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Measurements of magnetic fields on T Tauri stars

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Abstract. Stellar magnetic fields including a strong dipole component are believed to play a critical role in the early evolution of newly formed stars and their circumstellar accretion disks. It is currently believed that the stellar magnetic field truncates the accretion disk several stellar radii above the star. This action forces accreting material to flow along the field lines and accrete onto the star preferentially at high stellar latitudes. It is also thought that the stellar rotation rate becomes locked to the Keplerian velocity near the radius where the disk is truncated. This paper reviews recent efforts to measure the magnetic field properties of low mass pre-main sequence stars, focussing on how the observations compare with the theoretical expectations. A picture is emerging indicating that quite strong fields do indeed cover the majority of the surface on these stars; however, the dipole component of the field appears to be alarmingly small. On the other hand, at least one accretion model which takes into account the non-dipole nature of the magnetic field provides predictions relating various stellar and accretion parameters which are present in the current data.

Keywords. Accretion, accretion disks, 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). The first detailed magnetospheric accretion model for CTTSs was developed by Uchida & Shibata (1984). This model includes both accretion of disk material onto the star as well as the formation of a shock driven bipolar outflow; however, rotation is ignored. Camenzind (1990) first considered the rotational equilibrium of a CTTS with a kilogauss strength dipolar magnetic field accreting matter from a circumstellar disk. Electric currents in the stellar and disk magnetospheres are found to offset the angular momentum accreted with the disk material, producing an equilibrium rotation rate with the disk truncated close to the corotation radius. A wind is then driven off the disk outside the corotation radius. Variations of this magnetospheric accretion model have been studied analytically or semi-analytically, sometimes without an attendant outflow (Königl 1991; Collier Cameron & Campbell 1993) and sometimes with (Shu *et al.* 1994). In all cases, the field truncates the inner disk at or close to corotation and an equilibrium rotation rate (P_{rot}) is established which depends on the (assumed) dipolar field strength, the stellar mass (M_*), radius (R_*), and the mass accretion rate ($\dot{M}$) in the disk. The relationships published in these papers can be used to predict the stellar field strength on CTTSs for which measurements for the other parameters exist. The predicted field variations from star to star correlate extremely well from study to study, even though the magnitude of the predicted fields can vary substantially from one study to another due to different assumptions regarding the efficiency of the field and disk coupling, ionization state in the disk, and so on (Johns–Krull *et al.* 1999b; Johns–Krull 2007).

Observationally, support for magnetospheric accretion in CTTSs is significant and is reviewed elsewhere in this volume. 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. As discussed below, spectropolarimetric measurements are often at odds with this assumption. On the other hand, it is expected that even for complex magnetic geometries, the dipole component of the field should dominate at distance from the star where the interaction with the disk is taking place, so the dipole assumption may not seriously contradict current theory. In the case of the Sun, the dipole component appears to become dominant at $2.5R_\odot$ or closer (e.g. Luhmann *et al.* 1998). For expected disk truncation radii of 3 – 10 R_* in CTTSs, this suggests the dipole component will govern the stellar interaction with the disk. Additionally, 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. Another concern 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, Calvet & Hartmann (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, 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. Here, we review magnetic field measurements on TTSs, paying particular attention to how the magnetic field data agrees or not with the predictions of magnetospheric accretion models for young stars. We refer the reader to the contribution by Alecian in this volume for a review of magnetic field measurements on higher mass Herbig Ae/Be stars.

2. Techniques

Virtually all measurements of stellar magnetic fields make use of the Zeeman effect. Typically, one of two general aspects of the Zeeman effect is utilized: (1) Zeeman broadening of magnetically sensitive lines observed in intensity spectra, or (2) circular polarization of magnetically sensitive lines. When an atom is in a magnetic field, different projections of the total orbital angular momentum are no longer degenerate, shifting the energy levels taking part in the transition. In the simple Zeeman effect, a spectral line splits into 3 components: 2 σ components split to either side of the nominal line center and 1 unshifted π component. The wavelength shift of a given σ component is

$$\Delta\lambda = \frac{e}{4\pi m_e c^2}\lambda^2 g B, \tag{2.1}$$

where g is the Landé g-factor of the specific transition, B is the strength of the magnetic field, and λ is the wavelength of the transition. Evaluating the constants, the wavelength shift is

$$\Delta\lambda = 4.67 \times 10^{-7}\ \lambda^2 g B \text{ mÅ}, \tag{2.2}$$

where λ is in Å and B is in kG. One thing to note from this equation is the λ^2 dependence of the Zeeman effect. Compared with the λ^1 dependence of Doppler line broadening mechanisms such as rotation and turbulence, this means that observations in the IR are generally more sensitive to the presence of magnetic fields than optical observations.

