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Letter to the Editor

A Doppler image of the weak T Tauri star V 410 Tau

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Abstract. We have monitored the weak-lined T Tauri star V410 Tau spectroscopically for six nights in 1992. We detected periodic line-profile variations that are used to obtain a Doppler image of this star, the first of a pre-main sequence T Tauri star. Inverse solutions from three moderately-strong absorption lines show consistent surface inhomogeneities of the effective temperature distribution of up to 1200 K cooler and at least 500 K hotter than the nominal photospheric temperature of 4400 K. Our maps thus verify the proposed existence of hot spots on weak-lined T Tauri stars. All features are evident at low and very high latitudes even covering the rotational pole but not a cool polar cap-like spot as seen previously for several other active stars.

Key words: stars: activity – stars: imaging – stars: V410 Tau – stars: pre-main sequence

1. Introduction

V410 Tau (BD +28°637, V = 10.6–11.2 mag, K4) is a rapidly-rotating weak-lined T Tauri star and has been named "the Sun at one million years" (Herbst 1989) and as such is a very important object for studying the time evolution of solar-like magnetic activity and the underlying dynamo. Its periodic photometric variability is well documented (Rydgren & Vrba 1983, Vrba et al. 1988, Herbst 1989, Bouvier & Bertout 1989, Herbst & Levreault 1990, a.o.) and believed to be due to cool starspots on its surface rotating in and out of view. The full amplitude of these light variations reached a record value of 0.6 mag in V in 1986/87, the largest amplitude of any spotted star ever observed. From its fast rotation (P_{rot} = 1.871 days) and its interior being (presumably) fully convective, one expects to see very strong magnetic activity in agreement with the observed large photometric amplitude.

Furthermore, an inhomogeneous surface brightness distribution causes bumps and depressions in the absorption line profiles that vary due to the rotation of the star. To detect these profile variations one needs high-resolution high-S/N spectra (Vogt 1988). In the case of V410 Tau, the wavelength region containing the neutral lithium line at 6707 Å has been observed frequently because lithium is an age indicator and quite abundant in pre-main sequence stars (Strom et al. 1989). Thus, profile variations in the Li I 6707 Å line had already been noted for V410 Tau by several investigators (e.g. Basri et al. 1991, Patterer et al. 1993, Bouvier 1993) but no Doppler map has been published so far.

In this Letter we present the first Doppler image of a T Tauri star obtained from three different absorption lines from two chemical species, calcium and iron. The image reconstructions from the neutral lithium line at 6707 Å require a more intensive treatment of the strength and shape of the local line profile in the lithium-rich atmosphere of V410 Tau and will be discussed in more detail in a forthcoming paper.

2. Observations and data reduction

A total of 27 spectra of V410 Tau were obtained with the Penn State Fiber Optic Echelle (FOE) and T2KB CCD at the 2.1-m telescope of the Kitt Peak National Observatory (KPNO) on six nights of a seven night run in 1992 November. Exposure times ranged from 50 to 60 minutes. Given that V410 Tau has a rotational period of 1.8710 days (Vrba et al. 1988), phase smearing is only about 0.02 rotations per observation. All observations presented in this paper were phased with the ephemeris of Vrba et al. (1988) of

$$HJD = 2446861.629 + 1.8710E. \quad (1)$$

The longest gap in phase coverage of the data is about 0.13 stellar rotations. The wavelength coverage was 3850–9050 Å, with resolution R = 12000. Further details for the FOE may be found in Ramsey & Huenemoerder (1986) and Ramsey et al. (1987).

Each observing night various calibration images were obtained for processing of that night's data. The average of several bias frames was subtracted from every non-bias exposure to correct for the zero integration time response of the CCD. Several flat field frames were obtained and averaged to correct for pixel-to-pixel variations in CCD sensitivity. Note that flat field division must be done after extraction of object and flat field spectral orders for data obtained with fiber-fed instruments (see Hall et al. 1994). Wavelength calibration was obtained by observing the known spectrum of a thorium-argon hollow cathode lamp. Wavelength correction for "drift" of the CCD due to small temperature changes in the spectrograph room may be obtained

