SPECTROPOLARIMETRY OF THE CLASSICAL T TAU STAR TW HYDRAE

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Received 2006 July 25; accepted 2006 September 10

ABSTRACT

We present high-resolution ($R \approx 60,000$) circular spectropolarimetry of the classical T Tauri star TW Hydrae. We analyze 12 photospheric absorption lines and measure the net longitudinal magnetic field for six consecutive nights. While no net polarization is detected in the first five nights, a significant photospheric field of $B_z = 149 \pm 33$ G is found on the sixth night. To rule out spurious instrumental polarization, we apply the same analysis technique to several nonmagnetic telluric lines, detecting no significant polarization. We further demonstrate the reality of this field detection by showing that the splitting between right and left polarized components in these 12 photospheric lines shows a linear trend with Landé $g$-factor times wavelength squared, as predicted by the Zeeman effect. However, this longitudinal field detection is still much lower than that which would result if a pure dipole magnetic geometry is responsible for the mean magnetic field strength of 2.6 kG previously reported for TW Hya. We also detect strong circular polarization in the He i 5876 and Ca ii 8498 emission lines, indicating a strong field in the line formation region of these features. The polarization of the Ca ii line is substantially weaker than that of the He i line, which we interpret as being due to a larger contribution to the Ca ii line from chromospheric emission in which the polarization signals cancel. However, the presence of polarization in the Ca ii line indicates that accretion shocks on classical T Tauri stars do produce narrow emission features in the infrared triplet lines of calcium.

Key words: stars: individual (TW Hya) — stars: magnetic fields — stars: pre–main-sequence — techniques: polarimetric

1. INTRODUCTION

T Tauri stars (TTSs) are newly formed low-mass stars that have recently become visible at optical wavelengths. These young, roughly solar mass stars are still contracting along pre-main-sequence evolutionary tracks in the H–R diagram. It is generally believed that classical T Tauri stars (CTTSs) are still surrounded by disks of material that are undergoing accretion onto the central star, producing excess emission in both lines and continuum at multiple wavelengths. Magnetospheric accretion models are the most popular description of the accretion process. Strong, stellar magnetic fields are believed to regulate the accretion and confine disk material to flow onto the stellar surface along the field lines (e.g., Camenzind 1990; Königl 1991; Cameron & Campbell 1993; Shu et al. 1994). These models generally assume the magnetic structure of TTSs to be dipolar and require magnetic field strengths that vary over a wide range of values, with the field on some stars as high as several kilogauss (see Johns-Krull et al. 1999b). Such high field strengths should be measurable by using the most magnetically sensitive diagnostics.

On the other hand, direct magnetic field measurements are difficult, since TTSs are relatively faint and display various spectral peculiarities. The most successful approach for measuring fields on late-type stars in general has been to measure the Zeeman broadening of spectral lines in unpolarized light (e.g., Robinson 1980; Saar 1988; Valenti et al. 1995; Johns-Krull & Valenti 1996; Johns-Krull et al. 1999b, 2004). This method is more efficient at infrared wavelengths thanks to the $\lambda^2$ dependence of Zeeman broadening compared to the $\lambda^1$ dependence of Doppler broadening. While a sensitive measure of field strength, Zeeman broadening measurements give little information on the magnetic field geometry.

Another direct method for measuring magnetic fields is to detect net circular polarization in Zeeman-sensitive lines. Generally, Zeeman $\sigma$-components are elliptically polarized, and the components of opposite helicity are split to either side of the nominal line wavelength. A net longitudinal component of the magnetic field makes components of Zeeman-sensitive lines distinguishable through a right-circular polarizer (RCP) and left-circular polarizer (LCP). The separation between the line observed in RCP and LCP light is

$$\Delta\lambda = \frac{e}{4\pi m_e c^2} \lambda^2 g_{\text{eff}} B_z = (9.34 \times 10^{-7})\lambda^2 g_{\text{eff}} B_z \; \text{mA},$$

