THE MAGNETIC FIELDS OF CLASSICAL T TAURI STARS

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ABSTRACT

We report new magnetic field measurements for 14 classical T Tauri stars (CTTSs). We combine these data with one previous field determination in order to compare our observed field strengths with the field strengths predicted by magnetospheric accretion models. We use literature data on the stellar mass, radius, rotation period, and disk accretion rate to predict the field strength that should be present on each of our stars according to these magnetospheric accretion models. We show that our measured field values do not correlate with the field strengths predicted by simple magnetospheric accretion theory. We also use our field strength measurements and literature X-ray luminosity data to test a recent relationship expressing X-ray luminosity as a function of surface magnetic flux derived from various solar feature and main-sequence star measurements. We find that the T Tauri stars we have observed have weaker than expected X-ray emission by over an order of magnitude on average using this relationship. We suggest the cause for this is actually a result of the very strong fields on these stars, which decreases the efficiency with which gas motions in the photosphere can tangle magnetic flux tubes in the corona.

Subject headings: accretion, accretion disks — line: profiles — stars: atmospheres — stars: formation — stars: magnetic fields — stars: pre–main-sequence

1. INTRODUCTION

It is now generally accepted that accretion of circumstellar disk material onto the surface of a classical T Tauri star (CTTS) is controlled by a strong stellar magnetic field (e.g., see review by Bouvier et al. 2007). It is within the disks around these low-mass pre-main-sequence stars that solar systems similar to our own form. Understanding the processes through which young stars interact with and eventually disperse their disks is critical for understanding the rotational evolution of stars and the formation of planets. A key question is to understand how young stars can accrete large amounts of disk material with high specific angular momentum, yet maintain rotation rates that are observed to be relatively slow (e.g., Hartmann & Stauffer 1989; Edwards et al. 1994). This problem is solved in current magnetospheric accretion models by having the stellar magnetic field truncate the inner disk, typically near the corotation radius, and channel the disk material onto the stellar surface, most often at high stellar latitude.

Support for magnetospheric accretion in CTTSs is significant. Current models can account for the relatively slow rotation of most CTTSs (Camenzind 1990; Königl 1991; Collier Cameron & Campbell 1993; Shu et al. 1994; Paatz & Camenzind 1996; Long et al. 2005). Studies of the spectroscopic and photometric variability of CTTSs have been interpreted in terms of magnetically controlled accretion (e.g., Bertout et al. 1988, 1996; Herbst et al. 2001; Alencar et al. 2001) with the magnetic axis inclined to the rotation axis in some cases (e.g., Kenyon et al. 1994; Johns & Basri 1995; Bouvier et al. 1999; Romanova et al. 2004). Models of high-resolution Balmer line profiles, computed in the context of magnetospheric accretion, reproduce many aspects of observed line profiles (Muzerolle et al. 1998, 2000). Such models can also reproduce aspects of the observed Ca ii infrared triplet lines (Azevedo et al. 2006). T Tauri stars (TTs) are observed to be strong X-ray sources indicating the presence of strong magnetic fields on their surfaces (see Feigelson & Montmerle 1999 for a review), and several TTs have been observed to have strong surface magnetic fields (Basri et al. 1992; Guenther et al. 1999; Johns-Krull et al. 1999b, 2004 [hereafter Paper I and Paper II, respectively]; Yang et al. 2005, hereafter Paper III), and strong magnetic fields have been observed in the formation region of the He i emission line at 5876 Å (Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004; Symington et al. 2005; Yang et al. 2007), which is believed to be produced in a shock near the stellar surface as the disk material impacts the star (Beristain et al. 2001).

Despite these successes, open issues remain. Most current theoretical models assume the stellar field is a magnetic dipole with the magnetic axis aligned with the rotation axis. However, recent spectropolarimetric measurements show that the fields on TTs are probably not dipolar, either aligned with the rotation axis or not (Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004; Daou et al. 2006; Yang et al. 2007). On the other hand, it is expected that even for complex magnetic geometries, the dipole component of the field should dominate at a distance from the star where the interaction with the disk is taking place, so this may not contradict current theory. In the case of the Sun, the dipole component appears to become dominant at 2.5 R⊙ or closer (e.g., Luhmann et al. 1998). For expected disk truncation radii of 3R∗–10R∗ in CTTSs (see below and Table 1), this suggests the dipole component will govern the stellar interaction with the disk. In addition, Gregory et al. (2006) show that accretion can occur from a truncated disk even when the stellar field geometry is quite complex; however, no study has considered the torque balance between a star and its disk in the case of a complex stellar field geometry.

Magnetospheric accretion models for CTTSs have been developed by a number of investigators. Königl (1991) first applied the work of Ghosh & Lamb (1979) to CTTSs, showing that an equilibrium state could exist if the stellar field was strong enough. In this model, the field truncates the disk a little inside the corotation radius. Additional authors have studied this equilibrium state, using different assumptions regarding the details of how the
stellar field couples to the disk. Paper I examined the models of Königl (1991), Collier Cameron & Campbell (1993), Shu et al. (1994), and Long et al. (2005).

Several authors have performed numerical simulations of magnetospheric accretion. Typically, aligned stellar dipole fields are assumed, and the simulations examine the instabilities that can result between the star, its magnetosphere, and the disk. Many studies find that winds and/or jets are produced (e.g., Hayashi et al. 1996; Goodson et al. 1997, 1999; Miller & Stone 1997; Ferreira et al. 2000; Romanova et al. 2005). These studies usually examine only a few select cases and generally do not address how the rotation of the star may evolve: it is a fixed parameter of the model. These simulations may be testable through variability studies (see Goodson et al. 1999). Recently, Long et al. (2005) presented numerical simulations, again assuming an aligned dipole field geometry, with the aim of determining if a time-averaged equilibrium rotation rate is established. Despite variability in the accretion and wind flows, these authors found that the star attains an equilibrium rotation rate with the disk truncated inside, but close to, the corotation radius. Long et al. (2005) used the results of their simulations to derive a relationship for the equilibrium rotation period of CTTSs (their eq. [12]). This can be solved for the stellar magnetic field strength and results in an equation with the same dependence on the stellar ($M_*$, $R_*$, $P_{\text{rot}}$) and accretion parameters ($\dot{M}$), as found for Königl (1991) and Shu et al. (1994), as given in Paper I. It should be noted, however, that Matt & Pudritz (2004, 2005a) have recently asserted that the spin-down torque produced on the star in magnetospheric accretion models may be up to an order of magnitude lower than most previous investigators have calculated. Matt & Pudritz (2005b) suggest that an accretion-powered stellar wind is responsible for spinning down CTTSs.

