The Magnetic Fields on T Tauri Stars

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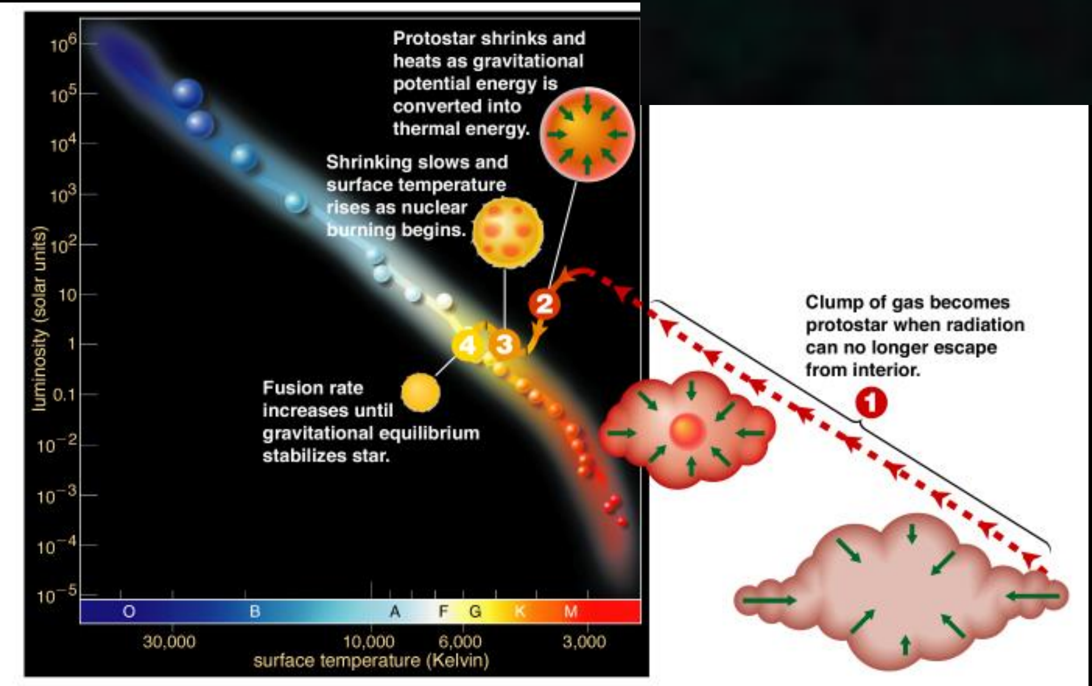
