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Spectroscopy of low mass pre-main sequence stars: photospheric spots and chromospheric activity

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Abstract. We present high resolution spectra in the 6532-6745 Å wavelength range of 9 rapidly rotating ($v \sin i >$ 25 km/s) T Tauri stars. Among these stars, V410 Tau and HD 283572 have been monitored in more detail, covering 2.2 and 3.2 rotational periods, respectively. The data allow us to study the changes of the profiles of the H_α and several absorption lines. These changes are supposed to be related to the chromospheric emission and to the cold spots, respectively.

From the absorption line profiles of some lines of V410 Tau, the presence of several spots can be inferred. We have found that the equivalent width of some absorption lines varies according to the rotational period. There is a range for the amplitude of these variations, the maximum value corresponding to the Li I 6708 line (0.53–0.65 Å). Maximum equivalent widths are observed near the minimum of the light curve. The fact that these variations have not been previously detected may be partially due to the large amplitude of the continuum variability at the time of our observations. The H_α emission profile in V410 Tau also varies according to the rotational period. The data indicate a coincidence in longitude between the largest spot and the region in which the narrow emission component of the H_α line arises.

For HD 283572, some metallic absorption lines indicate the presence of a polar spot but the equivalent widths of all the observed lines present constant values, except for H_α. Variable emission contributes to the H_α absorption line and, due to the position of its maximum on the light curve, the region responsible for this emission could be related to the polar spot.

For the other stars of our sample the spectra present new information about their variability. HP Tau/G2 and, probably, VSB 78, show asymmetries in the Li I 6708 line, as expected from cold spots.

Key words: stars: activity – stars: individual: V410 Tau – stars: individual: HD 283572 – stars: pre-main sequence

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1. Introduction

T Tauri stars (TTSs) are low mass ($\lesssim 2\,M_\odot$) pre-main sequence objects at first classified, among other properties, by their large H_α equivalent width (W_{H_α}, > 5 Å). Nevertheless, most of the objects selected in this way turned out to be only a fraction of the whole TTSs class known as the classical TTSs (CTTSs), being the weak line TTSs (WTTSs), those with an $W_{H_\alpha} \leq 10$ Å, the important fraction of the class. Nowadays, in a simple picture, the CTTSs are considered as star-disk systems in which accretion still plays a moderate-to-important role and is responsible for the ultraviolet and infrared excesses and for at least part of the variability. The WTTSs, on the other hand, do not show signs of accretion; an enhanced solar type activity and/or circumstellar (inhomogeneous) material is observed in some of them (for a review about TTSs see e.g. Appenzeller & Mundt 1989; Bertout 1989; Bertout 1994).

Among the mechanisms believed to be responsible for the variability of the TTSs, cold spots are probably the best studied. Cold spots seem to be the main cause of variability in WTTSs and are interpreted as stellar analogues of solar spots, covering areas one or two orders of magnitude larger. Other phenomena associated with this magnetic activity (flares, chromospheric and coronal emission) have also been observed in WTTSs (see e.g. Bertout 1989). Until this decade the characteristics (temperature and size) of the spots could only be derived from the optical photometric light curves. However, in recent years, spectroscopic observations have become a powerful tool for studying these cold spots, because these large regions ($\sim$ 3-20% of the stellar surface) at $\sim$ 1000 K below the photospheric temperature can considerably alter the profile of the photospheric lines (e.g. Vogt & Penrod 1983, Vogt et al. 1987). The bumps generated on the absorption line profiles shift in wavelength as the star rotates. In order to get the information about the spots that could not be obtained from pure photometry (that is, the shape and location of the spots) the Doppler Imaging technique was developed (Vogt & Penrod 1983). This technique obtains, as the solution of an *inverse* problem, the temperature distribution on the stellar surface from the distorted line profiles of photospheric line profiles.

This kind of study has been carried out on Ca I, Fe I and Li I lines (e.g. Strassmeier et al. 1994; Joncour et al. 1994a,b; Rice & Strassmeier 1996). However, some Li I and Ca I lines deserve special comments. The resonance Li I 6708 line (doublet: 6707.74 and 6707.89 Å) has been chosen because it is not blended with other lines, except for a very weak line at 6707.44 Å that is believed to be due primarily to Fe I (Soderblom et al. 1993), and because the high Li abundance in TTSs makes it one of the strongest photospheric lines in these stars. Since the line strength is very sensitive to the temperature (the ionization potential of Li is 5.37 eV), it is not easy to predict the way the line profile will change due to a cold spot. On one hand, one would expect the line to be much stronger in the spot, due to the increased population of neutral lithium atoms and, thus, the spot should show up as a dip in the line profile at the projected velocity of the spot. But, on the other hand, if the changes are due mainly to the decrease in continuum intensity, the reduced continuum coming from the spotted region, compared to that of the *immaculate* photosphere, will cause the appearance of an emission bump in the absorption profile (Vogt & Penrod 1983, Basri et al. 1991). As for the equivalent width ($W_{Li\,I}$), it should be enhanced in dark spots but reduced in the bright facular regions which usually accompany spots, according to solar observations (Giampapa 1984). The behaviour of the line thus depends on the interplay between line formation in these two regions (Basri et al. 1991).

A theoretical discussion of the behaviour of the $W_{Li\,I}$ in a spotted star was presented by Barrado y Navascués (1996). He concluded that although cold spots can produce large changes in the $W_{Li\,I}$, the presence of faculae can, in certain cases, cancel these changes, leaving the $W_{Li\,I}$ unaltered. Soderblom et al. (1993) had wondered if the effects of surface spots might lead to the spread in Li abundances seen in the Pleiades. They discussed evidence against the changes of the $W_{Li\,I}$ in some stars whose variability is attributed to cold spots; nevertheless, significant variations have been found in two pre-main sequence binaries and, probably, in two active stars and the star HII 3163 (Patterer et al. 1993; Robinson et al. 1986; Soderblom 1996).

The behaviour of the Ca I lines (ionization potential of 6.113 eV) is also not easy to predict because Ca is almost completely ionized in the normal stellar photosphere of G and K type stars, but almost completely neutral in the spots (Vogt & Penrod 1983). The Ca I 6717 line is not expected to vary as strongly as the Li I 6708 does and this might reflect its reduced sensitivity to temperature and its sensitivity to chromospheric heating, because it is formed higher in the atmosphere (Basri et al. 1991).

In order to study the behaviour of these lines and other, not strongly temperature sensitive lines, we carried out high resolution spectroscopic observations on a sample of TTSs. Simultaneous H_α measurements were also obtained. We present the analysis of the variability of the observed lines and discuss it in the frame of the solar type activity in pre-main sequence stars.

Table 1. Sample of stars sorted by right ascension. Except when mentioned in the text, $v\sin i$, spectral types and types are taken from Herbig & Bell (1988) (HBC). Types correspond: *wt* to WTTS, *su* to SU Aur like stars and *tt* to CTTS. In the last column, the brightness in the V band is given. Uncertain or compromise values are indicated by (:).

HBC N.	Star	Spec. Type	Type	$v\sin i$ km s^{-1}	V (mag)
29	V410 Tau	K3 V	wt	77 ± 1	10.82
380	HD 283572	G5 IV	su	110 ± 20	9.04
43	UX Tau A	K0 V	wt	24.9 ± 1.7	10.69
415	HP Tau/G2	G0:nIII	su	100 ± 20	11.1:
79	SU Aur	G2 III	su	66.2 ± 4.6	8.93
84	CO Ori	F8:e V	su	48.3 ± 15.8	9.83
85	GW Ori	G5	tt	43.0 ± 2.5	9.80
534	VSB 48	G0 IV,V		131 ± 13	11.72
222	VSB 78	F7V		56 ± 9	11.97

2. The sample of stars

There are three important requirements in order to analyze cold spots through their spectroscopic fingerprints: a high rotational velocity projected along the line of sight ($v\sin i$), a signal to noise ratio larger than ~ 50 and a short enough integration time (about a few per cent of the rotational period). The first one ensures that the Doppler effect is the dominant broadening effect and that the lines will be wide enough to show the bumps; a good signal to noise ratio will allow us to recognize the bumps and short integration times are essential to avoid appreciable shifts of the bumps during the exposure. These requirements severely constrained the sample accessible to TTSs with a brightness at the V band ≤ 11 mag and $v\sin i > 25$ km/s. Our sample consists of the 9 stars, most of them WTTSs[1], indicated in Table 1.

