The Magnetic Fields on T Tauri Stars

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Disks: A Natural Product of Star Formation

1. Clump of gas becomes protostar when radiation can no longer escape from interior.
2. Fusion rate increases until gravitational equilibrium stabilizes star.
3. Shrinking slows and surface temperature rises as nuclear burning begins.
4. Protostar shrinks and heats as gravitational potential energy is converted into thermal energy.

[Diagram showing the stages of star formation with a luminosity diagram and a visual representation of gas clumps forming into a protostar.]
• T Tauri Stars are optically visible
• Late Type stars (G – M)
• Ages of a few million years
• Come in 2 flavors: CTTS and W/NTTS
• CTTS disks diagnosed by IR radiation
• Accretion onto star produces optical/UV excess
Disks Are Commonly Observed Around Young Stars

- Now Imaged in the Optical, IR, and Radio
- However, most of our knowledge comes from spectral energy distributions
Spectral Energy Distributions

- **Class 0**: Proto-stellar cores
- **Class I**: Young star with a disk has formed but substantial envelope remains
- **Class II**: Envelope has largely dissipated, star and disk remain - CTTS
- **Class III**: Just the star - NTTS
Disk Lifetimes: Frequency vs. Age

This is the dust disk lifetime
Disk Regulated Rotation

- Edwards et al. (1993)
- NTTS have a range of rotation periods
- CTTS are clustered near 9 days
- Results have been questioned by Stassun et al. (1999)
- See also Herbst et al. (2000)
Theory gives field at some point in the disk
Theoretical Predictions

Konigl (1991):

\[ B_* = 3.43 \left( \frac{\varepsilon}{0.35} \right)^{7/6} \left( \frac{\beta}{0.5} \right)^{7/4} \left( \frac{M_*}{1 M} \right)^{5/6} \left( \frac{\dot{M}}{10^{-7} M \text{ yr}^{-1}} \right)^{1/2} \left( \frac{R_*}{1.0 R} \right)^{-3} \left( \frac{P_*}{1.0 d} \right)^{7/6} \text{kG} \]

Cameron & Campbell (1993):

\[ B_* = 1.10 \gamma^{-1/3} \left( \frac{M_*}{1 M} \right)^{2/3} \left( \frac{\dot{M}}{10^{-7} M \text{ yr}^{-1}} \right)^{23/40} \left( \frac{R_*}{1 R} \right)^{-3} \left( \frac{P_*}{1 d} \right)^{29/24} \text{kG} \]

Shu et al. (1994):

\[ B_* = 3.38 \left( \frac{\alpha_x}{0.923} \right)^{-7/4} \left( \frac{M_*}{1 M} \right)^{5/6} \left( \frac{\dot{M}}{10^{-7} M \text{ yr}^{-1}} \right)^{1/2} \left( \frac{R_*}{1 R} \right)^{-3} \left( \frac{P_*}{1 d} \right)^{7/6} \text{kG} \]
Theoretical Predictions

<table>
<thead>
<tr>
<th>Star</th>
<th>$M_\ast$ ($M_\odot$)</th>
<th>$R_\ast$ ($R_\odot$)</th>
<th>$\dot{M}$ ($M_\odot$ yr$^{-1}$)</th>
<th>$P_{\text{rot}}$ (days)</th>
<th>$B_\ast^a$ (G)</th>
<th>$B_\ast^b$ (G)</th>
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<td>630</td>
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Note: Magnetic field values are the equatorial field strengths assuming a dipole magnetic field.

- $^a$ Magnetic field values from the theory of Königl 1991.
- $^b$ Magnetic field values from the theory of Cameron & Campbell 1993.
- $^c$ Magnetic field values from the theory of Shu et al. 1994.
Theoretical Predictions

![Graph showing theoretical predictions](image)
Measuring Fields from Zeeman Broadening

\[ \Delta \lambda = \frac{e}{4\pi mc^2} \lambda^2 g_{\text{eff}} B \]

\[ \varepsilon \text{ Eri (K2 V)} \]
\[ B = 1.44 \text{ kG}, \ f = 9\% \]
\[ \lambda = 1.56485 \mu m \]
\[ g_{\text{eff}} = 3.0 \]
Early Measures of TTS Magnetic Fields

- Basri et al. (1992)
- Zeeman desaturation of optical line
- $R = 60,000$ spectra
- NTTS Tap 35 $B_f \sim 1000$ G
- NTTS Tap 10 $B_f < 1500$ G
More Recent Field Measurements

- Guenther et al. (1999)
- Zeeman desaturation of optical lines
- Possibly detected fields on 4 stars: CTTS and NTTS

\[ B_f \sim 2.5 \text{ kG} \]
What Can Go Wrong

- Guenther et al. (1999)
- LkCa 16, $r_{\text{max}} = 0.71$, $B_f \sim 2$ kG
- Same Fe I lines used
- No Magnetic Field
- Temperature Error of 300 K

![Graph 1](image1)

