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Possible detection of a magnetic field in T Tauri

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Abstract. Medium-resolution ($R \simeq 15\,000$) circular spectropolarimetry of T Tauri is presented. The star was observed twice: on November 11, 1996 and January 22, 2002. Weak circular polarization was found in photospheric absorption lines, indicating a mean surface longitudinal magnetic field $B_{\parallel}$ of 160 ± 40 G and 140 ± 50 G at the epoch of the first and second observations respectively. While these values are near the detection limit of our apparatus, we belive that they are real. One can conclude from our data that $B_{\parallel}$ of T Tau does not significantly exceed 200 G, which is much less than surface magnetic field strength of the star (>2.3 kG) found by Guenther et al. (1999) and Johns-Krull et al. (2000). We discuss possible reasons for this difference.

Key words. stars: pre-main sequence – stars: magnetic fields – stars: individual: T Tau

1. Introduction

Classical T Tauri stars (CTTSs) are low mass pre-main sequence stars that have accretion disks (Bertout 1989). Magnetic fields are belived to play a crucial role in the evolution of CTTSs angular momentum and in the interaction between the central star and the circumstellar matter. Surface magnetic fields ∼1 kG are expected from theoretical arguments for these objects – see e.g. Shu et al. (2000) and references therein.

No field has been directly detected in CTTSs until recently, although several attempts have been made (Babcock 1958; Brown & Landstreet 1981; Johnstone & Penston 1986, 1987). Two groups independently succeded in detecting magnetic fields on T Tau, LkCa 15 (Guenther et al. 1999; Johns-Krull et al. 2000) and BP Tau (Johns-Krull et al. 1999a,b).

Two general methods have been used to measure the magnetic field of T Tau. The first one is based on the fact that magnetic fields produce an enhancement of line equivalent widths that vary with magnetic sensitivity (Lande factor and line splitting pattern). With this technique one can derive the product of the surface magnetic field strength, B, and surface filling factor f, i.e. $B \cdot f$-value – see Basri et al. (1992) for details. In the case of T Tau, for example, Guenther et al. (1999) found $B \cdot f = 2.35 \pm 0.15$ kG, which means the average value of B itself is ≥2.3 kG.

The other direct method for detecting magnetic fields is to look for net circular polarization in Zeeman-sensitive lines. Generally, Zeeman σ components are elliptically polarized, with the components of opposite helicity split to either side of the nominal wavelength λ_0. If there is a net longitudinal component of the magnetic field on the stellar surface, net polarization results in a shift between Zeeman-sensitive lines observed in right- and left-circularly polarized (RCP and LCP) light. The shift is

$$\Delta\lambda_{\rm rl} \simeq 9.3 \times 10^{-7} g\, \lambda_0^2\, B_{\parallel}, \quad \text{mÅ} \qquad (1)$$

where g is the Lande factor of the transition, which we adopt from the VALD database (Kupka et al. 1999). Here we give the mean longitudinal magnetic field averaged over the star including limb darkening, $B_{\parallel}$, and λ_0, expressed in kG and Å respectively.

Only upper limits of $B_{\parallel}$ were found in the case of T Tau with this technique: 1000 G (Babcock 1958) and 810 G (Brown & Landstreet 1981) at the 3σ level. We present here results of our more sensitive spectropolarimetric measurements of T Tau's longitudinal magnetic field. The following set of T Tau's atmospheric parameters were adopted: $T_{\rm eff} \simeq 5250$ K, (K0 V spectral type), $\log g = 3.73$ (White & Ghez 2001) and solar metallicity.

2. Observations

We observed T Tau with the 6 m telescope of the Special Astrophysical Observatory on November 21, 1996 and January 22, 2002. The Main Stellar Spectrograph (MSS – Panchuk 2001) equipped with the polarimetric analyzer (Najdenov & Chountonov 1976; Chountonov 1997) was used. The analyzer splits the incoming beam into two parallel beams that are offset from one another along the spectrograph slit by 5 arcsec. One beam contains the RCP component of the

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Table 1. Journal of observations.

