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Astron. Astrophys. 316, 164–172 (1996)

ASTRONOMY AND ASTROPHYSICS

# Doppler imaging of stellar surface structure

## II. The weak-lined T Tauri star V410 Tauri

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Received 12 May 1995 / Accepted 16 March 1996

**Abstract.** We present a new Doppler image of the rapidly-rotating weak-lined T Tauri star V410 Tauri and compare this new map with one previously published from observations taken over a year earlier. We find cool spots at both equatorial latitudes and at high latitudes with the high latitude spots being cooler and showing greater area and having greater longevity than the equatorial spots. A comparison of the two maps shows little relative change in the positions of the equatorial spots compared to the spots at high latitude suggesting very little differential rotation and what there is appears to be in the same sense as the Sun. Global spot lifetime would appear to be on the order of the time interval between the two maps, that is about a year. There are several hot features evident supporting the claim for the existence of such features based on our map of Nov. 1992.

**Key words:** stars: activity of – stars: imaging – stars: individual: V 410 Tau

### 1. Introduction

Sunspots and starspots are useful tracers of stellar activity and magnetic field structures in solar-type stars. Maps of the spot distributions of late-type stars have been obtained by Doppler imaging: inverting a series of observed spectral line profiles into an "image" of the stellar surface. Here we present the second paper in a series of papers on Doppler imaging of stellar surface structure aimed at a better understanding of the sunspot-starspot connection in late-type stars. Since the development of spot distributions and their associated magnetic fields may be key diagnostics of stellar evolution onto the main sequence, our current objective is to map the surface of a true pre-main-sequence object: a T Tauri star.

The best candidate is V410 Tau, an object which is thought to be a close counterpart to the Sun at an age of only one million years (Herbst 1989) that has been observed at virtually all wavelengths (e.g. Feigelson et al. 1991 and references therein). V410 Tau is a weak emission-line T Tauri star (WTT) with little infrared excess, leading to the conclusion it is "naked" i.e. without a significant circumstellar disk. The lack of a substantial disk means we can reliably image its photosphere. Its large photometric variability of up to ~0.5 mag is attributed to starspots that are rotating in and out of view (e.g., Vrba et al. 1988, Bouvier & Bertout 1989, Herbst 1989, Petrov et al. 1994).

The main obstacle in obtaining high-resolution spectra of V410 Tauri is the star's relative faintness ($V$ = 10.6–11.2 mag, K4). Normally, high-resolution Doppler imaging at $\lambda/\Delta\lambda \approx$ 50,000 is limited to stars brighter than $V \approx 9.5$ mag. However, spectral simulations for Ap stars have demonstrated that accurate maps are recovered even when the spectral resolution is as low as $1/5 \times v \sin i$ (Piskunov & Wehlau 1990). Consequently, first Doppler images of V410 Tau were based on KPNO-PennState spectra at a resolving power of 12,000 and $S/N$ of 120–150 (Strassmeier et al. 1994) and, independently, by Joncour et al. (1994) based on observations at Haute Provence at a resolution of 32,000 and $S/N$ of 50–115.

In this paper we present and analyse new high-quality and – so far – superior data for V410 Tau obtained with the Canada-France-Hawaii telescope (CFHT) at a resolution of 27,000 and $S/N$ of around 200:1 and compare this new map with our previous map obtained one year earlier.

### 2. Observations and data phasing

All spectroscopic observations were obtained with the 3.6-m CFHT during December 22–29, 1993 spanning almost four rotational cycles of V410 Tau. A 2048×2048 pixel CCD (Lick2 chip, with 15$\mu$ pixels) was used with the 600-l mm$^{-1}$ mosaic grating in first order with the f8.2 camera resulting in a resolving power of 27,000 or, equivalently, 0.24 Å for a resolution element at $\lambda_c$ = 6430 Å. All data were reduced in the same standard fashion using IRAF and included standard bias subtraction, flat

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**Table 1.** Spectroscopic observation log

| HJD (244+) | phase (phot) | $\theta$ (° ) | $\lambda_c$ (Å) | exp. time (min) |
|---|---|---|---|---|
| 9344.8337 | 0.433 | 156 | 6430 | 60 |
| 9344.9218 | 0.480 | 173 | 8500 | 60 |
| 9344.9802 | 0.511 | 184 | 6700 | 60 |
| 9345.0282 | 0.537 | 193 | 6430 | 60 |
| 9345.9726 | 0.041 | 15 | 6430 | 72 |
| 9346.0291 | 0.072 | 26 | 6700 | 72 |
| 9350.7314 | 0.583 | 210 | 6430 | 65 |
| 9350.8123 | 0.627 | 226 | 6700 | 57 |
| 9350.8654 | 0.655 | 236 | 8500 | 60 |
| 9350.9168 | 0.682 | 245 | 6430 | 60 |
| 9350.9888 | 0.721 | 260 | 6700 | 60 |
| 9351.0487 | 0.753 | 271 | 6430 | 60 |
| 9351.7230 | 0.113 | 41 | 6430 | 60 |
| 9351.7915 | 0.149 | 54 | 6700 | 60 |
| 9351.8882 | 0.201 | 72 | 6430 | 60 |
| 9351.9030 | 0.209 | 75 | 6700 | 45 |
| 9351.9382 | 0.228 | 82 | 6430 | 54 |
| 9351.9777 | 0.249 | 90 | 6700 | 50 |
| 9352.0202 | 0.272 | 98 | 6430 | 67 |