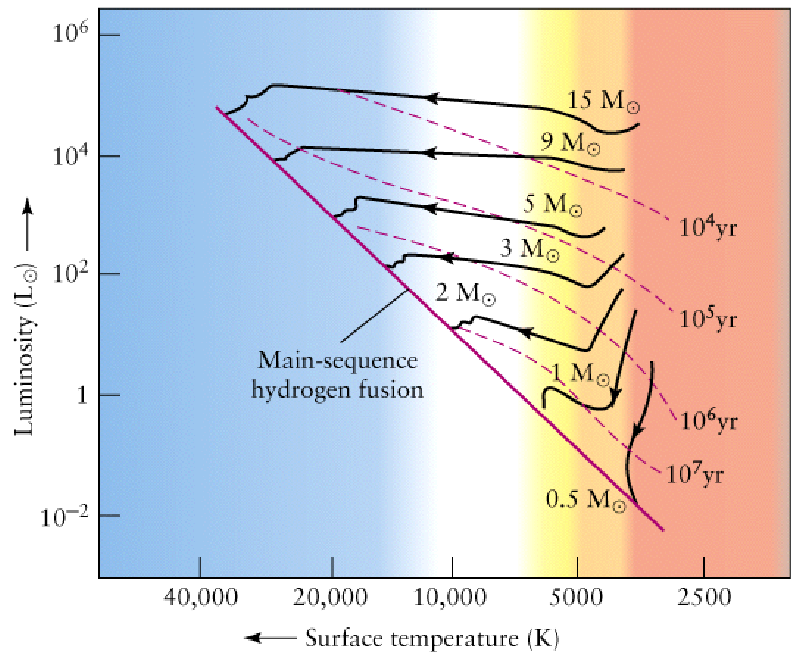
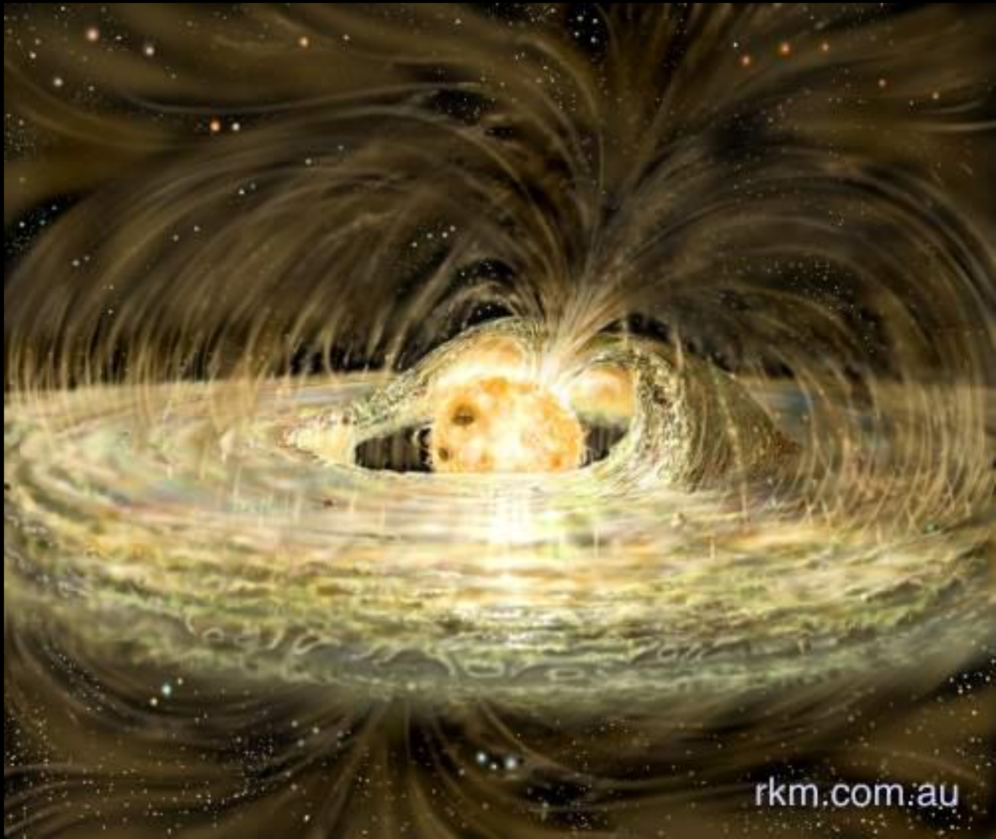
Disks: A Natural Product of Star Formation