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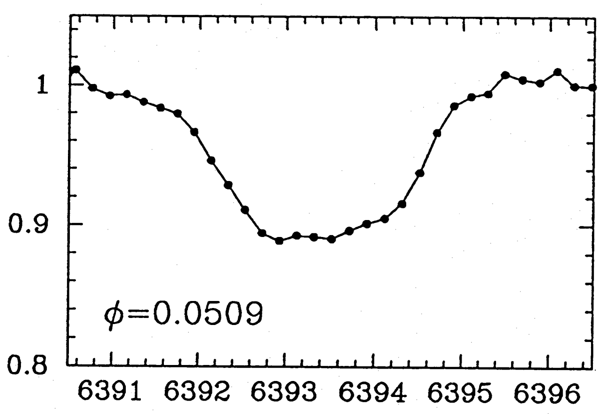

Fig. 1. Example of a typical "unprepared" spectral line profile of V410 Tau. Shown is the Fe I 6393 Å line at rotational phase 0.0509. S/N is estimated to be 150:1 and the resolving power is 12 000.

by measuring the wavelengths of telluric features, such as the O_2 A and B bands, in the spectra.

Before the spectra are used for the Doppler-imaging analysis we deconvolve the instrumental profile and smooth the observed spectra to suppress high-frequency noise below the FWHM of the instrumental profile of 0.433 Å. The average observed Doppler width of 3.2 Å is sampled seven times by the instrumental profile. Spectral simulations for Ap stars by Piskunov & Wehlau (1990) have demonstrated that accurate maps are recovered even when the spectral resolution is as low as $1/5 \times v \sin i$.

Figure 1 shows an example of a Fe I 6393 Å line profile of V410 Tau before smoothing and deconvolution. Signal-to-noise (S/N) ratio is estimated to be ≈150:1.

3. Results and discussion

For the maps in this paper local line profiles were computed from a numerical solution of the equation of transfer with model atmospheres from ATLAS9 (Kurucz 1993). A grid of models with $\log g = 4.0$, solar abundances, and $T_{\rm eff} = 5000$ to 3500 K in steps of 250 K were used. From these atmospheres, local line profiles were computed for Fe I 6393 Å, Ca I 6717 Å, and Ca I 6439 Å with $\log gf$ values of −1.62, −0.61, and −0.20, respectively. The computer code for the line profile inversion is a modified version of the code described by Rice et al. (1989). For our computations for V410 Tau we adopted a Thikhonov regularization instead of a maximum entropy regularization. Figure 2 shows the Fe I 6393 Å observations and the fits from the inverse solution. Only 22 out of the 27 available spectra were used. Table 1 lists the adopted stellar parameters for V410 Tau.

Table 1. Adopted stellar parameters for V410 Tau

Parameter	value
Effective surface temperature	4400 K
Rotational velocity ($v \sin i$)	77 $\mathrm{km\,s^{-1}}$
Inclination i	70°
Radial-tangential macroturbulence	1.5 $\mathrm{km\,s^{-1}}$
Microturbulence	0.5 $\mathrm{km\,s^{-1}}$

Figure 3 presents the average image from three spectral lines and Fig. 4a-c show the individual maps from these three lines.

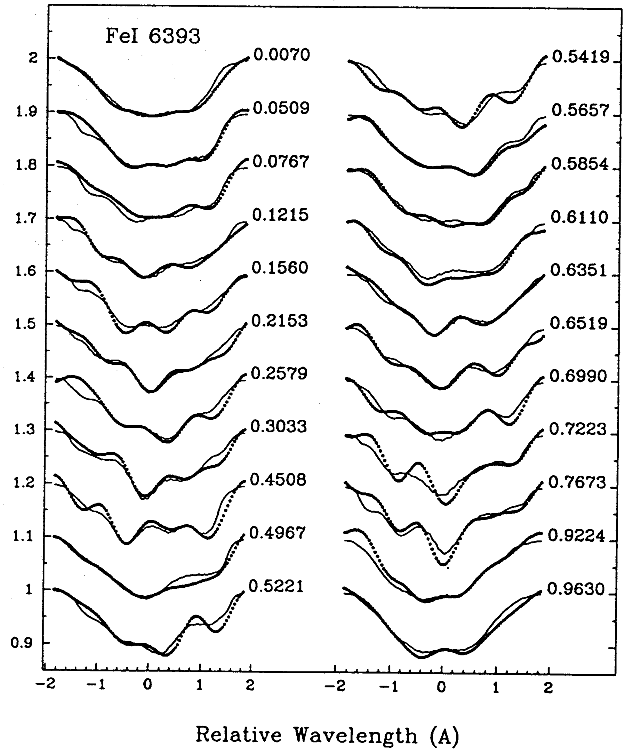

Fig. 2. Observed and computed line profiles for Fe I 6393 Å. The mean error for the fits of the Fe I 6393 Å line is 0.45, while 0.44 and 0.56 for the Ca I 6717 Å and Ca I 6439 Å lines (not shown), respectively.

