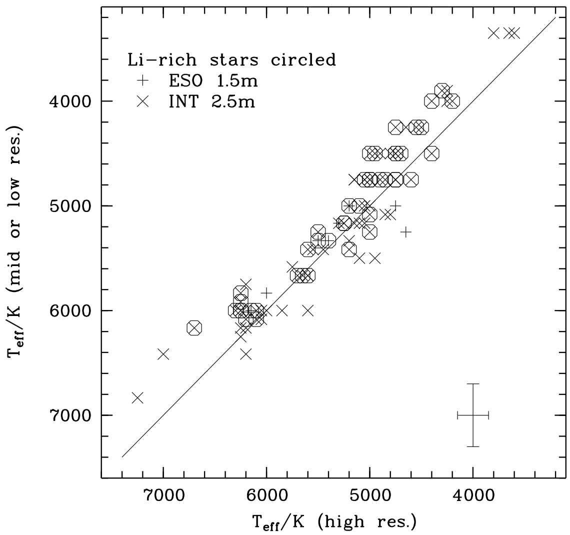

Fig. 2. Low-/medium-resolution temperatures vs. high-resolution temperatures. Plotted are T_{eff} from M97 and A96 versus those from our high-resolution spectra. Data from low resolution are shown as +, and from medium resolution as ×; stars with lithium are circled. Typical error bars and a diagonal line representing the 1 : 1 relation are also shown.

Table 3. Lithium equivalent widths at different resolutions. Lithium 6708Å equivalent widths from both CASPEC (this work, ±0.02Å) and M97 are compared, with indication of their resolution and the spectral types. Also listed are (preliminary) equivalent widths as given by N95c. Data from M97 and N95c have a precision of about ±0.05Å.

	CASPEC	M97 (and/or N95c)		
Designation	W_λ	W_λ	res.	Sp.T.
RXJ0219.7-1026	0.13	0.14 [a]	mid	K4
HD 15526	0.19	0.28	low	G8
RXJ0237.3-0527	0.09	0.07 [a]	mid	K5
RXJ0251.8-0203	no	0.06 [a]	mid	K6
RXJ0255.8-0750S	$\leq$ 0.05 [b]	$\leq$ 0.1	mid	K7-M0
RXJ0312.8-0414NW	0.20 [c,d]	0.2	low	G0
RXJ0312.8-0414SE	0.25 [d]	0.3	low	G8

Remarks: (a) From N95c. (b) Holds for both components of this SB2. (c) SB2 in CASPEC spectrum, but no clear variability could be detected in four high-resolution spectra in the blue, possibly due to the large brightness difference between the two stars. (d) Components NW and SE are separated by 14″.

results from the literature (M97, N95c), obtained at resolutions of ∼ 1Å.

For RXJ0219.7-1026, the data given by M97 and N95c agree with our CASPEC result. For RXJ0237.3-0527, N95c gave an accurate value, while M97 regarded the line as possibly being noise. In the case of RXJ0251.8-0203, however, we find no lithium with CASPEC, i.e. W_λ(Li) ≤ 0.05Å, while N95c reported a lithium detection which was regarded as noise by M97. In RXJ0255.8-0750S, neither M97 nor we find any lithium. We conclude from this limited comparison that spectra at a medium resolution of ∼ 0.7 to 1.5Å yield reliable W_λ(Li) values.

In two out of three cases discussed above, the low-resolution spectra overestimated W_λ(Li) compared to the CASPEC spectra. There are only ten lithium-rich stars in our sample which were only observed either at low resolution and/or with low S/N (c.f. M97), three of which we observed again with CASPEC. For the remaining seven stars we regard the lithium data (by M97) as upper limits. We do not regard these stars as being lithium-rich.

There is some indication in the literature of a tendency to overestimate W_λ(Li) in low-resolution spectra, due to insufficient resolution (c.f. Walter et al. 1988, Gómez et al. 1992). This is being studied further by Covino et al. (1997) in a large sample of ROSAT discovered Lithium-rich late-type stars. They find a similar trend in spectra with a detection threshold of ∼ 0.15Å.

4. Which stars are PMS stars ?

In order to investigate the evolutionary status of our stars, we require an estimate of their age. We cannot, however, assume a distance to place them on evolutionary tracks, because most of these stars are far from any cloud material, and it is not certain that they are associated with clouds. Instead, we compare their W_λ(Li) values with those of stars in young clusters and also with bona-fide TTS.

4.1. Lithium in young stellar clusters

For our comparison with W_λ(Li) in young clusters, we have selected IC 2602 and the Pleiades, which have equivalent width, $v \cdot \sin i$, and T_{eff} measurements available from the literature with precision similar to ours. In addition, they have ages in the range of interest, i.e. between 10^7 yrs, typical of wTTS and post-TTS, and 10^8 yrs, typical of ZAMS stars. In Fig. 3 we plot W_λ(Li) versus log T_{eff} for IC 2602 and Pleiades stars. The symbol sizes are proportional to $v \cdot \sin i$. The motivation for including rotational data here is that lithium depletion may depend on rotation in the sense that rapidly rotating stars tend to deplete their lithium at a slower rate than slowly rotating stars (Soderblom et al. 1993, Martín & Claret 1996). For IC 2602 we use data from Randich et al. (1997) and Stauffer et al. (1997). For the Pleiades we adopt the results by Soderblom et al. (1993) and García López et al. (1994). We converted colors to T_{eff} following Bessell (1979, 1991).

In the top panel of Fig. 3, we draw a line similar to Soderblom et al. (1993), representing the upper envelope of W_λ(Li) values of the Pleiades. This upper envelope is determined by the more rapidly rotating stars (large circles). Among the K-type stars we find the so-called ultra-fast rotators, which still have relatively large lithium equivalent widths. In order to show the dependence of lithium depletion on rotation more clearly, we draw also a line representing the upper envelope of W_λ(Li) values in slowly rotating stars (small circles).

We repeat these lines in the lower panel of Fig. 3. Many of the IC 2602 stars show stronger lithium than stars in the Pleiades. An additional upper envelope to these stars is also shown (dashed line), for comparison with our new sample south of Taurus.

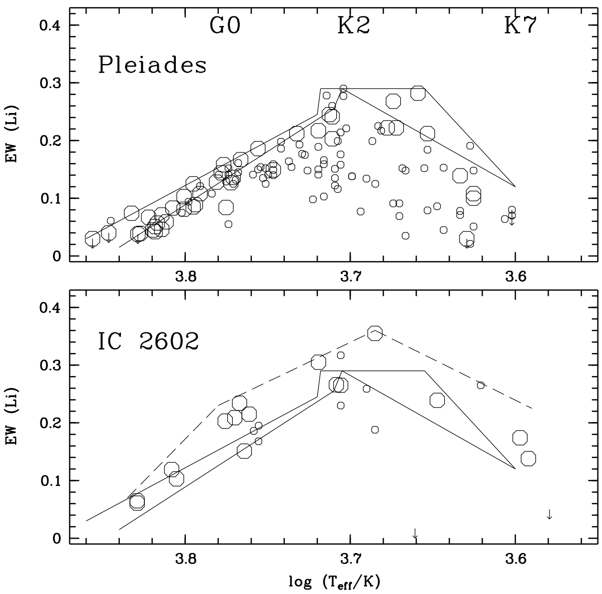

Fig. 3. Lithium strength of Pleiades and IC 2602 stars. Plotted is W_λ(Li) in Å versus log T_{eff} for the Pleiades (upper panel) and IC 2602 (lower panel). Small symbols are for $v \cdot \sin i \leq 15\ km\ s^{-1}$, and large symbols for $v \cdot \sin i > 15\ km\ s^{-1}$. Shown in both panels are the same lithium upper envelopes (full lines) for rapid and slowly rotating Pleiades stars (see text); in the lower panel, we also indicate the upper lithium envelope for IC 2602 stars (broken line).