3. Observations

The spectra were obtained in January 5-10 1993 with the Coudé spectrograph of the 2.2m telescope at the Calar Alto Observatory (Almería, Spain), using both the f/3 and f/12 cameras of the spectrograph. In the f/3 camera the detector was a TEK 24 μm CCD with 1080x1030 pixels and the dispersion was 8.67 Å/mm. The f/12 was equipped with a GEC 22.5 μm CCD with 791x1155 pixels and the dispersion was 2.06 Å/mm. The f/3 camera spectra cover the range 6532–6745 Å, including, among others, the Li I 6708, Ca I 6717 and H_α lines. The f/12 camera spectra cover the range 6688 - 6740 Å and include the Li I 6708, Ca I 6717 lines. A Th-Ar lamp was used for wavelength calibration. The spectral resolution, determined by the FWHM of the comparison lines, is ~ 0.5 Å (f/3 camera spectra) and ~ 0.22 Å (f/12 camera spectra). Seeing was $\sim 0\farcs7$–$1''$. Fluxes were not calibrated. Data reduction was carried out with the Image Reduction and

[1] Herbig & Bell (1988) have classified as *SU Aur like stars* the late type F to K stars with an H_α equivalent width smaller than 10 Å and a weak emission at Ca II, very broad absorption lines ($v\sin i > 50$ km/s), and relatively high luminosity. Some stars of our sample match this definition.

Table 2. Spectroscopic observations of V410 Tau and HD 283572 from January 1993. The last column indicates, in the decimal part, the phase and, in the fractional part, the number of the rotational period in our sequence. Phases were calculated using the ephemeris mentioned in the text and they correspond to mid-exposure time.

Date (start)	U. Time (start)	Exposure time (s)	Camera	Period, phase
Star:	V410 Tau			
5 Jan	19:05:11	1800	f/3	1.325
5 Jan	19:52:46	1800	f/3	1.342
6 Jan	18:37:07	1800	f/3	1.849
6 Jan	19:13:34	1800	f/3	1.862
6 Jan	22:33:31	1800	f/3	1.937
6 Jan	23:07:02	1800	f/3	1.949
7 Jan	22:19:33	1800	f/3	2.466
7 Jan	22:52:25	1800	f/3	2.478
8 Jan	21:15:21	2700	f/12	2.979
8 Jan	22:06:45	2700	f/12	2.999
8 Jan	23:10:50	1800	f/3	3.019
8 Jan	23:43:33	1800	f/3	3.031
9 Jan	19:42:03	1800	f/3	3.476
9 Jan	20:16:18	1800	f/3	3.489
9 Jan	20:59:56	2700	f/12	3.508
9 Jan	21:47:13	2700	f/12	3.526
10 Jan	01:17:58	1800	f/3	3.601
10 Jan	20:24:3	1800	f/3	4.027
11 Jan	00:34:42	1800	f/3	4.119
11 Jan	01:07:21	1800	f/3	4.132
Star:	HD283572			
5 Jan	20:35:30	1800	f/3	1.987
6 Jan	19:51:11	1800	f/3	2.613
6 Jan	21:59:17	1800	f/3	2.670
7 Jan	18:21:47	1800	f/3	3.219
8 Jan	01:34:58	1800	f/3	3.413
8 Jan	18:55:24	1800	f/3	3.880
8 Jan	19:45:39	1800	f/12	3.903
8 Jan	20:25:17	2400	f/12	3.923
9 Jan	00:18:37	1800	f/3	4.025
9 Jan	18:13:09	1800	f/3	4.507
10 Jan	00:44:44	1800	f/3	4.682
10 Jan	18:14:16	1800	f/3	5.153
10 Jan	18:56:36	2700	f/12	5.176
10 Jan	19:52:03	1200	f/12	5.195
10 Jan	23:58:48	1800	f/3	5.308

Analysis Facility (IRAF[2]). A log of the observations, including exposure time and universal time of the observations, is listed in Tables 2 and 3.

4. V410 Tau

V410 Tau is one of the WTTSs most often studied. Basri & Batalha (1990) derived a K2 spectral type for it, although it had been previously classified as K7 (Cohen & Kuhi 1979) and as K4 (Bouvier et al. 1986). The H_α equivalent width (W_{H_α}) varies between $\simeq 0$ and $\simeq 3$ Å (Herbig & Bell 1988).

The photometric data compiled by Herbst (1989) from 1982 to 1989 show a year to year, perhaps cyclic, smooth change in the amplitude of the light curve between $\simeq 0.25$ and $\simeq 0.60$ mag in the V band. He concluded that the same two large spots have been present on the star for at least 6 years and that the changes in their relative longitudes account for the changes in shape and amplitude of the light curves. Petrov et al. (1994) presented data for the period 1986-1992 and were able to reproduce the light curves with one spot which changes size and temperature.

From the 1982 – 1989 light curve a period of 1.8710 days was obtained and it was considered to be the rotational period of the star (Herbst 1989). Nevertheless, Herbst (1989) noticed that a revised value of $1\overset{d}{.}8714$ would remove the linear trend observed in the difference between observed and computed times of minimum. From the photometric observations carried out between 1986 and 1992, Petrov et al. (1994) derived a period of $1\overset{d}{.}872095 \pm 0\overset{d}{.}000022$. With the new period the trend in the difference mentioned is still smaller, although a slight trend is left. Due to this recalculation of the rotational period, different

Table 3. Spectroscopic observations of the other stars of our sample. All spectra were taken with the f/3 camera.

Star	Date (start)	U. Time (start)	Exposure time (s)
UX Tau A	6 Jan 1993	20:33:58	1800
UX Tau A	6 Jan 1993	21:11:01	1800
UX Tau A	9 Jan 1993	22:43:41	1800
UX Tau A	9 Jan 1993	23:20:27	1800
HP Tau/G2	7 Jan 1993	19:44:59	1800
HP Tau/G2	7 Jan 1993	21:08:16	1800
HP Tau/G2	10 Jan 1993	21:06:14	1800
HP Tau/G2	10 Jan 1993	21:38:57	1800
SU Aur	5 Jan 1993	23:40:23	1800
SU Aur	6 Jan 1993	23:40:41	1800
SU Aur	7 Jan 1993	19:06:01	1800
CO Ori	7 Jan 1993	21:44:00	1800
CO Ori	9 Jan 1993	00:55:03	1800
CO Ori	11 Jan 1993	01:46:10	1800
GW Ori	6 Jan 1993	00:48:47	1800
GW Ori	6 Jan 1993	01:34:24	1800
GW Ori	10 Jan 1993	22:14:10	1800
GW Ori	10 Jan 1993	22:46:51	1800
VSB 48	6 Jan 1993	03:13:45	1800
VSB 48	8 Jan 1993	02:20:27	1800
VSB 78	7 Jan 1993	01:34:03	2400
VSB 78	7 Jan 1993	02:31:41	1800
VSB 78	8 Jan 1993	02:59:43	1800
VSB 78	9 Jan 1993	01:30:36	1800
VSB 78	9 Jan 1993	02:07:07	1800
VSB 78	9 Jan 1993	02:40:04	1800
VSB 78	10 Jan 1993	02:31:52	1800

[2] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

ephemeris have been used in order to compute the phases of the spectra in the literature.

V410 Tau is an optimum candidate for a spectroscopic study of spots because of its large $v \sin i$, $\simeq 77$ km s^{-1}, average brightness, ~ 10.9 mag in the V band, and amplitude of the light curve (see above and Table 1). The first distorted profiles of the Li I 6708 line were published by Basri et al. (1991) and later Patterer et al. (1993) confirmed their observations. Doppler images have been obtained for January 1990, November 1992, December 1993 and January 1994 by Joncour et al. (1994a), Strassmeier et al. (1994), Rice and Strassmeier (1996) and Hatzes (1995), respectively. All these Doppler images show a large cold feature at high latitude and smaller cold features at low latitudes.

Table 4. Mean, minimum and maximum equivalent widths (Å) of some absorption lines in V410 Tau. It is also indicated whether each equivalent width varies or not.

λ (Å)	Mean	Minimum	Maximum	Variable
6548	0.23	0.17	0.28	No
6574	0.47	0.39	0.55	Yes
6594	0.45	0.42	0.51	Yes
6599	0.18	0.14	0.21	No
6609	0.26	0.24	0.30	Yes
6634	0.25	0.23	0.28	No
6644	0.18	0.15	0.20	No
6664	0.24	0.22	0.30	No
6679	0.25	0.21	0.28	No
6708	0.59	0.53	0.65	Yes
6718	0.31	0.26	0.35	Yes

4.1. Results

Our observations cover 2.2 rotational periods with 20 spectra. The phase sorted spectra are shown in Fig. 1. Phases were calculated using the ephemeris of Vrba et al. (1988) (hereafter VHB):

$$HJD = 2446861.629 + 1.8710E.$$

Bumps and their variation with phase can be recognized in the Li I 6708 line and, less easily, in the Ca I 6717 line. Among the other lines, only some of them show changes similar to those observed in the Li I line. We have realized that the lines that do not show such behaviour correspond to blends of lines in which the distortions of each component mask those of the other. The distortions of the line profiles of the Li I 6708 and the other metallic absorption lines are similar; this indicates that for this star the effect of the changes due to the continuum are larger than those due to the ionization fraction of the Li. In addition, the H_α emission on the phase sorted spectra also shows a smooth variation versus phase (Sect. 4.3).