The process of averaging maps from several spectral lines ensures that spurious features from one line will be suppressed in the average map. Unfortunately, we had no simultaneous photometry of V410 Tau, so no continuum light variations were employed by the mapping routine. This adds considerable uncertainty in the reconstruction of the map, especially for the surface temperatures. Nevertheless, the synthetic broad-band photometry from the line-profile output gave consistent amplitudes of $\Delta V \approx 0.37$ mag and $\Delta(V-I) \approx 0.12$ mag for the three different lines.

The resulting maps show a large cool asymmetric feature at very high latitudes even touching the visible rotation pole in case of the Ca I 6439 Å and Ca I 6717 Å lines, but not a full polar "cap". The iron line shows practically the same feature but puts some of the high-latitude part (at longitudes ≈ 45 − 100°) closer to the equatorial regions. All three lines require a small hot spot near a longitude of ≈ 270° and recovers its latitude such that it separates the large cool feature near the visible pole. Another similar hot spot shows up in the other hemisphere and could, if real, indicate a north-south symmetry of the magnetic field should these hot spots be plage-like features but could also be indicative of impact regions from circumstellar mass accretion.

It is possible that part of the north-south symmetry seen at around a longitude of 180° (e.g. in the Fe I map in Fig. 4) could be an artifact of the inversion procedure due to hemisphere mirroring with the cool dominant high-latitude feature near the visible pole. This could be caused by the high inclination of the stellar rotation axis of 70°. Nevertheless, the different lines produced very similar maps with excellent latitudinal coincidence and we are quite confident in the reality of the overall temperature distribution of the average map.