Date	Target	V	n	t_e	S/N
22.11.1996	ε Tau	3.5	5	220	300
	T Tau	9.9	3	3600	150
21.01.2002	75 Tau	5.0	3	1320	300
	ε Tau	3.5	3	600	300
	T Tau	9.9	3	7200	100
24.01.2002	HD 30466	7.3	1	1400	200

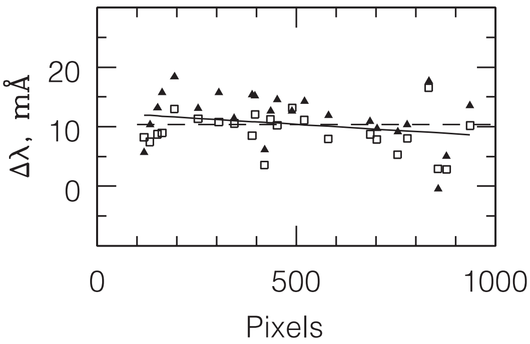

Fig. 1. $\Delta\lambda_{\rm rl}$-values measured in ε Tau's spectra observed before (filled tiangles) and after (open squares) T Tau. See text for details.

spectrum and the other the LCP component. As a result, two spectra with opposite circular polarization ~200 Å in length were projected onto an 1160×1024 pixel CCD. The spectral band 6300−6500 Å was observed in 1996 and 6600−6800 Å in 2002. The width of MSS's slit was 0.5″ providing a 2-pixel spectral resolution of $R = \lambda/\Delta\lambda \simeq 15\,000$.

Spectra were processed as follows. Dark current, night sky emission and detector bias as well as cosmic ray traces, were removed in the standard way, using routines from the MIDAS software package. A spectrum of a thorium-argon lamp was used for wavelength calibration. We then identifed spectral lines adopting line information from the VALD database (Kupka et al. 1999). The shifts between positions of identical lines in spectra with opposite circular polarization in the same image, $\Delta\lambda_{\rm rl}$, were derived by means of a Fourier cross-corellation method. The method appears to be relatively insensitive to uncertainties in the continuum level position and gives the ability to evaluate the displacement of line profiles as a whole (Klochkova et al. 1996).

We took into account systematic instrumental effects (SIEs) in different ways, reducing the 1996 and 2002 observations. In the first case, we used observations of the G9.5 III star ε Tau, which presumbly has a negligible field. Specifically, we assumed that nonzero values of $\Delta\lambda_{\rm rl}(\lambda)$ in ε Tau's spectrum result from instrumental effects only and used them to correct $\Delta\lambda_{\rm rl}$-values in the spectrum of T Tau – see Romanyuk et al. (1998) for more details. For this reason, our November 21, 1996 observations were organized in the following way: initially we observed ε Tau, then T Tau and then ε Tau again. Approximate signal-to-noise ratio (S/N) of individual spectra, number of observed spectra, n, visual magnitude V, and total exposure time, t_e (in seconds) for each target are presented in Table 1.

In the case of the 2002 observations, SIEs were removed as follows. Between exposures the phase compensator was advanced 1/2 wave length in order to reverse the sense of the circular polarization recorded in the two spectra. For each target, the wavelength of a given line in the RCP and LCP spectra is recorded in the first exposure ($\lambda_1^{\rm r}$, $\lambda_1^{\rm l}$) and in the second ($\lambda_2^{\rm r}$, $\lambda_2^{\rm l}$). Then we calculated

$$\Delta\lambda_{\rm rl} \equiv \lambda^{\rm r} - \lambda^{\rm l} = \frac{\left(\lambda_1^{\rm r} - \lambda_1^{\rm l}\right) + \left(\lambda_2^{\rm r} - \lambda_2^{\rm l}\right)}{2},$$

which is expected to be free of the main instrumental effects – see Johns-Krull et al. (1999b) for details.

Information on the January 2002 observations is also presented in Table 1, where now n stands for the number of pairs of individual observations of any particular star, between which the phase compensator was rotated.

3. Results

3.1. 1996 observations

Figure 1 presents values of $\Delta\lambda_{\rm rl}(\lambda)$ derived from all the ε Tau spectra observed immediately before and after observations of T Tau. The $\Delta\lambda_{\rm rl}(\lambda)$ dependence was approximated with a linear function $\Delta\lambda_{\rm rl} = a \cdot N + b$, where N is the pixel number, for both observations. We found $a = (-2.8 \pm 2.6) \times 10^{-3}$ mÅ per pixel, $b = 10.5 \pm 1.4$ mÅ for the open squares in Fig. 1 and $a = (-5.3 \pm 3.4) \times 10^{-3}$ mÅ per pixel, $b = 14.4 \pm 1.9$ mÅ for black triangles in Fig. 1.