The simplest model of the spectrum from a magnetic star assumes that the observed line profile can be expressed as $F(\lambda) = F_B(\lambda) * f + F_Q(\lambda) * (1 - f)$; where F_B is the spectrum formed in magnetic regions, F_Q is the spectrum formed in non-magnetic (quiet) regions, and f is the flux weighted surface filling factor of magnetic regions. The magnetic spectrum, F_B, differs from the spectrum in the quiet region not only due to Zeeman broadening of the line, but also because magnetic fields affect atmospheric structure, causing changes in both line strength and continuum intensity at the surface. Most studies *assume* that the magnetic atmosphere is in fact the same as the quiet atmosphere because there is no theory to predict the structure of the magnetic atmosphere. If the stellar magnetic field is very strong, the splitting of the σ components is a substantial fraction of the line width, and it is easy to see the σ components sticking out on either side of a magnetically sensitive line. In this case, it is relatively straightforward to measure the magnetic field strength, B. Differences in the atmospheres of the magnetic and quiet regions primarily affect the value of f. If the splitting is a small fraction of the intrinsic line width, then the resulting observed profile is only subtly different from the profile produced by a star with no magnetic field, and more complicated modelling is required to be sure all possible non-magnetic sources (e.g. rotation, pressure broadening, turbulence) have been properly constrained.

In cases where the Zeeman broadening is too subtle to detect directly, it is still possible to diagnose the presence of magnetic fields through their effect on the equivalent width of magnetically sensitive lines. For strong lines, the Zeeman effect moves the σ components out of the partially saturated core into the line wings where they can effectively add opacity to the line and increase the equivalent width. The exact amount of equivalent width increase is a complicated function of the line strength and the true Zeeman splitting pattern (Basri *et al.* 1992). This method is primarily sensitive to the product of B multiplied by the filling factor f. Since this method relies on relatively small changes in the line equivalent width, it is very important to be sure other atmospheric parameters which affect equivalent width (particularly temperature) are accurately measured.

Measuring circular polarization in magnetically sensitive lines is perhaps the most direct means of detecting magnetic fields on stellar surfaces, but it is also subject to several limitations. When viewed along the axis of a magnetic field, the Zeeman σ components are circularly polarized, but with opposite helicity; and the π component(s) is(are) absent. The helicity of the σ components reverses as the polarity of the field reverses. Thus, on a star like the Sun that typically displays equal amounts of $+$ and $-$ polarity fields on its surface, the net polarization is very small. If one magnetic polarity does dominate the visible surface of the star, net circular polarization is present in Zeeman sensitive lines, resulting in a wavelength shift between the line observed through right- and left-circular polarizers. The magnitude of the shift represents the surface averaged line of sight component of the magnetic field (which on the Sun is typically less than 4 G even though individual magnetic elements on the solar surface range from ~ 1.5 kG in plage to ~ 3.0 kG in spots). Several polarimetric studies of cool stars have generally failed to detect circular polarization, placing limits on the net magnetic field strength present of $10 - 100$ G (e.g. Vogt 1980; Brown & Landstreet 1981; Borra, Edwards & Mayor 1984). The interpretation resulting from these studies is that the late-type stars studied (primarily main sequence and RS CVn types) likely have complicated surface magnetic field topologies which display approximately equal amounts of opposite polarity field which results in no detectable net magnetic field. On the other hand, stars with strong dipole components, such as the magnetic Ap stars, show quite strong circular polarization in their photospheric absorption lines (e.g. Mathys 2004 and references therein). If CTTSs do have strong dipole components, circular polarization should be detectable in photospheric absorption lines.