The observed bumps suggest that there are two spots on the star, at longitudes about 20° and 250°, and probably a third one, at a longitude of 175° (0° being the centre of the visible hemisphere at phase 0). These longitudes are obtained from the phase at which the different bumps cross the centre of the line. A careful look at the f/12 camera spectra reveals two bumps at the positions where the f/3 camera spectra only show one; this means that we are, in fact, detecting groups of spots. The spot at a longitude of 250° is probably the largest one because it is associated with the strongest bumps; this result agrees with the photometric (Petrov et al. 1994) and spectroscopic data (see below) already published. In order to compare our data with previously published spectra the year to year variations of the amplitude of the light curve must be taken into account. The spectroscopic data we used for the comparisons spans from January 1990 to February 1994 and within these dates the amplitude of the light curve in the V band increased from 0.40 mag to 0.55 mag. Our Li I 6708 profiles (Fig. 1) are similar to those of the Fe I 6393 line obtained by Strassmeier et al. (1994) in November 1992 and to the Ca I 6639 line profiles by Hatzes (1995) obtained one year later. This similarity was expected because the same spots have been present in the star during the last 7 years (Petrov et al. 1994).

In order to measure equivalent widths, the spectra were normalized and three measurements were obtained for each line, taking into account possible indeterminations of the continuum level. This procedure was carried out independently by each of us. The whole set of measurements provided a mean value and error for each line at each phase. The variability, versus phase, of the equivalent width of the H_α, Li I, Ca I, and other metallic lines is shown in Fig. 2. The equivalent width of some lines varies according to the rotational period (e.g. Li I, Ca I and Fe I lines), the maximum equivalent width being observed near minimum brightness. The amplitude of the variation is different for each line and a maximum amplitude is observed for the Li I line (0.53-0.65 Å). For other lines (e.g. Ni I 6644) no variation of the equivalent width can be recognized. Table 4 presents the mean, minimum and maximum equivalent widths obtained for different lines as well as an indication of the existence of periodic variations. It should be noted that the observed variations do not change when the contribution of the continuum (R_c band) is taken into account.

4.2. The variability of the Li I 6708 line

The periodic variation that we have observed for the $W_{Li\,I}$ (Fig. 2) has not been reported previously. Patterer et al. (1993) obtained $W_{Li\,I}$ in the range between 0.52 and 0.64 Å and considered that their data were consistent, within the margin of error, with a constant value of 0.55 Å.Welty & Ramsey (1995) concluded that the $W_{Li\,I}$ variability they observed was not statistically significant. Nevertheless, we note that their data show larger scatter in November 1992 than in December 1993.

The detection of this variability may be related to the variable amplitude of the light curve. The maximum amplitude around these years was expected for the 92/93 season (there is some uncertainty due to the lack of photometry after 1993) and, thus, it is possible that the $W_{Li\,I}$ could only be clearly detected on those dates, when the amplitude in the V band was about 0.60 mag. Patterer et al. (1993) presented data from Oc-

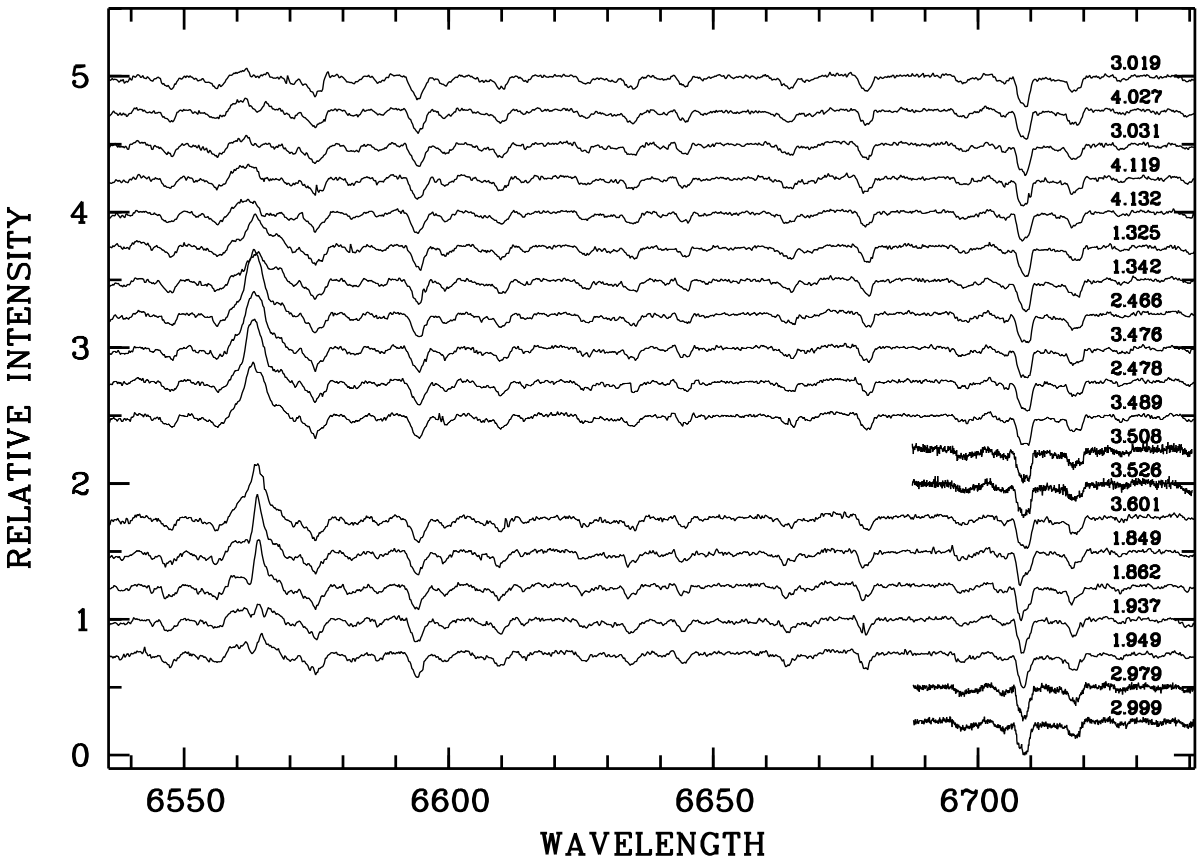

Fig. 1. The 6532-6745 Å spectra of V410 Tau. For each spectrum the phase is indicated following the convention established for Table 2.

tober 1990, near the amplitude minimum (0.4 mag in V) and Welty & Ramsey (1995) found much a higher chance of detection of this variability for their November 1992 data, than for their December 1993 data. In this respect, it is worth noting that at least for some of the stars for which Soderblom et al. (1993) did not find variations of $W_{Li\,\mathrm{I}}$, the amplitude in the V band is $\leq$ 0.1 mag. We conclude that with respect to the $W_{Li\,\mathrm{I}}$ variations the amplitude of the continuum variability might play an important role. The absence of such a variability in HD 283572 (Sect. 5) supports this hypothesis. A systematic study of $W_{Li\,\mathrm{I}}$ during minimum amplitude of the V410 Tau light curve would be very valuable.

There are also remarkable changes in the average $W_{Li\,\mathrm{I}}$ published in the last decade, as Martín & Claret (1996) pointed out. These values range from 0.36 Å (Basri et al. 1991) to 0.59 Å (this paper). We have found no correlation between this average value and the amplitude of the light curve, and the spectral resolution is not a factor to be taken into account, because it has always been larger than 12000. However, the averaged value of $W_{Li\,\mathrm{I}}$ and the intensity of the H_α emission could be related to each other. In fact, the data published by Welty & Ramsey (1995) and ours suggest that the lower the H_α emission intensity, the larger the average $W_{Li\,\mathrm{I}}$. Considering that the contribution of the faculae to the $W_{Li\,\mathrm{I}}$ can compensate that of the spots (Barrado y Navascués 1996), the correlation mentioned can be explained as an effect of the faculae that simultaneously contribute to the $W_{Li\,\mathrm{I}}$ and to the H_α emission line. The larger this contribution is, the stronger the emission of the H_α is, and the smaller the changes of the $W_{Li\,\mathrm{I}}$ are within a rotational period.

