Pre-main sequence lithium burning

I. Weak T Tauri stars

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Abstract. We report high-resolution spectroscopic observations for a sample of 38 T Tauri stars (TTS), complemented by UBVRI photometry of 13 TTS, and CCD VRI photometry for 2 visual binaries. Based on these observations and data taken from the literature, we derive lithium abundances in 53 TTS, concentrating on weak-line TTS (WTTS). The sample spans the range in spectral types from K0-M3, approximated to masses between 1.2 and 0.2 M⊙.

Our study of the statistical distribution of lithium abundances in WTTS gives the following results: (1) At luminosities \( \geq 0.9 \, L_\odot \) the Li abundances are remarkably uniform. The mean value, \( \log N(\text{Li})=3.1 \), coincides with the “cosmic” lithium abundance. (2) We find strong evidence for PMS lithium burning. Significant Li depletion appears below 0.5 \( L_\odot \) in the mass range 0.9-0.2 M⊙ and increases towards lower luminosities. Current theoretical evolutionary models do not seem to fit consistently the observed pattern of Li abundances in the whole mass range. In particular, at the lower mass end (0.4-0.2 M⊙), the observed luminosity of the Li burning turning point is about a factor 4

*Based on observations made with the William Herschel, Isaac Newton and Jacobus Kapteyn telescopes, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.
higher than predicted by the models. At masses 1.2-1.0 \( M_{\odot} \) the observations imply less PMS Li burning than theoretically expected.

Investigation of a possible relation between lithium and rotation in TTS shows that:
(1) Low Li abundances appear only among stars with low \( v \sin i \). Fast rotators with masses around 0.8 \( M_{\odot} \) do not show evidence for strong Li depletion towards lower luminosities as slow rotators do. (2) In a sample restricted to only K5-K7 stars with photometrically measured rotational periods, we find that the angular momentum spread before Li burning begins is larger than a factor 10.

Lithium depletion associated to angular momentum loss during PMS evolution is not required to explain the observed abundances. The observations suggest that the efficiency of PMS Li burning in the mass range 0.9-0.7 \( M_{\odot} \) is reduced in the presence of rapid rotation.

Key words: stars: pre-main sequence – stars: late-type – stars: abundances – stars: rotation – convection

1. Introduction

The presence of the Li I resonance line has usually been a useful criterion for identifying low-mass pre-main sequence (PMS) stars (Walter et al. 1988, Martín et al. 1992a, Pallavicini et al. 1992, Bouvier & Appenzeller 1992). Low-mass stars spend their first few million years of life as T Tauri stars (TTS), and gradually evolve into post T Tauri stars (PTTS), which represent a longer, yet scarcely observed (Jones & Herbig 1979), phase of evolution.

T Tauri stars are commonly divided in two subtypes: classical TTS (CTTS), which generally accommodate to the original criteria defining the T Tauri class (Herbig 1962), and weak TTS (WTTS), which lack most of the properties typical of the CTTS. However, the distinction between CTTS and WTTS is sometimes complicated because the emission lines span a continuous range of strengths and are usually variable. Furthermore, there is a region in the Hertzsprung-Russell (H-R) diagram where CTTS and WTTS are mixed, which corresponds to totally convective PMS Hayashi tracks. In the region of the H-R diagram closer to the main-sequence, on the radiative PMS Henyey tracks, only WTTS and PTTS are found (e.g. Martín et al. 1992a).

Theoretical evolutionary models face considerable uncertainties to theorize the evolution of PMS stars (cf. Mazzitelli 1989). Observations of lithium abundances in TTS are
a test to PMS models because they can be confronted with Li depletion predictions. The problem of Li burning has been considered in a number of theoretical papers, from the pioneering work of Bodenheimer 1965, to recent papers, e.g., Pinsoneault et al. 1990, Swenson et al. 1990 and D’Antona & Mazzitelli 1993. The importance of Li depletion in PMS stars is not only limited to PMS evolution itself, but it has far-reaching implications. For example, in the calibration of Li depletion mechanisms on the main-sequence (gravity waves, diffusion, winds, etc), the evolution of lithium in the Galaxy (the initial Li content of TTS is a measurement of the current Li abundance in molecular clouds), and the identification of substellar objects (preservation of Li in the brown dwarf regime, Rebolo et al. 1992, Magazzù et al. 1993a).

From an observational point of view, the high resolution spectroscopic data needed for performing lithium abundance studies in large samples of TTS have only recently become available (Magazzù & Rebolo 1989 and Strom et al. 1989a). Strom et al. made a comparative study of Li I λ670.8 nm equivalent width measurements in TTS and αPer cluster members (age ≈ 50 Myr). Their main results were: (1) The maximum Li abundances found in TTS were at least 0.3 dex. higher than the maximum abundances in αPer stars, implying that either (a) there is significant PMS Li depletion in stars more massive than the Sun, or (b) the molecular clouds associated to TTS are lithium rich with respect to αPer. (2) For TTS less massive than the Sun the scatter in Li abundances was about 1 dex., but no correlation of Li with age and mass was found. In a more recent work Basri et al. 1991 showed that the Li abundances of Strom et al. 1989 had to be taken with extreme caution because of the high uncertainties involved in the analysis. The main sources of uncertainty were veiling corrections, effective temperatures and the details of the abundance analysis procedure.

Very recently Magazzù et al. 1992 improved the analysis of Li abundances in TTS, and reached the following conclusions: (1) The initial Li abundance of TTS is log N(Li)=3.2±0.2 (in the usual scale of log N(Li) = 12 + log(N_{Li}/N_{H})), in agreement with the cosmic Li abundance (interstellar medium, young clusters, meteorites). (2) There are hints of correlations between Li abundance, age and mass, but, unfortunately very few stars in their sample showed Li depletion, preventing detailed comparison with model predictions.

The latest published work on lithium in TTS is that of King 1993. His PMS stars belong to Orion Ic and have higher masses than previous works (1.5-2.8 M\(_{\odot}\)). King obtains Li abundances in the range 4.1≥log N(Li)≥1.2, and interprets these results in terms of PMS Li depletion, with initial abundance of order log N(Li)=4. However, King’s abun-
dances have been estimated from curves of growth published by Strom et al. 1989a, which have been shown to be inadequate by the considerations in Duncan 1991 and Magazzù et al. 1992. Hence, the results of King 1993 are probably affected by systematic effects.

The value of the initial lithium abundance of T Tauri stars remains controversial, and the details of when lithium depletion starts and how it proceeds with PMS evolution are still to be addressed by the observations. We have tried to approach these problems by concentrating our observations on WTTS, because of a number of reasons: (1) They have not been studied in detail by previous works, which mainly dealt with CTTS. (2) They are free from optical veiling effects which are a source of uncertainty in CTTS (Basri & Batalha 1990, Basri et al. 1991). (3) Their spectral types are more reliable than those of CTTS. (4) Their atmospheres are in a state near to equilibrium (Finkenzeller & Basri 1987). (5) Their positions in the H-R diagram are little affected by uncertain corrections of disk luminosity. (6) They occupy a a wider space in the H-R diagram than CTTS do. Therefore, the study of WTTS can be more informative and reliable, and possibly a necessary step towards understanding the complexity of the CTTS.

The Li abundances in WTTS presented in this paper provide clues about the initial conditions of PMS Li burning. In the next paper of this series (García López et al. 1993, Paper II) we will explore the final conditions of PMS Li burning through the study of Li abundances in low-mass members of the Pleiades cluster.

2. Observations

2.1. Program stars

Our sample has been selected from the Herbig & Bell 1988 catalogue (hereafter HBC). Usually WTTS are separated from CTTS attending to the observational criterion of Hα equivalent width less than 10 Å. The lack of a full physical understanding of the differences between the two subclasses of T Tauri stars prevents the definition of a clear borderline between them. Hence we chose to observed mainly TTS with small Hα equivalent width because we intended to focus on WTTS which had no lithium measurements at high resolution. Our limiting red magnitude was set at R≈14, and we only took stars with spectral type later than G0 and declinations higher that -20°. Thus, the bulk of the WTTS observed by us are in the Taurus star-forming region. There are no other selection

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10 Å = 1 nm, 10 mÅ = 1 pm. Following the recommendations of the Executive Committee of the IAU, we adopt the units of the International System.
effect in our sample apart from those exposed above and those inherited from the surveys where the stars were discovered (for instance bias towards strong X-ray emitters).