Given the theoretical uncertainty involved with magnetospheric accretion, we can try to use observations to test whether the disk locking scenario proposed by the equilibrium models actually holds in CTTSs. One of the first attempts at this is the work of Stassun et al. (1999), who find no correlation between rotation period and the presence of an infrared (IR) excess indicative of a circumstellar disk in a sample of 254 stars in Orion. However, IR excess alone is not a good measure of the accretion rate. Muzerolle et al. (2001) note that current theory predicts a correlation between rotation period and mass accretion rate, which they do not observe. Muzerolle et al. (2001) suggest that variations in the stellar magnetic field strength from star to star may account for the lack of correlation. Indeed, Paper I emphasizes that the assumption that the field in fact does not vary significantly from the corotation radius. Johns-Krull & Gafford showed that there are several stellar and accretion parameters that enter into the equilibrium relationship, and the stellar magnetic field remains the quantity measured for the fewest number of CTTSs. Due primarily to this lack of data, Johns-Krull & Gafford (2002) made the assumption that the field in fact does not vary significantly from star to star, and they looked for correlations among the remaining stellar and accretion parameters. The predictions based on aligned dipole field geometries are not present in the data; however, if the dipole assumption is dropped, Johns-Krull & Gafford showed that the predicted correlations are present in the samples they examined from CTTSs in Taurus.

The success of the Johns-Krull & Gafford (2002) study depends on the constancy of the magnetic field from one TTS to the next. From a dynamo perspective, this may be a good assumption. For cool main-sequence stars there is a well-defined positive correlation between magnetic activity indices (e.g., Ca II H and K emission, X-ray emission) and inverse Rossby number (the convective turnover time divided by the rotation period) with saturation setting at large inverse Rossby number (e.g., Vilhu 1984; Noyes et al. 1984). Johns-Krull et al. (2000) showed that, due to their long convective turnover times and relatively short rotation periods, TTSs generally all lie in the saturated portion of this relationship. On the other hand, most TTSs are fully convective or nearly so, so a solar-like interface dynamo (Durney

### TABLE I

| Star        | Spectral Type | $M_*$ $(M_\odot)$ | $R_*$ $(R_\odot)$ | $\dot{M} \times 10^8$ $(M_\odot$ yr$^{-1}$) | $P_{\text{rot}}$ (days) | $B_{\text{eq}}$ (G) | $B_{\text{eq}}$ (G) | $B_{\text{eq}}$ (G) | $B_{\text{eq}}$ (G) | $L_X$ $(10^{30}$ ergs s$^{-1}$) |
|-------------|---------------|-------------------|-------------------|----------------------------------------------|--------------------------|---------------------|---------------------|---------------------|---------------------|-------------------------|
| AA Tau      | K7            | 0.70              | 1.74              | 0.33                                         | 8.20                     | 1020                | 290                 | 1210                | 380                 | 0.439                   |
| BP Tau      | K7            | 0.70              | 1.99              | 2.88                                         | 7.60                     | 1850                | 620                 | 2180                | 880                 | 0.707                   |
| CY Tau      | M1            | 0.40              | 1.63              | 0.75                                         | 7.90                     | 1130                | 380                 | 1330                | 530                 | <0.627                  |
| DE Tau      | M2            | 0.32              | 2.45              | 2.64                                         | 7.60                     | 490                 | 190                 | 580                 | 230                 | <0.287                  |
| DF Tau      | M1            | 0.40              | 3.37              | 17.7                                         | 8.50                     | 680                 | 290                 | 790                 | 320                 | 0.646                   |
| DG Tau      | K7.5          | 0.65              | 2.05              | 4.57                                         | 6.30                     | 1610                | 560                 | 1900                | 760                 | <0.223                  |
| DH Tau      | M1.5          | 0.36              | 1.39              | 0.10                                         | 7.20                     | 350                 | 160                 | 640                 | 260                 | 1.318                   |
| DK Tau      | K7            | 0.68              | 2.49              | 3.79                                         | 8.40                     | 1190                | 410                 | 1400                | 560                 | <0.223                  |
| DN Tau      | M0            | 0.51              | 2.09              | 0.35                                         | 6.00                     | 320                 | 100                 | 380                 | 150                 | 0.564                   |
| GG Tau A    | K7            | 0.68              | 2.31              | 1.75                                         | 10.3                     | 1280                | 420                 | 1510                | 610                 | <0.107                  |
| GI Tau      | K6            | 0.93              | 1.74              | 0.96                                         | 7.20                     | 1900                | 560                 | 2240                | 900                 | 0.241                   |
| GK Tau      | K7            | 0.69              | 2.15              | 0.64                                         | 4.65                     | 390                 | 110                 | 450                 | 180                 | 0.241                   |
| GM Aur      | K7            | 0.70              | 1.78              | 0.96                                         | 12.0                     | 2540                | 800                 | 2990                | 1200                | 0.562                   |
| T Tau       | K0            | 2.30              | 3.31              | 4.40                                         | 2.80                     | 420                 | 110                 | 490                 | 200                 | 0.568                   |
| TW Hya      | K7            | 0.74              | 1.00              | 0.20                                         | 2.20                     | 950                 | 250                 | 1120                | 450                 | 1.380                   |

Notes.—All predicted fields are the equatorial magnetic field strength for an assumed dipolar magnetic field. In order, the predicted fields come from Königl (1991), Collier Cameron & Campbell (1993), Shu et al. (1994), and Long et al. (2005).
& Latour 1978) is likely very inefficient or nonexistent in these stars. Another possibility is a convective/turbulent dynamo, such as originally proposed by Durney et al. (1993). Recent studies by Chabrier & Küker (2006) and Dobler et al. (2006) do predict that dynamo action in fully convective stars does correlate with rotation rate. A final potential contributor to the fields of TTSs is primordial fields entrained in the star during the star formation process (e.g., Tayler 1987; Moss 2003). However, little is known about how these fields might vary from star to star in a given star formation region. As a result, additional measurements of the magnetic field strength on a sizeable sample of CTTs are required to test current magnetospheric accretion models.

