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The magnetic field of the planet-hosting star τ Bootis[★]

C. Catala,^{1†} J.-F. Donati,^{2†} E. Shkolnik,^{3†} D. Bohlender^{4†} and E. Alecian^{1†}

¹*Observatoire de Paris, LESIA, 5 place Jules Janssen, 92195 Meudon Cedex, France*

²*Observatoire Midi-Pyrénées, LATT, 14 avenue Edouard Belin, 31400 Toulouse, France*

³*NASA Astrobiology Institute, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822, USA*

⁴*National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada*

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ABSTRACT

We have obtained high-resolution spectropolarimetric data for the planet-hosting star τ Bootis, using the ESPaDOnS spectropolarimeter at the Canada–France–Hawaii Telescope (CFHT). A weak but clear Stokes V signature is detected on three of the four nights of 2006 June during which we have recorded data. This polarimetric signature indicates with no ambiguity the presence of a magnetic field at the star’s surface, with intensity of just a few gauss.

The analysis of the photospheric lines of τ Boo at ultra-high signal-to-noise ratio reveals the presence of an 18 per cent relative differential rotation. Tentative Zeeman–Doppler imaging, using our spectropolarimetric observations covering only a fraction of the star’s rotational phase, indicates a magnetic field with a dominant potential field component. The data are best fitted when a 3.1-d period of modulation and an intermediate inclination are assumed. Considering the level of differential rotation of τ Boo, this implies a rotation period of 3.0 d at the equator and of 3.7 d at the pole, and a topology of the magnetic field where its main non-axisymmetric part is located at low latitudes.

The planet is probably synchronized with the star’s rotation at intermediate latitudes, while the non-axisymmetric part of the magnetic field seems located at lower latitudes. Our limited data do not provide sufficient constraints on the magnetic field to study a possible interaction of the planet with the star’s magnetosphere. Investigating this issue will require data with much better phase coverage. Similar studies should also be performed for other stars hosting close-in giant planets.

Key words: stars: magnetic fields – stars: planetary systems.

1 INTRODUCTION

It has been recently conjectured that giant planets in close-in orbits can influence significantly the magnetic activity of their parent stars, through tidal interaction or via magnetic coupling between the star’s and the planet’s fields (Cuntz, Saar & Musielak 2000; Rubenstein & Schaefer 2000). Such a scenario is strongly suggested in the case of HD 192263, which has a planet with $M \sin i = 0.72 M_J$ orbiting at 0.15 au in 24.3 d, by the cyclical photometric variations with a similar period, stable over almost 4 yr (Henry, Donahue & Baliunas

2002; Santos et al. 2003). In addition, Shkolnik, Walker & Bohlender (2003) and Shkolnik et al. (2005) monitored the chromospheric activity of several giant planet-hosting stars in the Ca II H & K lines, and found clear evidence for cyclical variations of chromospheric signatures synchronized with the planet orbits in the case of two of them, HD 179949 (planet with $M \sin i = 0.98 M_J$, $P_{\text{orb}} = 3.09$ d, semi-major axis = 0.045 au) and ν And (planet with $M \sin i = 0.71 M_J$, $P_{\text{orb}} = 4.62$ d, semi-major axis = 0.059 au). These authors offer an interpretation of the interaction between the planet and the star’s magnetic field, in which Alfvén waves are generated by the slow relative azimuthal motion of the planet with respect to the stellar magnetic field.

The star τ Boo (F7V), which has a giant planet companion orbiting in 3.31 d at 0.049 au with a minimum mass $M \sin i$ of $4.4 M_J$ (Butler et al. 1997; Leigh et al. 2003), does not show such synchronized Ca II H & K line variations. Shkolnik et al. (2005) argue that this is consistent with their Alfvén wave model, if the star is tidally locked by its hot giant planet. Ca II H & K spectrophotometric monitoring of τ Boo during several seasons indeed suggests