The difference between the parameters of the fits for both datasets (squares and tringles) is whithin $2.5\,\sigma$, i.e. is not significant from a statistical viewpoint. Thus one can use the resulting linear function, derived from all points, to remove SIEs from $\Delta\lambda_{\rm rl}$-values in the spectra of T Tau. We found $a = (-4.1 \pm 2.2) \times 10^{-3}$ mÅ per pixel, $b = 12.4 \pm 1.2$ mÅ in this case – solid line in Fig. 1.

The a-value differs from zero by less than 2σ, which means that it is possible that the SIEs do not vary along the CCD. With this hypothesis we found the mean shifts are 11.8 ± 0.9, and 9.1 ± 0.7 mÅ for filled triangles and open squares respectively. The mean shift C derived for all points is 10.4 mÅ – dashed line in Fig. 1 – and standard error is $\sigma_C = 0.8$ mÅ, or $\sigma_C = 21$ G, assuming $g = 1$ and $\lambda_0 = 6400$ Å according to Eq. (1). The mean shifts for filled triangles and open squares differ from C less than $2\sigma_C$. Thus it appears resonable to use the mean C to remove SIEs, subtracting it from the measured wavelength shifts between right and left circularly polarized spectra of T Tau.

The corrected $\Delta\lambda_{\rm rl}$-values in T Tau's spectra were used to calculate $B_{\parallel}$ from Eq. (1). Resulting values of $B_{\parallel}$ are presented in Table 2 for each of three observed spectra – the last three columns of the table. In some cases, a given line profile was distorted due to cosmic ray events and thus was not used; these cases are marked with a dash. In fact, almost all absorption features in T Tau's spectra are blends of some number of lines, given in the first two columns. So we use an effective Lande factor, $g_{\rm eff}$:

$$g_{\rm eff} = \frac{\Sigma\, d_i\, g_i}{\Sigma\, d_i},$$

derived from averaging over individual lines which form the blend. Here g_i is the Lande factor of each line and d_i is its central depth. This approach appears resonable as long as the Zeeman splitting is less than the spectral resolution of our instrument. We adopted T Tau's d_i-values from the VALD database specifing log g and $T_{\rm eff}$ of the star as input parameters. Averaging over all lines gives $B_{\|} = +162$ G with standard error $\sigma_B = 30$ G due to measurment uncertainty. Adding the error due to the uncertainty in C, the total uncertainty is:

$$\sigma = \sqrt{\sigma_C^2 + \sigma_B^2} \simeq 37\,{\rm G}.$$

Thus, we estimate $B_{\|} = +160 \pm 40$ G from our 1996 observations.

3.2. 2002 observations

The $\Delta\lambda_{\rm rl}(\lambda)$-values for all sets of ε Tau's spectra are shown in Fig. 2. It can be seen that there is no statistically significant trend in these data around an average value $\Delta\lambda_{\rm rl} = -0.02 \pm 0.32$ mÅ. Assuming $g_{\rm eff} = 1$ and $\lambda_0 = 6700$ Å (the average wavelength of the spectral band), this value corresponds to $B_{\|} = -0.5 \pm 8$ G. Small values ($\Delta\lambda_{\rm rl} = -0.93 \pm 0.43$ mÅ or $B_{\|} = -20 \pm 10$ G) were also found for an additional giant star 75 Tau (K2 III). Thus, we conclude that the adopted method of SIEs removal works well and confirmed a posteriori our choice of ε Tau as a zero-field standard during the 1996 observations.

To illustrate the reliability of our technique we included the magnetic star HD 30466 in the target list of our 2002 observations. Babcock (1958) found $B_{\|} = +2320 \pm 340$ G and $B_{\|} = +1890 \pm 130$ G for HD 30466 from two independent observations. Profiles of the Cr I 6661.08 line in our HD 30466 RCP and LCP spectra are shown in Fig. 3: they are clearly shifted relative each other ($\Delta\lambda_{\rm rl} \simeq 126$ mÅ), indicating $B_{\|} \simeq +2.0$ kG, adopting $g = 1.48$ (Kupka et al. 1999).

As can be seen from Table 3, relative shifts of lines between spectra with opposite polarizations in T Tau's spectrum are much less, and we find $B_{\|} = +140 \pm 50$ G after averaging over all the data. The uncertainty is calculated by taking the standard error of the individual points.