fielding and aperture extraction. Numerous comparison-lamp spectra and flat-field spectra were obtained throughout the night to ensure an accurate wavelength calibration and removal of the pixel-to-pixel CCD variations, respectively. Table 1 is a summary of the spectroscopic observations of V410 Tauri where $\theta$ is the stellar longitude of the central meridian. The monitoring observations for Doppler imaging were done at two wavelengths centered at 6430 and 6680 Å while two snapshots were obtained at the 8500 Å wavelength region to cover two of the three Ca II infra-red triplet lines and a magnetically sensitive neutral iron line. Figure 1 is a comparison of representative V410 Tau spectra at 6430 and 6680 Å with that from a normal K3V star (HR 753). Note the strong lithium line at 6707 Å that is completely absent in the HR 753 comparison spectrum.

By observing V410 Tau at a resolving power of about 27,000 (resolution = 11 km s$^{-1}$) and selecting red wavelengths where the star is brighter ($I$ = 9.4; $R$ = 10.2), we achieved $S/N$ of about 200:1 per resolution element in exposure times of 60 min.

Doppler imaging requires good phase coverage of the full rotational cycle of the star. Substantial gaps in phase coverage will cause loss of information in the image about the phases of the incomplete phase coverage. Our phase coverage is such that we have a 0.29-phase gap between 0.753 and 0.041 so the image between longitudes of about 270 degrees through 0 degrees is less reliable but not completely false since all portions of this area were visible in four observations. The difficulty is that these observations were not distributed favourably throughout the full cycle of approach and recession on the visible hemisphere of the star. An upcoming article will deal with the loss of information in Doppler images as a result of incomplete phase coverage (Rice 1996).

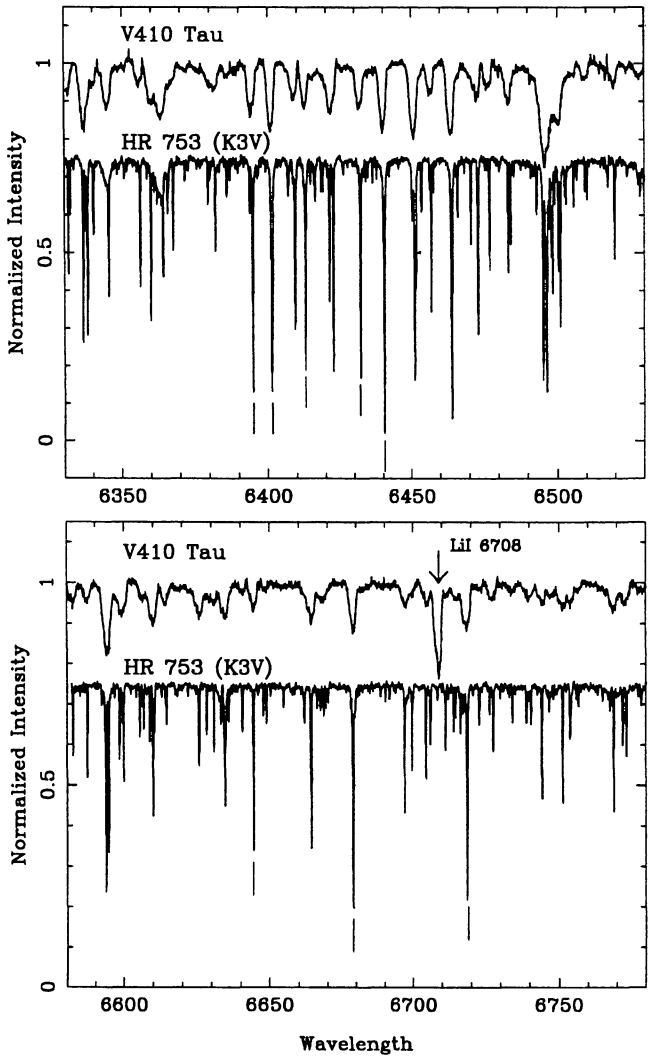


**Fig. 1.** Two representative spectra of V410 Tau (K4) at the 6430 Å wavelength region (top panel) and the 6700 Å wavelength region (bottom panel). A spectrum of the K3V star HR 753 is shown as a reference. The spectral lines used for Doppler imaging are marked with arrows. Note the strong lithium line in the spectrum of V410 Tau which is completely absent in HR 753.

Concurrent photometric data were kindly made available to us by Dr. Ed Guinan prior to publication and were obtained with the Four-College automatic photoelectric telescope (4C-APT, Dukes 1992) on Mt. Hopkins, Arizona during December/January 1993/94. The observations were made differentially with respect to HD 27159 as the comparison star and HD 76549 as the check star. All photometry has been transformed to match the Johnson $VRI$ system.

All line profiles and photometric data are phased with the revised photometric ephemeris of Petrov et al. (1994),

$$HJD = 2446659.4389 + 1.872095 \times E, \quad (1)$$

where the period is the long-term average photometric period between 1986 and 1993 which we interpret as the rotation period of the star, and the initial epoch is a time of minimum light.