4.3. H_α emission line variability

The H_α emission varies according to the period of the star. Fig. 3 shows the sequence of our H_α spectra superimposed on the light curve obtained by Petrov et al. (1994) during the 1992/93 season. Both sets of data were taken two months apart. Due to the trend in the difference between observed and computed times of minimum, phase 0.0 does not correspond, at the time of our observations, to the minimum of the light curve.

Just before the maximum brightness of the star, the H_α emission hardly fills the line. At maximum brightness, blueshifted weak emission appears. As the brightness of the star decreases a plateau is visible and upon it a narrower emission develops. Before the minimum brightness of the star the narrow component is blueshifted by $\simeq$ –20 km s^{-1} with respect to the centre of the plateau. A minimum velocity difference of $\simeq$ –3 km s^{-1} between the narrow component and the centre of the plateau is observed near the minimum brightness (phase 0.601; Fig. 3). After this point, the narrow component is redshifted by $\simeq$ +20–+30 km s^{-1}, its intensity decreases and a weak central absorption is

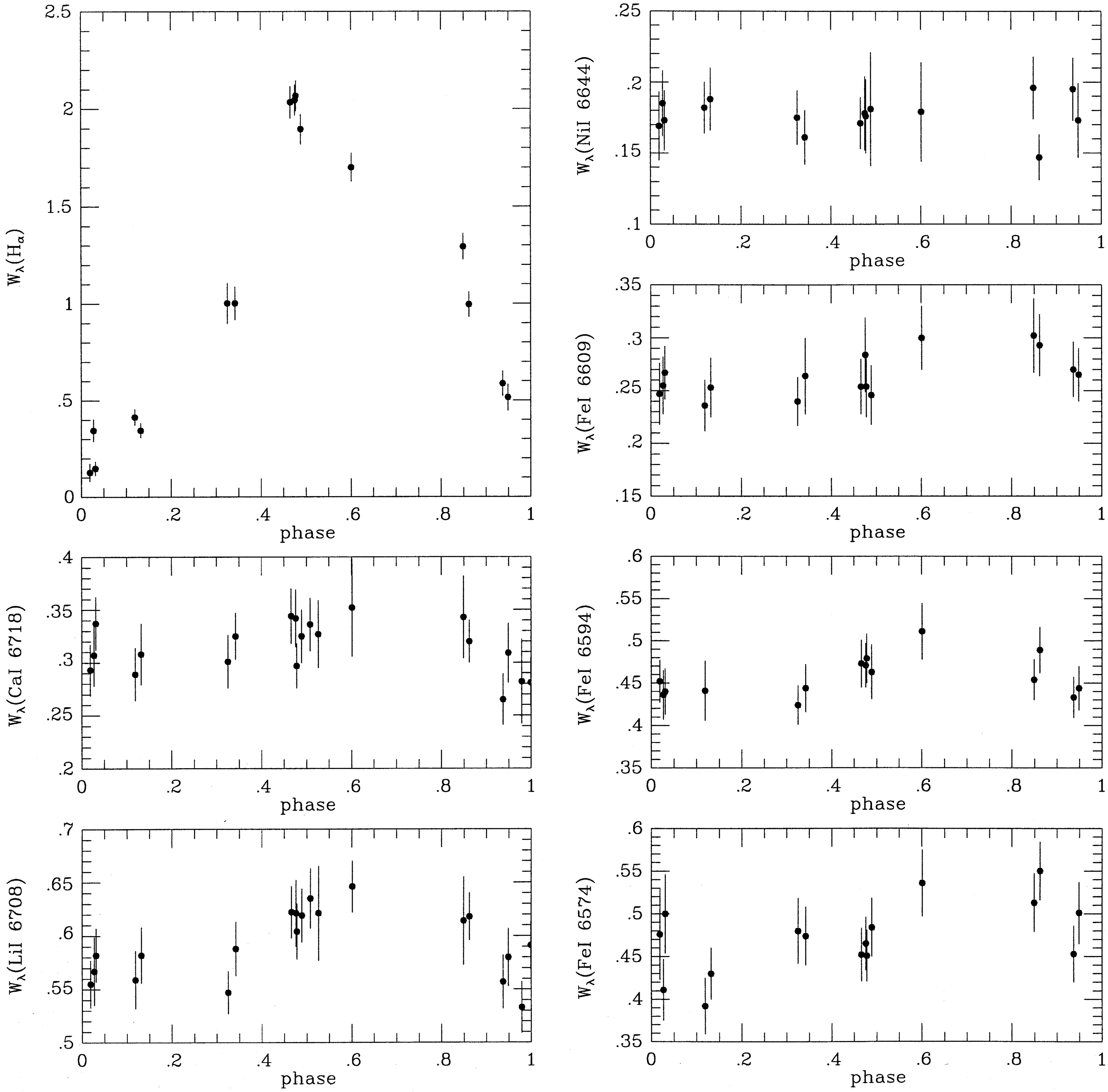

Fig. 2. Variability of the equivalent width versus phase of some of the lines observed in V410 Tau in the 6532-6745 Å wavelength range.

observed in the plateau. During the whole cycle, the centre of the plateau presents a heliocentric radial velocity of $\simeq$ +20 $\pm$ 5 km s^{-1}, similar to the stellar radial velocity ($\simeq$ +18 km s^{-1}, Herbig & Bell 1988). The width of the plateau at the continuum level is $\simeq$ 10.9 Å (500 km s^{-1}). This value is about three times larger than the FWHM of the narrow component ($\simeq$ 3 Å, 140 km s^{-1}).

The way the H_α profile varies point to a relation between the large cold spot and the region where the narrow emission component arises. When the brightness decreases, the largest spot must be entering the visible hemisphere towards the observer; during this period the narrow H_α emission is blueshifted. At minimum brightness, the largest spot crosses the central meridian and the narrow component presents a very small radial velocity with respect to the plateau. When brightness increases, the largest spot recedes from the observer, and the H_α narrow component is redshifted. At maximum brightness, both the largest spot and the narrow component are not observed. This behaviour indicates a coincidence at least in longitude between the largest spot and the region responsible of the narrow component. The

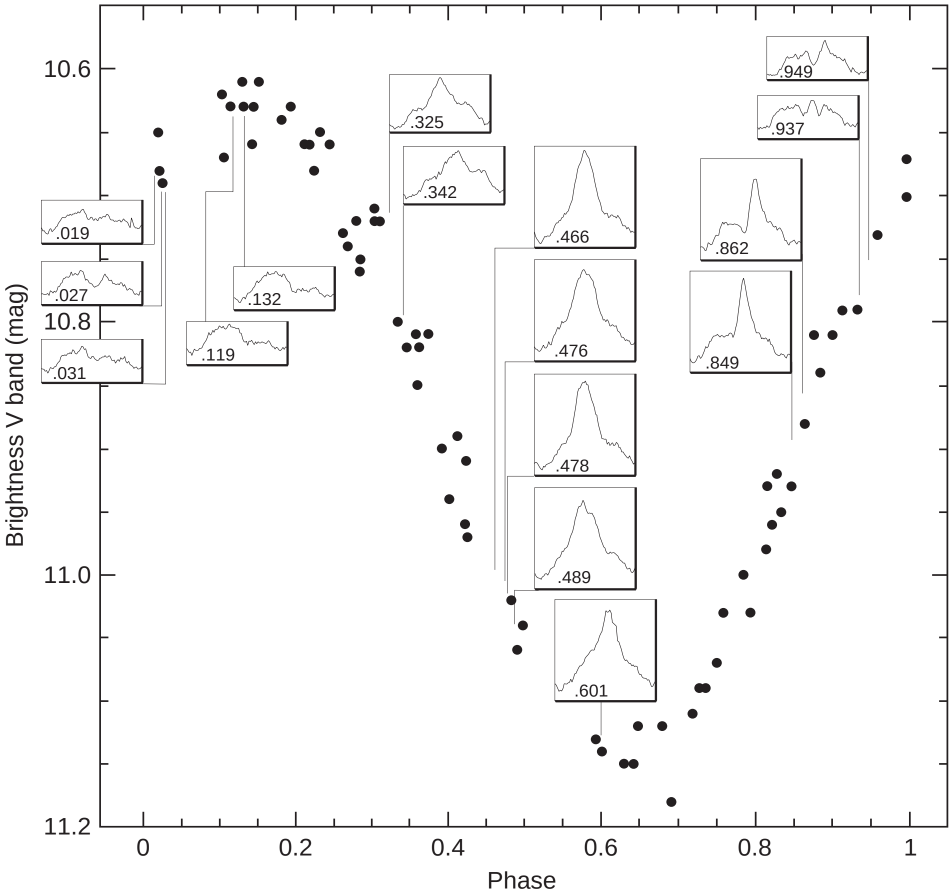

Fig. 3. Observed profiles of the H_α emission line of V410 Tau superimposed on the light curve obtained by Petrov et al. (1994) for the 1992/93 season. Phases refer to the VHS's ephemeris. The photometric data have been taken from the Herbst et al. (1994) catalogue.

small values of the blue and redshifts of this component suggest a high latitude for the emitting region. It is interesting to note that narrow emission components have been previously attributed to flares. Hatzes (1995) presented simultaneous observations of an intensification of the He I D_3 emission during an H_α peak that give support to the flare hypothesis. In the context of the flare activity of V410 Tau, Welty & Ramsey (1997) presented the strongest evidence for the detection of one of these flares in December 1993. Nevertheless, the duration of the narrow emission we observed let us discard this hypothesis. Other hot regions related to the solar-type activity must be responsible of the emission.