4. Discussion

From observations in 1996 and 2002, using different methods of SIE correction, we find similar (+160 ± 40 G and +140 ± 50 G) values of the mean surface longitudinal magnetic field in T Tau. As such small field values are close to the detection limit, it is very important to show that the measured wavelength shift is magnetic in origin. To test this we have measured relative shifts of the S II 6716.44 Å and 6730.82 Å forbidden emission lines in our 2002 spectra, which presumbly originate far from the star in a region with (nearly) zero magnetic field.

Table 2. Results of 21.11.1996 observations of T Tau.

Ion	λ	$g_{\rm eff}$	B_1	B_2	B_3
Ni I	6314.65	1.18	–	+203	+11
Ni I	6314.66				
Fe I	6315.31				
Fe I	6315.42				
Fe I	6315.81				
Fe I	6318.02	0.72	–	+638	−159
Ca I	6318.11				
Ni I	6322.16	1.39	–	+251	+88
Fe I	6322.68				
Ni I	6327.59	1.05	−14	+157	–
Cr I	6330.09	1.64	+262	−36	+177
Fe I	6330.85				
Fe I	6338.88	1.23	+500	+200	−123
Ni I	6339.11				
Ca I	6343.31	1.09	+18	–	+321
Fe I	6344.15				
Fe I	6355.03	0.98	+470	+110	–
Fe I	6358.63	1.49	+198	+35	+242
Fe I	6358.70				
Fe I	6393.60	1.15	+288	−46	+128
Fe I	6392.54				
Fe I	6400.00	1.35	+28	+365	−26
Fe I	6400.32				
Fe I	6411.11	1.49	+162	–	+248
Fe I	6411.65				
Fe I	6412.20				
Fe I	6430.85	1.24	−153	+399	−215
Ca I	6439.08	1.12	+210	+254	+313
Ca I	6449.81	1.10	+48	+8	+143
Co I	6450.08				
Co I	6450.25				
Ca I	6462.57	1.17	+588	+124	−158
Fe I	6462.71				
Fe I	6462.73				
Ca I	6471.66	1.20	+319	−53	+342
Ca I	6475.24	1.63	+105	+232	+430
Fe I	6475.62				

We found $\Delta\lambda_{\rm rl} = +0.8 \pm 1.4$ mÅ for these lines which would give 20 ± 35 G for $g_{\rm eff} = 1$. This result can be considered as evidence that the measured wavelength shift of the stellar absorption lines is magnetic in origin.

To further test if it is indeed possible to detect such a low $B_{\|}$ value from our spectra we performed the following test. The RCP and LCP spectra of 1D stellar atmosphere were calculated with the SYNTHMAG program (Piskunov 1998), assuming that log g and $T_{\rm eff}$ are equal to that of T Tau and $B = B_{\|} = 200$ G, i.e. with magnetic field lines perpendecular to the stellar surface. Profiles of lines within 6300–6500 Å spectral band were artifically broadened to take into account stellar rotation and spectral resolution and binned to the appropriate dispersion. Each of these artifical specra were used to produce three new ones by adding noise at the appropriate

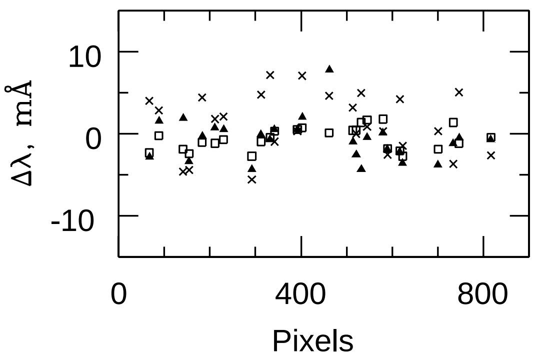

Fig. 2. $\Delta\lambda_{\rm rl}$-values derived from three pairs of ε Tau's spectra observed in 22.01.2002. See text for details.