(1)

where $g_{\text{eff}}$ is the effective Landé $g$-factor of the transition, $B_z$ is the strength of the mean longitudinal magnetic field in kilogauss, and $\lambda$ is the wavelength of the transition in angstroms (see Mathys 1988, 1991). The weights for individual $\pi$ and $\sigma$ components in the definition of $g_{\text{eff}}$ assume an optically thin medium, so equation (1) is only approximately true in our case of moderately strong photospheric lines. Previously, Johns-Krull et al. (1999a) did not detect polarization in the photospheric lines of the CTTS BP Tau, setting a $3\sigma$ upper limit on $B_z$ of $\pm 200$ G. Smirnov et al. (2003) report a longitudinal magnetic field of $B_z \sim 150 \pm 50$ G on the CTTS T Tau, which is very close to their detection limit, while their subsequent observation of T Tau (Smirnov et al. 2004) did not detect a significant field. In an effort to confirm the original Smirnov et al. (2003) detection, Daou et al. (2006) measure a
mean longitudinal field of $B_z = 12 \pm 35$ G on T Tau. Daou et al. (2006) use upper limits on $B_\nu$ on multiple nights along with the mean field strength detected on T Tau of $B \approx 2.4$ kG (Guenther et al. 1999; Johns-Krull et al. 2001) to seriously question the assumed dipole field geometry (see also Valenti & Johns-Krull 2004).

On the other hand, Johns-Krull et al. (1999a) discovered net polarization in the He I $\lambda 5876$ emission line on the CTTS BP Tau, indicating a net longitudinal magnetic field of $2.46 \pm 0.12$ kG in the line formation region. This He I emission line is believed to be produced, at least partially, in the shock region formed where disk material accretes onto the stellar surface (Hartmann et al. 1994; Edwards et al. 1994). Circular polarization in the He I line has now been observed in several CTTSs (Valenti & Johns-Krull 2004; Symington et al. 2005). These observations suggest that accretion onto CTTSs is indeed controlled by a strong stellar magnetic field.

While substantial observational evidence indicates strong fields on the surface of TTSs, the origin of the surface magnetic fields on TTSs are not clear. Interface dynamo models (e.g., Parker 1993) that are applied to solar-type main-sequence stars probably do not apply to TTSs, since their internal structure is significantly different from that of the Sun. Feigelson et al. (2003) summarize several theoretical considerations for the origin of TTS magnetic fields. One possibility is that a distributed dynamo due to turbulent convection could operate in TTSs and generate small-scale magnetic fields. These fields could also be amplified by differential rotation throughout the convective zone (Durney et al. 1993; Kitchatinov & Rüdiger 1999; Küker & Stix 2001), although surface differential rotation is weak or absent on TTSs (Johns-Krull & Valenti 1996). It is also possible that TTSs simply maintain a "fossil" magnetic field throughout the star formation process and do not have significant field contributions from dynamo processes (Taylor 1987; Mestel 1999; Moss 2003). More observational studies are needed to put further constraints on theories of the origin and evolution of magnetic fields on pre-main-sequence stars.

In order to gain further insight into the magnetic properties of young stars, we present an analysis of high-resolution spectroscopic observations of young stars. We focus on the TW Hya system (Valenti & Johns-Krull 2004). This system has been described by Valenti & Johns-Krull (1999) and Valenti & Johns-Krull (2004). The ZA was used with the two-dimensional coude cross-dispersed echelle spectrometer (Tull et al. 1995). This spectrometer provides a 2 pixel spectral resolution of $R = \lambda / \Delta \lambda \approx 60,000$ and enough space between the orders to interleave simultaneously stellar spectra of both circular polarization states. To reduce spurious linear polarization induced by the coude mirror rotation, the ZA control computer automatically updates the retardance of a Babinet-Soleil phase compensator (PC) fixed to the front of the ZA. The phase compensation is continually changed, as telescope orientation changes throughout an observation. Each night, two exposures of TW Hya were obtained. Before the second exposure, an achromatic half-wave plate (manufactured by Special Optics, model 8-9012-1/2) was inserted in front of the ZA + PC in order to switch the sense of circular polarization recorded in the two interleaved spectra. Analysing and averaging the results of this pair of exposures reduces potential sources of systematic/instrumental error in the measurements. All spectra were reduced using an echelle-reduction package developed by Valenti (1994) and described more fully in Hinkle et al. (2000). Wavelength solutions are determined from spectra of a Thorium-Argon lamp by performing a two-dimensional fit to the positions of lines on the detector as a function of $n$ and $n\lambda$, where $n$ is the echelle order.