For the photometric observations we chose WTTS in the HBC that lacked a complete set of UBVRI colors. Our aim was to derive the bolometric luminosities from our own photometric data with the ultimate goal of placing the WTTS in the HR diagram. Most of the stars observed photometrically were also observed spectroscopically.

2.2. Spectroscopy

Spectroscopic observations were conducted during three runs at the 2.5 m Isaac Newton telescope (INT), two runs at the 4.2 m William Herschel telescope (WHT), and one run at the 2.5 m Nordic Optical Telescope (NOT). A summary of the observing log is presented in Table 1. The name of the star in column 1 is that of the first name given in the HBC. Two stars are grouped together if they were observed simultaneously along the slit, i.e. they have angular separations between 2 and 120′. The time (in seconds) in column 3 is the total exposure time on the object, i.e. summing up the times of successive exposures. In column 4 we listed the telescope where the observation was made. The instrument used at the INT was the Intermediate Dispersion Spectrograph, while at the WHT we used ISIS (Unger et al. 1988), and at the NOT we employed the echelle spectrograph IACUB (McKeith et al. 1993). The various nominal dispersions and wavelength coverages in column 5 and 6 respectively, result from different combinations of gratings, cameras and CCD detectors. The FWHM effective resolutions are in the range 0.02 to 0.075 nm. When the spectral range was 21.2 nm or greater we could observe simultaneously Hα and the LiI \(^{\lambda} 670.8\) nm region (see Figures 1 to 3), but when it was smaller we missed Hα (see Figure 4). The last column of Table 1 provides an estimate of the final signal to noise ratio achieved on each object. The S/N is probably underestimated for the M-type stars because the true continuum is depressed by molecular absorption.

The data reduction was made with standard procedures available from the IMRED and the TWODSPEC packages in IRAF. Each image was de-biased, flat fielded, and background subtracted. The spectra were wavelength calibrated using exposures of a CuAr lamp taken after each object frame. The rms of the third order polynomial dispersion solutions were lower than 0.001 nm.

\(^2\)IRAF is distributed by National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
Table 1. Spectroscopic Observations

| Name                | Date       | Exp | Tel. | Disp. (nm pix$^{-1}$) | Range (nm) | S/N |
|---------------------|------------|-----|------|------------------------|-------------|-----|
| HBC                 |            |     |      |                        |             |     |
| V819 Tau            | 08.03.90   | 1800| INT  | 0.022                  | 13.0        | 50  |
| CZ,DD Tau           | 09.03.90   | 1800| INT  | 0.036                  | 21.2        | 50,80 |
| 040234+2143         | 10.03.90   | 1800| INT  | 0.022                  | 13.0        | 50  |
| 040047+2603W,E      | 27.12.90   | 3600| WHT  | 0.037                  | 43.7        | 30,35 |
| 041559+1716         | 27.12.90   | 2400| WHT  | 0.037                  | 43.7        | 105  |
| V927 Tau            | 28.12.90   | 3600| WHT  | 0.037                  | 43.7        | 35   |
| Anon 1              | 28.12.90   | 3000| WHT  | 0.037                  | 43.7        | 75   |
| V710 Tau A,B        | 29.12.90   | 1600| WHT  | 0.037                  | 43.7        | 40,35 |
| IS Tau              | 30.12.90   | 1800| WHT  | 0.037                  | 43.7        | 60   |
| 1E0255+2018         | 30.12.90   | 900 | WHT  | 0.037                  | 43.7        | 95   |
| V807,GH Tau         | 31.12.90   | 1200| INT  | 0.036                  | 21.2        | 50,130,50 |
| V928 Tau            | 31.12.90   | 2800| INT  | 0.036                  | 21.2        | 70   |
| Wa Tau/1            | 31.12.90   | 1200| INT  | 0.036                  | 21.2        | 200  |
| 035120+3154SW,NE    | 31.12.90   | 1200| INT  | 0.022                  | 13.0        | 80,80 |
| 042916+1751         | 31.12.90   | 1200| INT  | 0.036                  | 21.2        | 70   |
| V773 Tau*           | 02.01.91   | 1200| INT  | 0.022                  | 13.0        | 150  |
| Hubble 4            | 03.01.91   | 1200| INT  | 0.022                  | 13.0        | 80   |
| HV Tau              | 05.01.92   | 3600| INT  | 0.022                  | 13.0        | 50   |
| 035135+2528NW,SE    | 23.01.92   | 1500| INT  | 0.037                  | 46.8        | 80,100 |
| 040142+2150SW,NE    | 23.01.92   | 1800| INT  | 0.037                  | 46.8        | 20,20 |
| 040012+2545N,S      | 24.01.92   | 1200| INT  | 0.037                  | 46.8        | 50,50 |
| 042835+1700         | 24.01.92   | 1500| INT  | 0.037                  | 46.8        | 80   |
| 042835+1700         | 24.01.92   | 1500| INT  | 0.037                  | 46.8        | 80   |
| 28.02.93            | 1000       | WHT | 0.037 | 47.3        | 100        |
| 045251+3016         | 24.01.92   | 1400| INT  | 0.037                  | 46.8        | 110  |
| LkCa21              | 24.01.92   | 1800| INT  | 0.037                  | 46.8        | 90   |
| 032641+2420         | 17.12.92   | 3600| NOT  | 0.014                  | 4.8         | 35   |
| BD+24.676           | 17.12.92   | 1800| NOT  | 0.014                  | 4.8         | 90   |
| 041529+1652         | 28.02.93   | 1000| WHT  | 0.037                  | 47.3        | 100  |
| 043124+1824         | 28.02.93   | 1000| WHT  | 0.037                  | 47.3        | 100  |

Note: (*) V773 Tau was re-observed five times with same exposure time and resolution on the nights from 3 to 5 January 1992.
In Fig. 1 we display the spectra of program stars observed at the WHT. Note that the position of the Li I λ670.8 nm line is marked. We have ordered the stars in this and the following figures from earlier to later spectral type (downwards). Note the absence of the Li I resonance line in the spectra of the two components of the visual binary NTTS040047+2603. In Fig. 2 and Fig. 3 we display in a similar fashion spectra obtained at the INT. Note that Wa Tau/c and NTTS042835+1700 show double lines (see individual remarks at the end to this section). In Fig. 4 we present our higher resolution spectra. Note that V773 Tau has strongly asymmetric line profiles. Due to the scarcity of known double-lined spectroscopic binaries among T Tauri stars (Mathieu et al. 1989), the finding that NTTS042835+1700 and V773 Tau are likely to be such binaries is of special interest and requires further observational effort to determine the orbital parameters.

2.3. Photometry

Broad band UBVRI photometry in the Johnson-Cousins standard system was obtained at the 1 m Jacobus Kapteyn telescope. We used the People’s photometer (cf. Martín et al. 1992a and references therein) for 13 stars and the CCD camera for 2 close visual binary systems. In Table 2 we have listed the Julian dates, visual magnitudes and colors of the objects observed with the photoelectric photometer, and in Table 3 we give the results from the CCD photometry. The visual binaries HV Tau and V710 Tau have angular separations smaller than 10′′ (see next subsection for more comments). An account of our CCD photometric observations of close visual pre-main sequence binaries is given elsewhere (Martín 1993a).

2.4. Remarks on individual stars

A by-product of our observations is varied information on stars with different peculiarities.

1. **CZ Tau and DD Tau**: This couple of TTS (separation ∼ 1′) have very different spectral properties. CZ Tau is a WTTS while DD Tau is a CTTS. Gómez de Castro & Pudritz 1992 have drawn attention on DD Tau because it may be the first case where the forbidden line emission region of a T Tauri wind has been resolved into focal nodes. We find that the radial velocity (in the local standard of rest) obtained from the Li I resonance line in the spectrum of DD Tau is 27±5 km s^{-1}, while that of CZ Tau is 11±6 km s^{-1}. The radial velocity of the molecular cloud around DD Tau is 6.7 km s^{-1} (Edwards & Snell 1982). Hence, the radial velocity of DD Tau shows a significant discrepancy with respect to the cloud. This could be an indication that DD Tau is a spectroscopic binary, but should be confirmed by monitoring of radial velocity variations. We also note that
### Table 2. Photometric Observations