3. Zeeman broadening measurements

3.1. *The equivalent width method*

TTSs typically have $v \sin i$ values of 10 km s^{-1}, which means that observations in the optical typically cannot detect the actual Zeeman broadening of magnetically sensitive lines because the rotational broadening is too strong. Nevertheless, optical observations can be used with the equivalent width technique to detect stellar fields. Basri *et al.* (1992) were the first to detect a magnetic field on the surface of a TTS. They studied two TTSs showing no evidence for accretion, the so-called weak line or naked TTSs (WTTSs or NTTSs). Basri *et al.* find a value of $Bf = 1.0$ kG on the NTTS Tap 35. This detection is illustrated in Figure 1. Here, the abscissa, $S(1000)$ is the *magnetic sensitivity* of each photospheric line. It is the line equivalent calculated from a photospheric model with a magnetic field of 1000 G divided by the line equivalent width calculated for the same atmosphere but with no magnetic field. The ordinate is the ratio of the observed equivalent widths of the lines in Tap 35 divided by the observed equivalent width in the lines of the inactive main sequence star 61 UMa, which has a similar spectral type to Tap 35 (see Basri *et al.* 1992 for additional details). In addition to Tap 35, Basri *et al.* also observed the NTTS Tap 10, finding only an upper limit of $Bf < 0.7$ kG. Guenther *et al.* (1999) apply the same technique to spectra of 5 TTSs, with apparent significant field detections on two stars; however, these authors analyze their data using models different by several hundred K from the expected effective temperature of their target stars, which can introduce artifacts in equivalent width analyses. In principle, the equivalent width technique can separately measure B and f; however, in practice this is quite difficult and the technique primarily gives a measure of the product Bf (see Basri *et al.* 1992; Guenther *et al.* 1999). While measurements of actual Zeeman broadening as described below can give more detailed information about the magnetic fields on TTSs, that method is biased towards stars with intrinsically narrow line profiles, and hence is generally less usefull when studying rapidly rotating stars. Line blending makes equivalent width measurements more difficult in rapidly rotating stars as well; however, the equivalent width method used on IR lines (where the density of lines is lower in many regions) is likely to be the only way to get robust mean field measurements on high $v\sin i$ TTSs.

3.2. *Zeeman broadening of infrared Ti* I *lines*

As described above, observations in the IR help solve the difficulty in detecting direct Zeeman broadening. There are two principle IR diagnostics that have been utilized for magnetic field measurements in late-type stars. The first is a series of Zeeman sensitive Fe I lines at 1.56 μm, including one with a Landé-g value of 3.00 at 1.5649 μm (e.g. Valenti *et al.* 1995, Rüedi *et al.* 1995). These Fe I lines have a relatively high excitation potential, and as a result are best used to study G and early K type stars. To date, no TTS magnetic field measurements have been made using these lines; however, Guenther & Emerson (1996) demonstrate the suitability of these lines for TTS magnetic field work and present observations of these lines in Tap 35 which give an upper limit of $Bf < 2000$ G, consistent with the result of Basri *et al.* (1992) described above. For later spectral types such as the majority of TTSs with field measurements, lower excitation potential lines are best. There are several Ti I lines near 2.2 μm which are suitable for magnetic field

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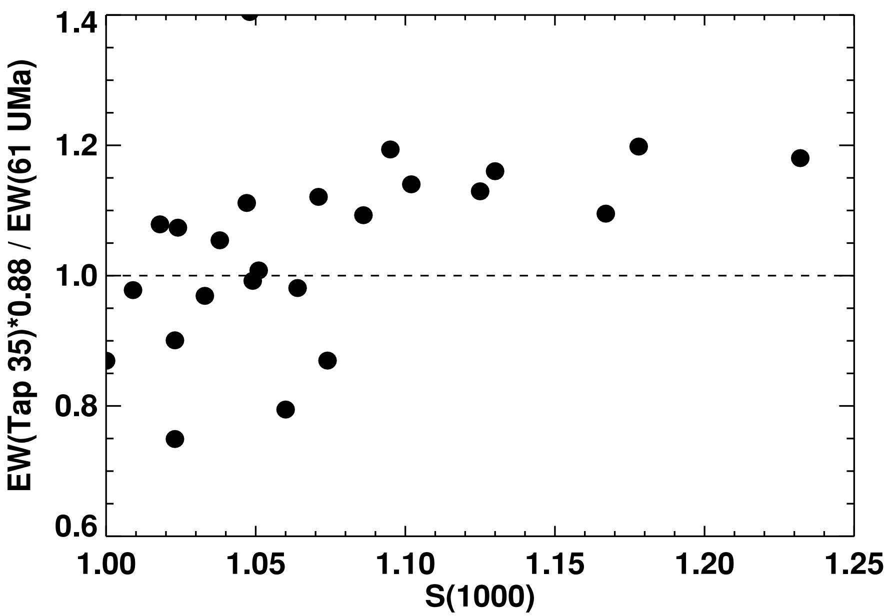

Figure 1. The first field detection on a TTS. Data is taken from Basri *et al.* (1992). The abscissa gives the magnetic sensitivity of each observed line, while the ordinate gives the ratio of the line equivalent width observed in Tap 35 divided by that observed in the inactive reference star 61 UMa. The positive correlation here demonstrates the presence of a magnetic field.

work on late K and M stars. Saar & Linsky (1985) first made use of these lines to study the magnetic field on the dMe flare star AD Leo. By far, observations of these K band Ti I lines have yielded the most information on the magnetic fields of TTSs, starting with the measurement of the magnetic field on BP Tau given by Johns–Krull *et al.* (1999b). These authors found that the broadening of the Ti I lines in BP Tau could not be well fit assuming a single magnetic field component with some value of B and f. Instead, they find that a distribution of magnetic field strengths is required. For example, one fit includes atmospheric components with field strengths of 0, 2, 4, and 6 kG magnetic fields, with individually determined filling factors which sum to 1.0. This distribution of magnetic field strengths can be characterized by the mean field $\bar{B} = \Sigma B_i f_i = 2.6 \pm 0.3$ kG for BP Tau.