Most of the G-type dwarfs in IC 2602 have not yet spun down (Stauffer et al. 1997), whereas in the Pleiades most of them are slow rotators. In IC 2602, G-type stars are essentially on the ZAMS, while stars of spectral type K are still slightly above the ZAMS (Randich et al. 1997). Similarly, very late M-type Pleiades may also be above the ZAMS. We conclude from this that stars with W_λ(Li) only slightly stronger than the Pleiades upper envelope(s) can be as young as IC 2602, i.e. $\sim 3 \cdot 10^7$ yrs old (Stauffer et al. 1997). K- and M-type stars among them are still in the PMS stage, while (solar-mass) G-type stars with lithium as strong as in IC 2602 stars have just arrived on the ZAMS. Stars above the upper envelope of lithium in IC 2602 stars are much younger still, and are well above the ZAMS.

4.2. Lithium in bona-fide T Tauri stars

In this section we compare the location of bona-fide TTS in central Taurus with the Pleiades upper envelopes, focussing again only on stars having W_λ(Li), $v \cdot \sin i$, and T_{eff} known with precision and accuracy similar to our own. We take these data from the literature (see listing in N95b) and convert spectral types to T_{eff} as before, using the Bessell (1979, 1991) conversion for consistency. In Fig. 4 we plot W_λ(Li) versus log T_{eff} for bona-fide TTS, all of which were discovered prior to the ROSAT mission. We adopt high-resolution W_λ(Li) values, in order of precedence, from Patterer et al. (1993), Marcy et al. (1994), Basri et al. (1991), Martín et al. (1994), Magazzù et al. (1991), and Walter et al. (1988). We plot upper limits for lower

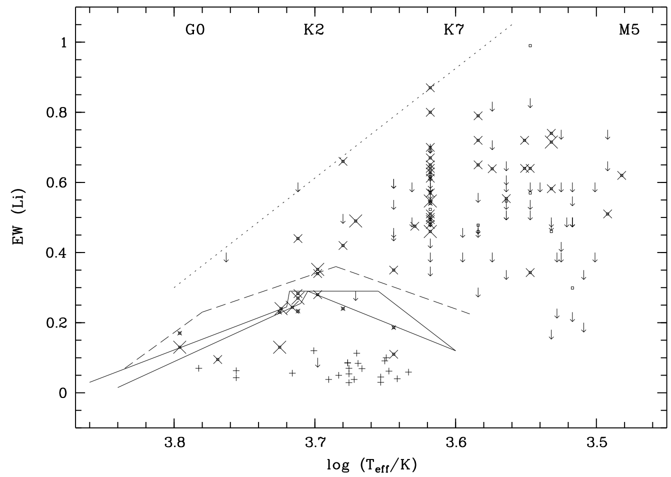

Fig. 4. Lithium strength of T Tauri stars in Taurus. We show W_λ(Li) versus log T_{eff} for bona-fide TTS in central Taurus, with crosses for data from high-resolution ($\sim$ 1Å) spectra (symbol size as in Fig. 3, and dots for TTS with unknown $v \cdot \sin i$) and upper limits for data from low-resolution spectra. RS CVn-type stars are represented by small plusses (+). Also shown are the lithium upper envelopes for the Pleiades (full lines) and IC 2602 (broken line), as well as an upper envelope to the lithium values for TTS (dotted line).

resolution data from Herbig et al. (1986), Strom et al. (1989), Cabrit et al. (1990), Gómez et al. (1992), Gregorio-Hetem et al. (1992), Briceño et al. (1993), Hartigan et al. (1994), Feigelson et al. (1994), Kenyon et al. (1994b), Torres et al. (1995), Kenyon & Hartmann (1996), and Walter et al. (1988).

The figure shows that most 'bona-fide TTS' indeed lie well above the Pleiades upper envelope(s), as expected for their young ages. The upper envelope to the W_λ(Li) data for 'bona-fide' TTS, which we have represented by a dotted line, can be taken as the *observed initial lithium strength*, and corresponds here to log N(Li)$\sim$ 3.3, in the customary scale of log N(H)= 12. Also plotted in Fig. 4 are RS CVn-type SB stars, for which we adopt data on lithium and spectral type from Pallavicini et al. (1992). Some of our lithium-rich stars south of Taurus are SBs, show lithium, and at least one of their components has an early K spectral type, all of which are typical of RS CVn systems. They are also X-ray active. However, since all RS CVn stars lie well below the Pleiades upper envelopes, objects in our sample lying above those lines are almost certainly not RS CVn-type stars.

Martín (1997) has recently discussed a diagram similar to our Fig. 4, and claims that there is a 'post-TTS gap', i.e. a lack of M-type TTS with W_λ(Li) below 0.4Å. We see no evidence of such a gap in our Fig. 4, and we note that Martín (1997) omitted some 15 M-type TTS with low lithium in his plot. The four M-type TTS with the lowest lithium are (from left to right in Fig. 4) NTTS 040047+2603 E, NTTS 040142+2150 SW, HN Tau/c, and Briceño CIDA 2. These stars and others in this part of the diagram must be very young TTS, since M-type stars deplete their lithium very quickly.

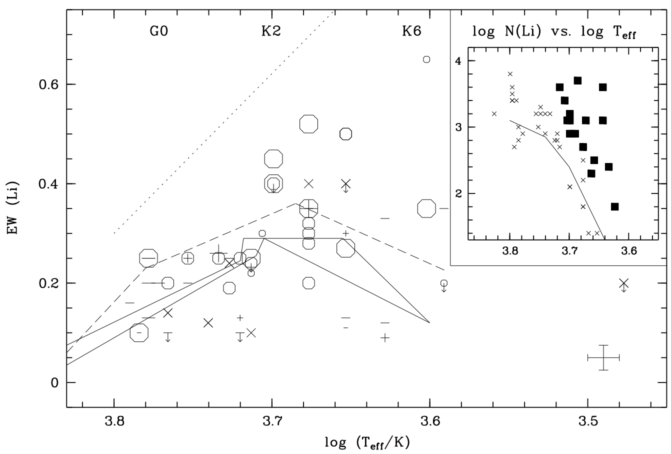

Fig. 5. Lithium strength for stars south of Taurus. W_λ(Li) versus log T_{eff} for lithium-rich stars in our sample, with symbol sizes and upper envelopes as in Figs. 3 and 4. Stars with RV consistent with Taurus membership are represented with circles, those with $RV \geq 21.5\ km\ s^{-1}$ with plusses, and those with $RV < 13.5\ km\ s^{-1}$ with horizontal bars. Stars with either RV or $v \cdot \sin i$ unknown are shown as crosses. Upper limits to W_λ(Li) for stars with low resolution or low S/N spectra (c.f. M97) are indicated with arrows. Typical error bars are shown in the lower right. The plot in the upper right shows the lithium abundances log N(Li) versus log T_{eff} for new PMS stars (filled symbols) and other lithium-rich stars (crosses); typical Pleiades abundances are indicated by a line.

As an interesting side point, we note that a few stars, previously classified as TTS, lie well below the Pleiades upper envelopes (Fig. 4). The implication is that these objects have depleted their lithium, are already on the ZAMS, and are located at a distance of less than $\sim 140\ pc$. This cautions against using only the equivalent widths as the basis for PMS classification (i.e., larger than, e.g., 0.1 or 0.2Å), without taking into consideration also the spectral type and $v \cdot \sin i$. The four 'TTS' which lie well below the lines are (from left to right in Fig. 4) SAO 76411 A, NTTS 035120+3154 SW, SAO 76411 B (upper limit), and NTTS 042835+1700, with W_λ(Li) according to Walter et al. (1988), Gómez et al. (1992), Patterer et al. (1993), Martín et al. (1994), and Hartigan et al. (1994). We exclude these four objects from the comparison of our new PMS stars with 'bona-fide' TTS in central Taurus.