To that end, we have been conducting observations of TTSs at the NASA Infrared Telescope Facility (IRTF) to measure the Zeeman broadening of several K-band Ti I lines, which are prominent in the spectra of cool stars. The first use of this line to measure a field on a TTS is in Paper I, where we lay out most of the basics of our observation and analysis technique. Details have been expanded on somewhat in Papers II and III. In particular, in Paper III, it was shown that errors in effective temperature of \( T_{\text{eff}} \) as well as errors of 0.5 dex in \( \log g \) result in errors of less than 10% in the derived mean magnetic field on TTSs. This is because we are measuring actual Zeeman broadening of the photospheric absorption lines instead of some secondary effect such as a change in line equivalent width. As a result, it is no longer necessary to perform the detailed analysis of optical high-resolution spectra to obtain the best estimates of \( T_{\text{eff}} \) and \( \log g \) in order to obtain a good magnetic field measurement. What is needed is a good estimate of \( v \sin i \), and all the stars in our sample have reliable measurements from the literature. Here we focus on CTTs for which we have the ancillary data required to predict the stellar magnetic field strength from magnetospheric accretion models. To do that, we use the equations (1)–(3) given in Paper I for the studies of Königl (1991), Collier Cameron & Campbell (1993), and Shu et al. (1994), and we use equation (12) of Long et al. (2005). In order to make the field predictions, we need stellar and accretion parameters. Rotation periods come from Bouvier et al. (1993, 1995), with the exception of TW Hya, which comes from Mekkaden (1998). Spectral type, stellar radius, and the mass accretion rate for most stars come from Gullbring et al. (1993) on the 3.0 m telescope at the NASA IRTF on Mauna Kea in Hawaii. Observations occurred during four observing runs: (I) 1996 December 10–12, (II) 1997 December 14–20, (III) 2000 January 7–12, and (IV) 2004 November 23–28 (see Table 2). On the first run a 1.0″ slit gave a FWHM of \( \approx 4.7 \) pixels on the 256 \( \times \) 256 InSb array detector, corresponding to a spectral resolving power of \( R \equiv \lambda / \Delta \lambda \approx 21,500 \). For the second and fourth runs, a 0.5″ slit yielded a FWHM of \( \approx 2.8 \) pixels on the detector giving \( R \approx 36,000 \). For the third observing run, the same 0.5″ slit yielded a spectral resolving power of only \( R \approx 27,000 \). (Soon after run III, CSHELL was serviced to restore the spectral resolution.) CSHELL uses a continuously variable filter (CVF) to isolate individual orders of the echelle grating. Each star was observed in three settings, each covering \( \approx 0.0057 \mu \text{m} \). The first setting (1) contains two strong Ti I lines at 2.2211 and 2.2233 \mu \text{m}. The second (2) contains two more strong Ti I lines at 2.2274 and 2.2311 \mu \text{m}. The third setting (3) centered at 2.3120 \mu \text{m} contains \( \approx 9 \) CO lines from the \( v = 2 \)–0 first-overton band.

Each star was observed at two positions along the slit separated by 10″. Multiple pairs of exposures were made of each CTT. Total exposure time varied from object to object and from wavelength setting to wavelength setting. The minimum exposure time was 20 minutes, and the maximum was 1.5 hr. A typical total exposure time was 1 hr. Taking the difference of each image pair with the star moved along the slit removed detector bias, dark current, and the average background due to night-sky emission. Difference images were flat-fielded using a normalized spectrum of an internal continuum lamp that fully illuminated the slit. Stellar spectra were extracted following the procedure described in Paper I, which includes the determination of an oversampled slit function and optimal extraction of the spectrum. Wavelengths were determined by fitting \( n \lambda \) as a function of line position for 7–10 lamp emission lines and then dividing by the order number, \( n \), of the desired spectral region. Calibration lines from several orders were obtained by changing the order-sorting CVF while keeping the grating fixed. In addition to CTTs, each night we observed hot, rapidly rotating stars spanning a range of air masses. Using these data, all spectra shown in this paper have been corrected for telluric absorption. For each CTT in our sample, Table 2 gives a log of when the star was observed and which wavelength settings were covered.

### Table 2

| Star    | Observing Run | Wavelength Setting |
|---------|---------------|--------------------|
| AA Tau  | III           | 1, 2, 3            |
| BP Tau  | II            | 1, 2, 3            |
| CY Tau  | IV            | 1, 2, 3            |
| DE Tau  | III           | 1, 2, 3            |
| DF Tau  | II            | 1, 2, 3            |
| DG Tau  | III           | 1, 2, 3            |
| DH Tau  | III           | 1, 2, 3            |
| DK Tau  | II            | 1, 2, 3            |
| DN Tau  | III           | 1, 2, 3            |
| GG Tau A| III           | 1, 2, 3            |
| GI Tau  | III           | 1, 2, 3            |
| GK Tau  | III           | 1, 2, 3            |
| GM Aur  | I             | 2                  |
| T Tau   | II            | 1, 2, 3            |
3. ANALYSIS

The most successful approach for measuring fields on late-type stars in general has been to measure Zeeman broadening of spectral lines in unpolarized light (e.g., Robinson 1980; Saar 1988; Valenti et al. 1995; Johns-Krull & Valenti 1996; Papers I, II, and III). In the presence of a magnetic field, a given spectral line will split up into a number of components depending on the atomic structure of the levels contributing to the line. Taking into account rotational and turbulent broadening, a strong magnetic field typically produces a change in the shape of magnetically sensitive line profiles. There are several Ti i lines in the K band that are excellent probes of magnetic fields in late-type stars (e.g., Saar & Linsky 1985), and here we observe four of them (see § 2). In addition to the four strongly Zeeman-sensitive Ti i lines, our wavelength settings also cover a relatively weak, but detectable, Sc i line at 2.2265 μm, which has reduced Zeeman sensitivity due to lower Landé g-values. We also observe several magnetically insensitive CO lines near 2.313 μm that serve as a check on our values of $v \sin i$ and turbulent broadening terms. Since we are observing CTTSs, there is some concern that these lines could form in the disk and trace disk kinematics instead of stellar properties. This issue was studied for CO by Casali & Eiroa (1996) and Johns-Krull & Valenti (2001). Both studies find that the K-band CO lines of the vast majority of CTTSs arise in the stellar photosphere, and the CO lines observed below are fully consistent with formation on the star. Based on their behavior as a function of effective temperature, the Ti i lines in the K band appear to trace similar temperature material as that traced by the CO (Wallace & Hinkle 1997). In addition, the limited studies of TTSs that show no K-band excess (Johns-Krull et al. 2004; Paper III) reveal Ti i and CO line profiles with the same qualitative behavior as that found below: CO lines well matched by rotationally broadened stellar photosphere models and excess broadening in the magnetically sensitive Ti i lines. We therefore assume that the line profiles are dominated by the stellar photosphere.