Robust Zeeman broadening measurements require Zeeman insensitive lines to constrain nonmagnetic broadening mechanisms. Fortunately, numerous CO lines at 2.31 μm have negligible Landé-g factors, making them an ideal null reference. These CO lines are well fit by synthetic stellar models with only rotational and turbulent broadening. In contrast, the 2.2 μm Ti I line spectra are best fit by a model with a distribution of field strengths as described above (and see Figure 2). A total of 16 TTSs now have magnetic field measurements based on observations of the K band Ti I lines (Johns–Krull *et al.* 1999b; Johns–Krull, Valenti & Saar 2004; Yang, Johns–Krull & Valenti 2005; Johns–Krull 2007). These studies show that strong magnetic fields appear to be ubiquitous on TTSs. The mean magnetic field strength, $\bar{B}$, of most TTSs is ~ 2.5 kG. Thus, on these low surface gravity stars, the magnetic pressure dominates the photospheric gas pressure (see Johns–Krull *et al.* 2004; Johns–Krull 2007).

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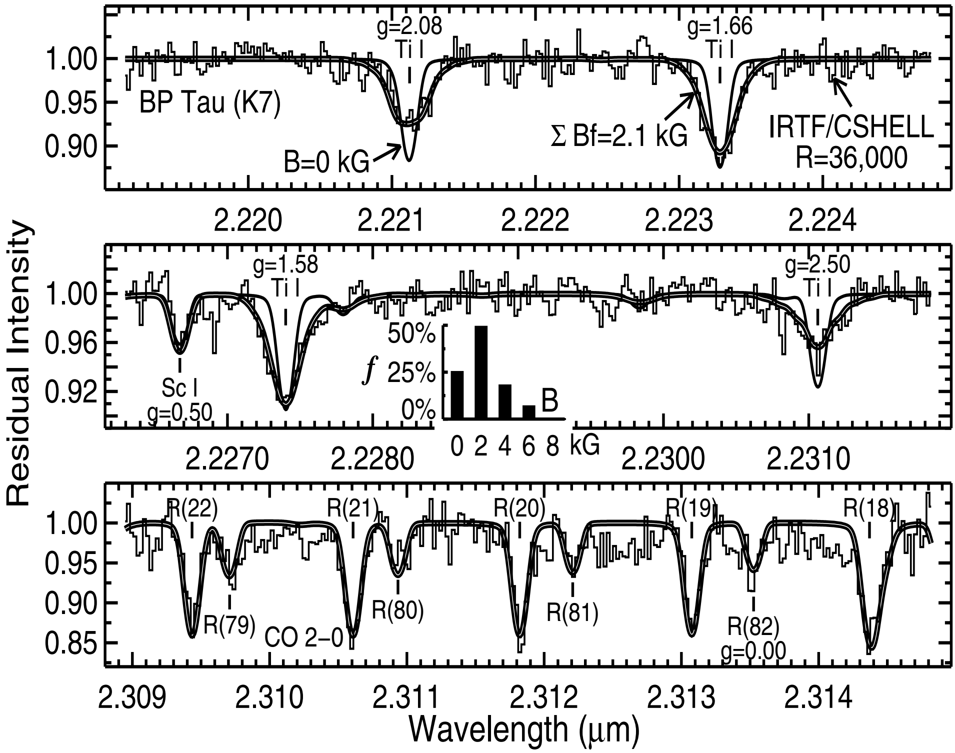

Figure 2. An IRTF/CSHELL spectrum of the K7 CTTS BP Tau (histogram) is compared with synthetic spectra based on magnetic (doubled curve) and nonmagnetic (single curve) models. Zeeman insensitive CO lines are well fit by both models. The Zeeman sensitive Ti I lines are much broader than predicted by the nonmagnetic model. The magnetic model reproduces the observed spectrum, using a distribution of magnetic field strengths (inset histogram) with a mean of 2.1 kG (Johns–Krull 2007) over the entire stellar surface. The effective Landé-g factor is given for each atomic line.

4. Spectropolarimetry and magnetic field topology

Zeeman broadening measurements are sensitive to the distribution of magnetic field strengths, but they have limited sensitivity to magnetic geometry. In contrast, circular polarization measurements for individual spectral lines are sensitive to magnetic geometry, but they provide limited information about field strength. The two techniques complement each other well, as we demonstrate below.