Table 1 summarizes the observations discussed here.

3. ANALYSIS

3.1. Photospheric $B_z$

We use 12 photospheric absorption lines that have relatively large Landé $g$-factors to measure the longitudinal field, $B_z$, on TW Hya. These lines are also relatively strong and not significantly affected by telluric absorption. The species we use, as well as their wavelengths and Landé $g$-factors, are listed in the first three columns of Table 2.

Our analysis technique is as follows. We cross-correlate the LCP and RCP line profiles and measure the wavelength separation between the two spectra for each line. Using equation (1), we convert the measured wavelength separation for each line into a longitudinal magnetic field. We then use a Monte Carlo analysis to estimate the uncertainties in our measured wavelength separations. First we fit a Gaussian curve to the observed intensity profile, which is the sum of the LCP and RCP spectra for each wavelength separation. By adding noise comparable to that in our observations to the Gaussian curve, we construct a pair of synthetic observations (one represents the LCP and the other the RCP component). Then we analyze these profiles in the same way as we handle the actual observations and obtain a line separation.

Table 1: Observations and Results

| UT Date       | UT Time | Total Exposure Time (s) | $B_z^a$ (G) | σ |
|---------------|---------|-------------------------|------------|---|
| 1999 Apr 21... | 03:54   | 4300                    | 66         | 40|
| 1999 Apr 22... | 04:12   | 4700                    | 54         | 56|
| 1999 Apr 23... | 03:44   | 4700                    | 84         | 32|
| 1999 Apr 24... | 03:38   | 4700                    | 82         | 61|
| 1999 Apr 25... | 04:48   | 4700                    | 47         | 48|
| 1999 Apr 26... | 03:37   | 4700                    | 149        | 33|

* Photospheric field strength.
that is then translated into magnetic field strength using equation (1). For each individual spectral line on each night, we execute the Monte Carlo process above 100 times and measure the apparent shift (we have tried shifts of 0 and 0.5 pixels) between the synthetic LCP and RCP spectra. We then adopt the standard deviation of the corresponding Monte Carlo results as the uncertainties in our measurement of $B_z$. The results for each photospheric line for each of the six nights are listed in the last six columns of Table 2. The weighted mean field values and their uncertainties for the six nights are listed in Table 1. The night-to-night variation is plotted in Figure 1 (bottom).

The mean longitudinal field value on 1999 April 26 is 149 ± 33 G, well over the 3σ limit. If this field strength and uncertainty estimate are accurate, it represents the largest magnitude of $B_z$ detected at a significant level on a low-mass pre-main-sequence star and one of the highest $B_z$ values detected for any low-mass star (see Donati et al. 2006). To rule out spurious instrumental polarization, we apply the same technique to analyze six magnetically insensitive telluric absorption lines and find the observed wavelength separations between the LCP and RCP spectra of these lines. The telluric lines are narrower than the stellar photospheric lines, allowing wavelength separation to be measured more precisely, yielding smaller uncertainties in $B_z$ and placing tighter limits on spurious instrumental polarization. In order to translate the observed wavelength separations into magnetic field strengths for comparison we assign a $g_{\text{eff}}$ value for the telluric lines of 0.93, which is determined from the weighted mean value of $\sqrt{\text{g}_{\text{eff}}^2}$ for the 12 photospheric lines, where the weights are uncertainties in the photospheric field measurements. The field estimates from the telluric lines are given in Table 2 for each night. The recovered field strengths for the telluric lines are all consistent with no magnetic field (as they should be) to within the errors, which are typically ~28 G (1σ).