4.3. Lithium in our new stars south of Taurus

We now compare the W_λ(Li) of our stars with the lithium upper envelopes of the Pleiades and IC 2602 stars, in order to estimate their ages relative to these clusters (Fig. 5). In discussing the location of our stars in this diagram, we refer in the following to 'relevant upper envelope' as the envelope corresponding to the appropriate rotational velocity bin (rapidly or slowly rotating).

Of the 56 stars listed in Table 1, seven have only upper limits for W_λ(Li) (fourth group in the table), so that we are left with 49 lithium-rich stars. As seen in Fig. 5, 33 out of these 49 show lithium stronger than the relevant Pleiades upper envelope(s) (first three groups in Table 1). We define a 'lithium excess' as the difference between the W_λ(Li) of each of these stars and the W_λ(Li) level of the relevant Pleiades upper envelope at that star's spectral type. These stars will be referred to as *lithium-excess stars*, and the excesses are listed in the last column of Table 1. As noted in N95c, their lithium abundances are consistent with a typical age of a few times 10^7 yrs, comparable to IC 2602 stars. Although several of these lithium-excess stars lie only very slightly above the relevant upper envelope and, due to errors in the W_λ(Li) measurements, may in fact have weaker lithium than the Pleiades, there are as many stars just below the upper envelope(s), so that the statistics on the fraction of stars above the upper envelope(s) should be essentially correct. We note also that there are eleven stars with W_λ(Li) even stronger than in IC 2602 stars; their lithium strength is comparable to 10^6 to 10^7 yr old 'bona-fide' TTS.

The RASS counterparts listed in Table 2, on the other hand, have W_λ(Li)$<$ 0.1Å and, hence, may already be on the ZAMS. Since many of the $\sim 6 \cdot 10^8$ yr old nearby Hyades stars have been detected by RASS, stars in our sample without detected lithium may in fact be either $\sim 10^9$ yr old main-sequence stars, or even post-main sequence stars, e.g. X-ray active RS CVn stars. But we cannot expect to have detected all nearby 10^8 to 10^9 yr old stars (nor all RS CVn-type stars), so we cannot strictly compare directly the number of RASS source counterparts without detected lithium with the lithium-rich RASS sources – nor should we compare the number of lithium-rich stars with all stellar RASS counterparts.

Among the 33 lithium-excess stars in Fig. 5, 15 have spectral type late F or G (third group in Table 1). Their lithium strength is comparable to that of G-type stars in IC 2602. Since G-type stars in IC 2602 have already arrived on the ZAMS (Stauffer et al. 1997, Randich et al. 1997), we conclude that our 15 lithium-rich RASS counterparts with spectral types late F or G are at a similar stage in their evolution, i.e. may have already arrived on the ZAMS. Still, these stars are probably not older than $\sim 3 \cdot 10^7$ yrs, the age of IC 2602. However, as seen in Fig. 4, there are also no *G-type* bona-fide TTS in central Taurus known with (high-resolution) lithium strength above the upper envelope of the (G-type) IC 2602 stars.

The other 18 lithium-excess stars in our sample all have spectral type K. Stars of this spectral type in IC 2602 appear not to have arrived yet on the ZAMS (Randich et al. 1997), and are thus considered PMS stars. Therefore, we regard these 18 objects as new PMS stars – regardless of whether or not their RV is consistent with Taurus or Orion membership. Their lithium abundances (listed in Table 1) are shown in Fig. 5 and lie above the typical Pleiades abundances.

Nine of 18 new PMS stars are located inside (or projected onto) the λ Ori cloud, including the 4 stars with the strongest lithium excess in our sample (second group in Table 1). The λ Ori cloud is a ~ 2 to $6 \cdot 10^6$ yr old part of the Orion cloud complex (Duerr et al. 1982), located at a distance of $\sim 450\ pc$. Several of these 9 stars share the RV of Orion (see below), and may be unrelated to Taurus. The nine remaining K-type lithium-excess stars (first group in Table 1) have lithium abundances ranging

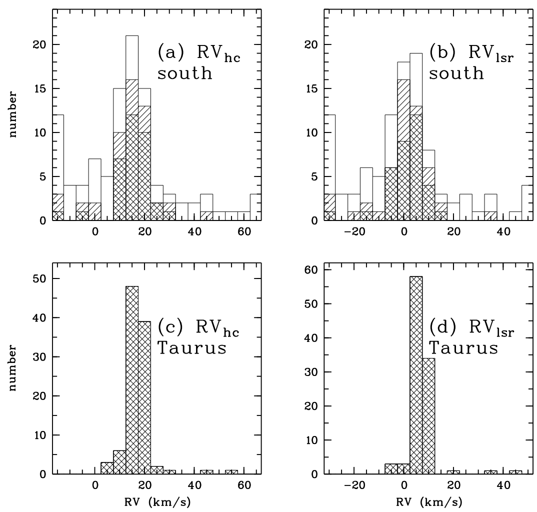

Fig. 6a–d. Radial velocities. Lithium-excess stars are cross-hatched, stars with weaker lithium are hatched, and stars with undetected lithium are unhatched. **a** and **b** show the heliocentric and local standard-of-rest RV distributions for our new stars south of Taurus; **c** and **d** are for bona-fide TTS in central Taurus (references to RV data in N95b).

from 1.8 to 3.2, clearly above the Pleiades abundance. Two of them, RXJ0344.8+0359 and RXJ0444.7+0814, were classified as dubious PMS stars ('PMS?') by M97. The spectrum of the first of these was presented as typical for wTTS in N95c.

The nine K-type PMS stars in the first group in Table 1 are located south of Taurus, far from any gas material. Also in the same general area are the 15 objects in group 3, with lithium as strong as IC 2602 (i.e., age $\sim 3 \cdot 10^7$ yrs), and those in group 5 (16 stars), which have weaker lithium (below the Pleiades envelope) and are probably $\sim 10^8$ yrs old. If we exclude one of the stars in the latter group that is projected against the λ Ori region, the fraction of PMS stars south of Taurus (and far from any cloud material) compared to ZAMS stars is 9:(15+16−1), i.e. $\sim 1:3$.

4.4. Radial velocities

The heliocentric radial velocities of 'bona-fide' TTS in central Taurus peak at 17.4 ± 2.1 $km\ s^{-1}$ (Hartmann et al. 1986). In this paper we consider the RV of a lithium-rich star to be consistent with central Taurus if $13.5\ km\ s^{-1} \leq RV < 21.5\ km\ s^{-1}$, which represents a 2 σ interval around the mean. Members of the Orion T association – which, projected onto the sky, is located next to the Taurus clouds, but behind at a distance of $\sim 450\ pc$ – have $RV \sim 25.5\ km\ s^{-1}$ (Hartmann et al. 1986). We will consider stars with $21.5\ km\ s^{-1} \leq RV < 29.5\ km\ s^{-1}$ to be possible members of the Orion association. A total of 16 (seven) lithium-rich stars in Table 1 are possible members of Taurus (Orion), as far as RV are concerned.

In addition to having a sharp peak in heliocentric RV, TTS in the Taurus T association also populate a narrow box in the proper motion (μ_α, μ_δ) plane (Jones & Herbig 1979), and they share the RV of the nearby clouds (Herbig 1977). The internal velocity dispersion in both RV and proper motion is only 2 to 3 $km\ s^{-1}$ (Hartmann et al. 1986, Jones & Herbig 1979). However, these studies were restricted to small samples consisting almost exclusively of young cTTS. As soon as older, more evolved and dispersed stars are included with the cTTS, these internal dispersions are expected to become larger.

The 33 lithium-excess stars in our sample display a RV distribution that peaks near 17 $km\ s^{-1}$, the same as that of previously known TTS in central Taurus (see Fig. 6a and 6c). Similary, both populations also show a peak near the same RV_{lsr} value. The complete sample of objects we studied, however, shows a wider RV distribution due to the contribution of older field ZAMS stars. The slightly broader wing in Fig. 6a towards larger RV is probably due to overlap with Orion members, while the slightly broader wing towards smaller RV may be due to PMS stars born in Taurus, which were subsequently ejected and are now moving towards us.