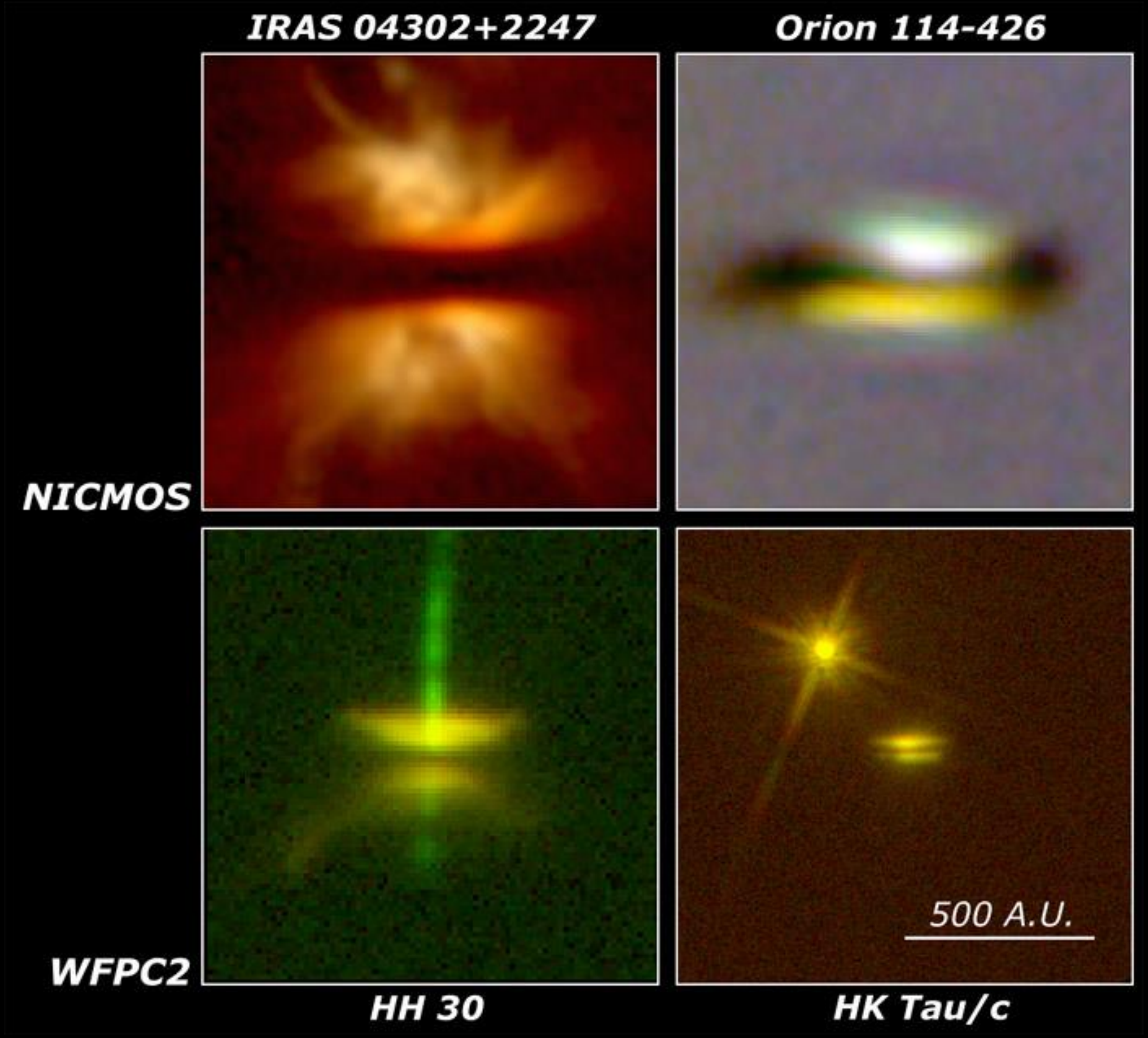
T Tauri Stars: Revealed Low Mass Young Stars