Another way to confirm the reality of the photospheric $B_z$ measurement on the last night of observation is to look for a correlation between the measured wavelength shift and the $g_{\text{eff}}$ of each line. This is perhaps the best way to establish the

**TABLE 2**

**PHOTOSPHERIC FIELD MEASUREMENTS**

| Species | $\lambda$ (Å) | $g_{\text{eff}}$ | $B_z$ (G)       |
|---------|---------------|------------------|----------------|
|         |               |                  | Apr 21 | Apr 22 | Apr 23 | Apr 24 | Apr 25 | Apr 26 |
| Ca i    | 6166.4        | 0.50             | 186 ± 393 | −78 ± 532 | 258 ± 343 | −450 ± 586 | 76 ± 316 | −448 ± 321 |
| Fe i    | 6180.2        | 0.64             | 150 ± 350 | −269 ± 418 | −79 ± 307 | −338 ± 516 | −20 ± 349 | 280 ± 247 |
| Fe i    | 6200.3        | 1.51             | 173 ± 150 | −79 ± 158 | 52 ± 102 | 74 ± 226 | 238 ± 143 | 113 ± 84 |
| V i     | 6213.4        | 2.00             | −6 ± 111 | 30 ± 159 | 108 ± 113 | 145 ± 224 | −277 ± 156 | 92 ± 86 |
| Fe i    | 6322.6        | 1.51             | 47 ± 133 | 14 ± 328 | 31 ± 117 | −110 ± 227 | 283 ± 235 | 79 ± 117 |
| Fe i    | 6330.8        | 1.22             | 12 ± 199 | 233 ± 258 | 75 ± 148 | 74 ± 281 | −41 ± 194 | 13 ± 123 |
| Fe i    | 6335.3        | 1.16             | 222 ± 161 | 244 ± 245 | 190 ± 118 | 540 ± 273 | 162 ± 196 | 280 ± 138 |
| Fe i    | 6336.8        | 2.00             | 76 ± 144 | 107 ± 237 | 122 ± 92 | 245 ± 199 | 114 ± 140 | 157 ± 89 |
| Ti i    | 6359.8        | 1.20             | 34 ± 145 | 197 ± 231 | 110 ± 112 | 71 ± 217 | 317 ± 148 | 359 ± 111 |
| Al i    | 6696.0        | 1.16             | 50 ± 258 | 101 ± 337 | −39 ± 304 | 123 ± 462 | −11 ± 372 | 111 ± 267 |
| Fe i    | 8468.4        | 2.50             | 43 ± 66 | 22 ± 101 | 47 ± 57 | 50 ± 107 | −53 ± 92 | 181 ± 74 |
| Fe i    | 8757.1        | 1.50             | 142 ± 168 | 106 ± 149 | 131 ± 103 | 35 ± 170 | −112 ± 181 | 156 ± 140 |
| Telluric| 8139.5        | 0.90             | −33 ± 88 | 24 ± 93 | 55 ± 95 | −153 ± 89 | −62 ± 65 | −75 ± 243 |
| Telluric| 8140.5        | 0.90             | 17 ± 48 | 124 ± 51 | 14 ± 55 | 78 ± 62 | 35 ± 76 | −21 ± 72 |
| Telluric| 8141.5        | 0.90             | −33 ± 45 | −30 ± 64 | −31 ± 44 | 21 ± 69 | −78 ± 81 | 25 ± 57 |
| Telluric| 8146.1        | 0.90             | −10 ± 69 | −4 ± 71 | 44 ± 68 | −38 ± 58 | −21 ± 79 | 33 ± 61 |
| Telluric| 8147.0        | 0.90             | 64 ± 68 | 58 ± 82 | 34 ± 66 | −8 ± 68 | −27 ± 83 | 27 ± 69 |
| Telluric| 8150.0        | 0.90             | −3 ± 37 | 3 ± 47 | −10 ± 47 | −82 ± 66 | −37 ± 73 | −17 ± 51 |
| He i    | 8576.0        | 1.00             | −1806 ± 114 | −1506 ± 112 | −1790 ± 149 | −1583 ± 159 | −1471 ± 143 | −1776 ± 96 |
| Ca ii   | 8498.0        | 1.07             | −212 ± 57 | −289 ± 59 | −323 ± 36 | −392 ± 62 | −402 ± 64 | −180 ± 34 |