![Graph 2](image2)

$$r = 0.75, \text{Conf.} = 99.98\%$$
A Good Example


McDonald Observatory 2dCoude

$\nu \sin i = 4.5$ km/s

GJ 825 (M1.5V)
GJ 880 (M2V)
GJ 752 (M3V)
GJ 725 (M3.5V)
EV Lac (M4.5V)
GJ 876 (M5V)
Getting Rid of the TiO


$B = 3.8$ kG
$f = 60\%$

$g_{\text{eff}} = 1.10$
$g_{\text{eff}} = 2.49$
Going to the Infrared

\[ \Delta \lambda = \frac{e}{4\pi mc^2} \lambda^2 g_{\text{eff}} B \]

\( \varepsilon \) Eri (K2 V)
\( B = 1.44 \) kG, \( f = 9\% \)
\( \lambda = 1.56485 \) \( \mu \)m
\( g_{\text{eff}} = 3.0 \)
• Johns-Krull, Valenti, & Koresko (1999)
• NASA IRTF (3m) + CSHELL spectrometer
• $R \sim 35,000$ spectra
• Excess Broadening Clearly Seen in the Ti I line
Spectrum Synthesis

- Full Stokes radiative transfer (Valenti & Piskunov 1998)
- Line data checked against solar models/observations
- NextGen model atmospheres (Allard & Hauschildt 1995)
- Magnetic field lines assumed radial at the stellar surface
- Distribution of field strengths allowed
- Magnetic regions have same structure as quiet regions **
- Other relevant stellar parameters determined from high resolution (60,000) optical spectra or adopted from the literature
Inactive K Dwarfs

GJ 380 (K7V)
61 Cyg B (K7V)
B=0 Model
TW Hya: CTTS

Yang, Johns-Krull, & Valenti (2005)
Hubble 4: NTTS

Johns-Krull, Valenti, & Saar (2004)
## Predicted vs. Observed Mean Fields

<table>
<thead>
<tr>
<th>Star</th>
<th>$M_*$ (M$_\odot$)</th>
<th>$R_*$ (R$_\odot$)</th>
<th>$M \times 10^8$ (M$_\odot$yr$^{-1}$)</th>
<th>$P_{\text{rot}}$ (days)</th>
<th>$B_{\text{Kon}}$ (kG)</th>
<th>$B_{\text{Cam}}$ (kG)</th>
<th>$B_{\text{Shu}}$ (kG)</th>
<th>$B_{\text{obs}}$ (kG)</th>
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<td>AA Tau</td>
<td>0.53</td>
<td>1.74</td>
<td>0.33</td>
<td>8.20</td>
<td>0.81</td>
<td>0.24</td>
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<td>BP Tau</td>
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<td>1.99</td>
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<td>GM Aur</td>
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<td>0.90</td>
<td>0.24</td>
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Predicted vs. Observed Mean Fields

![Graph showing predicted vs. observed magnetic fields with correlation coefficient r = 0.08 and probability P_f = 0.79](image)

- Observed Magnetic Field (kG)
- Predicted Magnetic Field (kG)

**Correlation Data:**
- $r = 0.08$
- $P_f = 0.79$
The Surface of a T Tauri Star?

- The optical continuum forms in something like the solar chromosphere.
- Polytropic models of TTS structure indicate that $B$ field dominates only in outer 0.5-1.0%.
Observed Fields & X-ray Emission

Pevtsov et al. (2003)

Johns-Krull (2007)
Circular Polarization

\[ \Delta \lambda = \frac{e}{4\pi mc^2} \lambda^2 g_{\text{eff}} B \]

\( e \) Eri (K2 V)

\( B = 1.44 \text{ kG}, f = 9\% \)

\( \lambda = 1.56485 \mu\text{m} \)

\( g_{\text{eff}} = 3.0 \)
Field Geometry: Polarization from a Dipole

For $<B> = 2.4 \text{ kG}; \ Be = 0.69 \text{ kG}$

- Brown & Landstreet (1981)
- T Tau $B_Z < 816 \text{ G}$
- Predicted $320-1280 \text{ G} \times 0.31 = 99-400 \text{ G}$
- $<B> = 2.4 \text{ kG}$ gives $B_Z = 950 \text{ G}$

- RU Lup: $B_Z < 494 \text{ G}, B_p < 1400 \text{ G}$
- GW Ori: $B_Z < 1.1 \text{ kG}, B_p < 3.2 \text{ kG}$
- CoD-34 7151: $B_Z < 2.0 \text{ kG}, B_p < 5.8 \text{ kG}, B_{\text{pred}} < 0.4 \text{ kG}$
The Close Circumstellar Environment

Shu et al. (1994)

Theory gives field at some point in the disk
New Polarization Observations of TTS

- Johns-Krull et al. (1999a)
- McDonald Observatory 2.7m
- \( R = 60,000 \) echelle spectrometer
- Zeeman Analyzer (Vogt 1980)
The Photospheric Field of BP Tau

Johns-Krull et al. (1999a)

<table>
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<tr>
<th>Line</th>
<th>$\lambda$ (Å)</th>
<th>$g_{\text{eff}}$</th>
<th>$r - l$ (mÅ)</th>
<th>$\sigma_{r-l}$ (mÅ)</th>
<th>$B_z$ (G)</th>
<th>$\sigma_{B_z}$ (G)</th>
<th>$r - l$ (mÅ)</th>
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$^a$ This is the mean of the four Fe I lines.