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†E-mail: Claude.Catala@obspm.fr (CC); Jean-Francois.Donati@obs-mip.fr (J-FD); shkolnik@ifa.hawaii.edu (ES); david.bohlender@nrc-cnrc.gc.ca (DB); Evelyne.Alecian@obspm.fr (EA)

rotation periods ranging between 2.6 and 4.1 d, depending on the season (Henry et al. 2000). This large interval is indicative of a possible differential rotation at the star's surface, active regions being located at different latitudes during different seasons. The planet orbital period is therefore possibly identical to the rotation period of the star at a particular latitude. Moreover, recent ultra-high precision photometric monitoring using the *MOST* asteroseismology satellite (Walker et al. 2003; Matthews et al. 2004) indicates the possible presence of an active spot located near the subplanetary longitude, stable over more than 100 orbits (Walker et al. 2006). Finally, high-precision linear polarization monitoring of τ Boo reveals very low amplitude modulation of the fractional linear polarization, although the origin of such modulation is still unclear (Lucas, Hough & Bailey 2006).

Clearly, the direct detection of a magnetic field at the surface of τ Boo, and the determination of its topology, would constitute a powerful way of investigating the possible relationship between the planet and the star's magnetism. This would be a first step of a more complete statistical study of magnetic fields in stars hosting hot giant exoplanets, aimed at characterizing the interaction of exoplanets with the magnetic field of their parent stars.

This Letter presents the first direct detection of the magnetic field of τ Boo, and a tentative mapping of its topology from our fragmentary data set. Section 2 describes the observations and data reduction. In Section 3, we present the results of our analysis, concerning the differential rotation of the star's surface, the magnetic field intensity and topology, as well as the rotation period and inclination angle of the star. Section 4 provides a general conclusion and comments on future prospects of this work.

2 OBSERVATIONS AND DATA REDUCTION

We used the ESPaDOnS spectropolarimeter installed on the 3.6m Canada–France–Hawaii Telescope (Donati et al., in preparation). The star τ Boo was observed during four nights in 2006 June, each night for durations ranging from 20 to 60 minutes. Table 1 presents the log of the observations.

The data were obtained in the polarimetric configuration of ESPaDOnS, yielding a spectral resolution of about 65 000. All spectra were recorded as sequences of four individual subexposures taken in

Table 1. Journal of ESPaDOnS observations of τ Boo. The last column gives the peak signal-to-noise ratio (S/N) per velocity bin of 2.6 km s^{-1} , obtained at wavelengths near 700 nm. The orbital phases are calculated using the ephemeris of Collier Cameron (private communication, see text). The phase origin is taken as the time of planet opposition.

UT date (dd/mm/yy)	HJD (2 400 000+)	Orbital phase	t_{exp} (s)	S/N
13/06/06	538 99.75127	0.4785	800	2000
13/06/06	538 99.76233	0.4820	600	1700
13/06/06	538 99.77276	0.4855	600	1700
13/06/06	538 99.78216	0.4879	600	1700
13/06/06	538 99.79145	0.4914	600	1700
13/06/06	538 99.80073	0.4938	600	1700
17/06/06	539 03.78645	0.6966	600	1700
17/06/06	539 03.79580	0.7002	600	1700
18/06/06	539 04.78201	0.9974	600	1600
18/06/06	539 04.79143	0.0009	600	1600
19/06/06	539 05.83950	0.3169	1200	1500
19/06/06	539 05.85570	0.3217	1200	1400

different configurations of the polarimeter, in order to yield a full circular polarization analysis, as described in Donati et al. (1997) and Donati et al. (2006, in preparation). No linear polarization analysis was performed. The data were reduced with the automatic reduction package 'LIBRE-ESPRIT' installed at CFHT (Donati et al. 1997; Donati et al., in preparation). Stokes I and Stokes V spectra are obtained by proper combinations of the four subexposures, while check spectra, labelled as N spectra, are calculated by combining the subexposures in such a way to yield a null spectrum, that can be used to verify the significance of the signal measured in Stokes V .