![Figure 1](image-url)  
**FIG. 1.**—Time series of $B_z$ values measured from different spectral lines. **Top:** Field values measured from the He i 5876 line. **Middle:** Field values measured from the Ca ii 8498 line. **Bottom:** Field values measured from 12 photospheric lines.
magnetic origin of the shifts and hence rule out any potential instrumental effects unaccounted for. We can rewrite equation (1) as follows:

$$\frac{\Delta \lambda}{(9.34 \times 10^{-7}) \lambda} = B_z g_{\text{eff}}.$$

(2)

In Figure 2 we plot the left-hand side of equation (2) against $g_{\text{eff}}$. The solid line marks the expected relationship for $B_z = 149$ G. The wavelength separations of the telluric lines (Fig. 2, diamonds) are all found to be close to zero, as they should be, since the molecular lines have negligible $g_{\text{eff}}$ and form in the weakly magnetized atmosphere of the Earth. Using all the data points in Figure 2, the reduced $\chi^2$, $\chi_i^2$, for the $B_z = 149$ G line is 0.68, corresponding to an 83% chance of being an acceptable model, while a best-fit horizontal line, indicative of an instrumental offset, yields $\chi_i^2 = 1.91$, corresponding to less than a 2% chance of being an acceptable model. The positive correlation shown in Figure 2 and the detailed statistical tests give confidence that the measured wavelength separations are indeed magnetic in origin, so that we do detect a rather strong longitudinal field on TW Hya above the 4 $\sigma$ limit.

Examination of Table 1 or the bottom panel of Figure 1 shows that while we find a value of $B_z$ larger than the 3 $\sigma$ measurement uncertainties only once, all measurements are systematically positive and agree with each other within the uncertainties. Given that TW Hya has an inclination close to 0°, little rotational modulation is expected (although see §3.2). Taking the weighted mean of all six nights data gives a value of $B_z = 90 \pm 17$ G.

3.2. Magnetic Fields in the Emission-Line Region

Significant polarization in the He I $\lambda$5876 emission line has been detected on several CTTSs. Johns-Krull et al. (1999a) first discovered this polarization and found $B_z = 2.46 \pm 0.12$ kG in the He I line formation region of BP Tau. Valenti & Johns-Krull (2004) found He I polarization in four CTTSs: AA Tau, BP Tau, DF Tau, and DK Tau. Symington et al. (2005) also detect He I polarization at greater than the 3 $\sigma$ level in three stars (BP Tau, DF Tau, and DN Tau) in their survey of seven CTTSs. While this He I line can form weakly in emission in naked TTSs (NTTSs), which are believed to lack close circumstellar disks and significant accretion, the strong He I emission of CTTSs is thought to form in the accretion shock region where disk material hits the stellar surface (e.g., Edwards et al. 1994; Hartmann et al. 1994).

Here we analyze our observations of TW Hya and find strong circular polarization in the He I $\lambda$5876 emission line as well. The same analysis technique used for the photospheric lines is applied. This He I line is a multiplet. The observed shift between the line observed in different circular polarization states described below is larger than the spacing between most of the multiplet members that make up this feature. As a result, the magnetic splitting is best described by the Paschen-Bach effect, hence $g_{\text{eff}} = 1.0$ for the line. (Even in the weak field limit of Zeeman broadening, LS coupling gives $g_{\text{eff}} = 1.11$ [Johns-Krull et al. 1999a], so the choice of treatment makes only a small difference on the resulting field values.) The measurements for each night are listed in Table 2, and the weighted mean of the net longitudinal field for all the nights together is $-1673 \pm 50$ G. A pair of representative LCP and RCP spectra is shown in Figure 3 (top). In addition to the 5876 Å line of He I, our spectrometer setting also contains the 6678 Å line of He I. This line is the singlet counterpart to the 5876 Å line and has $g_{\text{eff}} = 1.0$. Analysis of the 6678 Å line gives magnetic field values in the He I line formation fully consistent with the values from the 5876 Å line to within the measurement uncertainties (which are about a factor of 2 larger for the 6678 Å line, since this line is weaker than the 5876 Å line).