4.1. *The photospheric fields of T Tauri stars*

As mentioned above, existing magnetospheric accretion models assume that intrinsic TTS magnetic fields are dipolar; however, this would be unprecedented for cool stars. Nevertheless, the typical mean field (2.5 kG) measured is similar in magnitude to the dipole field strength required to truncate the accretion disk and enforce disk locking. Higher order multi-polar components of the magnetic field should fall off more rapidly with distance, so if the surface field on the star is dominated by higher order components, even stronger surface fields would be required on the star to produce the required field strength at the inner edge of the disk a few stellar radii from the surface of the star. If we assume for the moment that the mean fields described above are in fact dipolar, we can then ask what net longitudinal magnetic field, B_Z, should be measured using

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spectropolarimetry? The answer depends on the angle the dipole field axis makes with the line of sight. If the field axis is 90° from the line of sight, $B_Z = 0$. If the dipole axis is aligned with the line of sight, $|B_Z| \sim 0.64B_e$ where B_e is the equatorial value of the dipole field strength (B_e is the predicted field value tabulated in Johns–Krull *et al.* 1999b and Johns–Krull 2007). The exact value of the coefficient depends a little on the value of the limb darkening coefficient used. Assuming a dipolar field geometry observed at an angle of 45° bewteen the field axis and the line of sight, $|B_Z| \sim 800$ G if the mean field strength on the stellar surface is 2.5 kG.

Overall, there are relatively few measurements of B_Z for TTSs. Until recently, T Tau was the only TTS observed polarimetrically, with a 3σ upper limit of $|B_Z| < 816$ G set by Brown & Landstreet (1981). T Tau has been the focus of more recent study: Smirnov *et al.* (2003) report a detection of a net field of 160 ± 40 G on T Tau which was not confirmed by Smirnov *et al.* (2004) or Daou *et al.* (2006). Johnstone & Penston (1986, 1987) set 3σ upper limits on $|B_Z|$ on 3 TTSs: 494 G (RU Lup), 1110 G (GW Ori), and 2022 G (CoD-34 7151). Donati *et al.* (1997) used the rapid rotation of the diskless NTTS V410 Tau to effectively isolate strips on the stellar surface and detect net circular polarization from the star; however, no field strength was ascribed to these results. In addition, Donati *et al.* do not detect polarization on two other rapidly rotating TTSs. Yang *et al.* (2007) detect a net field of $B_Z = 149 \pm 33$ G on TW Hya on one night of their 6 night monitoring campaign on this star, finding only (3σ) upper limits of ~ 100 G on the other nights. Additional studies also only find upper limits (3σ) of 100–200 G on 4 additional CTTSs (Johns–Krull *et al.* 1999a; Valenti & Johns–Krull 2004). In light of the strong magnetic fields measured using Zeeman broadening techniques, the general absence of polarimetric detections strongly suggest the magnetic fields on TTSs are not dipolar, at least at the stellar surface. Again, as higher order terms will fall off more rapidly with distance, it is expected that the dipole component of the field will indeed dominate at distances of several stellar radii. However, measuring the fields at these distances is quite difficult. The only direct field measurement above the surface of a TTSs is the recent detection of circular polarization in the line profiles of FU Ori (Donati *et al.* 2005). Here, the fields detected are likely in the accretion disk, and the measured fields may not be anchored in the star at all.

4.2. *Magnetic fields in accretion shocks on CTTSs*

Johns–Krull *et al.* (1999a) made the surprising discovery of circular polarization in emission line diagnostics that form predominantly in the accretion shock at the surface of CTTSs. This circular polarization signal is strongest in the narrow component of the He I 5876 Å emission line, but it is also present in the Ca II infrared triplet lines (e.g. Yang *et al.* 2005). Valenti & Johns–Krull (2004) detect 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 3σ level in three stars (BP Tau, DF Tau, and DN Tau) in their survey of seven CTTSs, and Yang *et al.* (2005) detect polarization in this line in the CTTS TW Hya. All these stars are characterized by He I emission lines which have strong narrow components (NCs) to their line profiles (see Edwards *et al.* 1994 or Alencar & Basri 2000 for a discussion of NC and broad component, BC, emission in CTTSs). Smirnov *et al.* (2004) reported detections of circular polarization in the He I 5876 Å emission line of T Tau on all 3 nights they observed the star, though with significant variability from one night to the next (field measurements range from +350 G to +1100 G with no uncertainty estimates). T Tau's He I line is dominated by BC emission. Daou et al. (2006) observed T Tau on 2 nights, finding field values in the He I line of -29 ± 116 G on one night and