We subsequently applied the least-square deconvolution (LSD) method described in Donati et al. (1997) to construct average photospheric profiles both of the Stokes I and V parameters. The LSD technique builds the mean photospheric line profile, both in Stokes I and V by deconvolving the observed spectrum from a line mask including all lines present in a synthetic spectrum of the star. The line mask used here was computed using a Kurucz Atlas 9 model with $T_{\text{eff}} = 6250 \text{ K}$ and $\text{Log } g = 4.0$, and includes about 4000 lines with depth relative to the continuum larger than 0.4.

We measured the heliocentric radial velocity of τ Boo by fitting a Gaussian to the LSD I mean profile. The star's reflex motion due to the planet's revolution is clearly seen in our V_{rad} measurements, which agree with the planet ephemeris: $\text{JD}_0 = 2\,453\,450.984$ (time of opposition); $P_{\text{orb}} = 3.31\,245 \text{ d}$; amplitude = 0.474 km s^{-1} , eccentricity = 0, provided by Collier Cameron (private communication), with a residual dispersion of about 20 m s^{-1} . This ephemeris is within the error bar of that published by Shkolnik et al. (2005).

All Stokes I and V LSD profiles were subsequently converted to the star's rest-frame by correcting the velocity scale for the orbital motion.

3 RESULTS

3.1 Fundamental parameters of τ Boo

Most basic fundamental parameters of τ Boo are compiled in table 1 of Leigh et al. (2003), and we adopt them in the present Letter: spectral type F7V; $T_{\text{eff}} = 6360 \pm 80 \text{ K}$; $[\text{Fe}/\text{H}] = 0.27 \pm 0.08$; $M_V = 4.496 \pm 0.008$; mass $M_* = 1.42 \pm 0.05 M_{\odot}$; radius $R_* = 1.48 \pm 0.05 R_{\odot}$; age $1.0 \pm 0.6 \text{ Gyr}$.

The rotational parameters of τ Boo are less well known, in particular its rotation period P_{rot} , which is believed to be between 2.6 and 4.1 d (Henry et al. 2000). Several authors have suggested that the star's rotation and the planet's orbital motion are tidally locked, implying a rotation period of 3.31 d for the star (Leigh et al. 2003; Collier Cameron & Leigh 2004; Shkolnik et al. 2005). This hypothesis has never been directly verified observationally. The photospheric line profiles are reasonably well fitted assuming a turbulent velocity of 5.5 km s^{-1} and an homogeneous surface rotation with $v \sin i = 14.5 \pm 0.1 \text{ km s}^{-1}$ (see Section 3.2).

These values and error bars for P_{rot} , $v \sin i$ and R_* indicate an intermediate inclination of the rotation axis with respect to the line of sight, $30^\circ \leq i \leq 60^\circ$, the main uncertainty being related to the large error bar on P_{rot} . An inclination angle $i = 40^\circ$, corresponding to a rotation period identical to the planet's orbital period, is often considered as the most probable value (Leigh et al. 2003; Collier Cameron & Leigh 2004). However, a better direct determination of P_{rot} would be of great importance, as it would allow us to measure the inclination angle i with a better accuracy and reliability. Because the star's rotation axis and the planet orbital axis are certainly aligned, this would increase the accuracy of the planet mass determination.