| Object     | J.D.   | V     | U-B  | B-V  | V-R  | V-I  |
|------------|--------|-------|------|------|------|------|
| 1E0255+2018| 260.359| 11.99 | 0.89 | 1.19 | 0.72 | 1.37 |
|            | 260.364| 11.99 | 0.88 | 1.21 | 0.72 | 1.38 |
|            | 261.390| 12.01 | 0.89 | 1.19 | 0.72 | 1.38 |
|            | 262.395| 12.02 | 0.87 | 1.16 | 0.70 | 1.35 |
| V773 Tau   | 260.377| 10.88 | 1.11 | 1.36 | 0.86 | 1.70 |
|            | 261.395| 10.82 | 1.12 | 1.32 | 0.85 | 1.69 |
|            | 262.431| 10.87 | 1.13 | 1.35 | 0.86 | 1.69 |
|            | 263.563| 10.84 | 1.12 | 1.38 | 0.86 | 1.71 |
| V807 Tau   | 260.385| 11.22 | 0.27 | 1.23 | 0.82 | 1.69 |
|            | 263.440| 11.27 | 0.48 | 1.25 | 0.82 | 1.69 |
| Hubble 4   | 260.402| 12.74 | 1.16 | 1.59 | 1.06 | 2.18 |
|            | 263.433| 12.75 | 1.38 | 1.55 | 1.07 | 2.16 |
| Anon 1     | 260.415| 13.52 | 1.61 | 1.79 | 1.24 | 2.54 |
|            | 262.436| 13.56 | 1.64 | 1.75 | 1.24 | 2.53 |
| LkCa14     | 260.425| 11.68 | 1.01 | 1.23 | 0.72 | 1.39 |
| IS Tau     | 261.439| 15.44 | 2.10 | 1.46 | 2.87 |
| V928 Tau   | 261.452| 14.02 | 1.79 | 1.21 | 2.50 |
|            | 263.453| 14.07 | 1.52 | 1.73 | 1.22 | 2.49 |
| HV Tau     | 262.448| 14.33 | 1.05 | 1.69 | 1.31 |
|            | 263.446| 14.38 | 1.10 | 1.65 | 1.30 | 2.81 |
| VY Tau     | 262.455| 13.66 | 1.11 | 1.45 | 0.97 |
| St 34      | 262.464| 14.70 | 1.23 | 1.04 |
| FF Tau     | 264.456| 13.96 | 1.75 | 1.82 | 1.18 | 2.35 |
| Wa Tau/1   | 264.543| 10.34 | 0.49 | 0.94 | 0.50 | 0.90 |

Notes: J.D. = Julian Date - 2448000.0. The photometric system is the standard Johnson-Cousins UBVRI. Average errors are less than 0.05 mag., except where marked with "::" for errors between 0.05 and 0.1 mag. and ":::" for errors between 0.1 and 0.3 mag.
Table 3. Photometric Observations (CCD)

| Object       | J.D.  | V   | V-R | V-I  |
|--------------|-------|-----|-----|-----|
| DO Tau       | 272.430 | 13.84 | 1.38 | 2.54 |
| HV Tau A,B   | 272.430 | 14.49 | 1.45 | 3.01 |
| HV Tau C     | 272.430 | 17.25:: | 1.44:: | 2.32:: |
| V710 Tau A   | 336.313 | 14.33 | 1.18 |
| V710 Tau B   | 336.313 | 14.48 | 1.21 |

Notes: J.D. = Julian Date - 2448000.0. The photometric system is the standard Johnson-Cousins UBVRI. Average errors are less than 0.05 mag., except where marked with “::” for errors between 0.1 and 0.3 mag.

in DD Tau the [SII] emission around 673.0 nm (see Fig. 2) is not symmetrical; the blue peak is about 2 times higher than the red one.

2. **V710 Tau A and B**: Cohen & Kuhi 1979 estimate a difference in V of about 1 magnitude between the 2 components of this close visual binary (separation about 3″). We find a much smaller difference (see Tab. 3), which could be an indication that one or both components are highly variable. Our observations (both spectroscopic and imaging) were made under good seeing conditions. Blending of the two components was negligible.

3. **1E0255+2018**: This strong x-ray emitter (Fleming et al. 1989) has been reported to be a close visual binary with nearly-identical components (Martín et al. 1992b). The spectrum in Fig. 2 is the combination of the 2 components because we could not resolve them on the slit.

4. **Wa Tau/1**: Our spectrum reveals that this is a double-lined spectroscopic binary (Fig. 2). We do not detect the Li I line in any of the 2 components. The weak Hα emission may be due to chromospheric activity in a close binary system. In order to test this hypothesis Mathieu 1992 has re-observed this star and reports a short orbital period and center-of-mass velocity inconsistent with membership to the Taurus clouds. Thus, we exclude this star from our analysis.

5. **V773 Tau**: Three of our spectra show asymmetric line-shapes very suggestive of a double-lined pattern almost resolved. In Fig. 4 we present one of the spectra where this is clearly seen. Because of the uncertainty introduced by the different strengths of the photospheric lines of each component, we will not consider this star further in our
analysis of Li abundances.

6. **HV Tau**: It is a triple system composed of two close stars (resolved using speckle techniques) and a fainter visual companion (Simon et al. 1992). We have used our CCD data to derive the luminosity of HV Tau AB. Spectroscopic observations of the faint visual companion (HV Tau C) are under analysis (Magazzù et al. 1993b).

7. **NTTS42835+1700**: New double-lined spectroscopic binary (Fig. 3). The photospheric lines of both components have similar depths. We include this star in our analysis under the assumption that the components are identical. Mathieu 1992 reports that NTTS42835+1700 does not show double lines in 9 spectra he has inspected. In our spectrum of February 1993 (see Table 1) the star is also single lined. This suggest that the binary orbit may have a high eccentricity.

8. **BD+24.676**: The PMS evolutionary status of this star has been contested by Martín 1993b, who shows that it is in fact a spectroscopic binary with one evolved component. Thus, we exclude it from the abundance analysis.

### 3. Analysis

#### 3.1. Equivalent width measurements

In Table 4 we present equivalent widths of Hα (usually in emission), the Li I resonance line and some neighbouring strong absorption lines in the spectra of all program stars except the two DLS binaries V773 Tau and Wa Tau/1 (see remarks in previous section). The equivalent widths of NTTS42835+1700 were measured on the single-lined spectrum.

We estimate an average error bar of 5% in the equivalent width values at 1σ, coming mainly from uncertainty in the continuum placement. The metallic lines could not be accurately measured for spectral types later than about M1 because of the continuum modulation due to deep molecular bands and because they get weaker as the excitation temperature decreases.

We have compared our Li I measurements with those of different authors and find an agreement better than 15% for one star in common with Hartmann et al. 1987 and six in common with Walter et al. 1988. However, for other eight stars in common with the latter authors we find larger discrepancies, mainly in the sense that we obtain smaller equivalent widths. Walter et al. 1988 caution that their measurements are very uncertain, and thus we believe that there is no inconsistency with our results.

Those stars in our sample with Hα equivalent width stronger than -1.50 nm (-15 Å), namely DD Tau, V710 Tau A and V807 Tau, are not considered further because we
Table 4. Equivalent widths of program stars (pm)