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**Table 2.** Adopted parameters for V410 Tau

| Parameter | Adopted |
|---|---|
| Spectral type | K4 |
| $\log g$ | 4.0 |
| $T_{\rm phot}$ | 4400 K |
| $v \sin i$ | 77±2 km s$^{-1}$ |
| Inclination $i$ | 70° |
| Rotation period | 1.872095 days |
| Micro turbulence $\xi$ | 2.0 km s$^{-1}$ |
| Macro turbulence $\zeta_{\rm R} = \zeta_{\rm T}$ | 1.5 km s$^{-1}$ |
| log[$Ca$] abundance | –5.65 (= solar) |
| log[$Fe$] abundance | –4.41 (= solar) |
| log[$Li$] abundance | –8.45 (= solar) |
| log[$Ni$] abundance | –5.73 (= solar) |

**Table 3.** Spectral-line information

| Element | $\lambda$ (Å) | $\chi$ (e.V.) | $\log(gf)$ (-) |
|---|---|---|---|
| Fe I | 6393.602 | 2.43 | –1.62 |
| Fe I | 6400.013 | 3.60 | –0.03 |
| Fe I | 6411.659 | 3.65 | –0.32 |
| Fe I | 6430.852 | 2.18 | –1.85 |
| Ca I | 6439.075 | 2.51 | +0.40 |
| Ni I | 6643.629 | 1.68 | –2.29 |
| Fe I | 6677.994 | 2.69 | –1.51 |
| Li I | 6707.850 | 0.00 | +0.18 |
| Ca I | 6717.681 | 2.71 | –0.61 |

## 3. A Doppler image for late December 1993

All maps in this paper were generated with the Doppler-imaging code of Rice et al. (1989). Here we use a modified version of the original code, partially described by Piskunov & Rice (1994). A grid of model atmospheres with temperatures between $T_{\rm eff}$ = 3500 and 6250 K in steps of 250 K and fixed $\log g$ = 4.0 were taken from the ATLAS-9 CD (Kurucz 1993). For each model atmosphere local line profiles were computed under the assumption of solar abundances with a wavelength spacing of 0.008 Å. The broad lines of V410 Tau, combined with the 200-Å wavelength coverage of our spectra, are such that we can make use of nine lines summarized for convenience in Table 3. The combined image from all lines and the photometry is shown in Fig. 2. Note that in Fig. 6 the separate images from strong lines (Fig. 6a) and weak lines (Fig. 6b) are shown to illustrate the consistency with which lines of different strengths give the same image. The fit of the predicted relative light curve variation from this map compared to the observations for each of the V and I bandpasses is shown in Fig. 4. The fit to the observed profiles of the two lines Fe I 6430 Å and 6393 Å is shown in Fig. 5a and 5b to give some appreciation of the data used and the quality of the fit.

For comparison, the image from Strassmeier et al. (1994) has been converted to the same phasing as the image of this paper and is shown in Fig. 3 using an equivalent spherical projection.

This second image of V410 Tau calls for comparison with the first image to determine what changes have occurred in prominent features and what evidence there might be about differential rotation. One comment that needs to be made immediately is that there is an apparent difference in the average effective temperature between the two maps. The 1992 map has an average effective temperature that is less than the 4400 K given in Table 2. The effective temperature for the Doppler image is determined by the line strength and is subject to all of the problems associated with extracting the line profile from the raw data including continuum setting and scattered light. Further, the choice of atomic parameters, microturbulence and abundance will all alter the apparent effective temperature in the resultant map. In the map presented in this paper we have used a modified version of the Doppler imaging program, more lines and photometry obtained throughout the full rotational cycle with the result that the average effective temperature of the map is fairly close to the 4400 K suggested by the average colour of the star.

In general we note from both images now that there appears to be an abundance of cool spots at both equatorial and at high latitudes. The spots at higher latitudes appear larger, cooler and elongated as though stretched by shearing forces such as might be expected from substantial differential rotation or small differential rotation acting over a protracted time. One presumes that the likely interpretation is that the shear evident in these high latitude spots results from small differential rotation acting over a long time (presumably many years) since we will show that differential rotation is small for V 410 Tau and such large spots seem, from the evidence here and from photometric evidence (Hall 1991) to be very long lived. Approximately half of the spots seem to persist through the thirteen months between the maps with the higher latitude spots appearing to be cooler, larger, and more persistent.

Upon comparing the map features between the map of November 1992 and late December 1993, we find the two maps to have some striking similarities. In Table 4 spot features are identified by letter and the immediate impression upon comparing Fig. 2 with Fig. 3 is of the obvious persistence of the spots labelled A, B and C as seen in the two spherical projections at phases 0° and 90°. While not labelled as persistent spots, the extension of spot structure B down along longitude 270° as shown in the spherical projections at phase 270° is another obvious persistent feature. The feature labelled spot D is problematical since there are two rather strong features seen in 1992 that have apparently disappeared in late 1993 or alternatively in 1993 one of the features has disappeared leaving only one, or else the two features have merged. Probably the single most striking change is that a very strong feature of the 1992 map (spot G) at latitude 70° between longitudes 60° and 170° has apparently disappeared altogether. Of some interest perhaps is that a weak polar spot labelled H is now in evidence.