We also detect significant polarization in the Ca ii $\lambda$8498 emission line, as shown in the bottom panel of Figure 3. Nightly measurements are given in Table 2, and we measure a weighted
mean $B_z = -276 \pm 19$ G for all the nights together. We expect that the other members of the Ca ii infrared triplet (IRT) show similar levels of polarization, but they fall in the gaps in our spectral coverage and were not observed. The origin of the narrow IRT emission lines seen in many CTTSs (including TW Hya) is somewhat debated and is discussed further in § 4. Our detection of polarization in this line with the same polarity as the He i line suggests that the accretion shock contributes some emission to this component of the IRT. Our measured $B_z$ for the Ca ii line is 16% of our measured $B_z$ for the He i line, which suggests that at least 16% of the Ca ii emission comes from accretion regions with highly ordered magnetic fields. This is a lower limit, because the lower $B_z$ for Ca ii could also signify a larger contribution from regions of lower field strength (e.g., the accretion column) or mixed polarity (e.g., a radiatively heated sheath around the accretion footpoint, as proposed by Batalha et al. 1996). Nonshock contribution to the He i line could lower our estimate of 16%, but in the case of TW Hya the effect is almost negligible (see more on this issue at the end of § 4).

The time series of the measured field values from the He i and Ca ii lines, along with that from the photosphere, are plotted in Figure 1. The night-to-night variation of the polarization in the He i line shows a hint of periodicity. We adopt a rotation period $P = 2.2$ days for TW Hya from Mekkaden (1998) and fit a sine wave to the measured field values. The fit has $\chi^2 = 1.2$ for 3 degrees of freedom, indicating a 76% probability of being an acceptable model. However, we also fit a straight line to our data (representing a model with no variability) and find $\chi^2 = 6.30$ for 5 degrees of freedom, which has a significant 28% probability of representing an acceptable model. Both fits are shown in Figure 4. The Ca ii and photospheric lines do not show the same indications for periodicity; however, their relative uncertainties are much...
larger. Since our analysis is limited to six data points, the evidence for rotational modulation in the He i line is suggestive but remains inconclusive.

3.3. Hα Line Profiles

In Figure 5 we plot the Hα profiles from all six nights. The intensity of the Hα line varies and generally decreases with time, suggesting a possible decrease in the accretion rate on later nights. A variable blueshifted absorption component indicative of the wind from TW Hya also decreases with time over these six nights. This trend is consistent with a possible decrease in the accretion rate on later nights. While this is suggestive, further observations are needed to confirm this trend.

We looked for circular polarization in the Hα emission line as well. This line is very strong, which aids the detection of weak line shifts between the RCP and LCP light. However, since this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial. Small differences in the continuum normalization of the RCP and LCP profiles can produce spuriously large changes. We attempt to quantify this by repeating the analysis of the Hα profile using somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization. The difference between the results is somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization.

We also considered a linear polarization model to quantify this by repeating the analysis of the Hα profile using somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization. However, this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial.

4. DISCUSSION

Imaging of the circumstellar disk around TW Hya in the infrared (Krist et al. 2000; Trilling et al. 2001; Weinberger et al. 2002), millimeter (Wilner et al. 2000), and submillimeter (Qi et al. 2004) wavelengths all suggest that the inclination of the disk is close to 0°. Alencar & Batalha (2002) derived an inclination of 18°±10° from emission-line profile analysis. However, since this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial. Small differences in the continuum normalization of the RCP and LCP profiles can produce spuriously large changes. We attempt to quantify this by repeating the analysis of the Hα profile using somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization. However, this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial.