- 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

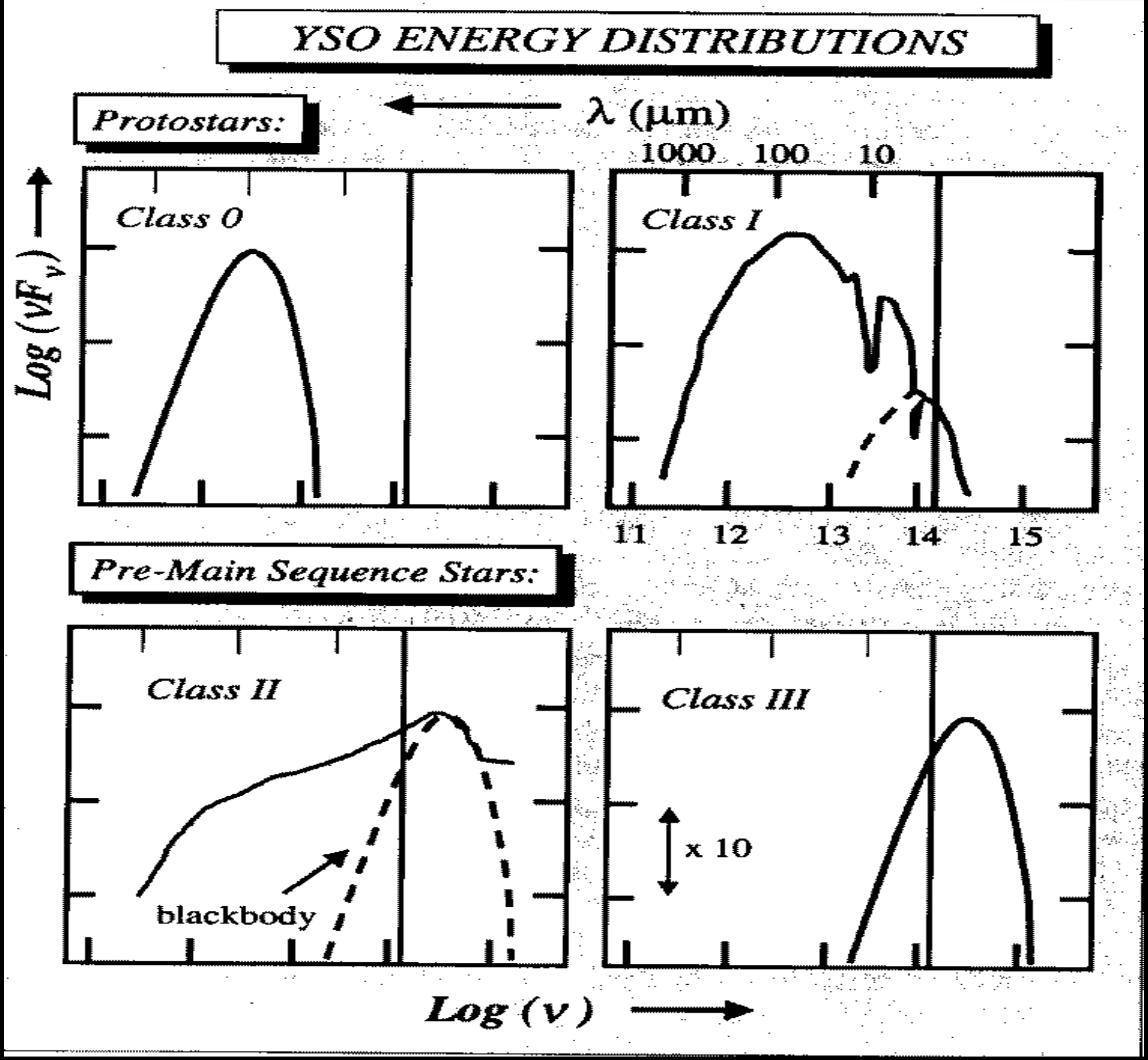


Disks Are Commonly Observed Around Young Stars