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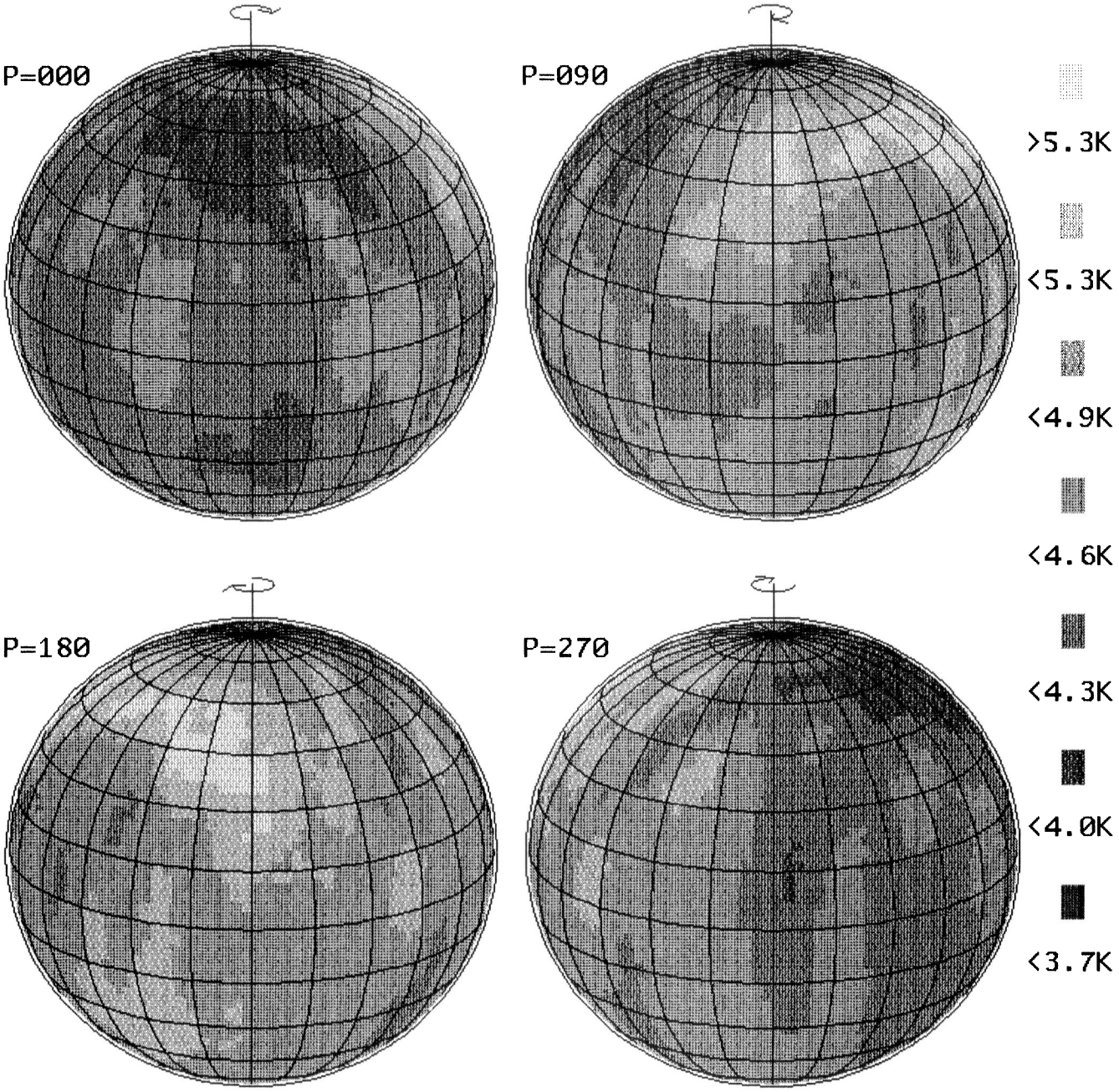


**Fig. 2.** Combined Doppler image of V410 Tau for late December 1993. These spherical projections represent the average of maps derived from the nine spectral lines listed in Table 2 and the photometry referred to in the text. The apparent phases of the images, representing the longitude of the central meridian, are shown to the upper left of each projection.

## 4. Differential rotation and hot spots

The features that the two maps have in common have moved very little relative to one another and relative to the phasing of the ephemeris. If there is a tendency to relative motion among the features at all it would appear that the equatorial features such as spot A have remained locked to the photometric phasing but that the prominent latitude +60° feature labelled B with its very conspicuous dual extensions to the south has migrated by perhaps 55° to 60° toward larger longitudes. If the spot identified as A is indeed the same feature in the map of December 1993 as the similarly located feature in the map of November 1992, and there has not been one or more full differential rotations between spot A and spot B within the thirteen months, then there would appear to be very little differential rotation on V 410 Tau and what little movement there is would imply a slightly slower rotation rate at higher latitudes. In particular this is the same as the sense of differential rotation on the Sun but much smaller than the differential rotation on the Sun. Since