Concerning the component that always fills the H_α absorption (the W_{H_α}, absorption line, for a K3 V star being ~ 1.3 Å) and, at least, part of the plateau, they must come from a region always visible. Because the plateau can be traced up to $\pm$ 250 km s^{-1}, this region could be corotating with the star at approximately $3R_\star$ or could represent a slow wind. The circumstellar origin of the plateau is not supported, however, by the very small infrared excess of the star (Strom et al. 1989), which could be related to its companion (Ghez et al. 1993).

The comparison between our spectra and those obtained by Petrov et al. (1994) and Hatzes (1995) reveals rather quick changes on the H_α emission. The profile of the plateau and the intensity of the narrow component relative to it change notoriously among the three groups of spectra. There are also important changes in the peak intensity relative to the continuum: the more prominent maximum detected by Petrov et al. (1994) reaches 2.0, while for Hatzes (1995) it is 1.6 and for us, less than 1.5. We consider rather improbable that these differences are due to continuum changes or to the selection of continuum around the emission line. All these values correspond to the minimum of the light curve and observations were carried out less than one year apart, thus we all must have observed the star near the maximum amplitude of the light curve. Besides, we get the smallest W_{H_α} and correcting it from the continuum changes, it would be still smaller. This points to a short time scale for the changes of the chromospheric activity, much shorter than that of the changes of the star spots, which seem to keep more or less the same characteristics along years.

There are, thus, three different time scales for the variability that has been observed in V410 Tau:

i) Variability with a period of 1.872 d due to the rotational modulation of brightness by cold spots. This variability is observed at the absorption lines, the continuum and the H_α emission line.

ii) Variability with time scale of months observed in the H_α emission and probably related to the chromospheric activity, circumstellar matter and/or winds.

iii) Variability with time scale of years observed in the amplitude of the light curve and related to the changes of the characteristics (size, temperature and location) of the spots.

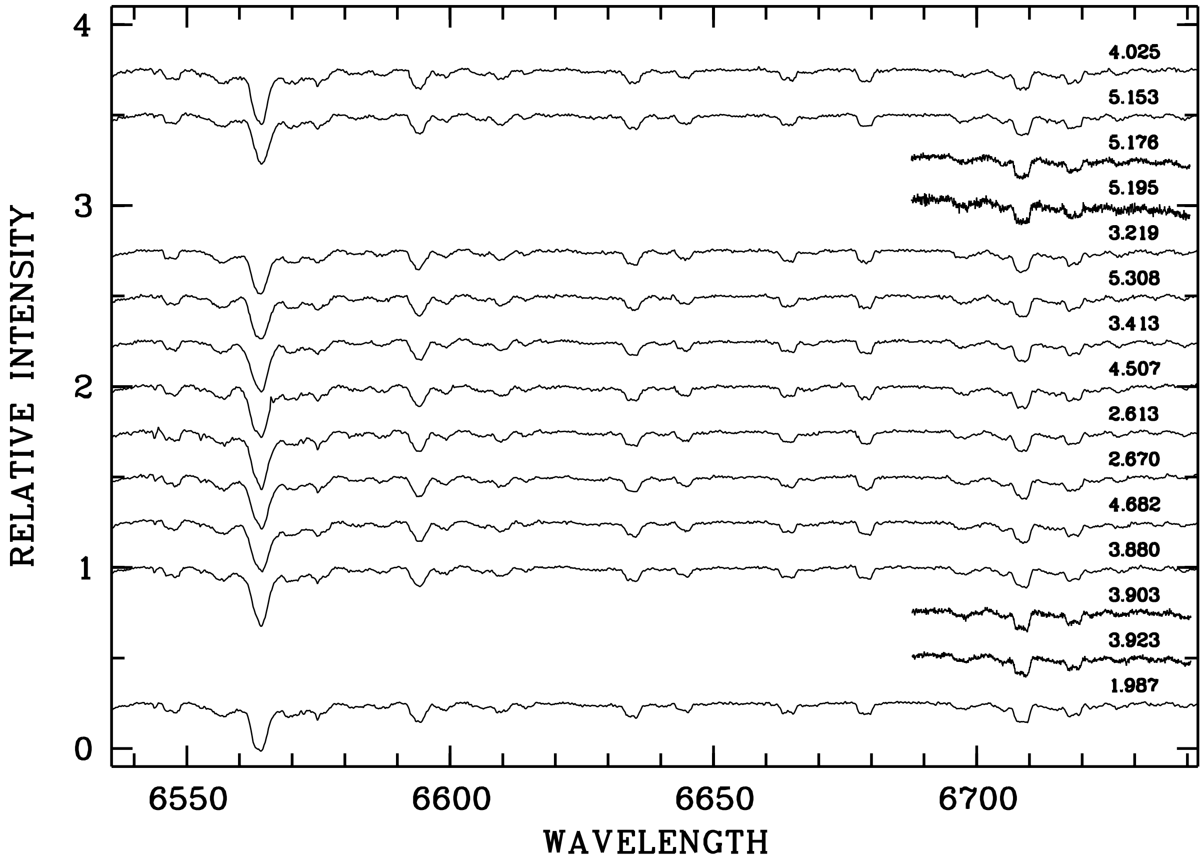

Fig. 4. The 6532-6745 Å spectra of HD 283572. For each spectrum the phase is indicated following the convention established for Table 2.

5. HD 283572

HD 283572 is a massive ($\sim 2\ M_{\odot}$) WTTS for which Walter et al. (1987) estimated a radius of 3.3 $R_{\odot}$. They studied the star in detail and obtained two values for $v \sin i$: 95 and 130 km/h from lines at 4000 and 5200 Å, respectively. They also found a strong chromospheric and coronal emission, with surface fluxes similar to those of the most active late type stars (excluding the TTSs). Evidences for IR or UV excess and a strong stellar wind have not been found (Walter et al. 1987). Although its Li abundance, high $v \sin i$ and radius point to a young star, rapid rotators are expected to keep anomalous Li I 6708 abundances (Martin & Claret 1996) and, thus, we could be dealing with an *evolved* WTTS.

The variability observed by Walter et al. (1987) in the V band is well described by a sinusoid with a peak-to-peak amplitude of 0.107 mag and a period of 1.548 days. Shakhovskaya (1990) carried UBVRI photometric observations from 1986 to 1989. Her results do not contradict the Walter et al. (1987) period, but there are both a phase shift between different seasons and changes in the amplitude of the light curves that could be explained by the change of distribution and size of the active regions. Skrutskie et al. (1996) presented JHK observations from November 1991 to April 1992 and they found variability with a a peak to peak amplitude around 0.2 mag at these bands, but they did not find any periodicity.

Joncour et al. (1994b) derived a Doppler image of HD 283572 from February 1993 spectroscopic observations of some Fe I, Ca I and Li I lines. The image reveals one large polar structure 1600 K colder than the surrounding photosphere. From the Doppler images they deduced that the minimum of the light curve occurred approximately at phase 0.07 in the Walter et al. (1987) ephemeris.