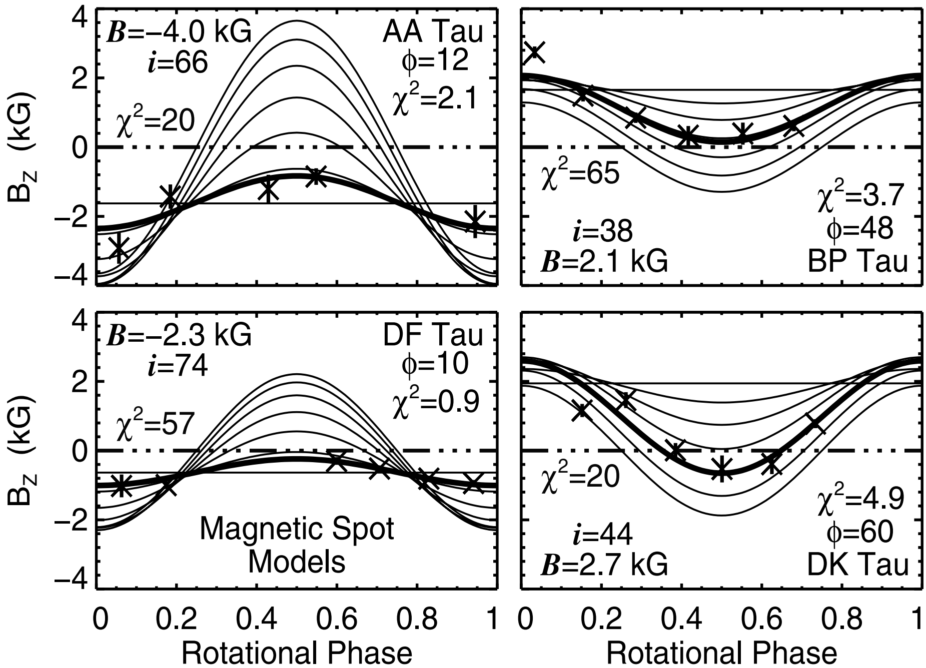

Figure 3. Crosses ($\times$) with vertical error bars indicate the net longitudinal magnetic field (B_z), measured on six consecutive nights using the He I 5876 Å accretion diagnostic. The family of curves show predicted B_z values for a simple model with radial magnetic field lines concentrated in a spot a latitude ϕ. Magnetic field strengths are constrained by independent Zeeman broadening measurements. Reduced χ^2 is 1-5 for the best fitting model, shown as a long dashed curve for each star. Reduced χ^2 is 20-60 for a model that assumes $B_z = 0$.

-43 ± 300 G on the second. TW Hya's He I line has a significant broad component, but Yang *et al.* (2005) do not report any polarization in this part of the line.

The NC of the He I emission is commonly associated with the accretion shock itself at the stellar surface, whereas the BC may have contributions from the magnetospheric accretion flow and/or a hot wind component (e.g. Beristain, Edwards & Kwan 2001). Since the BC of the He I emission line forms over a large, extended volume, its magnetic field strength should be weaker than at the stellar surface. In addition field line curvature may enhance polarization cancellation in the BC. As a result, circular polarization in the BC of the He I 5876 Å emission is predicted to be less than in the NC. Therefore, the result of Smirnov *et al.* (2004) for T Tau is quite surprising. Additional observations of T Tau and other CTTSs dominated by BC emission are needed to confirm the polarization detections. Such observations can strongly constrain the formation region of the BC emission. For example, it is difficult to see how formation of this component over an extend region such as in a hot wind can produce significant polarization characteristic of magnetic field strengths in excess of 1000 G.

The polarization measured in the He I lines is observed to be variable. Figure 3, taken from Valenti & Johns–Krull (2004), shows measurements of B_Z determined from the He I line on 6 consecutive nights for 4 CTTSs. The field values in the He I line vary smoothly on rotational timescales, suggesting that uniformly oriented magnetic field lines in accretion regions sweep out a cone in the sky as the star rotates. Rotational modulation implies a lack of symmetry about the rotation axis in the accretion or the magnetic field or both. For example, the inner edge of the disk could have a concentration