The goal in this paper is to measure the magnetic field on a sample of CTTSs by modeling the profiles of their K-band photospheric absorption lines. Our spectrum synthesis code and detailed analysis technique for measuring magnetic fields on TTSs is described in Papers I–III. Here, we simply review some of the specific details relevant to the results shown here. In order to synthesize the stellar spectrum, we must first specify the atmospheric parameters: effective temperature ($T_{\text{eff}}$), gravity (log g), metallicity ([M/H]), microturbulence ($v_{\text{mic}}$), macroturbulence ($v_{\text{mac}}$), and rotational velocity ($v \sin i$). Following Papers I–III, a fixed value of 2 km s$^{-1}$ is adopted for $v_{\text{mic}}$. Valenti et al. (1998) found that microturbulence and macroturbulence were degenerate in M dwarfs, even with very high quality spectra. Therefore, microturbulence is neglected here, allowing $v_{\text{mac}}$ to be a proxy for all turbulent broadening. Solar metallicity is assumed for all stars. We use $v \sin i$ values measured using the CO spectra presented here by Johns-Krull & Valenti (2001) for all the target stars analyzed in this paper. We adopt $v \sin i$ values from Hartmann et al. (1986) for CY Tau and GM Aur, and we adopt the $v \sin i$ value of Basri & Batalha (1990) for DG Tau. The $T_{\text{eff}}$ is based on spectral type using the calibration of Johnson (1966), and log g is estimated by placing objects in the H-R diagram. This typically produces uncertainties of <0.2 K in $T_{\text{eff}}$ and <0.5 dex in log g, which translate into uncertainties of 10% or less in the derived magnetic field values (Paper III). Once we have estimates of $T_{\text{eff}}$ and log g, we use the “next-generation” (NextGen) model atmosphere (Allard & Hauschildt 1995) from the published grid, which is closest to these values. In the range of interest here, the NextGen models are on a grid every 100 K (e.g., 3900, 4000, and 4100) in $T_{\text{eff}}$ and every 0.5 dex (e.g., 3.5, 4.0, and 4.5) in log g. For BP Tau, we use the NextGen model with $T_{\text{eff}} = 4100$ K, which is closest in temperature to the value we derived in Paper I (its spectral type of K7 suggests $T_{\text{eff}} = 4000$ K).

Finally, we solve for the K-band veiling in each star along with the stellar magnetic field properties. We initially decided to fit for a single veiling parameter that would apply to all three spectral regions we observe in each star. This turned out to not be practical, as a few stars could not be well fit by a single veiling value. The different wavelength regions for our stars were observed with a time interval between settings of several hours up to a couple of days. Classical TTSs regularly show significant variations in their K-band flux on timescales as short as a day (and occasionally shorter), likely as a result of accretion variability (Skrutskie et al. 1996; Eiroa et al. 2002). We therefore decided to let the veiling be a free parameter for each star in each of the three wavelength settings analyzed here.

The free parameters of our fit to the observed spectra are then the value of the K-band veiling in each wavelength region (this is the only free parameter in the CO wavelength region) and the magnetic field properties of the star. It was found in Papers I–III that the spectra of the TTSs studied there could not be fit with a single value of the magnetic field strength. Instead, a distribution of magnetic field strengths is required. It was also found that fits to the spectra are degenerate in the derived field values unless we limit the fit to specific values of the magnetic field strength, separated by about 2 K, which is the approximate “magnetic resolution” of our data. Therefore, we use the same limitations when fitting the data presented here. We assume the star is composed of regions of 0, 2, 4, and 6 K magnetic field, and we solve for the filling factor of each of these components. The different regions are assumed to be well mixed over the surface of the star—different components are not divided up into well-defined spots or other surface features. Another key assumption (which will be discussed further in § 5) is that the temperature structure in all the field regions is assumed to be identical for the purpose of spectrum synthesis: again, the fields are not confined to cool spots or hot plage–like regions. In total then, we fit for six free parameters: the three veiling values and the filling factor of the three nonzero field regions (the sum of the filling factors must be 1.0). In Figures 1 and 2 we show our spectral fits to two of our CTTSs: the first (DK Tau) with a high average surface field, and the second (DE Tau) with a low average surface field. We characterize the field on all our CTTSs by computing the mean magnetic field from our fits: $B = \Sigma B_i f_i$, where $B_i$ is the value of the field (0, 2, 4, and 6 K) in each fitted region and $f_i$ is the filling factor of these field components. The formal uncertainty in the fit to all our stars is quite small. The true uncertainty is dominated by uncertainties in the field resulting from errors in our adopted temperature and gravity, which as discussed above are ~10%. We therefore adopt this value for the uncertainty in our mean magnetic field for each star.

While DK Tau’s Ti i lines show obvious broadening relative to the nonmagnetic model in Figure 1, the situation is a little less clear for DE Tau in Figure 2. Blowing up the plot, it is apparent that all the Ti i lines are broader than the null field model, which is a good match to the width of the CO lines. This extra broadening in the Ti i lines can be quantified by a cross-correlation analysis as well. We construct a kernel that is the zero field model but with a $v \sin i = 1.0$ km s$^{-1}$ instead of 7 km s$^{-1}$, which is the measured value for DE Tau. We then cross-correlate this kernel with the observed DE Tau spectrum and fit the result with a Gaussian
Doing this on the CO portion of the spectrum (bottom panel of Fig. 2), we find a FWHM = 6.35 pixels. Cross-correlating the 1.0 km s\(^{-1}\) kernel with the actual fit to the CO lines (dashed line of Fig. 2, where \(v \sin i = 7.0\) km s\(^{-1}\)), we find the FWHM = 6.54 pixels (which is slightly greater—by 0.19 pixels—than for the observed spectrum). We can estimate the range of FWHM we should measure by taking the fit to the spectrum shown in the dashed line and adding random noise to it to simulate the signal-to-noise ratio (S/N) of our observed spectrum (115 for DE Tau). We then cross-correlate this synthetic data with the same kernel above and repeat this experiment 100 times. Doing so, we recover a mean FWHM of 6.54 pixels and find a standard deviation in our recovered FWHM values of 0.09 pixels. Thus, the FWHM we recover from the observations of the magnetically insensitive CO lines is only 2.1\% less than that recovered from the observed spectrum. We are therefore confident in the excess width of the Ti \(\text{i}\) lines in DE Tau (\(\bar{B} = 1.12\) kG) and in the other “low” field measurement stars (see below). The analysis of Paper III shows that even for these low mean field values, the uncertainty due to temperature and gravity errors again leads to a mean field uncertainty of \(\sim 10\%\), which is the field uncertainty adopted here.