5.1. Results

Our observations cover 3.2 rotational periods of the star with 15 spectra, shown in Fig. 4. Phases were calculated using the ephemeris of Walter et al. (1987),

$$HJD = 2445600.173 + 1.548E.$$

The bumps observed on the Li I 6708 line shift smoothly along the phase sorted spectra and are compatible with a spot crossing the meridian near phase 0.0. Since the wings do not ever seem to be distorted, the latitude of the spot must be high. The Li I 6708 high resolution (f/12 camera) profile at phase 0.176 and, mainly that at phase 0.195, show no structure on the lines, except for a flat bottom. The comparison with the Doppler

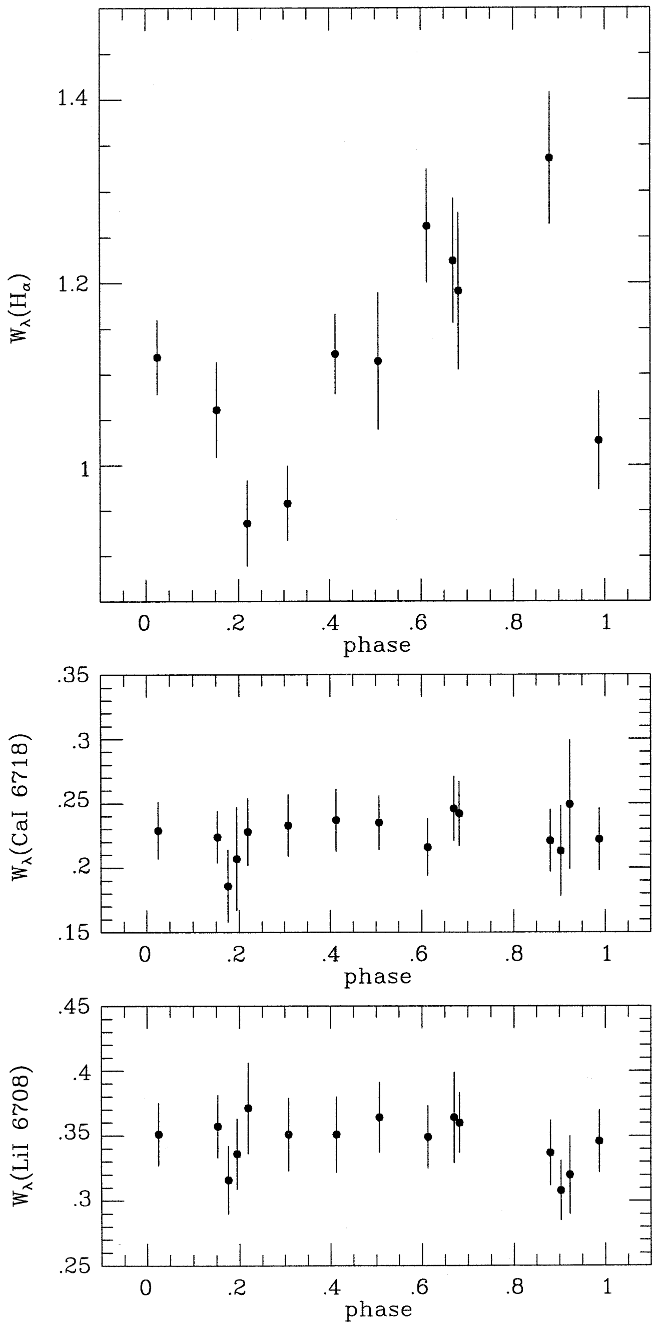

Fig. 5. Equivalent width versus phase of the H_α, Li I 6708 and Ca I 6717 lines observed in HD 283572.

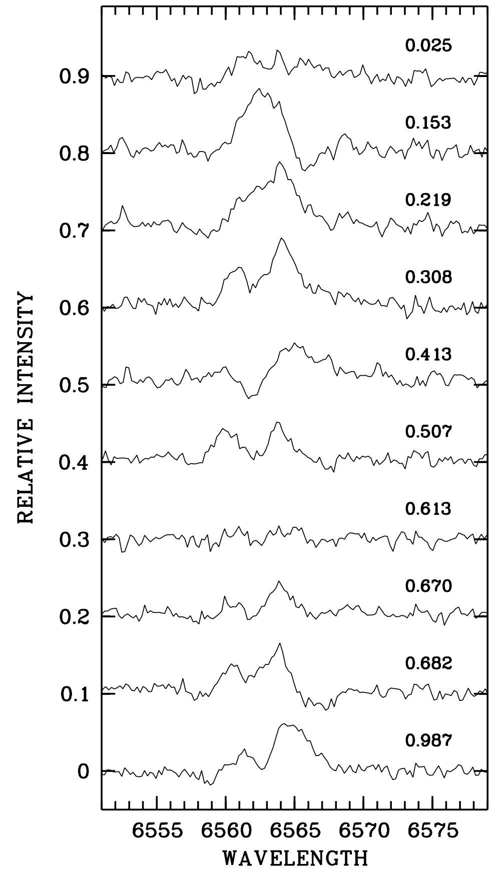

Fig. 6. Differences between the H_α profiles of HD 283572 observed at different phases and at phase 0.880. The residual spectra are labeled with the different phases.

images of Joncour et al. (1994b) indicates that we observed the spot just after it crossed the meridian.

A correspondence between the bumps on the Li I 6708 and Ca I 6717 lines is not observed. In fact, most of the spectra of the Ca I 6717 line show a central emission-like component which could be due to a chromospheric contribution.

Fig. 5 presents the equivalent widths of the H_α (see also below), Li I 6708 and Ca I 6718 lines as a function of the phase. No variation of the equivalent width is observed in the metallic lines. The mean equivalent width of several of them is given in Table 5. The mean $W_{Li\,I}$, 0.345 Å (Table 5), is similar to the value measured by Walter et al. (1987), 0.36 ± 0.05 Å. However, both values are substantially larger than that obtained by Patterer et al. (1993), 0.244 ± 0.039 Å.

Table 5. Mean equivalent widths of absorptions lines in HD 283572

λ (Å)	Equivalent width (Å)
6548	0.135 ± 0.011
6594	0.305 ± 0.012
6634	0.246 ± 0.009
6679	0.188 ± 0.007
6708	0.346 ± 0.016
6718	0.226 ± 0.016

5.2. *The partially filled H_α emission*

The mean W_{H_α} is 1.12 Å and it varies between 0.94 and 1.34 Å (Table 5). When plotted versus phase, this equivalent width follows a sinusoid with minimum at phase 0.2 (Fig. 5). Joncour et al. (1994b) obtained a very similar curve for the W_{H_α} versus phase, although it was consistent with both the rotational period of the star and half this period. The possible rotational modula-

Table 6. Mean equivalent width (Å) of some of the absorption lines (indicated by their wavelength in Å) in UX Tau A, HP Tau/G2, SU Aur, CO Ori, GW Ori and VSB 78.

Star	λ6548	λ6594	λ6664	λ6679	λ6708	λ6718
UX Tau A	0.16	0.36	0.16	0.16	0.37	0.20
HP Tau/G2		0.23	0.20	0.21	0.26	0.15
SU Aur	0.13	0.27		0.16	0.23	0.13
CO Ori	0.12	0.20	0.11	0.17	0.15	0.10
GW Ori	0.13	0.22	0.12	0.11	0.22	0.10
VSB 78		0.13			0.14	0.11

tion of the W_{H_α} suggested to them the presence of large-scale chromospheric structures above the stellar surface.

Changes in the H_α absorption profile can be recognized as small bumps near the line centre. In order to analyze these changes more quantitatively, we have selected the spectrum at phase 0.880 as a reference because of its symmetrical, almost Gaussian profile. In Fig. 6 we present the difference between each spectrum and the selected reference. Variable residual emission is observed in all spectra, except at phase 0.613. Two emissions peaks separated by $\simeq$ 140–160 km s^{-1} can be recognized at most phases. Between phases 0.153 and 0.413, the residual emission seems to shift towards longer wavelengths. The intensity of the residual emission varies with the phase. A maximum intensity is observed at phases $\simeq$ 0.2–0.3 and it is a factor $\simeq$ 10 higher that the minimum intensity observed at phase 0.613. It is noticeable that this maximum intensity is observed near minimum light (phase $\simeq$ 0.1, Joncour et al. 1994b). At this phase a maximum area of the spot is observed, suggesting a coincidence in longitude between the spot and the region in which the H_α emission arises. The partially filled H_α line supports the idea of an "evolved" WTTS and is compatible with a low level of magnetic activity. It is noticeable that Walter et al. (1987) did not find any residual emission in H_α in their 1982–1985 spectra, after comparison with a standard star. This suggests a long term variability of the chromospheric emission of HD 283572.

6. Other T Tauri stars with high $v\,\sin i$

We summarize here the results obtained for UX Tau A, HP Tau/G2, SU Aur, CO Ori, GW Ori, VSB 48 and VSB 78. The spectra of these stars are shown in Fig. 7 and 8. In some cases, high resolution spectra are presented here for the first time. In other cases, the spectra show structures not observed previously.