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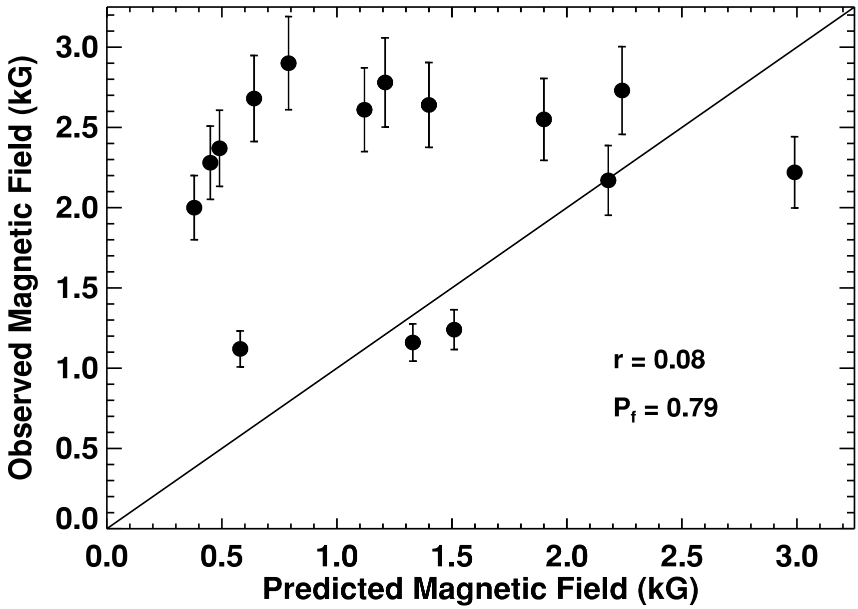

Figure 4. Measured mean magnetic fields as diagnosed by K band Ti I line profiles versus predicted fields using magnetospheric accretion models which assume disk-locking in CTTSs (taken from Johns–Krull 2007).

of gas that corotates with the star, preferentially illuminating one sector of a symmetric magnetosphere. Alternatively, a single large scale magnetic loop could draw material from just one sector of a symmetric disk. Many variants are possible. Figure 3 shows one interpretation of the He I polarization data. Predicted values of B_Z are shown for a simple model consisting of a single magnetic spot at latitude ϕ that rotates with the star. The magnetic field is assumed to be radial with a strength equal to the measured values of $\bar{B}$. Inclination of the rotation axis is constrained by measured $v \sin i$ and rotation period, except that inclination (i) is allowed to float when it exceeds 60° because $v \sin i$ measurements cannot distinguish between these possibilities. Predicted variations in B_Z are plotted for spot latitudes ranging from 0° to 90° in 15° increments. The best fitting model is the heavy curve. The corresponding spot latitude and reduced χ^2 are given on the right side of each panel. Large values of χ^2 on the left side of each panel rule out the hypothesis that no polarization signal is present. In all four cases, this simple magnetic spot model reproduces the observed He I time series. Similar results are found by Symington *et al.* (2005).

5. Confronting theory with observations

At first glance, it might appear that magnetic field measurements on TTSs are generally in good agreement with theoretical expectations. IR Zeeman broadening measurements indicate mean fields on several TTS of ~ 2 kG, similar in value to those predicted by magnetospheric accretion models (Johns–Krull *et al.* 1999b; Johns–Krull 2007). However, in detail the field observations do not agree with some aspects of the theory. This is shown in Figure 4 where the measured mean magnetic field strengths are plotted