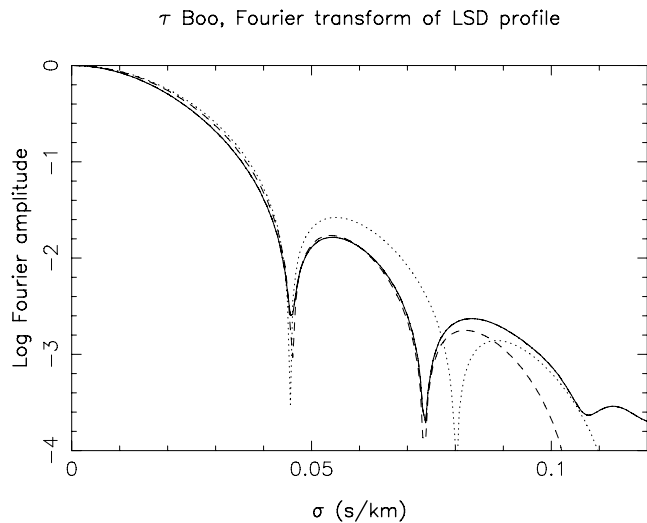


Figure 1. Fourier transform of the LSD average photospheric profile of τ Boo (solid line), compared to theoretical profiles assuming a solid rotation with $v \sin i = 14.5 \text{ km s}^{-1}$ (dotted line) and a differential rotation with a projected equatorial rotation velocity $V_{\text{eq}} \sin i = 15.9 \text{ km s}^{-1}$, a projected polar rotation velocity $V_{\text{pole}} \sin i = 13.0 \text{ km s}^{-1}$, and an inclination angle $i = 40^\circ$ (dashed line).

3.2 The differential rotation of τ Boo

We averaged all Stokes I profiles obtained during this run, evaluated in the star's rest frame, and calculated the Fourier transform of the resulting very high signal-to-noise ratio profile, in order to analyze the projected rotation and potentially the surface differential rotation of τ Boo, using the method described in Reiners & Schmitt (2003). These results are presented in Fig. 1, where the Fourier transform of the observed profile is compared to both rigidly rotating and differentially rotating models. We see clearly the first two zeros of the Fourier transform, and measure a ratio $q_2/q_1 = 1.60 \pm 0.02$ of the positions of these zeros. This value agrees well with, but has a better precision than, that measured by Reiners (2006), $q_2/q_1 = 1.57 \pm 0.04$. Rigidly rotating models include a turbulent velocity of 7.0 km s^{-1} (full width at half maximum, FWHM = 11.7 km s^{-1}), necessary to reproduce the photospheric profile, while the needed turbulent velocity in the case of differential rotation is only 5.5 km s^{-1} (FWHM = 9.2 km s^{-1}).

This value of q_2/q_1 , as well as the direct comparison of the Fourier transform of the observed profile with theoretical profiles, clearly demonstrates the presence of a significant surface differential rotation. The amount of differential rotation necessary to reproduce the photospheric profile depends on the inclination angle, which is not well known. With an inclination $i = 40^\circ$, which is the most probable value obtained when the star's rotation and the planet's orbital motion are assumed to be tidally locked, the photospheric profile can be reproduced assuming an 18 per cent relative differential rotation, with an equator (pole) projected rotation velocity of 15.9 km s^{-1} (13.0 km s^{-1}). This corresponds to a differential rotation $d\Omega \approx 0.4 \text{ rad d}^{-1}$. A lower inclination of $i = 30^\circ$, which is not ruled out for τ Boo (see Section 3.1), would lead to a relative differential rotation of only 15 per cent, with $V_{\text{eq}} \sin i = 15.9 \text{ km s}^{-1}$ and $V_{\text{pole}} \sin i = 13.5 \text{ km s}^{-1}$, i.e. a differential rotation $d\Omega \approx 0.3 \text{ rad d}^{-1}$.

The photospheric spots accompanying the magnetic structure described below may produce an asymmetric photospheric profile, which could impact the determination of differential rotation, as noted by Reiners & Schmitt (2003). However, we have verified that

there is very little asymmetry in the case of τ Boo, by comparing the profile to a mirror version of itself. Besides, the very similar values for the ratio q_2/q_1 found by Reiners (2006) and ourselves at randomly selected epochs provides further evidence that spots induce very little variability on the photospheric profile. We conclude that our determination of differential rotation in τ Boo is not significantly affected by photospheric spots.

3.3 Magnetic field

We detect a clear Stokes V signature on 2006 June 13, 17 and 19, while no Stokes V signal is seen in the spectra of June 18, 2006. The noise level in the LSD Stokes V profiles is of the order of 2 to 3×10^{-5} per spectrum, with a multiplex gain of about 25 in signal-to-noise ratio from the simultaneous use of all lines in the LSD mask. The equivalent noise level taking all recorded spectra into account is lower than 10^{-5} . As an example, Fig. 2 shows one of the Stokes I and V LSD profiles recorded on 2006 June 13, in which the Stokes V signal is clearly detected at more than 10σ , implying with no ambiguity the presence of a surface magnetic field.