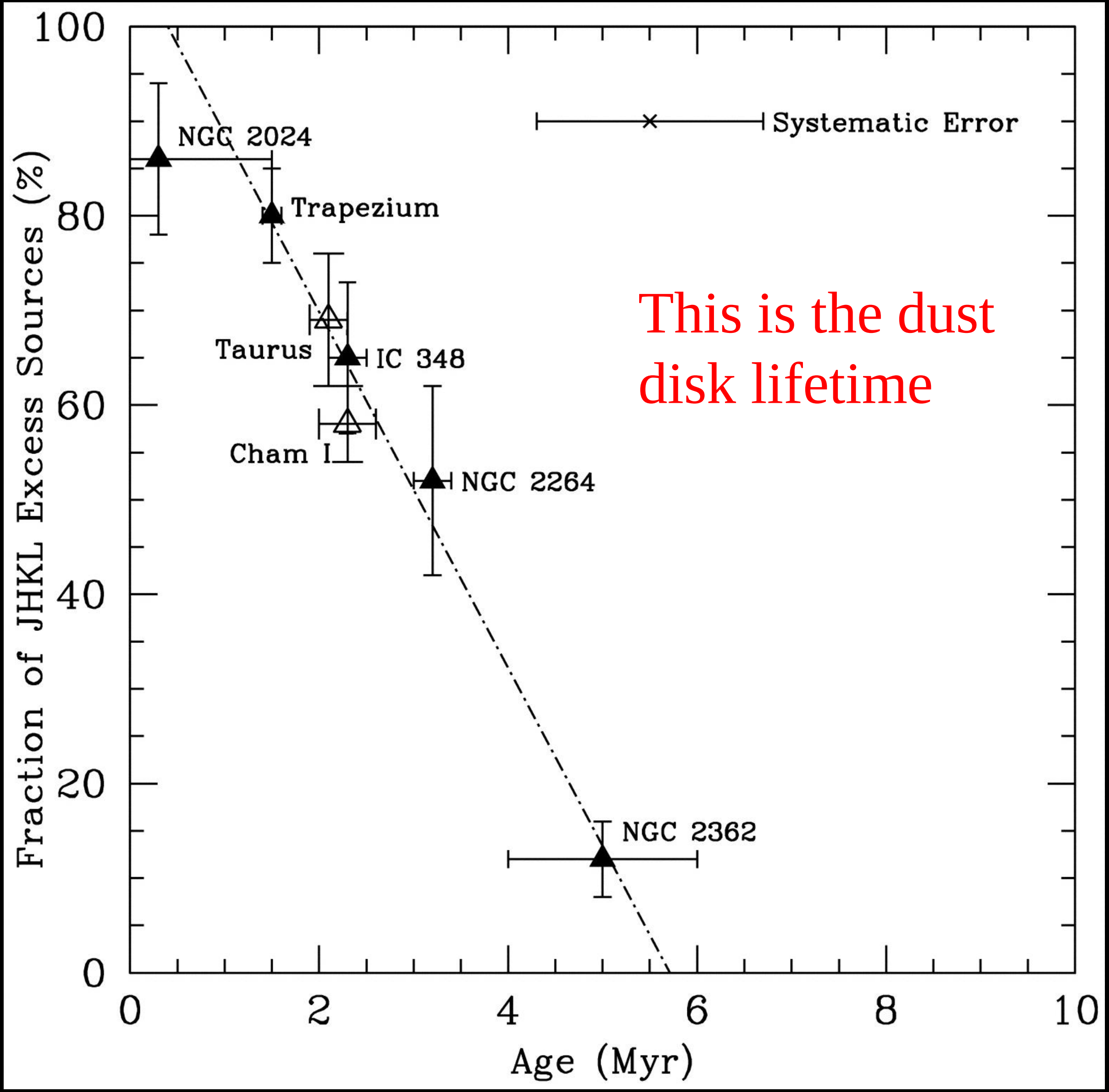
- Now Imaged in the Optical, IR, and Radio
- However, most of our knowledge comes from spectral energy distributions