The RV distribution of non-PMS stars (i.e. stars without lithium excess) is quite uniform and does not show any peak, which is consistent with these stars belonging to a foreground population of somewhat older stars. This is true for both the lithium-rich stars without lithium excess (compared to the Pleiades) and for stars with undetected lithium. Walter et al. (1988) reported a similar result for their (smaller) sample of EO sources in central Taurus: Stars with strong lithium absorption showed a RV distribution peaking at 16.3 ± 2.8 $km\ s^{-1}$, while stars in the same general direction but without lithium showed a flat distribution (with an additional peak at $\sim 40\ km\ s^{-1}$ corresponding to the Hyades cluster). Fig. 6c also shows a few 'bona-fide' TTS with RV far from the Taurus mean, as pointed out by Herbig (1977) and Neuhäuser et al. (1997).

4.5. Rotational velocities

One of the most difficult problems in our understanding of the PMS phase of low-mass stars is the angular momentum evolution. Since young stars appear to spin up from the wTTS phase to the ZAMS phase and rotate much more rapidly than main sequence stars, it is important to compare the $v \cdot \sin i$ distribution of our lithium-excess stars with that of 'bona-fide' TTS in central Taurus, as well as with stars in young clusters such as IC 2602, IC 2391, and the Pleiades. Rotational data for IC 2391 stars are taken from the work by Stauffer et al. (1989, 1997).

The $v \cdot \sin i$ distribution of lithium-excess stars south of Taurus shows a low-velocity peak between 10 and 20 $km\ s^{-1}$, as do the bona-fide TTS in central Taurus and also the IC 2602 and IC 2391 stars (Fig. 7). The high-velocity tail in the lithium-excess stars appears to end at 120 to 140 $km\ s^{-1}$ (Fig. 7a). For TTS in Taurus, the most rapidly rotating star shows $v \cdot \sin i = 100\ km\ s^{-1}$ (Fig. 7b); in the $\sim 3 \cdot 10^7$ yr old IC 2602 and IC 2391 clusters, the high-velocity tail lies further out at 150 to 200 $km\ s^{-1}$ (Fig. 7c); and in the Pleiades, $v \cdot \sin i$ can exceed 200 $km\ s^{-1}$ (Fig. 7d). This clearly illustrates a trend, present in the age range 10^6 to 10^8 yrs (c.f. Bouvier et al. 1997): The faster the most rapidly rotating stars are spinning, the older the cluster.

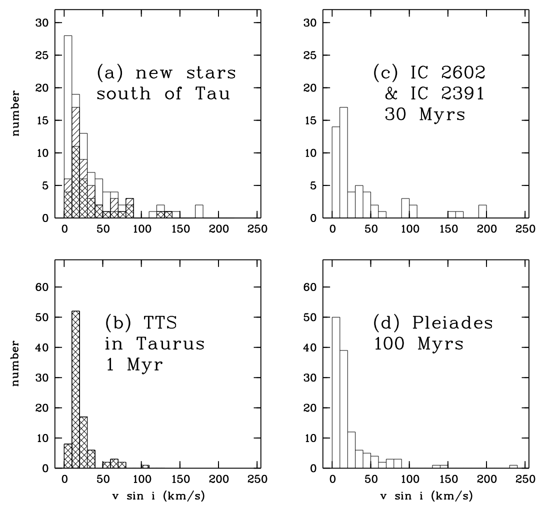

Fig. 7a–d. Rotational velocities. **a** New stars south of Taurus: lithium-excess stars are cross-hatched, older lithium-rich stars (without excess) are hatched, and stars with undetected lithium are unhatched; **b** bona-fide TTS in central Taurus; **c** IC 2602 and IC 2391 stars, and **d** Pleiades members.

The high-velocity tail of the lithium-excess stars south of Taurus is observed to be at $\sim$ 130 $km\ s^{-1}$, intermediate between those of the Taurus T association and the IC 2602/2391 clusters. This independent line of evidence leads again to an age estimate for our stars with lithium excess of the order of 10^7 yrs, rather than 10^8 yrs.

For the sample of stars with weak lithium or with undetected lithium, the distribution of $v \cdot \sin i$ is typical for a population of ZAMS and MS stars: A large peak at $v \cdot \sin i \ \leq\ 10\ km\ s^{-1}$ for many slowly rotating stars that have spun down to MS levels, a flat distribution in the range from $\sim$ 10 to $\sim$ 70 $km\ s^{-1}$, and very few stars at higher velocities, $v \cdot \sin i \ \geq\ 70\ km\ s^{-1}$. Of the stars in the lowest bin in Fig. 7a, most are main sequence stars with no detectable lithium, and only a few are ZAMS stars.

5. Binaries among RASS source counterparts

Our multiple RV observations of most of our stars have turned up a number of SBs, which we indicate in Tables 1 and 2. In addition, two more objects (RXJ0312.8-0414NW and RXJ0422.9+0141) were found to have double lines in our CASPEC spectra or by M97.

Among 18 new PMS stars (listed in the first two groups of Table 1), there are at least three SBs including one SB2, i.e. 17 %. One of them has spectral type K7-M0 with W_λ(Li) = 0.35Å, and must be very young. The time-scales of the observed variability in the high-resolution observations of these stars range from a few weeks to at least three years, the duration of our survey. Considering the frequency and precision of our observations, we estimate conservatively that we are most sensitive to periods up to $\sim$ 100 days. Mathieu (1994) reported an 11 $\pm$ 4 % fraction of SBs with periods up to $\sim$ 100 days among PMS stars, not far from our own result (which is based on only three SBs). The percentage of SBs in this period range among solar-type stars in the solar neighbourhood seems lower (7 $\pm$ 2 %; Duquennoy & Mayor 1991), although these are all small-number statistics.

Of the (candidate) ZAMS stars in groups 3 and 5 of Table 1, we performed repeated observations for 25 of them, and find at least 8 binaries, or roughly one third. Some of their characteristics are reminiscent of the RS CVn phenomenon. For example, all but one of these 8 binaries have spectral types late G or early K, which is quite typical for RS CVn-type systems. The lithium strength we observe is also not inconsistent with these being active systems: RS CVn binaries occasionally show lithium as strong as ZAMS objects (c.f. Pallavicini et al. 1992, and our Figs. 4 and 5). And X-ray activity is also common in RS CVn binaries, at similar levels as detected in our stars. Therefore, it would not be surprising if a few of the objects we have classified as candidate 'ZAMS' stars turned out to be RS CVn binaries.

Finally, among 55 stars with no detectable lithium (W_λ(Li) $\leq$ 0.1 Å, Table 2), we found between 32 and 36 SBs, i.e. more than half. Again, many of these have spectral types typical of RS CVn systems, which often have lithium below our detection threshold, so that there may be some such systems among these stars.

Our RV data also allow us to judge whether or not visual pairs among our program stars are physical. There are six such pairs in our sample, with separations between $2''$ and $14''$. The components were observed individually if the separation is at least $\sim 1''$. Proper motion information for these pairs is limited, and only available for the individual componentes in the case of BD+07 582.

The separation of the components of RXJ0312.8-0414 is $14''$, which is quite large for physical pairs if at the Taurus distance of $\sim$ 140 pc. Their RV differ by 0.9 $km\ s^{-1}$ (Table 1). Assuming masses derived from the spectral types, the maximum possible RV difference is $\sim$ 1.4 $km\ s^{-1}$. Component NW is an SB2 itself, and we do not yet know its center-of-mass velocity. Both stars show similar lithium excess. We conclude that this may well be a hierarchical triple system.

In the case of BD+07 582 ($4''$ separation), the components show indistinguishable RV but slightly different proper motions (Frink et al. 1997), so that we cannot be certain that this pair is physical. Component BD+07 582 B is known to be orbited by a closer companion at $0.2''$ separation, so that BD+07 582 is likely to be another hierachical triple. The relative motion of the $0.2''$ pair has been followed for many years, and it may soon be possible to solve for the orbit and derive individual masses and ages as well as the distance. Its lithium absorption is not larger than in the Pleiades, so we do not consider it to be a PMS star.

