New Measurements of T Tauri Magnetic Fields: Testing Magnetospheric Accretion

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Abstract. Current theories of magnetospheric accretion onto classical T Tauri stars (CTTS) predict specific magnetic field strengths on the stellar surface for a number of stars. Measuring the magnetic field strengths on these stars offers a unique opportunity to test our current understanding of the accretion process. Due to the wavelength dependence of the Zeeman effect, high spectral resolution observations in the K band offer the best opportunity for measuring the magnetic field strength, \( B \), and area filling factor, \( f \), of these fields on the surface of late-type T Tauri stars (TTS). Here, we discuss recent 2\( \mu \)m spectra of several magnetically sensitive Ti i lines and magnetically insensitive CO lines observed in half-dozen TTS (both CTTS and non-accreting naked TTS: NTTS). The limited sample available at this time shows no correlation with predicted magnetic field strengths from magnetospheric accretion theory.

1. Introduction

Classical T Tauri stars (CTTS) are pre-main sequence solar type stars which appear to accrete material from a circumstellar disk via magnetospheric accretion. This model posits that TTS possess strong dipolar magnetic fields which truncate the surrounding accretion disk, forcing accreting material to flow along

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the stellar field lines to the surface of the star (Uchida & Shibata 1984; Bertout, Basri, & Bouvier 1988; Camenzind 1990; Königl 1991; Cameron & Campbell 1993; Shu et al. 1994). Despite the general success of this picture, there remains relatively little empirical knowledge on the magnetic fields on TTS.

Johns–Krull, Valenti, & Koresko (1999b) examined 3 of the more detailed versions of the magnetospheric accretion theories and showed that they can be used to predict magnetic fields (ranging up to 10 kG) for several CTTS. The first detection of a photospheric magnetic field on a TTS was made by Basri, Marcy, & Valenti (1992). They measured the systematic enhancement of the equivalent width of magnetically sensitive absorption lines in the NTTS Tap 35, deriving a total magnetic flux of $Bf = 1.0 \pm 0.5$ kG. Guenther et al. (1999) apply this same technique to 5 additional TTS, possibly detecting fields on 4 stars, though the systematic effects of stellar atmospheric parameters was not explored for their individual target stars which can confuse the analysis (e.g. Basri et al. 1992).

Taking advantage of the wavelength dependence of the Zeeman effect (ratio of Zeeman splitting to Doppler width $\lambda_B/\lambda_D \propto \lambda$), Johns–Krull et al. (1999b) analyzed high resolution ($R = 60,000$) optical and IR ($R \sim 35,000$) K band spectra of the CTTS BP Tau. The optical spectra were used to accurately measure the stellar atmospheric parameters, and the IR spectra of a Zeeman sensitive Ti I line clearly showed excess line broadening, which was modeled with a distribution of magnetic field strengths with a total flux $\Sigma Bf = 2.8$ kG. The IR Zeeman broadening observations offer the best opportunity to constrain $B$ and $f$ separately, and thereby to test the current magnetospheric accretion models; however, as Johns–Krull et al. (1999b) point out, the shape of the Ti I line can also be reproduced with absorption line formation in the circumstellar disk of BP Tau. Observations of several magnetically sensitive and insensitive lines are needed to fully demonstrate the magnetic nature of the line broadening. Here, we report new K band observations which accomplish this goal.

2. Observations

High resolution ($R \sim 35,000$) K-band spectra of a half-dozen TTS were made at the IRTF on 14 – 20 December 1997 and 13 – 16 April 1998, using the CSHELL 1 – 5 $\mu$m echelle spectrometer (Tokunaga et al. 1990). Each star was observed in 3 wavelength settings: 2 settings containing a total of 4 magnetically sensitive Ti I lines and 1 setting containing 9 magnetically insensitive CO lines.

3. Analysis

For each TTS, we analyze the 4 Ti I lines and 9 CO lines in the K-band. For the BP Tau and Hubble 4, we follow Johns–Krull et al. (1999b) and fit high resolution optical spectra to determine key atmospheric parameters ($T_{\text{eff}}$, gravity, $v_{\text{sin} i}$, [M/H]) using state of the art stellar atmospheres (Hauschildt et al. 1999). For the other stars, we take literature values of these parameters. Again using model atmospheres from Hauschildt et al. 1999, synthetic line profiles were fit to the K band spectra to determine the photospheric magnetic field properties. As found by Johns–Krull et al. (1999b), a single magnetic component of strength, $B$, and filling factor, $f$, added to a non-magnetic component with filling factor
Figure 1. The histogram shows three K band spectra of the CTTS BP Tau (4 Ti I lines in the top 2 panels, and 9 CO lines in the bottom panel). The thin smooth line is a synthetic spectrum with no magnetic field, and the thick smooth line is the best fitting magnetic model with the distribution of magnetic field components shown in the figure inset ($\Sigma B f = 2.1$ kG).

(1-\(f\)) is inadequate to model the data. Therefore, we fit the observed spectra with a distribution of magnetic components with \(B\) ranging from 0 - 6 kG in 2 kG steps. For the CTTS, a constant level of pure continuum emission from the disk is also determined. This disk continuum is the only fitted quantity that has any effect on the CO line profiles – all other key parameters come from the optical fits or literature data. An example fit is shown for the CTTS BP Tau in Figure 1. Note the obvious broadening of the Ti I lines in the upper two panels and the lack of broadening seen in the CO lines of the lower panel. Table 1 lists the mean unsigned magnetic field, \(B\) (\(\propto\) total magnetic flux), for each star.

4. Discussion

The new IR data shows that for each TTS observed, the Ti I lines show excess broadening which can be well fit with a distribution of magnetic field strengths on the stellar surface. The magnetically insensitive CO lines show no excess broadening relative to that expected from a normal stellar photosphere, reinforcing the conclusion that the Ti I lines are tracing magnetic fields and not some other broadening mechanism such as Doppler broadening in a circumstellar disk.

Table 1 also gives the field strengths predicted by Königl (1991) taken from Johns–Krull et al. (1999b). At this time only 4 stars can be used for the compar-
Table 1. TTS Mean Fields Derived from CSHELL Spectra.

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>Class</th>
<th>Observed $B$ (kG)</th>
<th>Predicted $B$ (kG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble 4</td>
<td>K7</td>
<td>NTTS</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td>T Tau</td>
<td>K0</td>
<td>CTTS</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BP Tau</td>
<td>K7</td>
<td>CTTS</td>
<td>2.1</td>
<td>3.4</td>
</tr>
<tr>
<td>TW Hya</td>
<td>K7</td>
<td>CTTS</td>
<td>2.6</td>
<td>-</td>
</tr>
<tr>
<td>DK Tau</td>
<td>M0</td>
<td>CTTS</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>DF Tau</td>
<td>M2</td>
<td>CTTS</td>
<td>2.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Comparison between theoretical and observed values. While the observed field strengths are generally of the right magnitude, there does not appear to be any correlation between the observed and predicted magnetic field values. This may mean that our understanding of magnetospheric accretion is far from complete. On the other hand, Johns–Krull et al. (1999a) showed that the mean photospheric field of BP Tau is not dipolar as assumed in the simple theories. However, Johns–Krull et al. (1999a) did show that accretion onto BP Tau does occur along magnetic field lines. All together, this suggests that it may be the fraction of the star with large scale magnetic loops times the field at the base of these loops that is proportional to the theoretical predictions.

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