Spectral Energy Distributions



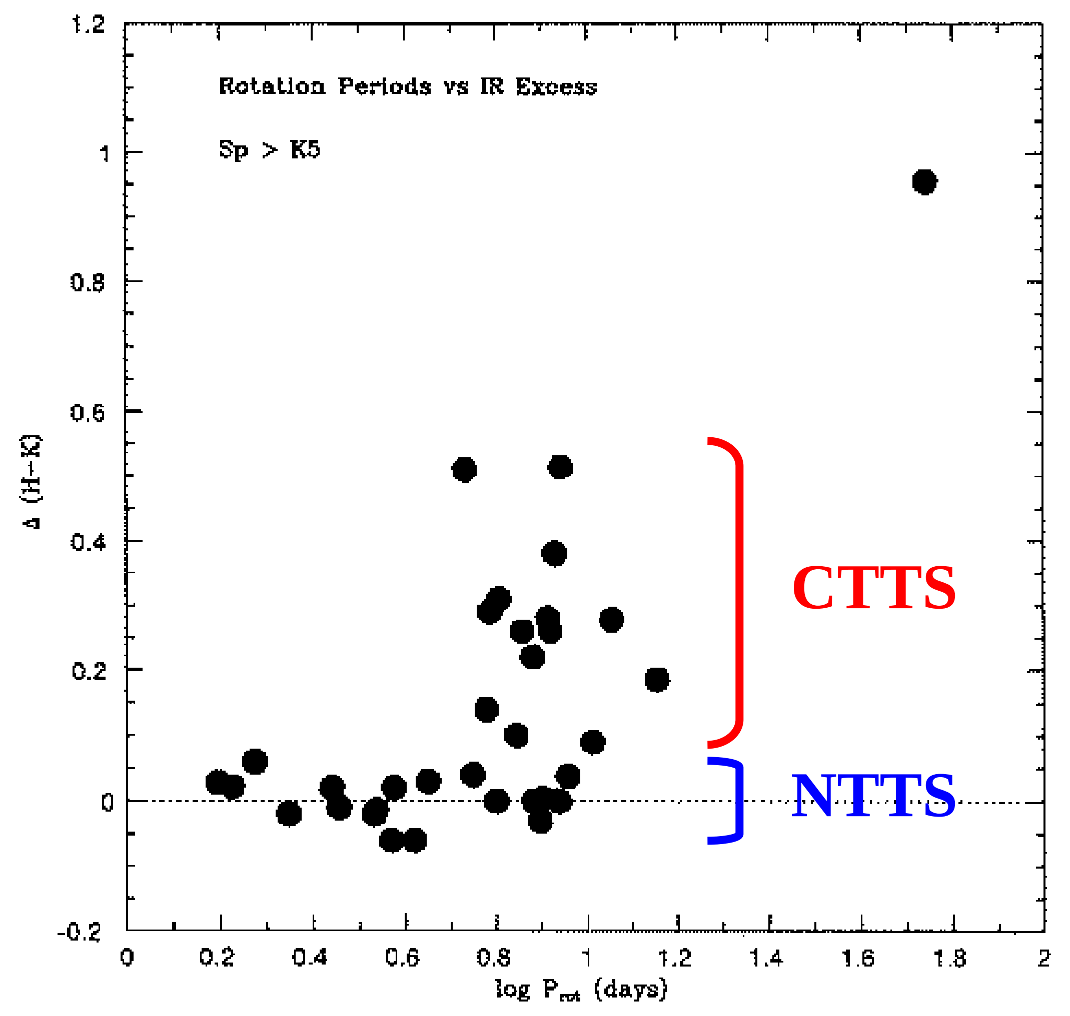
- Class 0: Proto-stellar cores
- Class I: Young star with a disk has formed but substantial envelope remains
- Class II: Envelope has largely dissipated, star and disk remain - CTTS
- Class III: Just the star - NTTS