The night-to-night variation in our measurements of the longitudinal field in the Hα line is small, only about 10% of the mean value, which is also consistent with a low disk inclination angle of TW Hya. Such a geometry allows a strong test of whether the magnetic field on TW Hya is primarily a dipole field with the magnetic axis aligned with the rotation axis. Yang et al. (2005) find the mean magnetic field strength in the photosphere of TW Hya to be 2.6±0.2 kG from infrared Zeeman broadening measurements. If we follow Alencar & Batalha (2002) and assume an inclination angle between 8° and 28°, and if the magnetic dipole axis is aligned with the rotation axis, the 2.6 kG mean field would predict a mean line-of-sight field in the photosphere of $B_z = 0.97 - 1.05$ kG. This is much higher than our maximum measured value, $B_z = 149 ± 33$ G, or our weighted mean from all nights, $B_z = 90 ± 17$ G. One possibility to explain the low longitudinal magnetic field values and yet retain a dipole field geometry is to assume that the magnetic axis is highly inclined from the rotation axis (i.e., has high obliquity, $\beta$). For example, Krist et al. (2000) use the model of Mahdavi & Kenyon (1998) and conclude that the photometric variability of TW Hya observed by Mekkaden (1998) can be explained if $i < 10^\circ$ and the field is a dipole with $\beta > 55^\circ$. If we take $i = 10^\circ$ and $\beta = 55^\circ$, the 2.6 kG mean field on TW Hya still implies a photospheric $B_z = 537$ G, again well above our upper limits for $B_z$ in the photosphere. If the photospheric field is globally dipolar, then $\beta$ must be significantly larger than 55°. If we ask what is required of a dipole field geometry to match the 2.6 kG mean field and the 149 G longitudinal field for the visible hemisphere of the star, we find that $i + \beta = 83.5^\circ$. However, in this case we have an additional constraint from the Hα polarization.

If the photospheric magnetic field on TW Hya is dipolar, then the magnetic poles must be nearly perpendicular to the line of sight at all rotational phases (see preceding paragraph). For such a magnetic geometry, material accreted from the corotation radius ($6.3R_*$; see Johns-Krull & Valenti 2001) will land within $13^\circ$ of the magnetic pole. This line is very strong, which aids the detection of weak line shifts between the RCP and LCP light. However, since this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial. Small differences in the continuum normalization of the RCP and LCP profiles can produce spuriously large changes. We attempt to quantify this by repeating the analysis of the Hα profile using somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization.

In Figure 5 we plot the Hα profiles from all six nights. The intensity of the Hα line varies and generally decreases with time, suggesting a possible decrease in the accretion rate on later nights. A variable blueshifted absorption component indicative of the wind from TW Hya also decreases with time over these six nights. Other than these general trends in the Hα line over these six nights, nothing dramatic occurs on the last night when the photospheric $B_z$ takes on its largest value.

We looked for circular polarization in the Hα emission line as well. This line is very strong, which aids the detection of weak line shifts between the RCP and LCP light. However, since this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial. Small differences in the continuum normalization of the RCP and LCP profiles can produce spuriously large changes. We attempt to quantify this by repeating the analysis of the Hα profile using somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization. However, this data was obtained with an echelle spectrometer that has a strong blaze function, continuum normalization under Hα is not trivial. Small differences in the continuum normalization of the RCP and LCP profiles can produce spuriously large changes. We attempt to quantify this by repeating the analysis of the Hα profile using somewhat different regions to fit the continuum, as well as using polynomials of order 4, 5, and 6 in the continuum normalization.

In this case, the longitudinal field of ~1.7 kG measured in the accretion region using the Hα line is only the small fraction projected onto the line of sight of the true magnetic field in this region. The minimum value of the true field is 1.7 kG/cos(83.5°−13°) = 5.1 kG. Such a strong field in the Hα line has not been observed in any of the previous studies now covering 11 CTTSs (Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004; Symington et al. 2005; Daou et al. 2006). We conclude that the surface topology of the magnetic geometry on TW Hya (and likely all CTTSs) is not a pure dipole. It is likely that the field topology at the stellar surface is dominated by small-scale structure such as is seen on the Sun. However, the dipole component of the field will fall off the least rapidly with distance from the star, so it may well be that the interaction of the stellar field with the disk is governed by a dipole geometry. Such a picture may explain the relatively smooth, sinusoidal-like modulation of the field traced in the Hα line of the CTTSs studied by Valenti & Johns-Krull (2004).