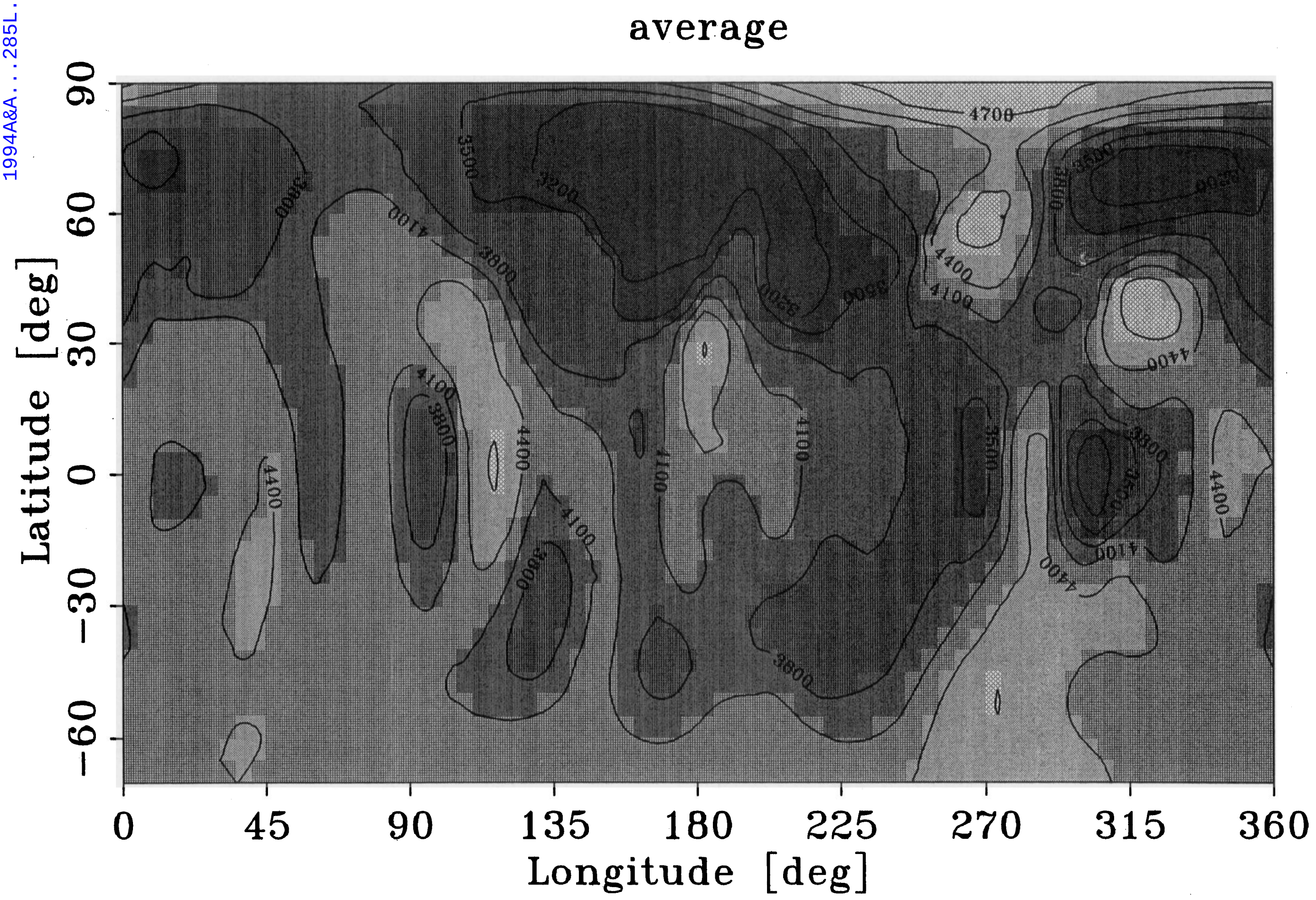

Fig. 3. Surface temperature map of V410 Tau obtained by averaging the maps from the individual lines. Each individual map in Fig. 4 was given equal weight. There is a dominant cool feature at very high latitudes but not quite a polar cap. Also, there appear to be several hot spots, most notably around a stellar longitude of 300°.

A second, also significant[1], "double" feature is located at the stellar equator at a longitude of ≈ 300° consisting of two small spots at 270° and 310°, respectively. The large sinusoidal bump amplitude in the profiles at these phases requires simultaneously a hot *and* a cool region close together on the surface of the star. Due to the large size of the effect, it is likely that this is indeed real but it can not be proven from our single observing run. More data are clearly needed.

The observed profiles around phase 0.0 – 0.5 (or 0 – 180° on the stellar surface) require cool features moving through the profiles rather quickly, as spots near the stellar equator would. Due to the poor latitude discrimination of the Doppler imaging technique at equatorial regions though, only somewhat elongated spots are recovered. Three small features appear, nevertheless, to be significant. They are centered at longitudes of 50°, 100° and 130° and latitudes of 0°, 0° and −30°, respectively. The latter two are separated by a small bright feature at zero latitude. Once again we believe that this bright feature is most likely real.

Persistent spots covering a star's rotational pole are seen from several Doppler images, e.g. on HR 1099 (Vogt 1988, Donati et al. 1992) and EI Eri (Strassmeier et al. 1991, Hatzes & Vogt 1992). These stars are evolved components in close RS CVn-type binaries and their surface activity might be influenced by the companion star. Thus, a better comparison for V410 Tau can be made with the Doppler images of AB Dor and LQ Hya, two young rapidly-rotating solar-type dwarf stars probably of the age of the Pleiades. While three maps of AB Dor by Collier-Cameron (1993) show a polar cap-like spot, the three maps of Kürster et al. (1992) only show a similar feature for *one* of their three observed epochs. However, maps of LQ Hya by Strassmeier et al. (1993) and Saar et al. (1994) indicate that this star does not have a polar spot at *any* observed epoch but several spots at latitudes as high as 60°. Although we need more Doppler maps for a larger sample to be conclusive, it is tempting to speculate that the appearance of a polar cap-like spot, if real by itself, depends upon a combination of stellar luminosity class and thus roughly stellar age and the time when the star is observed within its activity cycle. High-latitude features, on the other hand, seem to be common in all rapidly-rotating stars consistent with the theoretical interpretation put forward by Schüssler & Solanki (1992).

[1] i.e., when $\Delta T_{\rm phot-spot} \gtrsim 500$ K in case of S/N≈150:1 and without photometry