The components of the $2''$ pair RXJ0407.2+0113 both show lithium excess, and have indistinguishable RV. They almost certainly form a physical pair, or perhaps a hierarchical triple, since the northern component may be an SB1. The components of the visual pairs RXJ0210.4-1308 and RXJ0309.1+0324, both with separations of $2''$, appear to have different RV, but in each case at least one of the components seems to be a SB, so that

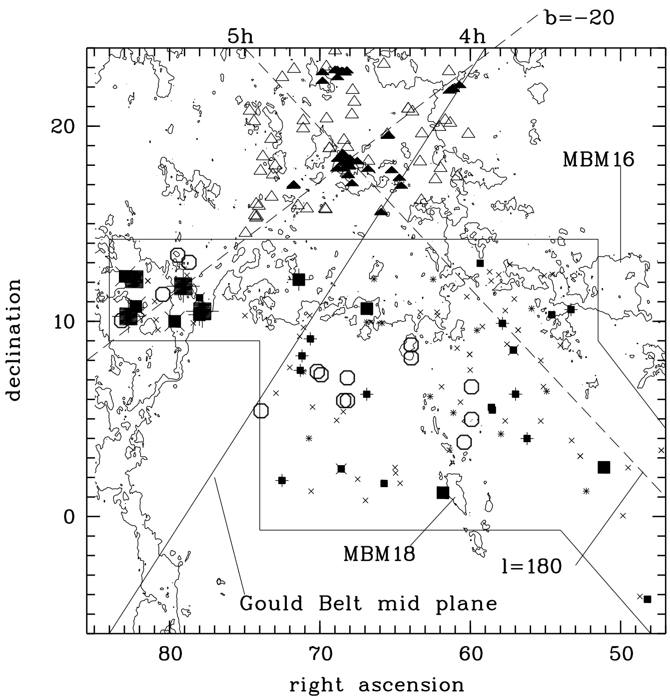

Fig. 8. Our area of study and IRAS map. Shown are two IRAS $100\mu m$ contours overlapping our study area (box). Symbols are as follows: New lithium-excess stars (filled squares); RASS sources with weak lithium ($*$); counterparts with undetected lithium ($\times$); previously known bona-fide TTS (filled triangles); and TTS discovered by W96 (open triangles). The lithium-excess stars in our sample (filled squares) have symbol sizes proportional to the lithium excess $\delta\ W_{\lambda}$(Li) listed in Table 1. Those with RV consistent with Taurus have a large + superimposed, and those with RV consistent with Orion have a large $\times$. There are no lithium-rich stars in the strip indicated in the lower right, which extends out of the figure boundaries to $\delta = -17$. Lynds clouds are also shown (circles).

the RV is variable. A final determination must await orbital solutions.

6. Discussion

Our study of RASS source counterparts south of the Taurus molecular clouds has turned up a number stars with spectral signatures typical of wTTS. Many, but not all, of these stars share the mean Taurus RV. Since there are no star-forming molecular clouds known in our study area, these observational facts are rather surprising, and we must consider the possible formation scenarios to account for them.

6.1. Spatial distribution of our stars compared to clouds

Since star formation takes place in molecular clouds, we address first the issue of whether the area we studied is clear of such material. The CO survey by Ungerechts & Thaddeus (1987) has no overlap with our area, since it was restricted to a region north of $\delta \sim 15°$. Magnani et al. (1985), on the other hand, found two small clouds in our study area, MBM 16 and MBM 18, the latter being identical to the Lynds cloud L1569. Lynds (1962) reported 15 additional small clouds in our study area, four of which are, however, near λ Ori, the north-western part of the Orion SFR, which is at the eastern edge of our study area.

While the molecular gas distribution and, hence, the Taurus T association, have usually been thought to be restricted to $\delta > 15°$, according to the CO survey by Ungerechts & Thaddeus (1987), we clearly see $100\mu m$ emission in the northern part of our study area, connected smoothly with the previously known molecular clouds north of $\delta = 15°$. There may also be molecular gas detectable in CO surveys in this area. Stars in our sample with the largest lithium excess are located north of $\delta = 10°$, and may have formed locally. Their lithium excess indicates that they are younger than $\sim 10^7$ yrs. We find several new lithium-excess stars at $\alpha > 75°$, which may belong to the λ Ori SFR, but most of the other lithium-excess stars are located several degrees off of any known gas or dust cloud. Stars showing small lithium excess may have dispersed out of the Taurus clouds by slow isotropic drifting. Two of them, RXJ0324.4+0231 and RXJ0407.2+0113S, are located far south of the Taurus clouds ($\sim 10°$), and may actually have been ejected from central Taurus.

Many of our lithium-excess stars share the Taurus mean proper motion, as do newly discovered PMS stars in central Taurus (Frink et al. 1997). This is based on motions from STARNET, which lists positions and proper motions for several million stars down to $V \sim 12$ mag (Röser 1996), derived by combining the Astrographic Catalog and the HST GSC1.2. The typical precision is a few milli arc seconds (mas) per year, comparable to other proper motion studies (e.g. Jones & Herbig 1979). However, the intrinsic scatter in the proper motions among lithium-excess stars south of Taurus is larger (7.6 $km\ s^{-1}$) than among TTS in central Taurus (5.4 $km\ s^{-1}$), both values include STARNET errors; or 6.8 $km\ s^{-1}$ in the south and 4.3 $km\ s^{-1}$ in the center after accounting for STARNET errors; all values according to Frink et al. (1997).

Our lithium-excess stars appear to share also the typical proper motion of the Cas-Tau association (Blaauw 1956, Walter & Boyd 1991), located somewhat to the west of the main Taurus clouds. The spatial extent and kinematics of this group is defined by 29 B-type stars. Their mean proper motion and RV is all but indistinguishable from the Taurus motion. The age of the Cas-Tau association is inferred to be ~ 3 to $4 \cdot 10^7$ yrs, i.e. older than typical for young TTS. However, since most of our stars south of Taurus all lie to the east of the eastern edge of the Cas-Tau association ($l \sim 180°$), it seems unlikely that many of our stars belong to Cas-Tau.

6.2. Dispersal of new PMS stars by slow drifting ?

While most TTS in Taurus are younger than a few times 10^6 yrs, some of them appear to be as old as several times 10^7 yrs. The majority of relatively old PMS stars may have moved out of their parent cloud complex by slow isotropic dispersal. Such older PMS stars would remain unrecognized in IR and $H\alpha$

surveys, and they would also have escaped detection in recent proper motion studies, which were restricted to small, on-cloud regions (Hartmann et al. 1991, Gómez et al. 1992). Some of the lithium-rich RASS source counterparts found here and also by Alcalá et al. (1995), N95c, A96, W96, Krautter et al. (1997), M97, and Wichmann et al. (1997b), could be such $\sim 10^7$ yr old post-TTS, i.e. wTTS on radiative tracks.

Having said this, there is, however, mounting evidence that some of these new PMS stars outside the clouds are *too young* to have moved to their present location with relatively small velocities.

Alcalá et al. (1997) determined ages for a number of lithium-rich stars in and around the Chamaeleon clouds, and found many of them to be $\sim 10^6$ yrs old – even those far from the clouds including M-type stars with strong lithium. We note, however, that it is possible to underestimate the age of a TTS if the assumed distance is too large. Alcalá et al. (1997) modeled a lithium-rich population with random distances between 120 and 180 pc, and found that such a population bears good resemblance with the spread in stellar properties observed when assuming the same distance (150 pc) for all stars. In order for the ages to be underestimated by more than an order of magnitude, these stars would need to be much closer than the clouds (as close as ~ 30 pc).