Hartmann (1998) gives an expression for the truncation radius for an assumed dipole field geometry (his eq. [8.72]) derived under the assumption of spherical accretion. As discussed by Bouvier et al. (2006, § 6.1), this is an upper limit for a disk geometry. If we assume that the dipole component of the field on TW Hya is responsible for our detection of $B_z = 149$ G on this star, we can use the equation from Hartmann (1998) to estimate a truncation radius. The estimate again depends on the inclination of the dipole component of the field with respect to our line of sight. If (as is generally the case for the Sun) we assume that the dipole component is aligned with the rotation axis, assuming that $i = 28°$ gives the strongest possible dipole component consistent with our $B_z$ detection, and this corresponds to an equatorial field strength of 260 G. Putting this into equation (8.72) from Hartmann (1998) yields a truncation radius of 3$R_*$, which is significantly less than the corotation radius of 6.3$R_*$.

Eisner et al. (2006) analyze K-band interferometry observations of TW Hya from Keck, along with previous K-band veiling and near-infrared photometric measurements, to conclude that the inner radius of the optically thin disk is around 0.06 AU, which corresponds to 13$R_*$ while there are additional techniques that could shed light on the exact location of this inner truncation radius (e.g., linear polarimetry is a powerful technique that may help in this regard, as discussed in Vink et al. 2005), the current data suggest that the system is not in equilibrium as assumed by magnetospheric accretion theories if the dipole component of the field alone is responsible for truncating the accretion disk. There are certainly higher order contributions to the total field at the surface of TW Hya that will contribute some field strength at the corotation radius, but just how much depends on the detailed field geometry. We suggest that more work is needed to verify
whether the fields on TTSs really are strong enough to truncate disks around these stars near the corotation radius for realistic magnetic field geometries.

As noted in § 3.2, the level of polarization in the Ca ii 8498 line is much less than that detected in the Hα line. The IRT lines of Ca ii likely have contributions from different regions in CTTSs. These lines sometimes show only broad components (BC), narrow components (NC), or a mixture of the two (e.g., Alencar & Basri 2000). It is generally accepted that the BC of the IRT originates in the accretion and/or wind flows associated with CTTSs, as this component is not observed in NTTSs. However, the origin of the NC of the IRT lines is not completely clear. The Ca ii 8498 line of TW Hya is dominated by a NC inside a photospheric absorption line. A chromospheric origin for the NC of the IRT lines in both NTTSs and CTTSs was proposed by Hamann & Persson (1992), Batalha & Basri (1993) and Batalha et al. (1996) echo this idea, although they further suggest that accretion activity in CTTSs can enhance the chromospheric emission. They suggest that this is due to the reprocessing of radiation produced in accretion shocks as the accreting material hits the stellar atmosphere. Another possible scenario results, since the accretion occurs along stellar magnetic field lines: the mean magnetic field is likely relatively weak and the direction of the field is not constant. Indeed, there are regions in the magnetosphere (if viewed nearly pole-on) in which the field directions are reversed. This mixture of polarities will reduce the separation of LCP and RCP line profiles. Depending on where the majority of the line forms, we expect the local field strength to be quite weak. For example, assuming a face-on disk for TW Hya and a dipolar-like magnetospheric accretion flow with the mean magnetic field in the corotation radius will be equal to the stellar value of that field multiplied by (B/Brrot)3. Taking our estimate above of 260 G for the equatorial value of the dipole component of the field at the corotation radius will be equal to the stellar value of that field multiplied by (R/St)3. A taking our estimate above of 260 G for the equatorial value of the dipole component of the field at the corotation radius will be equal to the stellar value of that field multiplied by (R/St)3.

We would like to thank the referee, J. Vink, for many useful comments and suggestions for improving the original manuscript. C. M. J.-K. and H. Y. would like to acknowledge partial support from the NASA Origins of Solar Systems program through grants NAG5-13103 and NNG 06GD85G made to Rice University.

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