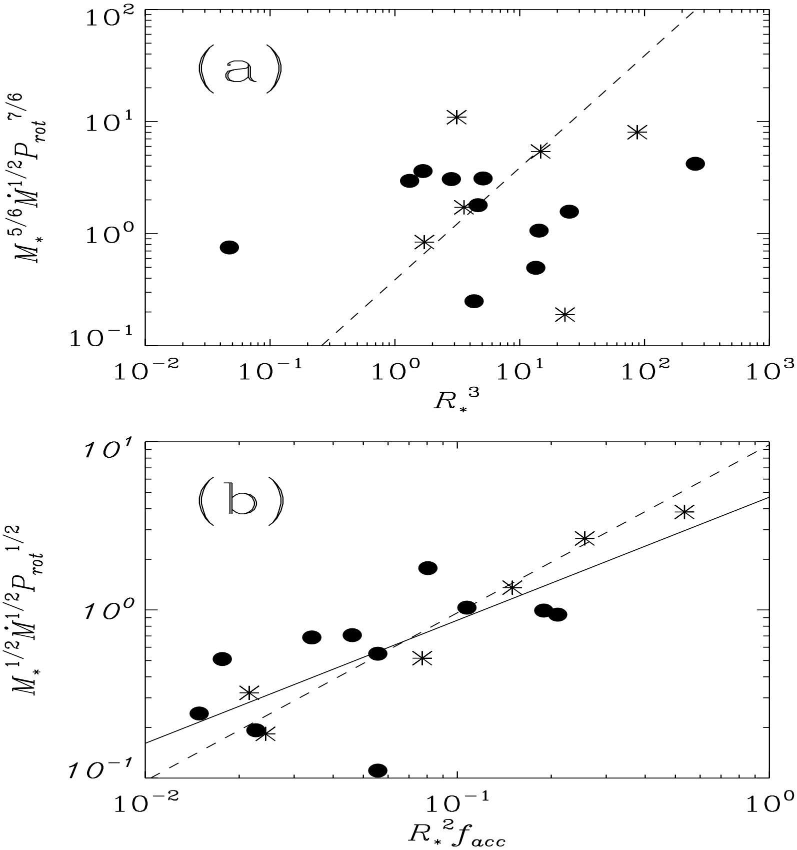

Figure 5. (a) The top panel shows the quantity $(M_*/M_\odot)^{5/6}(\dot{M}/1 \times 10^{-7}M_\odot yr^{-1})^{1/2}P_{rot}^{7/6}$ versus $(R_*/R_\odot)^3$ for the sample of stars from Valenti *et al.* (1993). Single CTTSs are shown in solid circels while CTTSs in binary systems are shown in asterisks. The dashed line shows the best fit line whose slope (1.0) is predicted by equation dipolar magnetospheric accretion models. (b) The bottom panel shows the quantity $(M_*/M_\odot)^{1/2}(\dot{M}/1 \times 10^{-7}M_\odot yr^{-1})^{1/2}P_{rot}^{1/2}$ versus $(R_*/R_\odot)^2 f_{acc}$ for the same sample of stars. This expression is derived without the assumption of a dipolar field, which requires the additional parameter f_{acc} which is the filling factor of accreting zones on each star. Shown in the solid line is the best fit line to the data, and shown in the dashed line is best fit line whose slope (1.0) is predicted non-dipolar accretion models.

versus predicted field strengths. Clearly, the measured field strengths show no correlation with the predicted ones. The field topology measurements give some indication to why there may be a lack of correlation: the magnetic fields on TTSs are not dipolar. On the other hand, the smoothly varying polarization detected in the He I accretion shock lines suggests that the region where the disk interacts with the stellar field is dominated by a simple magnetic field geometry. Since the dipole component of the field falls off the least rapidly with distance, it may well be that the stellar field at the disk truncation radius is dominated by the dipole component. The disk material then loads onto these field lines and accretes onto the star, landing at the surface in those regions which contribute the the large scale dipolar field. Perhaps then, the correct correlation to look for

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is between the predicted fields and the dipole component, or the predicted fields and the field in the He I region? Currently, there are not enough reliable measurements of either of these field diagnostics to look for such a correlation.

One potential test though is to look for other correlations predicted by magnetospheric accretion theory. As shown in Figure 4, the fields on TTSs are found to all be rather uniform in strength. Assuming the field is in fact constant from one TTS to the next, Johns–Krull & Gafford (2002) looked for correlations among the other stellar and accretion parameters relevant in the models, finding little evidence for the predicted correlations (Figure 5a). On the other hand, Johns–Krull & Gafford (2002) showed how the models of Ostriker & Shu (1995) could be extended to take into account non-dipole field geometries. Once this is done, current data do reveal the predicted correlations (Figure 5b), suggesting magnetospheric accretion theory is basically correct as currently formulated.

6. Conclusion

The current magnetic field measurements show that the strong majority of TTSs are covered by kilogauss magnetic fields. The observations also suggest these fields manifest themselves in a complicated surface topology and that the dipole component of the field is likely small on TTSs. Despite this surface complication, fields measured in the accretion shock on CTTSs suggest that the disk interacts with a primarily dipolar field geometry several stellar radii above the star. However, it is likely the strength of this dipole component is substantially weaker than current models require. Additional high precision spectropolarimetry is required to determine the true dipole component of the field (e.g. Donati *et al.* 2007), and new theoretical studies of magnetospheric accretion with realistic field geometries are urgently needed. Gregory *et al.* (2006) have made a first attempt in this direction, but additional work, including calculations of the torque balance are still needed.

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Discussion

Skinner: I wonder if you have any information about how the fields on these stars evolve with age?

Johns–Krull: My graduate student, Hao Yang, is working on this problem. We have measurements of several stars in the TW Hya association, which is about 10 Myr old compared to 1.5 – 3 Myr for Taurus which is where most of the field measurements I showed you come from. Right now, it looks like the fields in the TWA stars are stronger on average; however, these stars are smaller on average due to their older age, so it looks like magnetic flux might be conserved. These results are very preliminary at this point.

Lamzin: I don't really believe the distinction between NC and BC emission in the He I line, and the results of Smirnov *et al.* show that the entire He I line is polarized in T Tau, indicating it forms very close to the star.

Johns–Krull: I agree that these results are very interesting, and I think additional observations are needed to see how general they are.

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