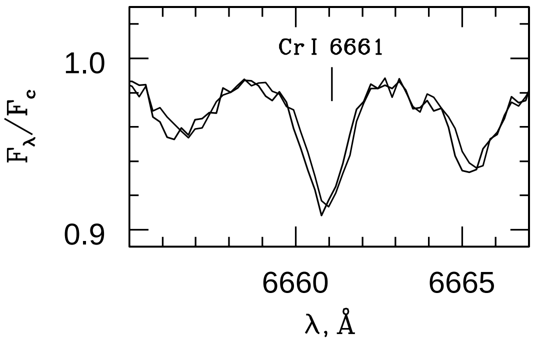

Fig. 3. A part of RCP (thin line) and LCP (solid line) spectra of HD 30466.

level. Finally we derived three pairs of RCP and LCP spectra with S/N-ratio near 100, as in the case of our 1996 and/or 2002 observations. By means of cross-corellation of RCP and LCP profiles we then found $B_{\|} = 164 \pm 32$ G in agreement with the initial value of 200 G. Therefore, we belive that we indeed have recorded T Tau's surface magnetic field $B_{\|} \sim 150$ G, in spite of the relatively large scatter of the individual mesurements – see Tables 2 and 3. Regardless, our observations show that T Tau's large-scale $B_{\|}$-value did not significantly exceed 200 G.

This value is much less than the average value of T Tau's surface magnetic field ($B > 2$ kG) found by Guenther et al. (1999) and Johns-Krull et al. (2000). This will result if there are regions with opposite polarity of magnetic field lines at the stellar surface. This could indicate the magnetic field of T Tau is non-dipolar. Note, however, that even in the case of a magnetic dipole, the observed $B_{\|} = 0$, if the dipole's axis is perpendicular to the line of sight. To demonstrate this more clearly we considered a magnetic dipole with equatorial field strength $B = 1.6$ kG and calculated using the SYNTHMAG program the relative shifts of RCP and LCP profiles of the Fe I 6430.8 line for different inclination angles β and then derived the "observed" longitudinal field. We found $B_{\|} \simeq 900$, 400 and 200 G for $\beta = 0°$, 60° and 75° respectively. The mean unsigned surface field values for these inclinations are 2.4, 2.2 and 2.1 kG respectively, i.e. close to values found by Guenther et al. (1999) and Johns-Krull et al. (2000).

T Tau is believed to have a low inclination to its rotation axis based on $v \sin i$ (Hartmann & Stauffer 1989) and rotation period measurements (Herbst et al. 1985). Therefore, one can expect that the magnetic axis is also close to the line of sight if it is aligned with or close to the rotation axis. Thus the low value of the average longitudinal magnetic field of T Tau we found can be interpreted in two possible ways: 1) as an indication of the non-dipole character of the stellar magnetic field, or 2) as evidence of a large ($\gtrsim 30°$) angle between the rotation and magnetic axes.

Table 3. Results of 22.02.2002 observations of T Tau.

Ion	λ	$g_{\rm eff}$	B_1	B_2	B_3
Fe I	6609.1	1.59	−161	−33	−76
Fe I	6609.7				
V I	6624.8	0.94	+768	−21	+918
Fe I	6625.0				
Fe I	6633.4	1.48	+576	+218	−299
Fe I	6633.8				
Fe I	6634.1				
Ni I	6643.6	1.31	–	−8	−182
Fe I	6663.2	1.53	+160	+58	+460
Fe I	6663.4				
Fe I	6677.9	1.35	+143	−207	−67
Fe I	6678.0				
Al I	6696.0	0.97	−101	−182	+545
Fe I	6696.3				
Al I	6698.7	1.25	+198	+633	−214
Fe I	6699.1				
Li I	6707.8	1.25	+79	+91	+87
Fe I	6710.3	1.69	−82	−162	−150
Ca I	6717.7	1.01	+7	+52	+232
Ti I	6743.1	1.01	+735	+633	+635
Fe I	6750.2	1.50	−201	−77	+736
Fe I	6752.7	2.01	−282	−161	+61
Ni I	6767.8	1.43	+192	−111	+646

5. Conclusion

Weak circular polarization has been found in photospheric absorption lines of T Tau, indicating a mean longitudinal magnetic field $B_{\|} \sim 150$ G. While this value is near the detection limit of our apparatus, we belive that it is real. In any case one can conclude from our data that $B_{\|}$ on T Tau does not significantly exceed 200 G, i.e. much less than surface magnetic field strength of the star (>2.3 kG) found by Guenther et al. (1999) and Johns-Krull et al. (2000). This could be the result of the non-dipole character of the magnetic field on T Tau or evidence of a large angle between the rotation and magnetic axes. More precise observations are necessary to distinguish between these possibilities.

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