| Object      | $H_\alpha$ | Ni\(\lambda 664.36\) | FeI\(\lambda 667.80\) | Li\(\lambda 670.78\) | CaI\(\lambda 671.77\) |
|-------------|------------|------------------------|------------------------|-----------------------|------------------------|
| HBC         | (nm)       | (pm)                   | (pm)                   | (pm)                  | (pm)                   |
| Anon 1      | -0.135     | 12.1                   | 12.6                   | 47.8                  | 26:                    |
| CZ Tau      | -0.64      |                        |                        | 46:                   | 28:                    |
| DD Tau      | -8.95      |                        |                        | 22.9                  |                        |
| GH Tau      | -1.085     | 12:                    | 11:                    | 65.6                  | 44:                    |
| Hubble 4    |            |                        | (-25.5)                | 61.2                  | 30.4                   |
| HV Tau      | -0.43      |                        |                        | 64:                   |                        |
| IS Tau      | -1.305     | 17.1                   | (1:)                   | 61.6                  | 26.4                   |
| Lk Ca 21    | -0.55      | 9.4                    | 25:                    | 71.5                  |                        |
| V710 Tau A  | -3.87      | 11.2                   |                        | 55.4                  | 31:                    |
| V710 Tau B  | -0.36      | 13.1                   |                        | 58.2                  |                        |
| V807 Tau    | -1.58      | 10.4                   | (7.2)                  | 48.8                  | 23.7                   |
| V819 Tau    |            |                        | 27.0                   | 62.2                  | 26.5                   |
| V927 Tau    | -0.87      | 6:                     |                        | 51:                   |                        |
| V928 Tau    | -0.083     | 14.1                   | (-16.2)                | 63.9                  | 44:                    |
| 032641+2420 |            |                        |                        | 28.3                  | 35.2                   |
| 035120+3154SW |          | 17:                    | 13:                    | 18:                   |                        |
| 035120+3154NE |          | 16.2                   | 22.3                   | 16.5                  |                        |
| 035135+2528NW | 0.47:      | 15:                    | 33.7                   | 24.0                  | 28:                    |
| 035135+2528SE | 0.18:      | 12.3                   | 29.5                   | 28.3                  | 24.5                   |
| 040012+2545N+S | -0.030    | 32:                    | 36:                    | 34:                   |                        |
| 040047+2603W | -0.37      | 12.8                   | 7                      | 12:                   | 18:                    |
| 040047+2603E | -0.85      | 9.5                    | 7                      | 12:                   | 18:                    |
| 040142+2150SW | -1.25     |                        | 7                      | 12:                   | 18:                    |
| 040142+2150NE | -0.66      |                        | 7                      | 12:                   | 18:                    |
| 040234+2143 |            |                        | (-8.7)                 | 34.3                  |                        |
| 041559+1716 | -0.14      | 18.1                   | 28.6                   | 46:                   | 27:                    |
| 041529+1652 | 0.05       | 16.0                   | 29.4                   | 18.6                  | 24.6                   |
| 042835+1700 | -0.037     | 13.0                   | 26.5                   | 11.0                  | 28.8                   |
| 042916+1751 | -0.056     | 22.1                   | 31.6                   | 49.4                  | 28.5                   |
| 043124+1824 | 0.09:      | 13.2                   | 19.5                   | 23.0                  | 21.0                   |
| 045251+3016 | -0.055     | 16.4                   | 26.8                   | 52.3                  | 29.3                   |

Notes: Negative equivalent widths indicate line emission. Numbers in parenthesis mean that the FeI\(\lambda 667.80\) line is filled or disappears due to HeI\(\lambda 667.81\) emission. Measurement errors are less than 5%, except where marked with a colon (error about 10%).
want to limit the study to moderate emission TTS. The stars GH tau, IS Tau and NTTS040142+2150SW have Hα strengths at the border of what may be regarded acceptable for a WTTS. We accept them because their Hα flux is moderate and they do not show any other emission lines in our spectral range.

In Table 5 we show equivalent widths of Hα and Li I for WTTS that have not been observed by us. The data are taken from published works quoted at the bottom of the table. For stars with more than one Li I measurement we place equal weight on all the data and take the mean as the value to be used for calculating the Li abundance. These stars from the literature represent 42% of the total sample of WTTS for which we derive Li abundances. We will refer to our program stars plus those taken from other works as the extended sample.

3.2. Effective temperatures

T Tauri stars are in general more luminous than main-sequence stars of the same spectral type. Hence, TTS cannot be regarded as luminosity class V stars. In fact, no definite class can be assigned to them because they span a wide range of luminosities. Relationships between the semi-quantitative parameters luminosity class and spectral type with the quantity effective temperature are needed for placing TTS in the H-R diagram, comparing with theoretical tracks and isochrones and deriving surface chemical abundances. The relationship adopted by Cohen & Kuhi 1979, which is basically the same of Johnson 1966 for class V stars, is still widely used in PMS studies, but more recent determinations are now available (Bessell 1979, de Jager & Nieuwenhuijzen 1987, Bessell 1991). Magazzù et al. 1991 and Magazzù et al. 1992 have adopted the relationship of spectral type with temperature of de Jager & Nieuwenhuijzen 1987 for luminosity class IV. This luminosity class may be roughly adequate for TTS lying in the upper part of PMS evolutionary tracks, but not for any T Tauri star. We prefer not to assume a priori any luminosity class, but instead to treat each TTS separately. We seek to obtain an effective temperature from the spectral type and the luminosity. For example, what is the $T_{\text{eff}}$ of a K7 T Tauri with log $(L/L_\odot)=0$? de Jager & Nieuwenhuijzen 1987 have defined the parameters $s$ and $b$ to quantify the spectral type and luminosity class respectively, and with the aid of their Table 6 it is possible to convert the spectral type and luminosity to values of $s$ and $b$. Using such values, the $T_{\text{eff}}$ follows directly from Table 5 and Fig. 5 of de Jager & Nieuwenhuijzen.

In our Table 6 we present various spectral type to $T_{\text{eff}}$ relationships. It is interesting to compare $T_{\text{eff}}$ values obtained from the scale adopted by Cohen & Kuhi with those
Table 5. Equivalent widths from the literature (pm)

| Object       | Hα (nm) | Li Iλ670.78 (pm) | Source            |
|--------------|---------|------------------|-------------------|
| DI Tau       | -0.10   | 69               | S                 |
| IP Tau       | -1.16,-0.80 | 48,52            | HSS,S             |
| IW Tau       | -0.37   | 44               | HSS               |
| Lk Ca 1      | -0.28   | 56               | HSS               |
| Lk Ca 3      | -0.14,-0.40 | 55,57            | HSS,S             |
| Lk Ca 4      | -0.49,-0.50 | 71,51            | HSS,S             |
| Lk Ca 5      | -0.25   | 55               | HSS               |
| Lk Ca 7      | -0.53,-0.30,-0.37 | 63,52,55,60,59 | BMB,G,HSS,S,W     |
| Lk Ca 14     | -0.09   | 60               | HSS               |
| Lk Ca 15     | -1.27   | 47               | HSS               |
| Lk Ca 19     | -0.05   | 45,48,43         | BMB,G,HSS         |
| S-R 12       | -0.36   | 70               | MRP               |
| Sz 65        | -0.33   | 61               | FB                |
| Sz 68        | -0.68   | 42               | FB                |
| Sz 82        | -0.66   | 57               | FB                |
| UX Tau A     | -0.665  | 43               | MMR               |
| UX Tau B     | -0.35   | 60               | MMR               |
| V827 Tau     | -0.30   | 57               | S                 |
| V830 Tau     | -0.20   | 64,65            | BMB,S             |
| V836 Tau     | -0.70   | 57               | S                 |
| 034903+2431  | -0.16   | 31,35            | BMB,W             |
| 042417+1744  | -0.05   | 28,28            | BMB,W             |
| 043230+1746  | -0.90   | 61,57            | G,W               |

Key to references: BMB = Basri, Martín & Bertout 1991, FB = Finkenzeller & Basri 1987, G = Gómez et al. 1992, HSS = Hartmann, Soderblom & Stauffer 1987, MMR = Magazzù, Martín & Rebolo 1991, MRP = Magazzù, Rebolo & Pavlenko 1992, S = Strom et al. 1989a, W = Walter et al. 1988.

Notes: Equivalent widths are given in pm and wavelengths in nm. A minus sign in the equivalent width means that the line is in emission.
obtained from other scales. For instance, if we compare with de Jager & Nieuwenhuijzen class V, we obtain the following differences: for spectral types G0-G2, K4-K5 and M1-M3 less than 50 K, but for spectral types in the range G4-K3 de Jager & Nieuwenhuijzen $T_{\text{eff}}$ values are always smaller than those of Cohen & Kuhi up to 136 K (at G8), whereas for K7 and M2-M5 holds the reverse situation, with differences up to 150 K (at K7).

Table 6. Spectral Type - $T_{\text{eff}}$ scales

| Sp.T. | C.K. | B. | de J.N. IV | de J.N. V |
|-------|------|----|------------|-----------|
| G0    | 5902 | 6000 | 5636       | 5943      |
| G2    | 5768 |      | 5458       | 5794      |
| G4    |      |      | 5284       | 5636      |
| G6    | 5500 |      | 5114       | 5475      |
| G8    | 5445 |      | 4943       | 5309      |
| K0    | 5236 |      | 4775       | 5150      |
| K1    | 5105 |      | 4624       | 4989      |
| K2    | 4954 | 5000 | 4480       | 4833      |
| K3    | 4775 |      | 4335       | 4690      |
| K4    | 4581 | 4500 | 4207       | 4540      |
| K5    | 4395 |      | 4080       | 4405      |
| K7    | 3999 | 4000 | 3870       | 4150      |
| M0    | 3917 | 3800 | 3630       | 3837      |
| M1    | 3681 | 3650 | 3507       | 3664      |
| M2    | 3499 | 3500 | 3411       | 3524      |
| M3    | 3357 | 3350 | 3341       | 3404      |
| M4    | 3228 | 3150 | 3280       | 3288      |
| M5    | 3119 | 3000 | 3221       | 3170      |

Key to references: C.K. = Cohen & Kuhi 1979, B. = Bessell 1979 (for G/K spectral types) and Bessell 1991 (for M spectral types), de J.N. = de Jager & Nieuwenhuijzen 1987.