Bouvier et al. (1997) placed 18 new wTTS found by W96 on the HR diagram. Most are few 10^7 yrs old, two are as young as $\sim 10^6$ yrs, and only one appears to be already on the ZAMS. They conclude that two thirds of such stars are genuine post-TTS. Wichmann et al. (1997a) obtained photometry for most of the new ROSAT wTTS found by Krautter et al. (1997) in and around the Lupus clouds, and found that all of those are above the ZAMS, most of them near the 10^7 yr isochrone, but several seem to be as young as $\sim 10^6$ yrs.

Additional evidence for the youth of these stars was presented by Carkner et al. (1997), who found that the VLA radio detection rate of the lithium-rich ROSAT sources is indistinguishable from the detection rate of previously known 'bona-fide' TTS, and also significantly larger than the detection rate of ZAMS stars such as the Pleiades. Thus, it would appear that not all lithium-rich objects found at large distances from molecular cloud material can be explained by slow isotropic drifting.

6.3. Are there run-away T Tauri stars ?

Our new PMS stars are located as far as 10° south of the southern border of the IRAS $100\mu m$ contours, i.e. up to 24° south of the southern border of the known Taurus CO clouds. Their birthplace could be anywhere on the clouds in Taurus. To have moved 20° (i.e. 50 pc at a distance of 140 pc) in $\leq 10^7$ yrs implies a line-of-sight velocity dispersion $\geq 5/\sqrt{3}\ km\ s^{-1} \simeq 3\ km\ s^{-1}$, which is consistent with the observed RV dispersion of 2.8 $km\ s^{-1}$. At a distance of 140 pc, a proper motion of 10 mas per year corresponds to 6.7 $km\ s^{-1}$.

In encounters within multiple protostellar systems, single (or close binary) stars can be ejected with high velocities (Sterzik & Durisen 1995), and are referred to as 'run-away TTS' (raTTS). Armitage & Clarke (1997) have studied the effect of close encounters on circumstellar disks and predict that ejected raTTS will very rapidly turn into wTTS without $H\alpha$ or near-IR excess, but should be detectable at $\geq 5\ \mu m$ from outer disk material. Such transition systems should rotate with periods similar to cTTS.

Many raTTS are expected to have been ejected with velocities larger than just a few $km\ s^{-1}$, so that this mechanism can easily explain the appearance of very young (10^5 to 10^7 yr old) TTS many degrees away from clouds.

Ejected raTTS are expected to show peculiar kinematics. For example, raTTS south of the Taurus clouds should have proper motions indicating that they are currently moving to the south relative to the motion of the Taurus cloud complex as a whole. Among the 17 lithium-excess stars in our sample south of Taurus that have known proper motions from Frink et al. (1997), none are moving south relative to Taurus. The catalogs from which these proper motions were extracted (STARNET and PPM) are magnitude-limited, and, hence, are biased against low mass stars. However, raTTS should be more frequent among the lowest-mass TTS, but may be less frequent among G- and K-type TTS (Sterzik & Durisen 1995), which constitute the majority of our sample. At face value, our data would therefore seem to suggest that there are less than ~ 10 % raTTS among PMS stars outside molecular clouds.

Of the lithium-excess stars south of Taurus with proper motions from Frink et al. (1997), six have RV very different from the mean of Taurus or Orion, but all six share the Taurus proper motion. Hence, their 3D space motions are consistent with them having been ejected from Taurus along the line of sight. Interestingly, their RV are all *smaller* than the mean of Taurus, indicating that they are moving towards us, relative to the clouds. The probability of this happening by chance is less than 2 %. Instead, we believe that this is simply because if they had been ejected in the opposite direction, we would probably not have detected them, since their greater distance would have made them too faint for detection in the RASS.

One of the stars we identify as a raTTS candidate among our new PMS is RXJ0511.2+1031. It is a K7 star with $H\alpha$ emission (M97) and W_λ(Li) = 0.65Å (the largest in M97). It is located in the λ Ori region. If it originated in Orion, it is now moving towards us with a velocity of $\sim 10\ km\ s^{-1}$ relative to the Orion SFR. This velocity converts to ~ 10 pc per million yrs, so that the star should still be more distant than ~ 400 pc if it originated in λ Ori at ~ 450 pc. Unfortunately, its proper motion has not yet been measured. Our repeated high-resolution spectra show no indications of binarity, and Sterzik et al. (1997) found no visual companions down to $0.6''$ separation and ΔR up to 7 mag. The small observed rotational velocity of only $\sim 5\ km\ s^{-1}$ for this star is consistent with the predictions for recently ejected raTTS (Armitage & Clarke 1997). This star has $V \simeq 14$ mag (from the GSC), while many other stars in our sample have $V \simeq 11$ to 12 mag (M97). Such a difference in brightness is expected for a difference in distance between Taurus and Orion.

Although there may be a few raTTS in our sample, it would be surprising if most of the new PMS stars found outside molecular gas regions were ejected raTTS, simply because of their large numbers. For example, there are as many new PMS stars in Chamaeleon off the clouds as there are on the clouds (Alcalá et al. 1995), so that the star formation efficiency and ejection rate would have to be very high. Accurate 3D kinematics, as well as an investigation of the rotational periods and spectral energy distributions along with binary statistics on larger samples, may eventually prove or disprove raTTS predictions.

6.4. *Can TTS form in small, turbulent cloudlets ?*

If cloud complexes are sufficiently turbulent, one would expect there to be small cloudlets scattered around the SFRs. These cloudlets could give birth to small groups of TTS, and may subsequently disperse. Stars formed in such cloudlets should show nearly identical 3D velocity vectors. This mechanism was proposed by Feigelson (1996) to explain the existence of young ROSAT source counterparts found at large distances from the regions of on-going star formation in Taurus and Chamaeleon.

Our data may have some bearing on this issue. As seen in Fig. 8, two of our lithium-excess stars are located near MBM16, and one other is quite close to MBM18 (= Lynds 1569). However, the RV of these clouds (as given by Magnani et al. 1996b) are different from those of the nearby lithium-excess stars, so we cannot conclude that these stars belong kinematically to these clouds. It is still possible, though, that they formed in these clouds but were subsequently ejected. And we cannot rule out that these clouds will form stars in the future. We find no evidence for star formation in cloudlets that have since dispersed, as represented by small remnant groups of TTS with similar velocity vectors. Apart from the lithium-excess stars which cluster on λ Ori, there are no small groups of stars seen in Fig. 8 with spatial clustering and/or parallel 3D motion.

It is not clear whether such small cloudlets as proposed by Feigelson (1996) can support star formation. Small clouds with masses typically around 10 $M_\odot$ may be gravitationally unbound and never form stars. Even in the high-latitude translucent cloud MBM40, with a mass of $\sim 40 M_\odot$, there is no evidence for star formation either in progress or recently completed (Magnani et al. 1996a).

As already pointed out by Feigelson (1996), one should expect different levels of lithium-excess and PMS stars of different ages to be mixed together in such populations outside cloud regions, namely, older PMS stars which dispersed slowly out of the clouds, young PMS stars that possibly formed in the cloudlets, and raTTS. Unfortunately, this mixing complicates the situation considerably.

6.5. *Are our stars yellow excess stars ?*

From data in Table 1 for lithium-rich off-cloud stars excluding upper limit measurements and stars on λ Ori, we find nine K-type stars (first group in Table 1), clearly young ($\leq 3 \cdot 10^7$ yrs old) PMS stars with lithium at least as strong as K-type stars in IC 2602. We also find 15 G-type stars (third group in Table 1) with lithium comparable with IC 2602 stars, i.e. ZAMS stars with ages of $\sim 3 \cdot 10^7$ yrs. Also, we find 15 stars (last group in Table 1 excluding one star on λ Ori) with lithium below the upper envelope of the Pleiades, which are probably also ZAMS stars of the same age as the Pleiades, i.e. $\sim 10^8$ yrs old. Hence, most of our lithium-rich stars are ZAMS stars, though not all of these ZAMS stars have the same age.