Fig. 1.—K-band spectra of DK Tau, shown in the black histogram. The top two panels show Zeeman-sensitive Ti \(\text{i}\) lines and a Sc \(\text{i}\) line. The bottom panel shows Zeeman-insensitive CO lines. The dashed curves show a model with no magnetic field. The smooth solid curves show the model fit for a star covered by a mixture of regions that include 0, 2, 4, and 6 kG fields. Here, the mean field strength averaged over the stellar surface is 2.64 kG.

Fig. 2.—Same as in Fig. 1, but for K-band spectra of DE Tau. Here, the mean field strength averaged over the stellar surface is 1.12 kG.

4. RESULTS

The results of our spectral fitting are given in Table 3. Reported here are the derived K-band veiling, \(r_K\), the surface averaged magnetic field, \(\bar{B}\), for each star, and a prediction for the X-ray luminosity based on the measured field values (discussed below). One star in our sample, GM Aur, was observed in only one wavelength setting: the Ti \(\text{i}\) setting (2) described above. Results for this star are somewhat less firm that for the others.

4.1. K-Band Veiling

We determine three estimates of the K-band veiling (\(r_K\)) for each star (one from each wavelength region) that we can compare against each other and against previous veiling estimates. In Table 3 we tabulate the mean value of \(r_K\) determined from the three settings and give as an uncertainty estimate the standard deviation.
deviation of the three \( r_K \) values. These veiling estimates generally agree with previous studies (Folha & Emerson 1999; Johns-Krull & Valenti 2001). We note, however, that by solving for the veiling in each wavelength region separately, our magnetic field results are free of systematic effects caused by differences in line strength between the actual star and our spectrum synthesis. Such differences are adjusted for by changes in the derived veiling values found here and the mean fields measured. We also looked for a correlation between the veiling found here compared to in Johns-Krull & Valenti (2001) and the mean field values. No correlation is found in either case.

For one star, T Tau, our derived \( r_K \) is substantially different than found in previous studies. At K0, T Tau is the earliest spectral type star in our study, and one of the earliest spectral type CTTSs known. The veiling of Johns-Krull & Valenti (2001) is derived based on a later spectral type template star. Similarly, Folha & Emerson (1999) report a veiling of \( r_K = 2.5 \) based on comparison with a later type template. The Ti \( i \) and CO lines used here get much weaker in the observed spectra of dwarfs and giants as you go from K7 to K0 (e.g., Wallace & Hinkle 1997). This difference in intrinsic line strength will artificially enhance the derived veiling for a K0 star when using a later template. The veiling we derive here is quite low, which might be the result of the line strength in our synthetic spectra being too low as a result of some error in the line data or the model atmosphere. To test this, we compared our model spectra for T Tau to observed spectra of the K0 dwarf, HR 166. This star was observed in setting (2) during the fourth observing run (see § 2). Valenti & Fischer (2005) report \( T_{\text{eff}} = 5221 \text{ K} \) and [M/H] = 0.16 for this K0 V star. We observe the lines in HR 166 to be quite weak, and the 2.2311 \( \mu \text{m} \) Ti \( i \) line is strongly affected by telluric absorption, so we ignore it here. We measure an equivalent width of \( W_{\text{eq}} = 49.4 \pm 4.8 \text{ m}\AA \) for the 2.2274 \( \mu \text{m} \) line based on the four spectra observed of HR 166. Our 0 kG synthetic spectrum for T Tau gives an equivalent width of \( W_{\text{eq}} = 58.0 \text{ m}\AA \), in good agreement with our observed value. The fact that the synthetic spectrum has a larger equivalent width means that we may actually be overestimating the veiling, not underestimating it; however, the correction is small (~0.2). Therefore, we suggest our veiling measurement for T Tau is reliable, and that previous estimates are too large as a result of the later type template stars used for comparison.

4.2. Magnetic Field Properties

4.2.1. Comparison with Magnetospheric Accretion Theory

Table 3 gives the mean magnetic field values, \( \vec{B} \), for each star analyzed here. These can be compared directly with the predicted field strengths given in Table 1. Figure 3 compares the values of \( \vec{B} \) we measure here with the predictions of magnetospheric accretion theory. As mentioned above, all four field predictions given in Table 1 are very well correlated with each other. From the standpoint of looking for a correlation between the observed and predicted fields, it does not matter which set of theoretical predictions we use. Figure 3 plots the predictions based on the work of Shu et al. (1994). As is quite evident from a visual inspection of the figure, there does not appear to be a correlation between the observed and predicted field values. We can quantify this by computing the linear correlation coefficient (also called Pearson’s \( r \) value) and its significance (e.g., Press et al. 1986). Computing this for the data in Figure 3, we find a correlation coefficient of \( r = 0.08 \), which has an associated false-alarm probability of 79%, indicating no correlation in the data at all. While there is no apparent correlation in Figure 3, the good news is that the observed fields generally lie on or above the line indicating equality. Thus, the measured fields on these CTTSs are approximately the right magnitude for magnetospheric accretion to work. We return to this point further in § 5 below.

When examining Tables 1 and 3 and Figure 3, worry may be aroused by the specific choice of mass accretion rates used. It is well known that mass accretion rates for CTTSs are difficult to measure, and estimates for specific stars can vary by an order of magnitude or more (see discussion in Gullbring et al. 1998). Fortunately, the predicted field strengths vary only as the square root of the mass accretion rate (Johns-Krull et al. 1999b), making them somewhat less sensitive to the problems associated with measuring the accretion rate. In addition, different studies generally do find good correlation of their measured accretion rates from star to star, even if they differ on the overall magnitude (again, see Gullbring et al. 1998). Therefore, we have some confidence that the variation of the predicted fields from star to star can be reasonably well estimated. In an effort to see how the

| Star      | \( r_K \) (0.77) | \( \vec{B} \) (kG) | \( B_{eq} \) (kG) | \( L_{X} \) (10\(^{30} \text{ ergs s}^{-1}) \) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| AA Tau    | 0.52 ± 0.09     | 2.78            | 1.02            | 4.32            |
| BP Tau    | 1.08 ± 0.25     | 2.17            | 1.03            | 4.42            |
| CY Tau    | 0.65 ± 0.21     | 1.16            | 1.04            | 1.36            |
| DE Tau    | 1.16 ± 0.17     | 1.12            | 1.04            | 3.34            |
| DF Tau    | 1.37 ± 0.15     | 2.90            | 1.04            | 20.7            |
| DG Tau    | 2.67 ± 0.41     | 2.55            | 1.00            | 8.19            |
| DH Tau    | 1.77 ± 0.49     | 2.68            | 1.42            | 2.20            |
| DK Tau    | 1.46 ± 0.23     | 2.64            | 1.02            | 9.27            |
| DN Tau    | 0.54 ± 0.09     | 2.00            | 1.01            | 4.51            |
| GG Tau A  | 0.35 ± 0.19     | 1.24            | 1.02            | 3.28            |
| GI Tau    | 1.00 ± 0.11     | 2.73            | 1.44            | 4.23            |
| GK Tau    | 1.47 ± 0.31     | 2.28            | 1.02            | 5.59            |
| GM Aur    | 1.25            | 2.22            | 1.02            | 3.51            |
| T Tau     | 0.45 ± 0.77     | 2.37            | 0.84            | 15.8            |
| TW Hya*   | 0.07 ± 0.04     | 2.61            | 1.76            | 1.13            |

* Veiling and field measurements taken from Paper III.