Although our observations cover only a small fraction of the rotational phase of τ Boo, we attempted to reconstruct this magnetic field from the set of Stokes V profiles at our disposal. We used the method fully described in Donati et al. (2006b), based on maximum-entropy image reconstruction of the field topology, approximated by a sum of successive spherical harmonics. We chose to limit the spherical harmonic decomposition to $\ell_{\text{max}} = 10$, after checking that the results are basically unchanged for all values of $\ell_{\text{max}} \geq 5$. Note that the projected rotation velocity at the equator of τ Boo ($V_{\text{eq}} \sin i = 15.9 \text{ km s}^{-1}$) is large enough to obtain more than 10 resolved elements around the star at the equator, so that the reconstruction should be accurate for spherical harmonics with $\ell \leq 5$, whereas the power of the reconstructed image on higher order harmonics is underestimated.

Because the inclination angle i and the star's rotation period P_{rot} are not well constrained, we reconstructed magnetic images for several values of both parameters, in the range $30\text{--}60^\circ$ for i and $2.6\text{--}4.1 \text{ d}$ for P_{rot} . The interval for P_{rot} is that given by Henry et al. (2000) for the probable photometric period of the star, while that

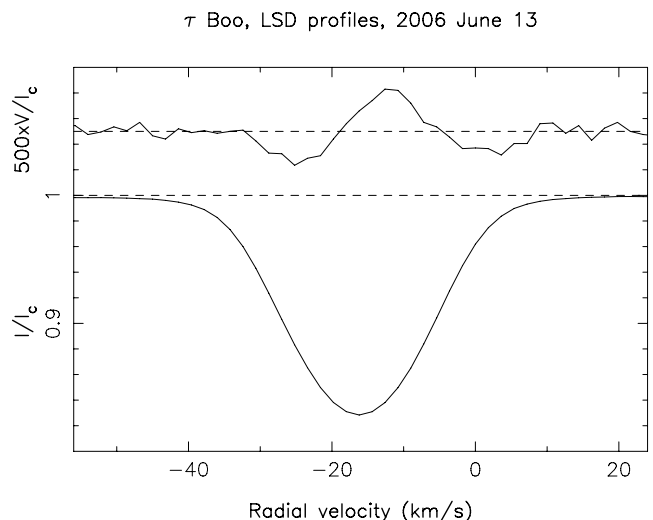


Figure 2. LSD unpolarized and circularly polarized profile of τ Boo, recorded on 2006 June 13. Note that the Stokes V profile is shifted vertically and expanded by a factor 500 for display purposes.

for i is discussed in Section 3.1. For each test couple (i, P_{rot}) we reconstructed the maximum-entropy magnetic image as in Donati et al. (2006b), compared the set of calculated Stokes V profiles to the observed ones, and calculated the corresponding reduced χ^2_v . We first explored solutions involving only potential fields, then introduced additional toroidal components in a second step. For the calculation of the reconstructed profiles, we used a Gaussian macroturbulence of 7 km s^{-1} , which leads to an excellent fit to the Stokes I profile when no differential rotation is introduced, as seen in Section 3.2.