Variations of the profile of some absorption lines are only observed in HP Tau/G2 and VSB 78. Table 6 contains the mean value of the equivalent width of some relevant absorption lines, including Li I 6708 and Ca I 6717 (data for VSB 48 are not included, see below). Variations in the equivalent width of metallic absorption lines are not observed in our spectra.

Table 7 lists the data obtained for the H_α line: equivalent width, radial velocity of the emission and absorption peaks and full width at 10% of the intensity level (FW01). The measurements referred as *absorption* correspond to absorptions in the profile, which go below the continuum. Absorption reversals have not been considered. In all the stars, except HP Tau/G2 and VSB 48, the H_α equivalent width is variable and in most of them variations of the radial velocities are also observed. In the following paragraphs we will briefly comment the results obtained for each star.

UX Tau A

Bouvier & Bertout (1989) observed that the brightness of this star varied with an amplitude of 0.26 mag in the V band and a period of 2.7 days. They attributed this variability to a cold spot, 700 K colder than the star photosphere, covering 11% of the stellar surface. Nevertheless, Vrba et al. (1993) could not find any periodicity for their entire dataset, nor for any data subset.

In our spectra (Fig. 7) the Li I 6708 line profile is always symmetric. The value of 0.37 Å we measured for its equivalent width is similar to that of 0.39 Å obtained by Balachandran and Carr (1994) and close to that of 0.43 Å obtained by Magazzú et al. (1991). Changes were not observed in the other metallic lines either.

The H_α profile shows three variable emission peaks (Fig. 7). The values measured for W_{H_α} (Table 7) are much larger than those obtained by Cohen & Kuhi (1979), Vrba et al. (1993) and Magazzú et al. (1991), that range from 2.8 to 6.4 Å.

HP Tau/G2

Vrba et al. (1989) observed a regular brightness variability of this star with a period of 1.20 ± 0.01 days and an amplitude at the V band of 0.08 mag. Assuming 5700 K for the temperature of the star, families of cold spots with temperature in the range 5200-5400 K and covering between 20% and 35% of the visible hemisphere fitted reasonably well the data. They pointed out the remarkable similarity between this star and HD 283572, being HP Tau/G2 only slightly more massive and evolved.

The Li I 6708 line profile is different in both spectra (Fig. 7). In the spectrum taken on 7^{th} January 1993, the Li I 6708 line presents a flat bottom, whereas in the spectrum taken on the 10^{th} a bump is observed on the red part of the line. This suggests the presence of a cold spot (or group of spots) which crosses the central meridian on the 7^{th}. This result and the large $v\,\sin i$ of the star make it a good candidate for further observations.

Variable H_α absorption is observed in our spectra (Table 7, Fig. 7). Herbig & Bell (1988) reported the existence of a faint emission peak on either side of the H_α absorption. The blueshifted peak can be identified in our spectra. Its equivalent width is very small and the variability suggested in Table 7 is probably not real. However, the large variation of the radial velocity may be considered real. No redshifted peak can confidentially be identified in our spectra.

SU Aur

Herbst et al. (1987) found a probable period of 1.55 or 2.73 days (the ambiguity arising because of the sampling frequency) for this star, but Gahm et al. (1993) did not confirm any of these periods. They observed variations of 0.3 mag in the V band.

Table 7. Characteristics of the H_α line of UX Tau A, HP Tau/G2, SU Aur, CO Ori, GW Ori, VSB 48 and VSB 78.

Star	Date (Jan 1993)	W_λ(em) (Å)	W_λ(ab) (Å)	v_{LSR}(em) (km s^{-1})	v_{LSR}(ab) (km s^{-1})	FW0.1 (km s^{-1})
UX Tau A	6	23.1		-76,+22,+120		468
	9	11.4		-84,+10,+112		465
HP Tau/G2	7	0.0	1.5	-198	+33	352
	10	0.0	1.0	-181	+72	337
SU Aur	5	6.0	0.1	-176,+49,+190	-19	551
	6	4.5	0.3	-181,+40,+189	-28	554
	7	5.6	0.2	-151,+35,+173	-35	539
CO Ori	7	9.0	0.1	-174,+63	-45	517
	9	7.2	0.2	-188,+69	-41	532
	10	4.7	0.5	-204,+70	-51	539
GW Ori	6	20.5		-81,+34		449
	10	24.2		-81,+22		449
VSB 48	6		1.5		+39	307
	8		1.4		+1	307
VSB 78	7	1.2	1.5	-96,+131	-324,+4,+289	509
	8	1.9	1.2	-103,+88	-301,+2,+276	423
	9	2.1	1.4	-81,+153	-335,+11,+381	600
	10	1.5	1.4	-67,+90	-335,+7,+336	554

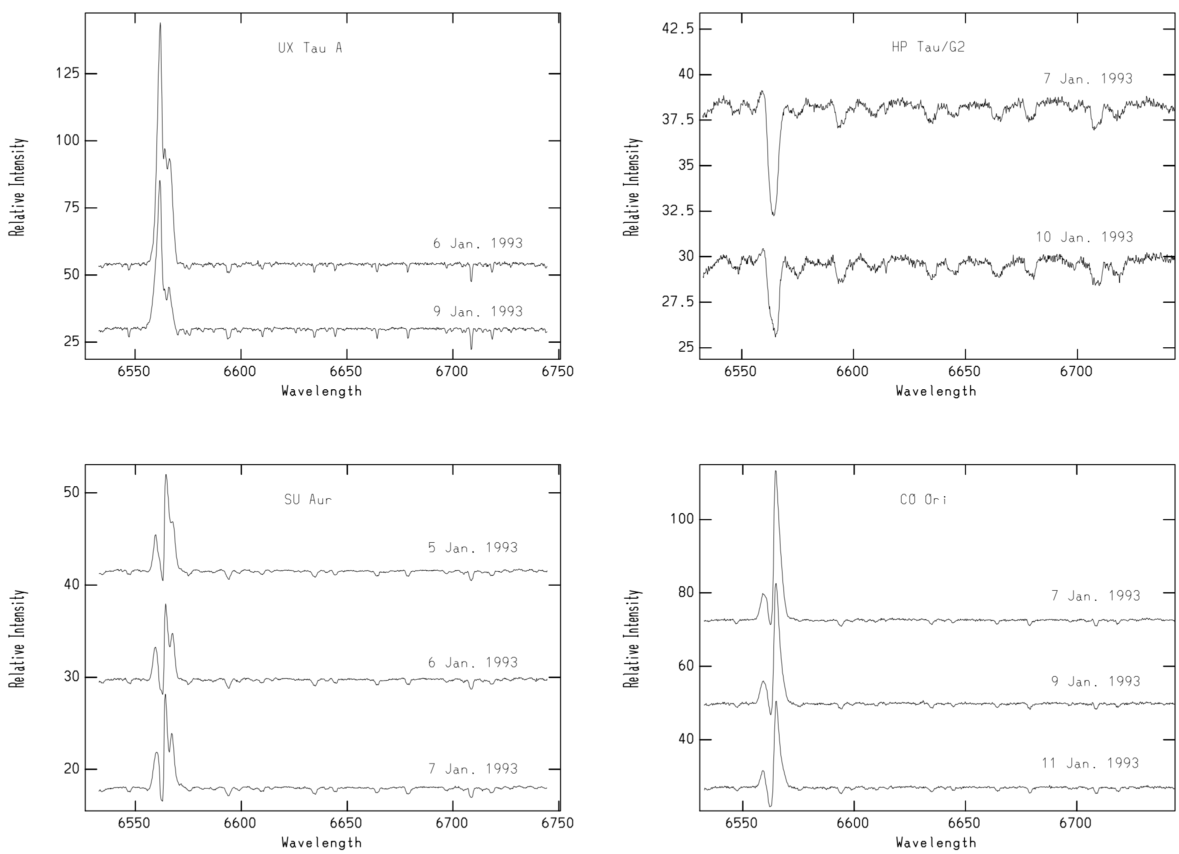

Fig. 7. The 6532-6745 Å spectra of UX Tau A, HP Tau/G2, SU Aur and CO Ori.