3.3. Luminosities and positions in the H-R diagram

Spectral types and bolometric luminosities for the majority of the WTTS have been taken from the literature. The references are given at the end of Table 7. We have classified
IS Tau and 1E0255+2018 as a K7 and a K6 star respectively through comparison of their line depths in the spectral region 666-675 nm with that of other WTTS of known spectral type. The star LkCa21 has been classified as M3 on the basis of the photometry reported in Bouvier et al. 1993b. Using our photometry (Tables 2 and 3) and that of Bouvier et al. 1993b (only for LkCa21), we have derived luminosities for Anon 1, Hubble 4, HV Tau, LkCa14, LkCa21, V710 Tau B and 1E0255+2018 in the following way. A red color excess was derived via comparison of the observed (V-R) color with that expected from the spectral type (Bessell 1979, 1991). (V-R) was chosen to minimize the contribution of possible blue and near-IR excesses (Strom et al. 1989b). The absolute extinction was obtained from the calibration of color excess vs. standard interstellar extinction given by Rieke & Leflohski 1985. The unreddened I color together with the bolometric correction corresponding to the spectral type (Bessell 1991), and a distance of 150 pc to the Taurus clouds, were used for obtaining the absolute luminosity. The visual binary 1E0255+2018 was assumed to be also at 150 pc, and the luminosity was equally divided between both components. We did the same with the double-lined spectroscopic binary NTTS 042835+1700. Our method of deriving luminosities gives consistent results when compared with those employed by Strom et al. 1989b and Walter et al. 1988. Very recently, Simon et al. 1993 have corrected the luminosity of TTS from the contribution of IR companions. We have adopted their luminosities for the stars in common.

The spectral types and luminosities adopted for the extended sample of WTTS are given in tables 7 and 8. Effective temperatures were calculated as explained in the previous section. Masses and ages were inferred from the position of the stars in the H-R diagram and comparison with PMS models. We have taken those of D’Antona & Mazzitelli 1993 (hereafter DAM) with updated opacities and convection theory (DAM’s set number 1). We also compared the H-R locations of the WTTS with the non-rotating models of Pinsonneault et al. 1990 (hereafter PKD) and found only modest differences in masses (less than 0.1 M⊙) and ages (up to a factor 2). In Fig. 5 we plot the WTTS in the the H-R diagram, together with the tracks and isochrones of DAM used to derive masses and ages.

3.4. Calculation of lithium abundances

Lithium abundances were obtained from comparison of the measured Li I λ670.8 nm equivalent widths with curve of growth calculations in LTE and NLTE conditions. We used the most recently available model atmospheres generated in LTE by Kurucz 1992 with solar metallicity, and gravities and effective temperatures in the range log g=3.0-
4.5 and $T_{\text{eff}} = 3500-6000$ K. The formation of the Li I resonance line was followed to the uppermost atmospheric layers, up to levels where the optical depth in the center of the Li I strongest component of the resonance doublet was less than 0.05. For very high Li abundances it was necessary sometimes to extrapolate to higher levels than considered in the model atmospheres. The extrapolation was made in the same way as explained in Magazzù et al. 1992.

In Fig. 6 we show a set of the LTE and NLTE curves of growth employed in this work. They were computed assuming a microturbulence velocity of 2 km $s^{-1}$. The computational method was described in Magazzù et al. 1992 (and references therein). However, the NLTE curves reported here are more accurate than those in Magazzù et al. 1992 because they were made using a 20-level Li atom model, rather than the simplified 6-level atom. We included 70 radiative and all possible collision (with hydrogen and free electrons) transitions. All the relevant references of cross sections, damping constants and oscillator strengths are the same as in Magazzù et al. 1992.

From Fig. 6 it can be seen that the NLTE corrections to the LTE calculations are typically smaller than 0.1 dex. in log $N$(Li). The Li I resonance line in TTS is more sensitive to typical errors in $T_{\text{eff}}$ or even log g than to NLTE effects. An uncertainty of $\pm 250$ K in $T_{\text{eff}}$, or 0.5 dex. in log g, translate into error bars in log $N$(Li) of about 0.4 dex. and 0.1 dex. respectively. The spectral types of WTTS are usually determined with accuracy better than one spectral subclass, but as we saw before there can also be errors inherent to the conversion from spectral type to $T_{\text{eff}}$. We assume an uncertainty of $\pm 150$ K in $T_{\text{eff}}$, $\pm 0.5$ dex. in log g, and 10% in observed equivalent width, which leads to a combined uncertainty in log $N$(Li) of $\pm 0.35$ dex. at 1 $\sigma$.

In Tables 7 and 8 we list the Li abundances of 46 WTTS and upper limits for another 4 WTTS. Note that the Li abundances of 1E0255+2018, NTTS040012+2545 and NTTS042835+1700 refer to the two nearly identical components of these binary systems and hence it increases to 53 the total of WTTS considered here. For the M3 stars (~3400 K) we extrapolated the predicted Li I $\lambda$670.8 nm equivalent widths according to a polynomial fit performed in the range 4000-3500 K, but no Li abundances could be derived for LkCa1 and V927 Tau because their effective temperatures are much lower than the model atmospheres available.
Table 7. Stellar parameters and lithium abundances of weak T Tauri stars

| Name          | Sp.T. | L/L⊙ | Ref. | T\textsubscript{eff} (K) | M/M⊙ | Age (Myr) | log g | log N(Li) | log N(Li) |
|---------------|-------|------|------|----------------|------|------------|------|----------|----------|
| Anon 1        | M0    | 0.77 | 1,2  | 3830            | 0.4  | 2          | 3.45 | 2.6      | 2.6      |
| CZ Tau        | M1.5  | 0.24 | 1.5  | 3590            | 0.35 | 2          | 3.78 | 2.05     | 2.1      |
| DI Tau        | M0    | 0.73 | 1.5  | 3826            | 0.4  | 2          | 3.34 | 3.25     | 3.2      |
| GH Tau        | M2    | 0.89 | 1.5  | 3520            | 0.25 | 0.4        | 3.03 | 2.9      | 2.9      |
| Hubble 4      | K7    | 0.95 | 1.2  | 4133            | 0.55 | 0.8        | 3.62 | 3.3      | 3.25     |
| HV Tau AB     | M2    | 0.65 | 3.2  | 3521            | 0.25 | 0.5        | 3.17 | 2.8      | 2.8      |
| IP Tau        | M0    | 0.5  | 1.1  | 3832            | 0.4  | 1          | 3.64 | 2.6      | 2.6      |
| IS Tau        | K7    | 1.08 | 2.5  | 4130            | 0.5  | 0.5        | 3.50 | 3.2      | 3.15     |
| IW Tau        | K7    | 1.12 | 1.4  | 4130            | 0.5  | 0.5        | 3.51 | 2.9      | 2.85     |
| Lk Ca 1       | M4    | 0.66 | 1.4  | 3288            | 0.2  | 0.5        | 3.14 | 3.05     | 3.0      |
| Lk Ca 3       | M1    | 0.98 | 1.5  | 3657            | 0.3  | 0.5        | 3.48 | 2.45     | 2.4      |
| Lk Ca 4       | K7    | 0.89 | 1.5  | 4130            | 0.55 | 1.0        | 3.65 | 3.3      | 3.25     |
| Lk Ca 5       | M2    | 0.38 | 1.4  | 3522            | 0.3  | 1          | 3.48 | 2.45     | 2.4      |
| Lk Ca 7       | K7    | 0.6  | 1.5  | 4133            | 0.6  | 2          | 3.86 | 3.25     | 3.2      |
| Lk Ca 14      | K7    | 0.88 | 2.2  | 4134            | 0.6  | 1          | 3.70 | 3.3      | 3.25     |
| Lk Ca 15      | K5    | 0.72 | 1.4  | 4385            | 0.8  | 3          | 4.01 | 3.1      | 3.0      |
| Lk Ca 19      | K5    | 1.55 | 4.4  | 4348            | 0.65 | 0.5        | 3.64 | 3.1      | 3.0      |
| Lk Ca 21      | M3    | 0.6  | 2.2  | 3400            | 0.2  | 0.5        | 3.05 | 2.9      | 2.9      |
| S-R 12        | M1    | 1.0  | 3.3  | 3660            | 0.3  | 0.5        | 3.13 | 3.15     | 3.1      |
| Sz 65         | K7/M0 | 0.35 | 5.5  | 3990            | 0.6  | 4          | 4.04 | 3.1      | 3.0      |
| Sz 68         | K2    | 3.0  | 5.5  | 4722            | 1.0  | 0.5        | 3.62 | 3.1      | 3.0      |
| Sz 82         | M0    | 0.5  | 5.5  | 3822            | 0.4  | 1          | 3.63 | 2.85     | 2.8      |
| UX Tau A      | K2    | 1.3  | 1.1  | 4740            | 1.1  | 3          | 4.03 | 3.6      | 3.4      |
| UX Tau B      | M1    | 0.5  | 1.1  | 3650            | 0.35 | 0.5        | 3.49 | 3.05     | 3.0      |
| V710 Tau B    | M3    | 0.3  | 3.2  | 3402            | 0.2  | 1          | 3.35 | 2.4      | 2.4      |
| V819 Tau      | K7    | 0.80 | 1.5  | 4136            | 0.6  | 1          | 3.66 | 3.3      | 3.25     |
| V827 Tau      | K7    | 1.11 | 1.1  | 4130            | 0.5  | 0.5        | 3.52 | 3.25     | 3.2      |
| V830 Tau      | K7    | 0.89 | 1.1  | 4134            | 0.6  | 1          | 3.69 | 3.5      | 3.35     |
| V836 Tau      | K7    | 0.6  | 1.1  | 4139            | 0.6  | 2          | 3.87 | 3.2      | 3.15     |
| V927 Tau      | M5.5  | 0.36 | 1.5  | 3101            | 0.15 | 0.5        | 2.99 |          |          |
| V928 Tau      | M0.5  | 1.3  | 3.3  | 3745            | 0.3  | <0.1       | 3.06 | 3.1      | 3.05     |