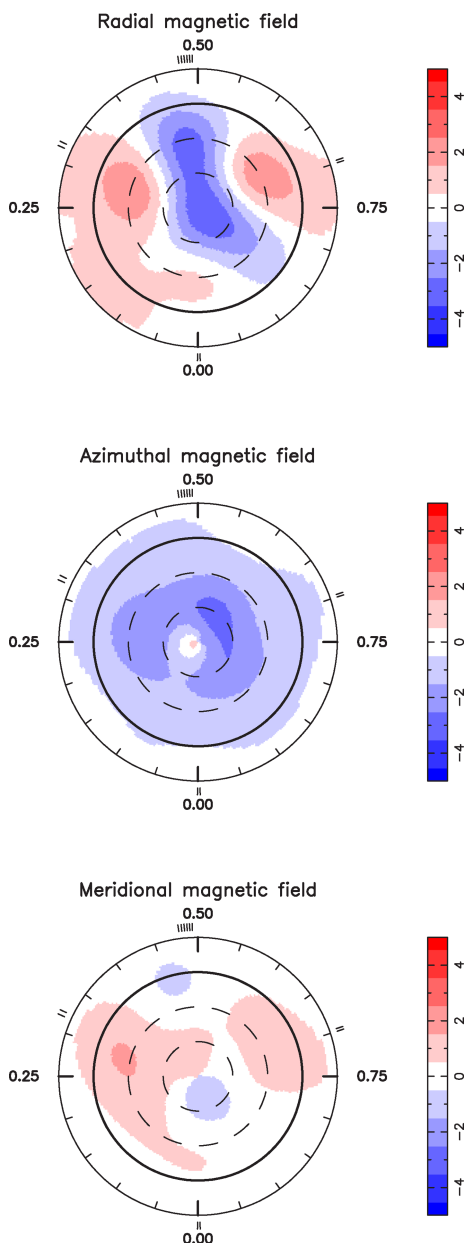


Figure 3. Maximum-entropy reconstructions of the magnetic topology of τ Boo, assuming that the global field can be expressed as the sum of a potential field and a toroidal field. The three components of the field are displayed from top to bottom (flux values labelled in G); the star is shown in flattened polar projection down to latitudes of -30° with the equator depicted as a bold circle and parallels as dashed circles. Radial ticks around each plot indicate orbital phases of observations, counted from the time of planet opposition.

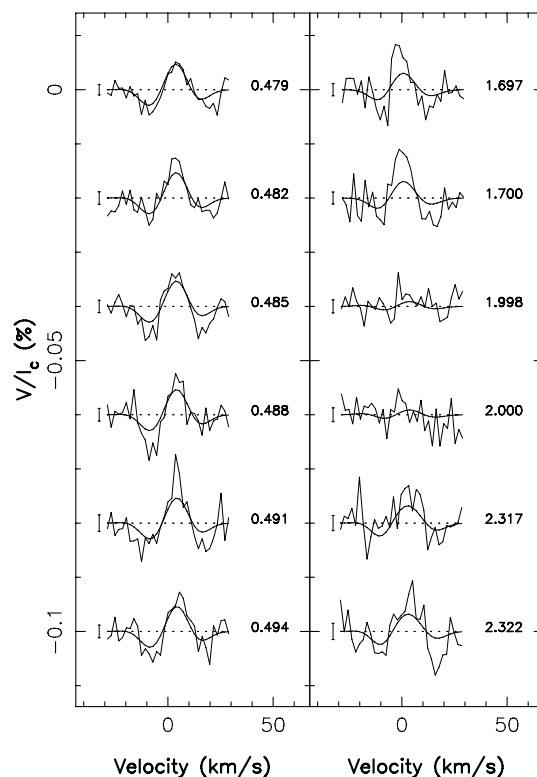


Figure 4. Maximum-entropy fit (thick lines) to the observed Zeeman signatures of τ Boo (thin lines). The planet orbital phase and cycle of each observation are written on the right side of each profile. The phase origin is the time of planet opposition. 1σ error bars are shown on the left side.

When no differential rotation is included, we find a clear minimum of χ^2_v at a period of 3.1 ± 0.1 d. Fig. 3 shows the reconstructed magnetic image of τ Boo, assuming this rotation period and an inclination angle $i = 40^\circ$, while Fig. 4 displays the corresponding fit to the data. Reconstructed maps for the same value of P_{rot} and other values of the inclination between 30° and 60° are only slightly different.

We find that the model represented by the reconstructed image leads to a fit of the circular polarization data with a reduced χ^2_v of 1, while the initial χ^2_v value with a model including no magnetic field is of the order of 2. However, our observations were collected at four epochs only, implying that the reconstructed image, as well as the conclusion concerning the rotation period of 3.1 d, must be taken with caution, and needs to be confirmed with further observations.