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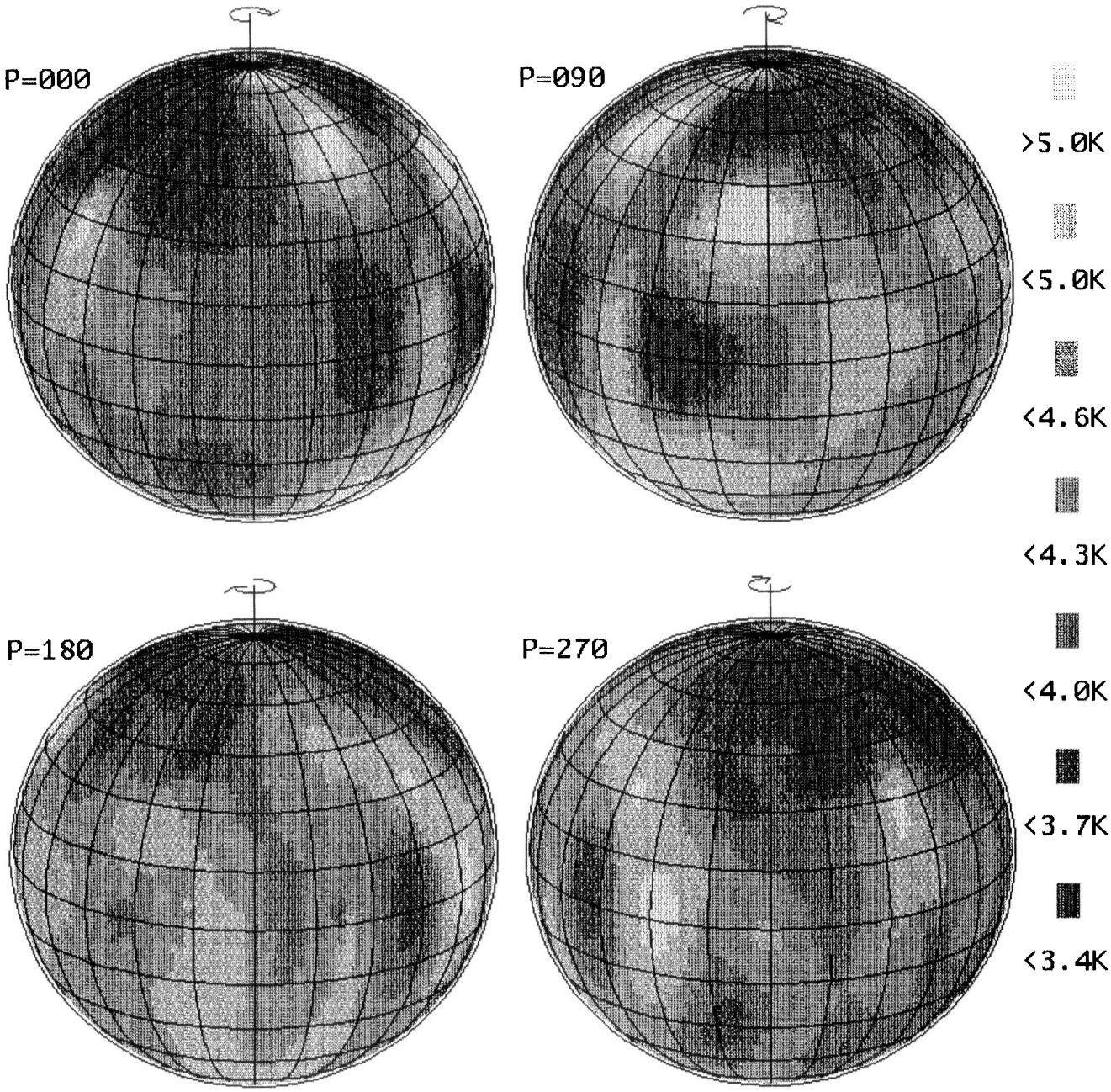


**Fig. 3.** Doppler image of V410 Tau for mid November 1992 replotted from Strassmeier et al. (1994) with the phase corrected to be consistent with the ephemeris adopted in this paper. This image can be compared directly with Fig. 2.

V 410 Tau has rotated by about 215 times during the interval between these maps, the difference in period between that at the equator and that at 60° would only be about 0.08%. If the relative rotation rate were described by the frequently used $sin^2\phi$ relation, we would have approximately

$$\Omega_{rel} = -0.2\ sin^2\phi \quad (^\circ/day) \tag{2}$$

where $\phi$ is the stellar latitude. The differential rotation parameter $\alpha$ representing the difference between equatorial and polar rotation rates divided by the equatorial rate is then about +0.0010 compared to a figure of +0.197 for the Sun or to a figure of about –0.02 from Doppler imaging of the RS CVn star UX Ari (see Vogt & Hatzes 1991). A very small value for differential rotation such as we have calculated here for V 410 Tau is not unexpected in a star of such short rotational period given the evidence from photometric data. Hall (1991) points out that the photometry indicates such short period stars seem to be nearly rigid rotators. What could not be determined from photometry though is the positive sense of the differential rotation.

Spots of higher photospheric temperature are seen in both maps. While generally the hotter spots were seen at intermediate

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**Table 4.** Changes in detected surface features between 1992 and 1993.

| Feature | latitude (°) | longitude (°) | apparent changes |
|---|---|---|---|
| *persistent* | | | |
| Spot A | 0 | 75 | size comparable but possibly weaker in 1993 |
| Spot B | +65 | 270 - 0 | displaced to larger longitude and smaller in 1993 |
| Spot C | –30 | 0 | possibly the visible extension of more southerly spots |
| *changes* | | | |
| Spot D | –30 | 250 | two spots replaced by one much weaker |
| Spot E | 0 | 30 | disappeared in 1993 |
| Spot F | 0 | 220 | disappeared in 1993 |
| Spot G | +70 | 60 - 170 | disappeared in 1993 |
| Spot H | +90 | 270 - 90 | a weak polar spot has appeared in 1993 |