References: 1. Strom et al. 1989b, 2. This work, 3. Cohen & Kuhi 1979, 4. Walter et al. 1988, 5. Simon et al. 1993.
Table 8. Stellar parameters and Li abundances of X-ray discovered WTTS

| Name            | Sp. | $L/L_\odot$ | Ref. | $T_{\text{eff}}$ (K) | $M/M_\odot$ | Age (Myr) | log g  | log N(Li) LTE | log N(Li) NLTE |
|-----------------|-----|-------------|------|----------------------|-------------|-----------|--------|---------------|----------------|
| 32641+2420 K1  | 0.50| 1, 1        | 4985 | 1.0                  | 15          | 4.49      | 3.4    | 3.15          |
| 34903+2431 K5  | 0.32| 1, 2        | 4391 | 0.85                 | 15          | 4.39      | 2.25   | 2.3           |
| 35120+3154SW G0| 0.77| 1, 1        | 5943 | 1.05                 | 50          | 4.63      | 3.1    | 3.0           |
| 35120+3154NE G5| 0.56| 1, 1        | 5600 | 1.0                  | 50          | 4.64      | 3.2    | 3.1           |
| 35135+2528NW K3| 0.22| 1, 1        | 4690 | 0.75                 | 40          | 4.62      | 2.15   | 2.2           |
| 35135+2528SE K2| 0.33| 1, 1        | 4835 | 0.85                 | 30          | 4.55      | 2.8    | 2.7           |
| 40012+2545N,S  | 0.16| 1, 1        | 4839 | 0.75                 | 50          | 4.81      | 3.35   | 3.15          |
| 40047+2603W    | 0.20| 1, 2        | 3524 | 0.3                  | 2           | 3.76      | <0.2   | <0.2          |
| 40047+2603E    | 0.20| 1, 2        | 3524 | 0.3                  | 2           | 3.76      | <0.2   | <0.2          |
| 40142+2150SW   | 0.17| 1, 1        | 3404 | 0.2                  | 2           | 3.60      | <0.5   | <0.5          |
| 40142+2150NE   | 0.16| 1, 1        | 3404 | 0.2                  | 2           | 3.62      | <1.0   | <1.0          |
| 40234+2143 M2  | 0.18| 1, 1        | 3524 | 0.3                  | 3           | 3.81      | 1.3    | 1.35          |
| 41529+1652 K5  | 0.17| 1, 1        | 4400 | 0.75                 | 30          | 4.62      | 1.45   | 1.55          |
| 41559+1716 K7  | 0.40| 1, 2        | 4142 | 0.75                 | 6           | 4.14      | 2.7    | 2.65          |
| 42417+1744 K1  | 0.89| 1, 1        | 4913 | 1.2                  | 8           | 4.29      | 2.8    | 2.75          |
| 42835+1700AB K5| 0.20| 1, 1        | 4400 | 0.75                 | 30          | 4.55      | 1.05   | 1.15          |
| 42916+1751 K7  | 0.62| 1, 1        | 4138 | 0.6                  | 2           | 3.85      | 3.15   | 3.05          |
| 43124+1824 G8  | 0.47| 1, 1        | 5445 | 0.95                 | 50          | 4.65      | 3.1    | 3.0           |
| 43230+1746 M2  | 0.22| 1, 2        | 3524 | 0.3                  | 2           | 3.74      | 2.55   | 2.5           |
| 45251+3016 K7  | 1.0 | 1, 1        | 4130 | 0.6                  | 1           | 3.63      | 3.15   | 3.05          |
| 1E0255+2018 K6 | 0.6 | 3, 3        | 4264 | 0.8                  | 3           | 4.04      | 3.0    | 2.9           |

References: 1. Walter et al. 1988, 2. Simon et al. 1993, 3. this work.

4. Discussion

4.1. The statistical distribution of lithium abundances

4.1.1. Homogeneity of the initial lithium abundance

The statistical distribution of Li abundances (in NLTE) of the extended sample of WTTS is shown in Fig. 7. About 85% of the WTTS have log N(Li) in the narrow range 3.4-2.9.
The distribution peaks around $\log N(\text{Li}) = 3.1$, and we interpret its shape as due to random errors around the initial Li abundance, with a long extension towards lower abundances, due to physical processes of PMS Li depletion. Thus, our analysis shows that the initial Li abundance in TTS coincides with the maximum Li abundances measured in various astrophysical contexts (open clusters, local interstellar medium, meteorites). Our result is also consistent with those of Magazzù et al. 1992 for a different sample of TTS (mainly CTTS). Taken together, all these results support the view that the lithium abundance of the interstellar medium around the Sun has remained fairly constant during the last $\sim 5$ Gyr.

In order to explore the homogeneity of the initial Li abundance in WTTS we restrict the sample to those stars with luminosity greater than $0.9L_{\odot}$. No evolutionary model predicts any Li depletion in PMS stars of any mass at such high luminosities. In this restricted sample, we find $\log N(\text{Li}) = 3.19$ with a r.m.s of 0.07 in LTE, and $\log N(\text{Li}) = 3.11$ with a r.m.s of 0.06 in NLTE. These numbers can be compared with the average LTE Li abundance in F-type members of the $\alpha$ Per and Pleiades clusters which is $\log N(\text{Li}) = 3.0\pm 0.1$ (Boesgaard et al. 1988). However, Martín & Rebolo 1993 found evidence for a small amount of Li depletion in the cooler stars of the Boesgaard et al. sample. Using the same Li abundance code as we have used in this work, Martín & Rebolo derived a mean NLTE Li abundance of $\log N(\text{Li}) = 3.13$ with a r.m.s of 0.03 for the hotter stars of Boesgaard et al. for which the theoretical models predict negligible Li depletion. Hence, the initial Li abundance of our sample of WTTS (mainly located in the Taurus molecular clouds) is the same as that of hot stars in $\alpha$Per and the Pleiades. In the next sections we will refer to $\log N(\text{Li}) = 3.1$ as the initial Li abundance.

The reasons why some authors have reported very high Li abundances in TTS are mainly two: (1) The use of atmospheric models that do not include all the layers where the LiI doublet is formed. This causes the computation to be cutoff before the line has fully formed and leads to overestimating the Li abundance required to produce strong Li lines. (2) The NLTE corrections, which push the Li abundances towards lower values when the line is saturated. Both these systematic effects conspire to produce the very high Li abundances presented by Magazzù & Rebolo 1989, Strom et al. 1989a, Basri et al. 1991 and King 1993. Our analysis, and those of Duncan 1991 and Magazzù et al. 1992, have used computations that include all the atmospheric layers where the Li doublet is formed, and we consistently find lower Li abundances on the average.
4.1.2. The decline of lithium

The tail of WTTS at low Li abundances seen in Fig. 7 is a strong evidence that processes of nuclear Li burning and convective material transport have been effective in this stars. During PMS evolution the dominant mixing mechanism is thought to be deep convection, evolving from total convection along the Hayashi tracks to gradually shallower convection along the radiative Henyey tracks. In this general framework Li is expected to be correlated with luminosity: as the PMS star contracts towards lower luminosities its central pressure and temperature increases and Li is destroyed. Of special interest is the determination of the luminosity at which the depletion starts to be seen on the stellar surface because it provides direct information on the central temperature.