FIG. 3.—Observed mean magnetic field strength, \( \vec{B} \), plotted vs. the predicted equatorial magnetic field strength from the Shu et al. (1994) treatment of the magnetospheric accretion model.
results presented here depend on the stellar and accretion parameters used for the stars studied. Table 4 gives the mass accretion rates and predicted fields for five relatively large studies that contain many of the stars observed here. Since the derived mass accretion rates depend to some extent on the mass and radius assigned to the star, in Table 4 the predicted fields are calculated using the mass and radius adopted for each star in the relevant study. The studies presented in the table are: Valenti et al. (1993, labeled VBJ), Hartigan et al. (1995, labeled HEG), Gullbring et al. (1998, labeled GHBC), Johns-Krull et al. (2001). We use the X-ray luminosity and X-ray luminosity on the Sun and cool stars, generally finding excellent correlation between these two quantities ranging over almost 11 orders of magnitude in each quantity. Pevtsov et al. (2003) study the relationship between magnetic flux and X-ray luminosity in the surrounding nonmagnetic photosphere. Similar results were shown here taken from Johns-Krull & Valenti (2000) and Johns-Krull et al. (2001). We use the X-ray luminosity—magnetic flux relationship of Pevtsov et al. (2003) with our magnetic field measurements and the stellar radii given in Table 1 to calculate the expected X-ray luminosity for each of our stars. These predicted X-ray values are given in the last column of Table 3. Figure 4 plots the measured X-ray luminosities from Table 1 versus these predicted X-ray values. All but one of the CTTSs in our sample show lower X-ray emission than would be predicted by their magnetic field properties, and many of them are low by more than an order of magnitude. Only TW Hya shows a higher level of measured X-ray emission relative to the prediction, and perhaps significantly, this CTTS is the star closest to the main sequence in our sample due to its age of ~10 Myr. We discuss this issue further in § 5.

4.2.2. Relationship to X-Ray Emission

Stellar magnetic fields are also believed to give rise to “activity” in late-type stars. Activity is typically traced by line emission or broadband emission at high-energy wavelengths such as X-rays. Pevtsov et al. (2003) study the relationship between magnetic flux and X-ray luminosity in the Sun and cool stars, generally finding excellent correlation between these two quantities ranging over almost 11 orders of magnitude in each quantity. Pevtsov et al. (2003) include preliminary measurements for six of the CTTSs shown here taken from Johns-Krull & Valenti (2000) and Johns-Krull et al. (2001). We use the X-ray luminosity—magnetic flux relationship of Pevtsov et al. (2003) with our magnetic field measurements and the stellar radii given in Table 1 to calculate the expected X-ray luminosity for each of our stars. These predicted X-ray values are given in the last column of Table 3. Figure 4 plots the measured X-ray luminosities from Table 1 versus these predicted X-ray values. All but one of the CTTSs in our sample show lower X-ray emission than would be predicted by their magnetic field properties, and many of them are low by more than an order of magnitude. Only TW Hya shows a higher level of measured X-ray emission relative to the prediction, and perhaps significantly, this CTTS is the star closest to the main sequence in our sample due to its age of ~10 Myr. We discuss this issue further in § 5.

4.2.3. Field Measurements and Pressure Equipartition

From the perspective of cool star research, the high apparent field strengths on these CTTSs is a little surprising. Spruit & Zweibel (1979) computed flux tube equilibrium models, showing that magnetic field strength is expected to scale with gas pressure in the surrounding nonmagnetic photosphere. Similar results were found by Rajaguru et al. (2002), who found that convective collapse of thin magnetic flux tubes will set a field strength limit of ~750 G in the photosphere of a star with $T_{\text{eff}} = 4000$ K and $\log g = 3.5$. Convective collapse is a mechanism for forming partially evacuated...
mechanism may not operate effectively at low flux tubes, and Rajaguru et al. (2002) find evidence that this mechanism may not operate effectively at low $T_{\text{eff}}$; however, they find a maximum field strength of $\sim 1300$ G if the field is to remain in pressure equilibrium with the surrounding unmagnetized photosphere. Field strengths set by such pressure equipartition considerations appear to be observed in G and K dwarfs (e.g., Saar 1990, 1994, 1996), and possibly in M dwarfs (e.g., Johns-Krull & Valenti 1996).

TTs have relatively low surface gravities and hence low photospheric gas pressures, so that equipartition flux tubes would have relatively low magnetic field strengths compared to cool dwarfs. Indeed, Safier (1999) examined in some detail the ability of TTs photospheres to confine magnetic flux tubes via pressure balance with the surrounding quiet photosphere, concluding that the maximum field strength allowable on TTs is substantially below the few detections reported at that time. The maximum field strength allowed for a confined magnetic flux tube is $B_{\text{eq}} = (8\pi P_g)^{1/2}$, where $P_g$ is the gas pressure at the observed level in the stellar atmosphere. Here, we take as a lower limit (upper limit in pressure) the level in the atmosphere where the local temperature is equal to the effective temperature. This is the approximate level at which the continuum forms, with the Ti i lines forming over a range of atmospheric layers above this level. Our computed values of $B_{\text{eq}}$ are given in Table 3. In Figure 5 we plot our observed mean magnetic field strengths versus these $B_{\text{eq}}$ values for our entire sample. In all cases, the observed mean magnetic field is greater than the field predicted by pressure equipartition arguments. In many cases the observed mean field exceeds $B_{\text{eq}}$ by a factor of more than 2.