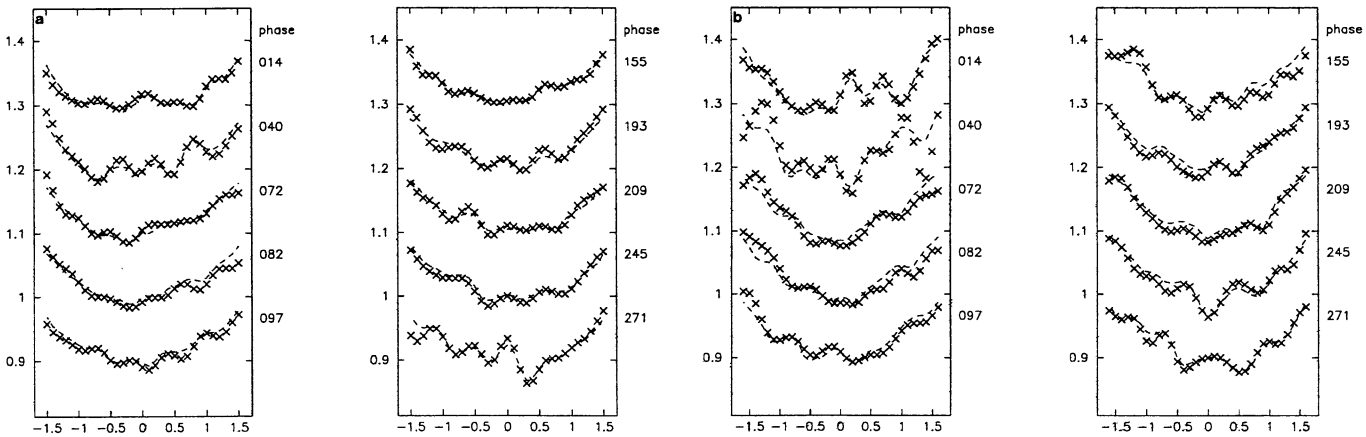


**Fig. 5a and b.** Observed (crosses) and computed (dashed lines) line profiles showing the fit from individual maps for **a** Fe I 6430 Å and **b** Fe I 6393 Å.

latitudes in the 1992 map, there was one small high temperature spot at a latitude of 0°. In the 1993 map there is an extended band of hotter features at a latitude of 50° extending from about 90° of longitude to about 190° of longitude. There may also be a similar feature at negative latitudes but weakened in contrast because of the large angle of the line-of-sight to the vertical. The northern feature is in the best observed hemisphere for this particular mapping occasion so the existence of this high temperature feature is fairly reliable.

Two spectra of V410 Tau were obtained at the infrared triplet lines of Ca II at $\lambda$ 8498 Å and $\lambda$ 8542 Å (Fig. 7). Their line cores within a $\approx$ 2-Å bandpass are usually thought to be of chromospheric origin and are seen in emission in solar plages (Shine & Linsky 1972). Both Ca II profiles in V410 Tau in Fig. 7 show pronounced double emission peaks near the line core. The peak-to-peak separation of the doubled emission feature is 2.95±0.10 Å ($\approx$ 100 km s$^{-1}$) and their full width at the bottom of the emission is 4.6±0.3 Å ($\approx$ 160 km s$^{-1}$). Theoretical line profiles computed by Linsky et al. (1979) for the K2 main-sequence star $\epsilon$ Eri showed clear emission features or shoulders but with a peak-to-peak width of only $\approx$ 0.5 Å and a full width of less than 1 Å whereas none of their observed profiles showed evidence for such emission features. Because of the large discrepancy of these widths we believe that the two emission features seen in V410 Tau, as well as at least part of the central residual line intensity, are not of chromospheric origin. Instead they could be formed by extended prominence-like structures or a wind. A similar scenario was invoked by Welty & Ramsey (1994) to model the excess H$\alpha$ profiles of V410 Tau but no conclusive model is available so far.

## 5. Discussion

Our original code to solve the inverse problem posed by surface mapping of stars was first applied to abundance mapping of Ap stars (e.g., Rice & Wehlau 1990, 1991, and references therein). More recently we have altered the code to obtain Doppler maps of the temperature variations on the surfaces of the spotted late-type RS CVn binaries UZ Lib (Strassmeier et al. 1996 = Paper I), HU Vir (Strassmeier 1994), EI Eri (Strassmeier et al. 1991) and of the rapidly-rotating, single FK Comae-type star HD 199178 (Strassmeier et al. 1996). One striking result from these maps is that we always found a cool starspot situated directly at the rotation *pole*, in contradiction to what we see on the Sun where sunspots occur only within ± 35° of the *equator*. However, since the previously mentioned stars are all giants or subgiants and,