$^b$ See discussion in text.

$^c$ The features that we measure in BP Tau are not stellar and are only meant as a wavelength reference.
Additional Spectropolarimetry

**TW Hya**

- Recall, $|B| = 2.6 \text{ kG} \rightarrow B_Z = 1040 \text{ G}$
- Yang, Johns-Krull, & Valenti (2006) find $B_Z < 150 \text{ G}$

\[
\Delta \lambda = \frac{e}{4\pi m_c c^2} \lambda^2 g_{\text{eff}} B_z = 9.34 \times 10^{-7} \lambda^2 g_{\text{eff}} B_z \ (\text{mÅ})
\]

**T Tau**

- Recall, $|B| = 2.4 \text{ kG} \rightarrow B_Z = 950 \text{ G}$
- Smirnov et al. (2003): $B_Z = 160 +/− 40 \text{ G}$
- Not confirmed by Smirnov et al. (2004)
- Daou, Johns-Krull, & Valenti (2006) find $B_Z < 105 \text{ G (3σ)}$
- Multiple observations rule out misaligned dipole at 97%
Polarization of Accretion Shock Material
Polarization of Accretion Shock Material

BP Tau: 2.4 kG

TW Hya: 1.8 kG

Johns-Krull et al. (1999a)
The Large Scale Field Likely Dipolar

Shu et al. (1994)

He I Polarization

Theory gives field at some point in the disk
Polarization of Accretion Shock Material: Time Series

Mahdavi & Kenyon (1998)
Predicted vs. Observed Polarization

![Graph showing predicted versus observed polarization with various markers for SR 9, BP Tau, AA Tau, DK Tau, and DF Tau. The x-axis represents Shu et al. Bz (kG) and the y-axis represents Observed Bz (kG).]
Assuming $B$ Constant


$$\left(\frac{R_*}{R_\odot}\right)^3 \propto \left(\frac{M_*}{1M_\odot}\right)^{5/6} \left(\frac{\dot{M}}{10^{-7} M_\odot \text{ yr}^{-1}}\right)^{1/2} \left(\frac{P_*}{1 \text{ day}}\right)^{7/6}$$

Cameron & Campbell (1993):

$$\left(\frac{R_*}{1R_\odot}\right)^3 \propto \left(\frac{M_*}{1M_\odot}\right)^{2/3} \left(\frac{\dot{M}}{10^{-7} M_\odot \text{ yr}^{-1}}\right)^{23/40} \left(\frac{P_*}{1 \text{ day}}\right)^{29/24}$$
Trapped Flux in the Shu et al. Model

Shu et al. (1994)

Theory gives field at some point in the disk
Trapped Flux

Johns-Krull & Gafford (2002):

• Trapped flux plus disk locking suggests: \( G, M_*, \dot{M}_D, & P_{rot} \)
• Stellar dipole moment, \( \mu_* \), should not enter *per se*
• The only combination which give units of magnetic flux is:

\[
\Phi = \alpha (GM_* \dot{M}_D P_{rot})^{1/2}
\]

• We can set this equal to \( 4\pi R_*^2 f_{acc} B_* \)
• Therefore, a unique prediction of Ostriker & Shu (1995) is:

\[
R_*^2 f_{acc} \propto M_*^{1/2} \dot{M}^{1/2} P_{rot}^{1/2}
\]
Observational Tests:

• Valenti, Basri, & Johns (1993)
• Low resolution, flux calibrated, blue spectra of a large sample of TTS
• Fit NTTS + LTE Hydrogen slab models to spectra of CTTS
• Give mass accretion rate and filling factor of slab emission

Conclusions

- **Magnetospheric Accretion Models**
  - Require magnetic field strengths from 0.1-5 kG for specific stars
  - Yield fields that differ by scale factors related to assumed coupling
  - Imply stellar field not simply function of mass, radius, and rotation

- **Zeeman Broadening Measurements**
  - Infrared sensitivity required to compensate for moderate rotation
  - Distribution of field strengths up to 6 kG in many T Tauri stars
  - Similar field strengths on most T Tauri stars (with and without disks)

- **Circular Polarization Measurements**
  - Photospheric absorption lines rule out global dipolar field
  - Helium emission line formed in accretion shock is strongly polarized
  - Rotational modulation implies magnetic field not rotationally symmetric
Conclusions

• **Comparison of TTS Field Measurements with Theory**
  - Mean fields show no correlation
  - Accretion shock fields show some correlation
  - Specific geometry of the fields likely the key
  - Trapped flux model of Shu et al. Supported by correlation analysis