4.2.4. Origins of the Strong Fields

Finally, we compare our mean field measurements with various stellar parameters in an effort to uncover the origin of the strong magnetic fields observed on these stars. We compare both the mean magnetic field strength, $\langle B \rangle$, and the total magnetic flux, $\Phi$, to a number of stellar parameters, including those thought to be important in the dynamo generation of magnetic fields. The results of these comparisons are summarized in Table 5. Given in this table is the Pearson linear correlation coefficient, $r$, and its false-alarm probability, $f_p$, which measures the degree to which the quantities being compared are correlated with one another. As

Table 5 shows, there is no significant correlation of $\langle B \rangle$ or $\Phi$ with any stellar parameter or common dynamo variable, including the convective turnover time, $\tau_c$ (values of $\tau_c$ were kindly provided by Y.-C. Kim and were computed using models described in Kim & Demarque [1996] with input physics described in Preibisch et al. [2005]). The most significant correlation found is $\Phi$ versus $L_{\ast}$; however, we must be careful with such a correlation due to the common role the stellar radius plays in both variables. The magnetic flux is $\Phi = B R_{\ast}^2$, and the stellar radius is calculated from the measured $L_{\ast}$ and $T_{\text{eff}}$. Thus, we expect to find a correlation, and when comparing $R_{\ast}$ versus $L_{\ast}$ we find $r = 0.73$ and $f_p = 0.002$. This correlation is stronger than that found using $\Phi$, suggesting the correlation of $\Phi$ with $L_{\ast}$ is driven entirely by the stellar radius, with the magnetic field playing no role. Interestingly, the next most significant correlation is $\Phi$ versus $T_{\text{eff}}$; however, this correlation is again likely driven by the correlation of $R_{\ast}$ with $T_{\text{eff}}$ ($r = -0.63, f_p = 0.01$), with the magnetic field playing...
no role. Within this sample of 15 CTTSs, we then find no correlation of the measured magnetic field values with any stellar or dynamo parameters.

5. DISCUSSION

We provide new measurements of the mean magnetic field strength on 14 CTTSs. The detected fields range from 1.12 to 2.90 kG. These measurements combined with previous reports of magnetic fields on TTSs (Basri et al. 1992; Guenther et al. 1999; Johns-Krull et al. 1999b, 2004; Paper III) suggest that the strong majority of TTSs are covered by kilogauss magnetic fields. As found in Papers I–III, we use a distribution of magnetic field strengths to fit the observed K-band Ti i profiles. We model this distribution as if it were a spatial distribution on the stellar surface: the model assumes distinct regions with different field strengths. A concern is that the distribution is in fact a distribution with depth in the magnetic regions. If this were the case, we would be overestimating the total filling factor of magnetic regions as well as the mean field strength. Observations of sunspots in the K band show that the Ti i lines in this spectral region display profiles characteristic of a single magnetic field value (e.g., Wallace & Livingston 1992), despite the likely variation of the field with depth in a sunspot (e.g., Mathew et al. 2003).

Therefore, we believe the field distributions found in Papers I–III and used here represent actual spatial distributions of field strengths on the stellar surface.

The observed mean field values for the CTTSs are all larger than the field strength for these stars predicted by pressure equilibrium arguments (Fig. 5). This suggests that the magnetic pressure dominates the gas pressure, in some cases by a significant amount, in the photospheres of these stars. If this is the case, there should be no field-free regions on these stars, although we do use a 0 kG field component when fitting their spectra. This issue is discussed in Papers I and II. In these papers, it was found that using fits with 0, 2, 4, and 6 kG components gave essentially identical mean field measurements as those from fits using 1, 3, 5, and 7 kG components. Thus, the data do not demand a field-free region, and such a region may not exist on these stars. With a strong magnetic field essentially covering the entire surface of TTSs, we expect to see some effect of the fields on the atmosphere, perhaps analogous to the fields of sunspots inhibiting convection (e.g., Foukal 1990). Such an effect might be diagnosed through the study of line bisectors (e.g., Gray 1982); however, little work in this area has been done for late K spectral types, so the intrinsic bisector shape for stars of this spectral type is unknown.

On the other hand, we may have evidence for the feedback of these strong fields on the star through the X-ray activity displayed by TTSs. Feigelson et al. (2003) find that X-ray emission in TTSs saturates on average at a level approximately an order of magnitude below that displayed by main-sequence stars. In addition to this apparent global reduction in X-ray emission of TTSs, observations also reveal that accreting young stars as a group show X-ray emission levels that are reduced by a factor of 2–3 relative to nonaccreting young stars, even after dependencies on mass and age are taken into account (Flaccomio et al. 2003; Stassun et al. 2004; Preibisch et al. 2005; Feigelson et al. 2007). At least two explanations have been advanced that can explain this difference between stars with and without accretion signatures. Preibisch et al. (2005) suggest that the higher density of mass-loaded accreting field lines prevents these portions of CTTS magnetospheres from heating up to temperatures required for X-ray emission. Jardine et al. (2006) present a model of TTS coronae with realistic levels of complexity and show that this can produce a similar range of X-ray emission levels as that which is observed in, for example, the Chandra Orion Ultradeep Project (COUP). Jardine et al. (2006) suggest that the presence of a disk, particularly in lower mass CTTSs, acts to strip the outer parts of the stellar corona, thereby reducing the total X-ray emission. This naturally predicts an anticorrelation between X-ray emission and the presence of a disk, at least in the lower mass young stars such as those studied here. While there is no observed correlation of X-ray emission with the presence or absence of an inner disk as diagnosed by K-band emission for the COUP data set (e.g., Feigelson et al. 2007), this coronal stripping may be related to the action of accretion. While these ideas may explain the factor of 2–3 difference in accreting versus nonaccreting young stars, they do not explain the order-of-magnitude reduction in X-ray emission for TTSs as a whole noted by Feigelson et al. (2003). Here, we find that the observed X-ray emission from our sample of CTTSs is substantially below what is expected given their strong magnetic field values (Fig. 4), often by more than an order of magnitude. While the origin of coronal heating in the Sun and solar-like stars is still debated, most theories assume it is due in part to convective motions moving and buffeting photospheric magnetic flux tubes (e.g., Fisher et al. 1998; Foukal 1990). We suggest that the strong magnetic fields that appear to cover the surface of TTSs reduce the efficiency with which convective motions can stress these stellar magnetic fields, which in turn results in reduced coronal heating relative to what would otherwise be expected.

The original motivation for this study was to test magnetospheric accretion models for CTTSs. Figure 3 shows the relationship between magnetic field strengths predicted from these models compared with the measured field strengths. Clearly, there is no correlation. Magnetospheric accretion models typically assume an aligned dipolar magnetic field at the surface of a CTTS. It is now fairly clear that the fields of TTSs are not dipolar (Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004; Daou et al. 2006; Yang et al. 2007). The magnetic geometry must be complicated at the surface of TTSs, as on the Sun and all other cool stars. However, the dipolar component may dominate at the inner edge of the accretion disk, several stellar radii from the surface. This notion is supported by observations of circular polarization in the narrow component of the He i emission line, which forms near the base of the accretion flows where the material strikes the stellar surface (Johns-Krull et al. 1999a). Time series polarization in this line shows smooth variations characterized by few if any polarity reversals, and are consistent with the idea that the disk is interacting with a dipole-like field geometry (Valenti & Johns-Krull 2004; Symington et al. 2005; Yang et al. 2007).