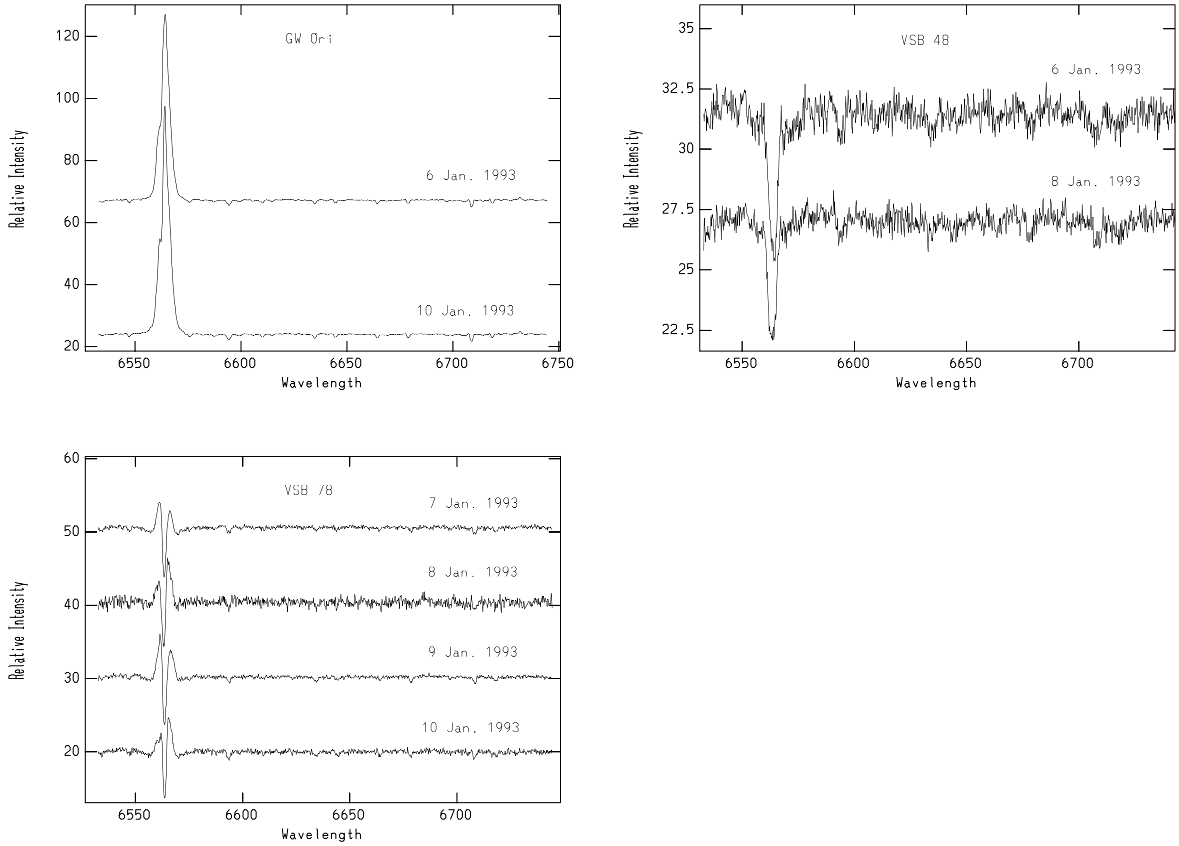

Fig. 8. The 6532-6745 Å spectra of GW Ori, VSB 48 and VSB 78.

In our spectra (Fig. 7) the Li I 6708 and Ca I 6717 lines do not present variations. The H_α spectra resemble some of those obtained by Johns & Basri (1995) and Fernández et al. (1995). Johns & Basri (1995) have analyzed them in the context of a symmetric wind.

CO Ori

CO Ori is well known for its variability (e.g. Holtzman et al. 1986). Herbst et al. (1987) reported a large amplitude irregular variability (≥ 2 mag). Herbst & Levreault (1990) did not find enhancements of the TiO when fainter and that suggested to them that a mechanism other than cold spots was responsible for the variability. Ultraviolet observations carried out by Eaton & Herbst (1995) supported the theory that obscuring material in the surroundings of the star must be the cause of the variability; they considered that CO Ori belongs to the "early type TTSs" defined by Herbst et al. (1994).

No structure can be recognized in the Li I 6708 line of our spectra, in spite of the relatively high $v \sin i$ (Fig. 7). This lack of bumps supports the hypothesis of the obscuring material as the cause of the variability. The intensity and radial velocity of the emission and absorption H_α components vary (Table 7). The double peaked H_α profile is slightly different from the single peaked H_α profile observed by Fernández et al. (1995), although the equivalent widths are comparable.

GW Ori

GW Ori is a single-lined spectroscopic binary with an orbital period of 242 days (Mathieu et al. 1991). Bouvier et al. (1986) and Gahm et al. (1993) found no periodicity with a time scale of days or weeks.

In spite of the 0.4 mag for the variability in the y Strömgren band observed by Gahm et al. (1993) in November 1982, we have not found asymmetries in the metallic lines (Fig. 8).

The H_α profile of GW Ori presents two emission peaks, and the radial velocity of the blueshifted one varies. The W_{H_α}(Table 7) is a factor 2 lower than that quoted by Herbig & Bell (1988) but comparable to that observed by Fernández et al. (1995). The [SII] 6716,6731 emission lines are present in our spectra.

VSB 48

VSB 48 (W68) is a not well studied young star. Its spectral classification ranges from F2 to G0, the Ca II H and K lines are present in emission, but no information on H_α has been reported so far (Herbig & Bell 1988). The brightness in the V band seems to be fairly constant (see references in Herbig & Bell 1988 and Neri et al. 1993).

Broad absorption lines are recognized in the spectra, but the noise prevents us from measuring them (Fig. 8). H_α is in absorption and seems to vary slightly in intensity (Table 7). The velocity of the minimum peak also varies. These data suggest that the H_α absorption is partially filled.

VSB 78

VSB 78 (W108) is a variable star with an amplitude ≥ 0.20 mag in the V band, although the time scale of the variability is not known due to the lack of continuous monitoring (see references in Neri et al. 1993). Spectral types from F7 V to G0 have been assigned to this star and, from a photometric study, Neri et al. (1993) suggested that F7 V is the more appropriate one. To the best of our knowledge no high resolution spectra of VSB 78 have been reported.

The spectra strongly suggest that the Li I 6708 line profile could be variable (Fig. 8). The H_α line presents two emission peaks, separated by a deep absorption and flanked by two weak absorptions, one at each side. The radial velocity and intensity of the H_α components vary. This profile is similar to that observed in XY Per E (Fernández et al. 1995). The small W_{H_α}(Table 7) suggests a WTTS type.

7. Concluding remarks

We have carried out high resolution spectroscopic observations in the 6532-6745 Å wavelength range of a sample of TTSs (Table 1), most of them WTTSs, on 6 consecutive nights. V410 Tau and HD 283572 have been monitored in more detail. We have analyzed the H_α and some photospheric line profiles. V410 Tau, HD 283572, HP Tau/G2 and, probably, VSB 78 show distortions in the photospheric line profiles, as expected from the cold spots previously suggested for some of them by photometric observations. Changes in the H_α line are observed for the whole sample, except, perhaps, for VSB 48.

The most important results obtained for V410 Tau are:

a) The equivalent width of several photospheric lines varies according to the rotational period of the star. The maximum amplitude of these variations is observed in the Li I 6708 line. The fact we observe these variations but that they have not been previously detected could be related to the large amplitude of the light curve at the time of our observations.

b) The average value of the $W_{Li\,\mathrm{I}}$ (0.59 Å) is larger than those reported previously. A possible relationship between the variation of the average $W_{Li\,\mathrm{I}}$ and the strength of the solar-type activity of the star at different epochs is suggested.

c) Periodic changes are observed in the narrow component of the H_α emission. The data indicate a coincidence in longitude between the largest cold spot and the region where the narrow emission arises.

d) The comparison between the observed H_α profiles and those published previously indicates that the H_α emitting regions vary with time scales of months. The time scale of these variations is shorter than that of the characteristics of the spots.

The photospheric line profiles of HD 283572 are compatible with the existence of a large polar spot previously reported. No variation of the equivalent width of the studied lines is observed, except for H_α. Residual H_α emission is detected. The region in which this residual emission arises could be related to the polar spot.

We note that the spectral types in our sample (from F7 to K3, Table 1) can be considered as *early* among the TTSs. This bias is due to the mentioned Doppler Imaging requirements (Sect. 2) and could explain the reason why for some stars it was difficult to detect distortions in the absorption line profiles. Rotation plays a very important role in the strength of the solar-like activity (stellar spots, chromospheric activity) in late type stars, but during the pre-main sequence stage the primary effect on the amplitude of the light curve (due to cold spots) corresponds to the depth of the convective zone, specifically, to the spectral type (Allain et al. 1996). The small amplitudes of the light curves due to cold spots of most of the stars of our sample could be due to their *early* spectral types: except for V410 Tau and UX Tau A, spectral types are earlier than or equal to G5. However, UX Tau A is the star with the smallest $v\,\sin i$ and distortions in its line profiles are hard to recognize. Rapid rotators of spectral type later than K0 thus seem to be the best candidates for a spectroscopic study of cold spots.

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