We obtain a field of only a few gauss at the star's surface, which is one of the weakest stellar magnetic fields detected so far. The solution presented in Figs 3 and 4 includes a toroidal component of the magnetic field. Introducing such a component leads to a field configuration containing about 15 per cent less information than when no toroidal field is assumed, indicating that it is likely present, although more data would be necessary to confirm its existence. The fit of the Stokes V profiles near orbital phase 1.7 is not entirely satisfactory, indicating that the magnetic field is probably slightly more complex than our model. Pushing the reconstruction procedure further to improve the fit near this phase would probably be poorly significant, as the reduced χ^2_v is already near 1. Only more complete data with better phase coverage will help improve the magnetic image.

When the 18 per cent relative differential rotation discussed in Section 3.2 is introduced in the reconstruction, we find a minimum

of χ^2_ν for an equatorial period of 3.0 d. The reconstructed image is identical to the one with no differential rotation, the configuration implying a rotation period of 3.1 d at the mean latitude of the magnetic spots. In this configuration, the rotation period at the pole is 3.7 d. We noted that the reconstructed image assuming an 18 per cent differential rotation contains 10 per cent less information than images assuming no differential rotation or a 30 per cent differential rotation. This result provides an independent confirmation of the level of differential rotation derived from line profiles in Section 3.2.

4 DISCUSSION AND CONCLUSION

Our data clearly indicate a surface relative differential rotation $d\Omega/\Omega$ of about 18 per cent, which corresponds to $d\Omega \approx 0.3\text{--}0.4 \text{ rad d}^{-1}$. This level of differential rotation, which is comparable to that observed in many other cool stars (e.g. Reiners 2006), is much higher than that of the Sun, and also significantly higher than predicted by Küker & Rüdiger (2005) for F-type stars. This behaviour is also discussed by Marsden et al. (2006) and Jeffers & Donati (2006). We find that the Stokes V profile variations are best modelled with a modulation period of 3.1 d and an inclination angle of about 40° . In this case, the differential rotation of τ Boo implies an equatorial (polar) rotation period of 3.0 d (3.7 d). It is interesting to note that this range of periods between equator and pole is not very different from that found by Henry et al. (2000) from spectrophotometric monitoring of the Ca II H & K lines over several years, possibly interpreted as an expression of surface differential rotation. The modulation period of 3.1 d corresponds to the star's rotation at a latitude of about 25° .

We have detected a weak magnetic field at the surface of τ Boo, with intensities of only a few gauss, i.e. similar to that of the Sun if it was observed in the same conditions. On the other hand, the magnetic field topology of τ Boo, even in the simplified description derived from our limited data set, seems more complex than that of the Sun. The reconstructed magnetic image of τ Boo indicates a dominant poloidal field, with the probable presence of a small toroidal component. More data would be needed to confirm the existence of this toroidal component. The differential rotation of τ Boo strengthens the idea that this component is present, as field toroidal components are often associated with surface differential rotation (Donati et al. 2003, 2006a). The modulation period of the magnetic signature (3.1 ± 0.1 d) seems to be different from the planet orbital period (3.31 d). However, our limited data do not provide strong constraints on the magnetic topology, and in particular are insufficient to allow us to model the whole magnetosphere, using field extrapolation techniques (e.g. Jardine, Collier Cameron & Donati 2002), and study how the giant planet may interact with the stellar magnetosphere and possibly trigger activity enhancements correlated with the planet's orbital motion.

The details of the star's magnetosphere and its potential interaction with the planet clearly need to be studied in the future. We note that a similar study for other planet-hosting stars would be of major interest, in particular for those stars for which activity in the Ca II H and K lines is observed, and possibly correlated with the

planet orbital motion, such as HD 179949 or ν And (Shkolnik et al. 2003, 2005). Such studies will require data providing a much better phase coverage and recorded on a longer time-scale than those presented here. Long spectropolarimetric monitoring of τ Boo and other planet-hosting stars will also be necessary to measure precisely their rotation and differential rotation.

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