With follow-up observations of *Einstein Observatory* sources, Gioia et al. (1984) and Micela et al. (1993) found more young late-type stars ('yellow excess') than expected from galactic models (Favata et al. 1992). Similary, Tagliaferri et al. (1994) found such an excess in young stars among EXOSAT X-ray sources. Based mainly on the lithium abundance, these yellow excess stars cannot be older than the Pleiades and some actually are PMS stars (Fleming et al. 1988, Favata et al. 1993, 1995, Schachter et al. 1996). ROSAT extreme UV samples also yield similar results (Hodgkin & Pye 1994, Jeffries 1995).

Most of these yellow excess stars are young F- and G-type stars. Our (late F- and) G-type lithium-excess stars, classified here as $\sim 3 \cdot 10^7$ yr old ZAMS stars, are also such yellow excess stars. However, our K-type lithium-excess stars, classified here as $\leq 3 \cdot 10^7$ yr old PMS stars, are different from yellow excess stars – as far as both spectral types and spatial distribution are concerned. While our PMS stars are near the Taurus SFR and on the Gould Belt, the yellow excess stars are located at high galactic latitude, but otherwise randomly scattered, i.e. they neither trace SFRs nor the Gould Belt. We expect there to be fewer PMS stars in the *Einstein Observatory* and ROSAT WFC off-cloud samples than in the W96, A96, and M97 RASS samples, because the RASS studies – including this work – investigate areas on or near SFRs and the Gould Belt, where there are more young and active stars.

Under the assumption of continuous star formation in the solar neighbourhood out to a few hundred parsecs, one would expect there to be ten times more 10^8 yr old stars than 10^7 yr old stars. Briceño et al. (1997, henceforth B97) have argued that most of the lithium-rich ROSAT source counterparts are 10^8 yrs old stars, rather than PMS stars. This is not quite in agreement with our results.

The B97 model is able to predict the distance distribution of X-ray active ZAMS stars per spectral type bin. As seen in their Fig. 5b, the G-type stars, which constitute the majority of the actually observed ROSAT counterparts, should have distances peaking at 130 to 140 pc. Their contention is that the ages for the RASS sources are underestimated due to an erroneuos distance assumption. However, the peak of their distribution is not far from the actual distance of the nearby SFR anyway, so if one assumes a distance according to the predictions of their model, the location in the HR diagram of RASS counterparts with known spectral types puts them clearly above the ZAMS (see Alcalá et al. 1997 for Chamaeleon, Bouvier et al. 1997 for central Taurus, and Wichmann et al. 1997a for Lupus). These two facts are difficult to reconcile, and suggest an inconsistency in the B97 model.

Palla & Galli (1997) have pointed out recently that continuous star formation cannot last as long as assumed by B97, because processes such as ambipolar diffusion cannot support star formation for that long. Therefore, the predicted number of

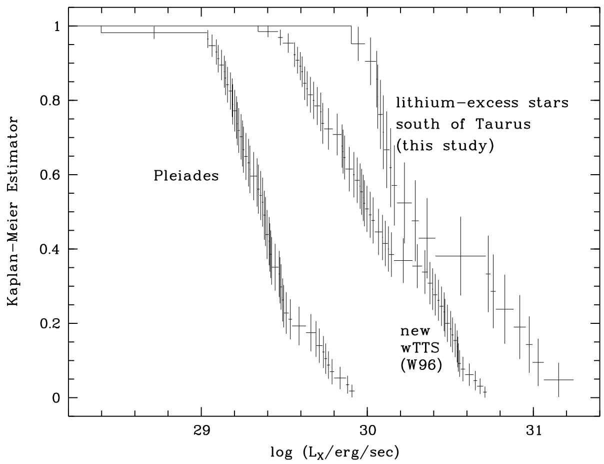

Fig. 9. X-ray luminosity functions. Plotted are the Kaplan-Meier estimators versus the X-ray luminosities log L_X in $erg\ s^{-1}$, for lithium-excess stars in our sample, RASS-detected new wTTS in central Taurus (W96), and RASS-detected Pleiades stars.

stars older than a few million years is probably overestimated. However, the Palla & Galli (1997) calculations do not rule out that the star formation process can last for as long as a few times 10^7 yrs, the typical age we find for the new PMS stars presented here.

The dependence of L_X on stellar age adopted by B97 is derived by linear interpolation between two reference points, Taurus TTS and Pleiades. We believe this approximation may have biased their estimate of the number of lithium-rich, X-ray active ZAMS stars in the field, since X-ray luminosities actually remain roughly constant up to ages of almost 10^8 yrs, rather than dropping sharply from TTS to Pleiades stars. The B97 assumption will lead to an overestimate of the number of $\sim 10^8$ yr old ROSAT sources, and to an underestimate of the number of 10^7 yr old ROSAT sources.

In our sample of pre-selected TTS candidates among ROSAT sources, we find only twice as many $\sim 10^8$ yr old stars as $\sim 10^7$ yr old stars, inconsistent with constant or continuous star formation, but instead indicating a recent episode of star formation. Also, neither our lithium-excess stars nor pre-selected TTS candidates seem to be distributed symmetrically around the galactic plane – as expected according to B97 – but instead appear to trace the SFRs along the Gould Belt (Sterzik et al. 1995, Wichmann et al. 1997b). Further discussion on the B97 model is given by Neuhäuser (1997).

6.6. *The X-ray luminosity function*

In this section we investigate the X-ray luminosities L_X of our lithium-excess stars as compared to well-known TTS and the Pleiades. The X-ray fluxes of all our stars are listed in M97; for the two stars from A96 in our sample, we convert the count rates given in A96 to fluxes using the method explained in N95b. The conversion from fluxes to X-ray luminosities requires an estimate of the distance, which is not known a priori for our stars. Hence we turn the problem around, and we use the X-ray luminosity distribution function (XLF) to put constraints on the typical distance of the new lithium-excess stars.

To begin with, we computed the Kaplan-Meier estimators for our lithium-excess stars by assuming, as a working hypothesis, a distance of 140 pc; we used the ASURV statistical software package (Feigelson & Nelson 1985). We compare in Fig. 9 the resulting XLF with that of newly discovered wTTS in central Taurus (W96). Many of these are projected onto, or lie close to cloud material, so that for those stars the adoption of a 140 pc distance is justified; also, Frink et al. (1997) found, that the W96 stars have proper motions consistent with Taurus membership. Also shown is the XLF for the Pleiades, assumed to be at 120 pc. For computing the XLF of our lithium-excess stars south of Taurus, we use only the stars in groups 1 and 3 of Table 1, i.e. we exclude the stars located at λ Ori, as they may be more distant than $\sim$ 140 pc.

If we now try to adjust the distance of the lithium-excess stars to match the Pleiades XLF, under the assumption that our stars are similar in age and should therefore have a similar XLF as the Pleiades, we find that this leads to a distance of only 49 pc. This is inconsistent with the indication, from observed X-ray hardness ratios, that the spectra of our stars show absorption by interstellar material, implying a considerably larger distance. Two-sample tests show that the population of new lithium-excess stars has X-ray hardness ratios indistinguishable from those of previously known wTTS, while the Pleiades are essentially unabsorbed, as far as their X-ray spectra are concerned. These differences are supported by our finding of excess lithium strength in our stars compared to the Pleiades, which is inconsistent with an age as high as $\sim 10^8$ yrs. A distance of 49 pc would also be inconsistent with the predictions from the B97 model for $\sim 10^8$ yr ROSAT source counterparts. Carkner et al. (1997) found that the VLA radio luminosity function of the W96 and N95c stars can be made to match the ZAMS radio luminosity function only if the new stars were placed at $\sim$ 40 pc, which again can be ruled out from the X-ray hardness ratios.