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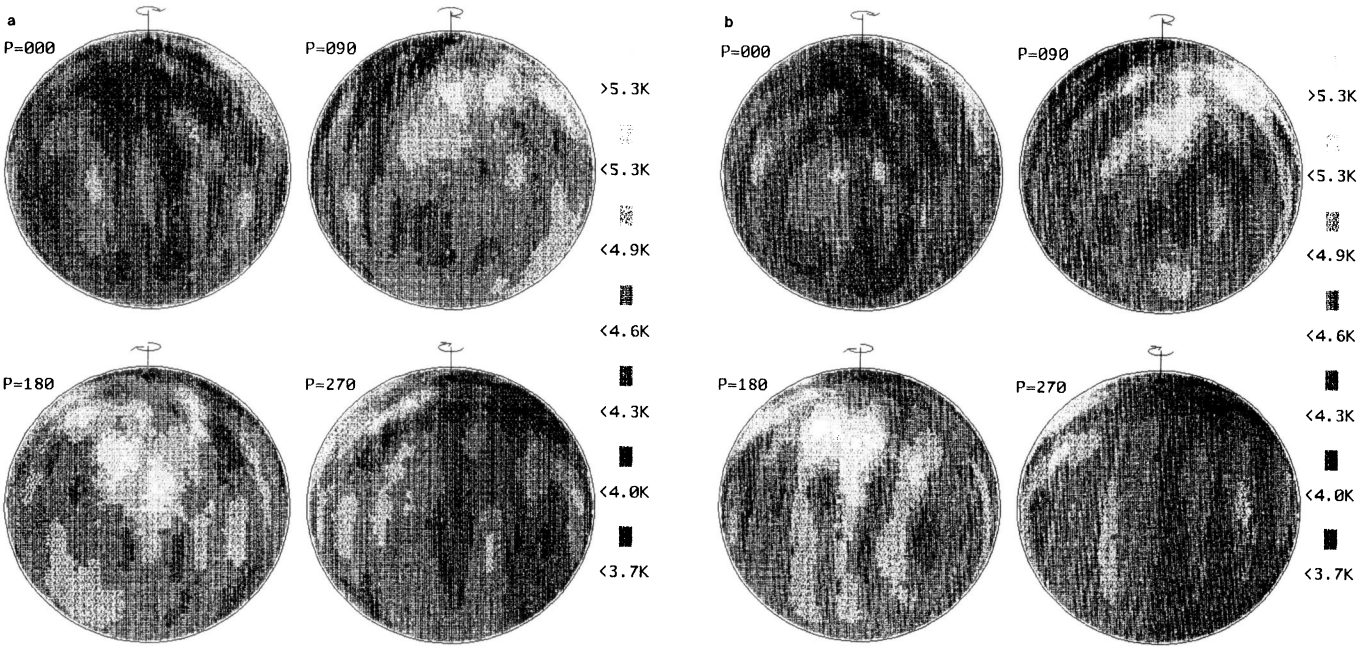


**Fig. 6a and b.** Spherical projections of the average maps of V410 Tau that are obtained by combining the maps obtained from **a** the three strongest lines Ca I 6439 Å , Fe I 6400 Å and Li I 6707 Å compared to **b** the maps from the remaining six much weaker lines. The three lines for the map in **a** have equivalent widths of 300 mÅ or more each and the remaining six lines are all about 150 mÅ each.

with the exception of HD 199178, are also components in a close-binary system, they are not directly comparable to the Sun.

To make a more direct solar comparison, we first observed a single dwarf star: LQ Hya = HD 82558. This star appears representative of the Sun in its youth, at about $\leq 7.5\ 10^7$ years (approximately the age of the Pleiades). In this case, we did *not* find a polar spot (Strassmeier et al. 1993) which was confirmed by independent observations of Saar et al. (1994). To complicate matters though, another suspected young object (HD 155555, K0V-IV) was observed at ESO by Kürster et al. (1992); their maps appear to show a large polar spot. However, it is not completely clear that this star is truly young, or even pre-main sequence (see Pasquini et al. 1991). Furthermore, our previous map of V410 Tau from 1992 did not show a cap-like polar spot but two big, cool features straddling the visible rotational pole. Similar, but not quite identical, polar features are seen in Joncour et al.'s (1994) image of V410 Tau from 1990 while a Doppler image of yet another weak T Tauri star, HDE 283572, by Joncour et al. (1994) reveals a large, cool cap-like polar spot very much like the ones observed for the rapidly-rotating evolved stars.

Bright spots in our first Doppler map of the WTT star V410 Tau led us to claim the existence of high temperature spots on the stellar surface that appeared to be 500 K in excess of the nominal photospheric temperature. Hot spots have been long thought to exist on classical T Tauri (CTT) stars due to accretion from the circumstellar disk (e.g. Bertout et al. 1988) but the weak-line T Tauri stars are all thought to be diskless. Although our result was not confirmed by the independent Doppler image of Joncour et al. (1994) we point out that their inversion method did not allow for spots with temperatures above nominal photospheric values. Thus their work couldn't have confirmed if the high temperature spots were actually there. Recently, Lamzin (1994) presented a re-analysis of $UBVRI$ light curves of the spotted T Tauri stars DN Tau and LkCa-19 (Bouvier & Bertout 1989) based on a spot geometry induced by magnetically controlled disk accretion on CTT stars and they succeeded in reproducing the light curves and their wavelength-dependent amplitudes with hot spots instead of cool spots, as done earlier by Bouvier & Bertout (1989).

In this paper we once again see high temperature photospheric spots with one especially large feature at a temperature of about 500 K above the nominal surface temperature for V 410 Tau. The large hot feature is elongated in longitude as are the strong high latitude cool spots and is in the range of longitudes on the star best covered by the observations. We must remind the reader that the line emission associated with many magnetic surface features such as plages and faculae tends to produce the effect of spurious cool spots in maps of photospheric temperature. Maps produced from the stronger lines most prone to exhibiting emission in such magnetic regions would have artificial cool spots compared to maps computed from weaker emission free lines. In this work we note that the hot features tend to persist even in the map of Fig. 6b which was constructed from weak lines only. Therefore it would seem that the hotter features seen here are regions of true elevated photospheric temperature. While the present observation supports the earlier claims of the existence of high temperature spots, there will continue to be controversy about the true nature of these features.