Magnetospheric accretion models use an assumed dipolar field geometry to predict which stellar magnetic field lines couple the stellar surface to the disk. Since the actual magnetic geometry is more complicated, the fraction of the stellar surface with field lines coupled to the disk (including those along which accretion will occur) can differ significantly from predicted values (see Gregory et al. [2006] for a discussion of this point). This means the relationships given in Paper I and used to calculate the predicted fields given in Table 1 are actually underconstrained, even though we have now measured $B$ at the surface. However, Johns-Krull & Gafford (2002) point out that a more general relationship for the Shu et al. (1994) model can be determined that does not rely on the assumption of a dipolar field geometry. This formulation characterizes the magnetic coupling in terms of the surface flux that threads the disk outside corotation, rather than the equatorial field strength of an assumed dipole, Valenti & Johns-Krull (2004) use the results of Johns-Krull & Gafford (2002) to derive an equation
for the filling factor of accretion zones, $f_a$, on CTTSs (their eq. [1]). We use our magnetic field results with this equation to predict $f_a$ for each of our stars. These accretion filling factors range from 0.57% to 3.09%, in good agreement with the range of observed $f_a$ values (Valenti et al. 1993; Calvet & Gullbring 1998). The predicted $f_a$ values range over a factor of 5.4, while the observed mean field strengths range over a factor of 2.6. In the original magnetospheric accretion models, $f_a$ is essentially assumed constant and the predicted field strengths range over a factor of 8 (Table 1). We suggest that $f_a$ is more likely than $B$ to vary by a large factor. Our measurements of $B$ support this conclusion. In addition, one could look for a correlation between the fields predicted in Table 1 and the fields anchored in the accretion flows and diagnosed by the He i line. Johns-Krull et al. (2001) do this, finding a good correlation; however, we caution that they only had a sample of four stars.

Given that the magnetic fields on the surface of TTSs may not be dipolar, one question that comes to mind is whether the observed fields on CTTSs are indeed strong enough to enforce disk locking in these young stars. The magnetospheric accretion models require some (although admittedly uncertain) field strength in the disk, several stellar radii above the star, to enforce disk locking. The dipole assumption can then be used to predict what field strength is implied at the stellar surface. If the field geometry is much more complex than this, a larger field strength will be required, since the higher order field components have a stronger dependence on radius than a dipole does. The contribution of the various field components at the inner disk edge is uncertain, but as mentioned above the He i observations suggest the dipole component may dominate. This field component is uncertain observationally, but it can be constrained through spectropolarimetry. Smirnov et al. (2003) report a marginal detection of a net field of 150 G on T Tau that was not confirmed by Smirnov et al. (2004) or Daou et al. (2006). Yang et al. (2007) detect a net field of 149 G on TW Hya on one night of their six night monitoring campaign on this star, finding only upper limits of ~100 G on the other nights. Other studies also only find upper limits (3 σ) of 100–200 G (Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004). The relationship between the net field observed spectropolarimetrically and the dipole component of the star depends on knowing the angle between the line of sight and the dipole axis; however, the general lack of detection suggests the dipole component on TTSs is small. For example, a dipole with a 3 kG polar field strength (as suggested for BP Tau by Symington et al. 2005) observed at an angle of 45° would produce a net field of 690 G, well above current detection limits. Accretion hot spots are expected to have essentially no effect on net field measurements from spectropolarimetry (Smirnov et al. 2005), since the accretion filling factors are typically ~1% (Valenti et al. 1993; Calvet & Gullbring 1998).

Compared with at least some of the predicted values in Table 1, the general lack of strong polarimetric field detections in TTSs might suggest the fields are actually too weak to enforce disk locking in these stars. However, the general agreement in magnitude between the predicted and observed accretion filling factors described above and in Valenti & Johns-Krull (2004) suggests that the trapped flux model of Shu et al. (1994; see also Ostriker & Shu 1995) can still enforce disk locking with the field strengths observed here. Indeed, Johns-Krull & Gafford (2002) find that this trapped flux model predicts correlations among stellar and accretion parameters that are actually observed in the data, whereas correlations based on assuming a dipole field geometry are not observed in the data. As spectropolarimetric field measurements get more precise, and the dipole component gets more constrained, comparisons with all the field predictions in Table 1 will become more critical. In addition, more theoretical work is called for to explore whether realistic magnetic field geometries and strengths can produce disk locking in magnetospheric accretion models. First steps in exploring the role of realistic field geometries in CTTS accretion have been made by Gregory et al. (2006); however, torque balance calculations still need to be made for these types of models.

Finally, we consider the origin of the strong fields observed in TTSs. Chabrier & Küker (2006) assert that primordial, or fossil, magnetic fields in fully convective stars can only survive for a timescale of $\tau_B \sim R_*^2/\eta$, where $R_*$ is the stellar radius and $\eta$ is the turbulent magnetic diffusivity. The value of $\tau_B$ works out to be of order 10–100 yr. Thus, Chabrier & Küker (2006) assert that the fields of fully convective stars, such as most TTSs, must be produced by a turbulent dynamo. On the other hand, Tayler (1987) and Moss (2003) suggest that primordial fields can survive much longer in pre-main-sequence stars. Chabrier & Küker (2006) and Dobler et al. (2006) both find that dynamo action in fully convective stars should correlate with rotation rate. Motivated by this, we looked for correlations between the observed magnetic fields and various stellar parameters including rotation (see § 4.2.4). No correlations were found, and indeed stars like CY Tau and DH Tau show very similar stellar properties ($T_{\text{eff}}$, mass, radius, rotation rate, and convective turnover time) but have mean fields that differ by over a factor of 2.3. In addition, the works of Chabrier & Küker (2006) and Dobler et al. (2006) generally find magnetic field strengths somewhat lower than the equipartition values, while the observed fields are significantly stronger than this. Additional constraints on fully convective dynamo models can also be made by comparing predicted field geometries with those derived from Zeeman Doppler imaging of fully convective stars. Donati et al. (2006) do this for an M dwarf, finding inconsistencies in the observed field geometry relative to the predictions. Therefore, it appears difficult for dynamo theories to produce the fields observed on TTSs. As a result, we suggest that the fields on these young stars may indeed be primordial in origin, as suggested by Tayler (1987) and Moss (2003).

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