6.7. *The Gould Belt scenario*

The Gould Belt (Gould 1874) was recognized long ago as a band of O-, B-, and early A-type stars inclined by some 18° to the galactic plane, and within $\sim$ 1 kpc of the Sun. Age estimates yield up to $\sim 6 \cdot 10^7$ yrs. The age of the Belt is the upper limit to the age of its stars. If star formation in the Belt has been continuous, then the mean age of its members should be half the Belt's age, i.e. $\sim 3 \cdot 10^7$ yrs. Several clouds such as Sco-Cen-Lup and ρ Oph appear to be part of this Belt. The origin of this structure is still a matter of debate, and for more details we refer the reader to reviews by Stothers & Frogel (1974) and Comerón (1996). It appears unlikely that both the Orion and Taurus complexes are part of the Belt, since they are located next to each other - as projected onto the sky – but at very different distances of $\sim$ 450 pc and $\sim$ 140 pc, respectively.

Indicated in Fig. 8 is the mid-plane of the Gould Belt. Its width is 10 to 15° (Comerón et al. 1994). All but two of our lithium-excess stars lie on the Gould Belt. Thus, it is possible that some of them are indeed $\sim 3 \cdot 10^7$ yr old members of the Gould Belt. Several stars with weak lithium absorption (but no excess) lie in the strip indicated in the lower right of Fig. 8. These stars have very weak lithium (hence, are $\sim 10^8$ yrs old, i.e. older than the Belt) and may constitute the population predicted by B97.

Krautter et al. (1997) and Wichmann et al. (1997a, 1997b) came to a similar conclusion regarding membership to the Gould Belt: They found many wTTS in and near the Lupus clouds, as well as scattered throughout the part of the Gould Belt near Lupus, but no lithium-rich stars outside the Belt. They did not find any stars with weak lithium absorption comparable to the ZAMS level, but this may be due to their spectral resolution, $\sim$ 2 to 3Å, which is too low to detect ZAMS stars with weak lithium. Fresneau et al. (1996) also found a few lithium-rich late-type stars in a proper motion selected search for members of the Gould Belt.

6.8. *A high-velocity cloud impact*

Whether or not the Taurus clouds are part of the Gould Belt, they are located south of the galactic plane and may have originated by a high-velocity cloud (HVC) impact (e.g. Franco et al. 1988, Lépine & Duvert 1994). This may provide an alternative explanation for the spatial distribution and kinematics of our lithium-excess stars. If a HVC impacted from the north side onto the galactic plane, then stars formed in this event would first move south, and then fall back down to the plane. Subsequently, the clouds and stars would oscillate around the plane. Since the Taurus clouds and their TTS are moving south, we conclude that this structure is not falling back.

Alternatively, the HVC might have hit the plane coming from the south, formed stars, and reversed its direction. Following Lépine & Duvert (1994), we then have the following scenario: The HVC hit the plane coming from the south and formed stars; clouds and stars reversed their direction and fell back onto the plane. While the clouds feel the friction from galactic plane material, the stars do not, so that they effectively got separated from their parent cloud (combing-out effect).

From the galactic gravitational potential (e.g. Stothers & Tech 1964) and the observed velocity of the Taurus clouds and associated TTS (4 $km\ s^{-1}$ to the south, away from the galactic plane) and their location (40 pc south of the plane), it is possible to infer the dynamics of the oscillations around the galactic plane. Assuming negligible resistance from interstellar material, the cloud passed through the galactic plane $\sim 8 \cdot 10^6$ yrs ago, and the maximum distance from the plane that will be reached is $\sim$ 65 pc, i.e. 25 pc south of the present Taurus cloud center. The combing-out of stars by passing through the galactic plane takes place every 3 to $4 \cdot 10^7$ yrs (c.f. Jones & Herbig 1979).

The stars that we observe south of the Taurus clouds may be those stars that were separated from their parent clouds during the last passage of the Taurus clouds through the galactic plane. They formed when the HVC hit the galactic plane coming from the south, which – given the calculation above – happened $\sim 3 \cdot 10^7$ yrs ago, consistent with our age estimate for the lithium-excess stars. We find these stars on average at $\delta \simeq 10°$, i.e. $\sim$ 10° south of the Taurus cloud center. At a distance of 140 pc, ten degrees correspond to 25 pc, i.e. exactly where the Taurus clouds and their TTS would reverse their oscillatory motion around the galactic plane. Stars just reversing their motion should show negligible proper motion. This can be tested using the proper motions listed by Frink et al. (1997). Although, as stated above, many of the lithium-excess stars do roughly share the mean Taurus (and/or Cas-Tau) proper motion, their mean proper motion in the north-south direction is $\mu_\delta = -9.7 \pm 2.1$ mas yr^{-1}, while the mean proper motion in the north-south direction of previously known TTS in central Taurus is -19.7 ± 1.6 mas yr^{-1}, i.e. significantly different. These data are consistent with the southernmost PMS stars being about to reverse their motion. We note that such a combing-out effect may also be observable in other SFRs, if they formed by HVC impacts. For example, Alcalá et al. (1997) do not observe new PMS stars in the eastern part of their study area surrounding the Chamaeleon clouds, as expected from the HVC impact scenario (Lépine & Duvert 1994).

7. Conclusions

We have obtained high-resolution spectra of 106 X-ray active late-type stars south of the Taurus clouds with the following results:

1. We find 33 stars south of Taurus with lithium stronger than Pleiades members of similar rotational velocity and spectral type. These stars display the spectral signatures typical of weak-line TTS. They include 15 late F- and G-type stars with lithium comparable to G-type IC 2602 stars, i.e. which may have already arrived on the ZAMS. Nine other stars show large lithium excess and are located in the λ Ori area, a region of ongoing star formation. These are PMS stars, possibly associated to that region. The remaining nine lithium-rich stars south of Taurus have spectral type K and lithium at least as strong as IC 2602 stars; these nine stars are also PMS stars, but are located far from any cloud.
2. Roughly $\sim$ 30% of lithium-rich ROSAT source counterparts show lithium as weak as $\sim 10^8$ yrs old stars (namely 16 stars, as listed in the last group in Table 1, among a total of 49 stars with detected lithium). Such stars are distributed all over the area studied, and therefore also outside the Gould Belt. This population may constitute the large ZAMS population expected by Micela et al. (1993) and also Briceño et al. (1997). However, we find in our pre-selected sample only twice as many 10^8 yr old stars as 10^7 yr old stars, indicating a recent epsisode of star formation.
3. If the young stars found far south of the Taurus molecular clouds did not form locally but in central Taurus, they must have traveled a large distance in their short life-times. The observed radial velocity dispersion of a few $km\ s^{-1}$ is consistent with the assumption that they have moved up to 20° in $\leq 10^7$ yrs. The new PMS star RXJ0511.2+1031, with spectral type K7 and a large lithium excess, may well be a

very young raTTS recently ejected from its birth place in λ Ori.

4. Most stars in our sample with lithium at least as strong as in IC 2602 stars are found projected onto the Gould Belt. We conclude that many of these may well be Gould Belt members, i.e. $\sim 3 \cdot 10^7$ yrs old. A few, however, are much younger.
5. Finally, our CASPEC echelle spectra have provided a precise measure of the W_λ(Li) of seven stars, and by comparison with previously obtained intermediate (mostly 0.7 - 1.5Å) and/or low resolution (2.5Å) data, we confirm that lithium equivalent widths can be overestimated in spectra with insufficient spectral resolution. We find that a resolution of about 1 Å is high enough to obtaining accurate W_λ(Li) values.

Unfortunately, with the data in hand it is not possible to distinguish unambiguously between (a) old and slowly drifting post-TTS; (b) Gould Belt or Cas-Tau members; (c) rapidly moving raTTS coming from either Orion, Taurus, or even the former Cas-Tau clouds; or (d) young TTS formed in turbulent cloudlets. To do this would require either measuring their distance precisely in order to place them correctly on the HR diagram, or determining accurate ages by other means. While the radial velocities presented here should be sufficiently precise, proper motions with better precision than those in Frink et al. (1997) are needed in order to trace the 3D space motion of these lithium-rich stars back to their place of origin.

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