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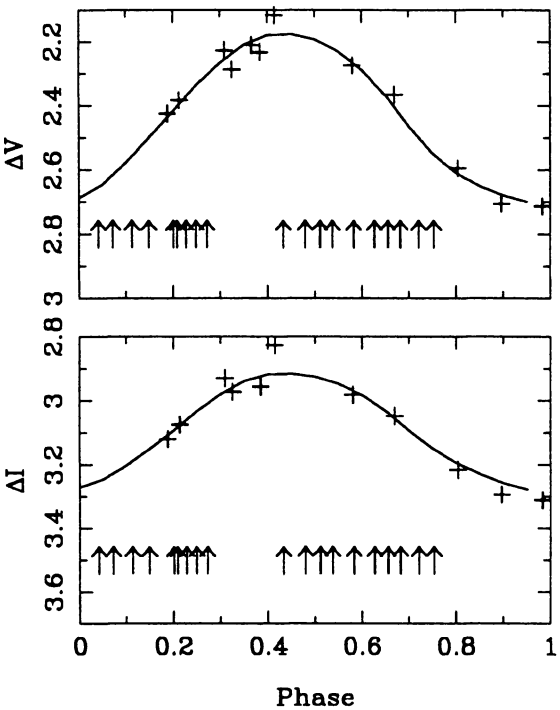


**Fig. 4.** The relative light curve variation of the map of V410 Tau for each of the V and I photometric bandpasses. The crosses represent the observed data, the solid line is the fit of the model and the arrows represent the phases of the spectroscopic observations.

Are these hotter regions very strong plages or faculae (perhaps the most likely explanation since V 410 Tau is a WTT) or could these regions of higher photospheric temperature be due to some residual disk accretion such as is seen on the CTT stars. The situation calls for simultaneous and multi-wavelength observations of selected WTT and CTT stars like the recent campaign on HDE 283447 by Feigelson et al. (1994).

While the accretion scenario is less likely and while V 410 Tau has apparently very little differential rotation, it is interesting to note that just recently Smith (1994) presented a spot model for pre-main-sequence stars with accretion and solar-like differential surface rotation. This model is based upon the assumption that the dipole magnetic field of CTT stars channels accreting material along field lines which thus impacts at high latitudes where the impacts generate hot spots. In contrast, the typical magnetic, i.e. cool, spots should appear predominantly at low latitudes because of the magnetic shear induced by the differential rotation at higher latitudes (a scheme introduced earlier by Hall & Busby 1990 to explain star-spot lifetimes on RS CVn binaries). Smith (1994) further concluded that cool spots on WTT stars should always appear at low latitudes within ±10–20° of the stellar equator – in apparent contradiction to all current Doppler images of WTT stars including this one of V 410 Tau and in contradiction to the magnetohydrodynamic modelling results put forward by Schüssler & Solanki (1992).

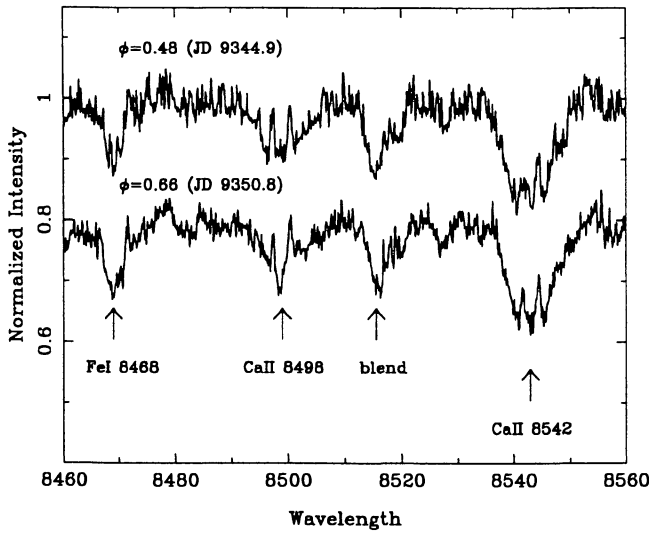


**Fig. 7.** Two spectra of V410 Tau showing the doubled emission lines in the core of the Ca II resonance line at λ8498 and at λ8542 Å. The spectrum at phase $\phi = 0.66$ has been shifted for better display.

## 6. Summary

Our main results can be summarized as follows:

1. Spots on the WTT star V 410 Tau are abundant and seen at both equatorial latitudes and at high latitudes.
2. Spots appear concentrated within a band of longitudes (i.e. concentrated to one side of the star) in this latest Doppler image.
3. Spots at higher latitudes appear more persistent (long lived), larger and cooler than the spots near the equator.
4. The average global spot lifetime, judged by changes between a previous map and the current one, must be about a year for V 410 Tau.
5. There would appear to be very little differential rotation and what little there is is in the same sense as that of the Sun. In spite of this claim though, the high latitude larger cool spots and bright spots have the appearance of features that are experiencing the longitudinal shear effect of differential rotation, probably because these are much older features.
6. There are obvious and well observed hot spot features on V 410 Tau in this map as was the case in the map of November 1992.

*Acknowledgements.* KGS is very grateful to the Austrian Fond zur Förderung der wissenschaftlichen Forschung for support under grant S7301-AST and S7302-AST and to the Austrian Academy of Sciences for grant OWF-40. JBR thanks the Natural Sciences and Engineering Research Council of Canada for their financial support of this work.

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1996A&A...316..164R



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