In Fig. 8 we have plotted the observed Li abundances against luminosities for the WTTS of our extended sample. We feel that comparison of Li abundances with luminosities is more meaningful than with ages or masses, because luminosity is a direct observable, while ages and masses are model-dependent. However, because of the great sensitivity of Li to mass, we take into account the theoretical masses by giving different symbols in Fig. 8 to stars in 4 bins of masses. There is a clear trend towards lower Li abundance at lower luminosity. All the WTTS with log N(Li)<2.4 have luminosities below 0.5 $L_\odot$. Hence, we may take this luminosity as a conservative estimate of where Li depletions begins to be significant. The largest Li depletions are found among the WTTS with lowest luminosities. Hence, in a qualitative sense the observed pattern of Li abundances is correlated with luminosity as theoretically expected, but there are a number of problems when detailed comparison with models is made.

We will enumerate the most important traits seen in Fig. 8:

1. WTTS in the mass range 0.2-0.4 $M_\odot$ present an abrupt decline of Li abundances below 0.4 $L_\odot$, implying that at this luminosity the internal conditions for Li burning are attained. The models predict that the luminosity at the start of Li burning is about 0.1 $L_\odot$, i.e. shifted by a factor 4 from the observed turning point. Since these stars are totally convective, we infer from the observations higher central temperatures in the luminosity range 0.4-0.2 $L_\odot$ than previously thought. This may not be surprising because of the large theoretical uncertainties at such low masses. More computations at these very low mass stars may provide useful tests to the opacities used by the models.

2. In the range 0.4-0.6 $M_\odot$ we only have stars at luminosities greater than 0.3 $L_\odot$, and they all have Li abundances near to the initial value. This is not inconsistent with
the models. It would be necessary to observe stars at lower luminosities to test the
models in this range of masses.

3. WTTS of about 0.8 $M_\odot$ (open squares in Fig. 8) show clear cases of Li depletion.
At these masses we have stars along all the PMS evolutionary track, including the
radiative approach to the ZAMS (Fig. 5). The non-rotating models of PKD for 0.8 $M_\odot$
predict Li depletions consistent with the lower envelope of Li abundances. We also find
consistency with the DAM model using the convection theory of Canuto & Mazzitelli
(CM) and Kurucz opacities (set 2). However, using the same opacities the DAM model
with mixing-length (MLT) convection theory overestimates the Li depletion. This may
suggest that the CM theory is better than the MLT, but the DAM model with MLT
treatment and Alexander opacities (set 3) is also consistent with the observations.
Hence, there is no clear difference in Li depletion predictions attributable to CM or
MLT convections theories and both of them seems a priori capable to fit the maxima
of Li depletion.

4. For the higher bin of masses (1.0-1.2 $M_\odot$) there are WTTS of widely different ages (1-
50 Myr), but we do not observe significant differences in Li abundances. We interpret
this result as evidence that the PMS Li burning at these masses is less than about
factor 2. The PKD and DAM models that predict Li depletions realistic for a 0.8 $M_\odot$
PMS star, also predict Li depletion of about 0.6 dex. at 1.0 $M_\odot$, which is not supported
by the observations. Martín & Rebolo 1993 have studied the secondary of the eclipsing
binary system EK Cep, which is a 1.12 $M_\odot$ star with age about 20 Myr. They find
a lithium abundance of log $N$(Li)=3.1 and compare it with Li abundances of $\alpha$ Per
and Pleiades stars. Taken this into account and our present results, we conclude that
there is virtually no PMS Li burning at masses between 1.2-1.0 $M_\odot$. The solar Li
abundance shows a Li depletion of about a factor 100, which must be a consequence
of mixing during MS lifetime.

Considering the whole range of masses, 0.2-1.2 $M_\odot$, we have not found a model able to
provide an acceptable fit to the global pattern of Li abundances. At 1.0 $M_\odot$ the models
should consider modifications in the input physics that reduce PMS Li burning. For
instance, using MLT convection theory, this would require a lower value of the mixing
parameter ($l/H_p$). At the lower mass end 0.4-0.2 $M_\odot$ the discrepancy between models
and observations is very serious. This casts doubts on the estimates of masses and ages
based on current evolutionary tracks and isochrones for M-type T Tauri stars.
4.2. Is there a link between PMS Li depletion and rotation?

In Fig. 9 we have plotted log N(Li) vs. v sin i for the extended sample of WTTS. The v sin i were taken from the HBC, although for some stars we have measured it in our spectra. These stars are Anon 1, IS Tau and 1E0255+2018; and the measurements are, respectively, <15, 25±10 and 30±10 km s⁻¹.

The most striking feature of Fig. 9 is that there are no fast rotators (v sin i ≥ 40 km s⁻¹) with low Li abundance. On the other hand, there is a large dispersion of abundances among the slow rotators. The high Li abundances in the fast rotators can be a real abundance effect or an artifact caused by the presence of cool spots at the stellar surface. However, several works have shown that there are no significant variations of the Li I doublet equivalent width in spotted stars (Basri et al. 1991, Martín 1993a, Pallavicini et al. 1993), and that the chemical abundances of elements other than lithium, i.e. Ca, Fe, Ti, are not larger in fast rotating stars than in the slow rotators (e.g. Balachandran et al. 1988, Martín 1993a). Thus, presently, there is no observational evidence that high Li abundances in fast rotating TTS may be due to spots.

The main source of uncertainty in plots like Fig. 9, is the inclination angle in the v sin i. In Fig. 10 we show the Li abundances of a limited sample of WTTS and CTTS against the equatorial rotational velocity (deduced from photometric periods, cf. Bouvier et al. 1993a). We have restricted the sample to K5-K7 single stars, corresponding to the theoretical mass range 0.9-0.5 M⊙, to reduce possible variations of both lithium and rotation with mass. In Table 9 we present the selected sample. The data on Li comes from Basri et al. 1991, reanalyzed using our curves of growth (Fig. 6), and from this work. The data on rotation comes from Bouvier et al. 1993a.

The straight lines in Fig. 10 join points of different ages (3 and 10 Myr) calculated by PKD for a mass of 0.8 M⊙. Each line corresponds to a value of initial angular momentum; the largest rotational velocities are for J₀=1.6 x 10⁴⁹ g cm² (model A2 of PKD), while the other two lines at lower rotation velocities are for models A1 and A0 of PKD, J₀=5 x 10⁴⁹ g cm², and 1.6 x 10⁴⁹ g cm², respectively. All the CTTS in Fig. 10, and all the WTTS, except for one, have Li abundances close to cosmic. The single WTTS with low Li abundance (NTTS034903+2431) does not rotate very fast, and presents less Li depletion than predicted by PKD. We believe that Fig. 10 illustrates the point that before Li depletion takes place there is already a wide angular momentum distribution, larger than one order of magnitude. Thus, potentially, the initial angular momentum may be an important factor in PMS Li depletion.
Table 9. Lithium and Rotation in TTS of spectral types K5-K7

| Name      | Sp.T. | R/R⊙ | v sin i | P_{rot} | v_{rot} | log N(Li) |
|-----------|-------|------|---------|---------|---------|-----------|
| BP Tau    | K7    | 2.0  | ≤10     | 7.6     | 11.8    | 3.2       |
| DK Tau    | K7    | 2.6  | 11.4    | 8.4     | 15.9    | 3.1       |
| GG Tau    | K7    | 2.6  | 10.2    | 10.3    | 12.9    | 3.3       |
| GM Aur    | K7    | 1.9  | 12.4    | 12.0    | 8.0     | 2.7       |
| IW Tau    | K7    | 2.4  | ≤9      | 5.6     | 22.0    | 2.8       |
| Lk Ca 4   | K7    | 2.2  | 26.1    | 3.37    | 32.9    | 3.2       |
| Lk Ca 7   | K7    | 2.0  | 13.0    | 5.64    | 18.0    | 3.2       |
| Lk Ca 15  | K5    | 1.6  | 12.5    | 5.85    | 13.9    | 3.0       |
| Lk Ca 19  | K5    | 2.2  | 18.6    | 2.24    | 47.6    | 3.0       |
| 034903+2431 | K5   | 1.2  | 29      | 1.6     | 38.0    | 2.3       |
| 042916+1751 | K7   | 1.7  | 27      | 1.21    | 70.2    | 3.05      |
| V819 Tau  | K7    | 1.8  | ≤15     | 5.6     | 16.3    | 3.2       |
| V827 Tau  | K7    | 2.2  | 18.5    | 3.75    | 29.6    | 3.2       |
| V830 Tau  | K7    | 2.0  | 29.1    | 2.75    | 36.3    | 3.3       |
| V836 Tau  | K7    | 1.6  | 29.1    | 7.0     | 11.7    | 3.1       |

Our Fig. 9 recalls Fig. 3a of Balachandran et al. 1988 for low-mass stars in αPer. These authors proposed two explanations:

1. Star formation over a time interval comparable with the timescale of Li burning. Our data does not support this hypothesis because we see cases of Li depletion among TTS younger than the αPer members. Furthermore, there is no apparent slow down trend with age in the PMS, but a bimodality of slow and fast rotators that becomes more pronounced from the TTS to αPer (Bouvier et al. 1993a).

2. Rapid rotational braking associated with enhanced Li depletion. Bouvier et al. 1993a found a systematic difference between the rotational velocities of WTTS and CTTS. The WTTS are on the average fast rotators and could be the progenitors of the very fast rotators in αPer and the Pleiades. On the contrary, CTTS spin more slowly than WTTS, and could be the progenitors of slow rotators in these clusters. Duncan 1993 and Soderblom et al. 1993 have shown that the rotational PMS evolution of solar-type stars can only be understood if the angular momentum loss prior to settlement on the
ZAMS is modest and rotation independent. Consequently, a mechanism of angular momentum loss during PMS evolution is not discarded by the previous works, but it is not required to explain the observed distributions of rotational velocities in young low-mass stars.

The evolutionary models of PKD have predicted PMS Li depletion associated to angular momentum loss. These authors could not explain the high Li abundances in fast rotators of $\alpha$Per and the Pleiades, and advocated that they resulted from late accretion along the Hayashi tracks. However, this view is not supported by the finding that CTTS rotate slowly. On the other hand, as we mentioned before, PKD models for non rotating stars, and the models without angular momentum redistribution predict Li depletion at 0.8 $M_\odot$ roughly consistent with the minima of Li abundances in slowly rotating WTTS. On the contrary, models with angular momentum redistribution overestimate the Li depletion at the same mass. Thus, there is no need to invoke a mechanism of PMS Li depletion associated to angular momentum loss to explain the observed lithium abundances in WTTS.

One possible drawback is if we could have missed any fast rotating TTS with low Li abundance. The census of the fast rotating TTS is probably more complete than that of the slow rotating because fast rotators are more active and hence easier to identify. If we have few fast rotators in our sample is because such cases are rare among TTS. Duncan 1993 has not found any case with $v \sin i > 50$ km s$^{-1}$ in a sample of 50 stars in the Orion Nebula region. We believe that there is a real lack of fast rotating TTS with low Li abundances in the range of masses and luminosities that we have studied. Our fast rotators are not particularly young or massive, since they span the ranges of masses 1.0-0.7 $M_\odot$ and ages 10-50 Myr.

As we saw in Fig. 10, TTS in the mass range 0.9-0.5 $M_\odot$ show a wide range of rotational velocities prior to Li burning. This initial spread in rotation increases by about a factor 2 during PMS evolution (cf. Soderblom et al. 1993). While slow-rotating WTTS destroy lithium at a rate consistent with standard models without angular momentum redistribution, fast-rotating WTTS seem to inhibit Li depletion. If an inhibiting process takes place in fast rotators during all PMS evolution, we could explain a large rotation-dependent dispersion of Li abundances among the K-type stars of the ZAMS.

Members of the young open clusters $\alpha$Per (50 Myr) and the Pleiades (100 Myr) offer the opportunity to study the final conditions of PMS evolution for masses lower than about 1.0 $M_\odot$. In Paper II we will study the Li abundances of low-mass stars in the
Pleiades, and we will discuss further the connection between PMS Li burning and rotation.

5. Conclusions

The main conclusions of this paper address the following points:

- **The initial lithium abundance:**
  
  The statistical distribution of Li abundances in weak T Tauri stars has a pronounced maximum at log N(Li)=3.1, in close agreement with the cosmic lithium abundance. We estimate that the initial Li abundance of TTS is remarkably homogeneous, log N(Li)$_{NLTE}$=3.11±0.06.

- **Pre-main sequence Li burning:**
  
  There is clear evidence for PMS Li burning in our sample. As expected the observations show that Li depletion increases towards lower luminosities. The starting point occurs at L$_*$ between 0.9 and 0.4 L$_\odot$ depending on the mass. At L$_*$ ≈ 0.2 L$_\odot$ there is great Li depletion (over a factor 100) among stars with M$_*$ < 0.5 M$_\odot$. The observed luminosity of the Li turnover at these masses is larger by a factor 4 than theoretically predicted.

  Models without rotation can fit the maxima of Li depletion at masses around 0.8 M$_\odot$, but the same models overestimate the depletion at masses around 1.0 M$_\odot$. We find that PMS Li burning in stars with similar mass than the Sun is less than a factor 2, implying that the solar Li abundance results from evolution on the main sequence.

- **Lithium and rotation:**
  
  At masses around 0.8 M$_\odot$ fast-rotating TTS do not show low Li abundances, while slow-rotating TTS show decreasing Li abundances with luminosity. There is no need for Li depletion associated to angular momentum loss since the observed minimum Li abundances can be accounted for by non-rotating models. We interpret the high Li abundances of the fast rotators as evidence for an inhibiting process of Li depletion associated to rapid rotation.

  We have shown that there is a wide range of rotation velocities in TTS with masses 0.9-0.5 M$_\odot$ before Li depletion starts to be noticed. Thus, differences in initial angular momentum and inhibition of Li depletion in fast rotators can produce a spread of Li abundances on the ZAMS for stars of the same mass (∼0.8 M$_\odot$).
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Figure captions:

**Figure 1:** T Tauri spectra taken with the ISIS spectrograph at the William Herschel telescope. The position of the Li I \( \lambda 670.8 \) nm feature is marked. All the continua have been normalized and displaced by a constant factor.

**Figure 2:** T Tauri spectra taken with the intermediate dispersion spectrograph (IDS) at the Isaac Newton telescope. Dispersion = 0.036 nm pix\(^{-1}\).

**Figure 3:** T Tauri spectra taken with IDS at the Isaac Newton telescope. Dispersion = 0.036 nm pix\(^{-1}\).

**Figure 4:** T Tauri spectra taken with IDS at the Isaac Newton telescope. Dispersion = 0.022 nm pix\(^{-1}\).

**Figure 5:** Our sample of weak T Tauri stars in the H-R diagram. Evolutionary tracks and isochrones are from set 1 of D’Antona & Mazzitelli 1993.

**Figure 6:** Curves of growth for the Li I resonance doublet. From above downwards the pairs of curves (one solid for LTE and one dashed for NLTE) have been calculated for \( T_{\text{eff}} \) of 3500, 4000, 4500, 5000 and 5500 K, respectively. In all computations we used log \( g = 4 \), microturbulence of 2 km s\(^{-1}\) and solar metallicity.

**Figure 7:** Statistical distribution of lithium abundances in our sample of weak T Tauri stars.

**Figure 8:** Lithium abundances in WTTS plotted against their bolometric luminosities. Superimposed are theoretical curves from set 1 of D’Antona & Mazzitelli 1993 for 0.8 (solid) and 0.4 M\(_{\odot}\) (dots and dashes), and from Table 1 of Pinsonneault et al. 1990 for the same masses (see text).

**Figure 9:** Lithium abundances in WTTS plotted against their projected rotational velocities. Open squares indicates measurements of vsini, whereas open triangles indicate upper limits on vsini.

**Figure 10:** Lithium abundances in WTTS (crosses) and CTTS (open squares) of spectral types K5-K7 plotted against their equatorial rotational velocities. The straight lines join points of ages 3 and 10 Myr, calculated by Pinsonneault et al. 1990 for 3 different values of initial angular momentum (models A0, A1 and A2), at the same mass of 0.8 M\(_{\odot}\).

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