Disk Lifetimes: Frequency vs. Age



This is the dust disk lifetime

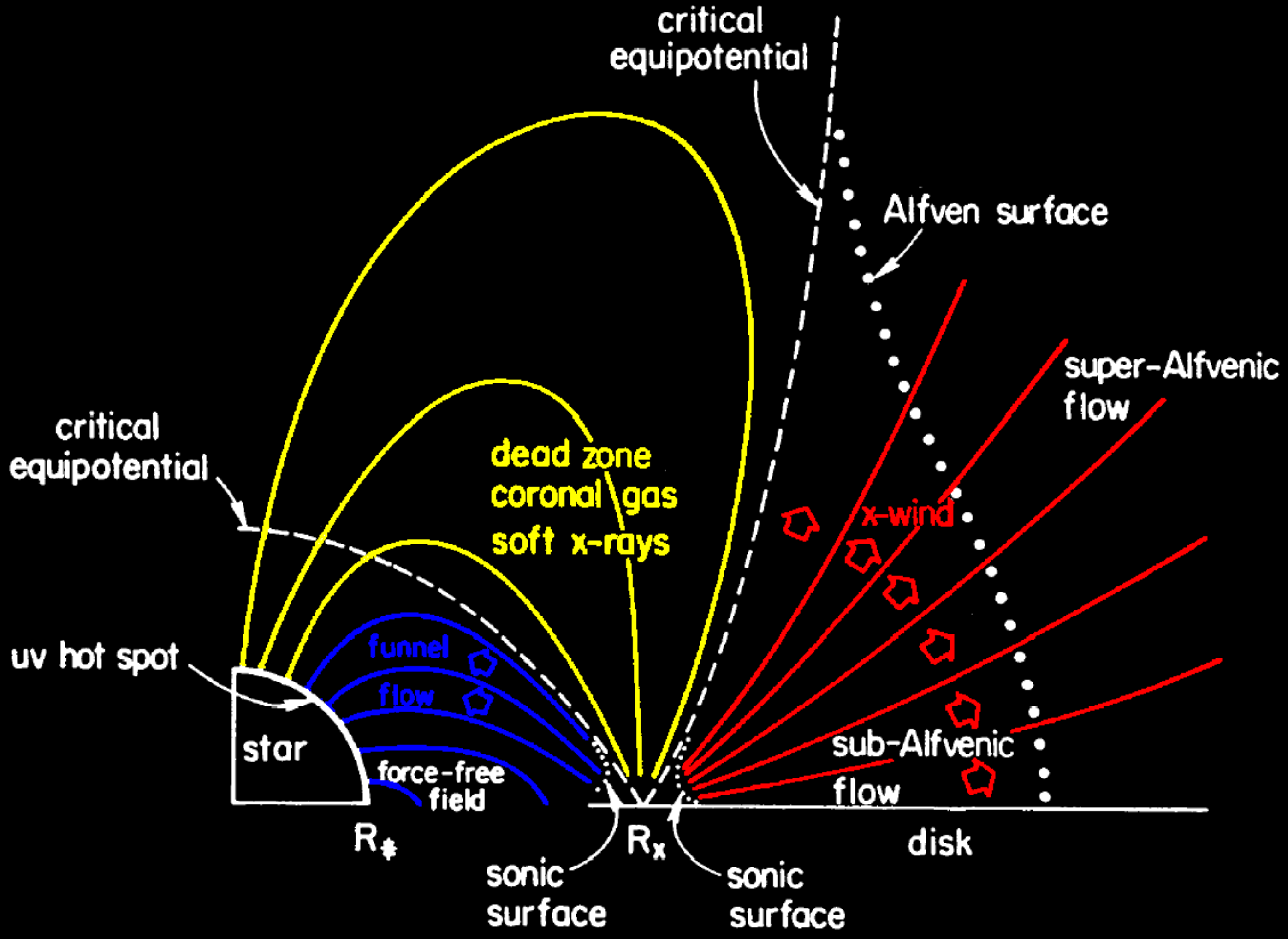
Disk Regulated Rotation



- 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)

The Close Circumstellar Environment

Shu et al. (1994)



Theory gives field at some point in the disk

Theoretical Predictions

Konigl (1991):

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

Cameron & Campbell (1993):

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

Shu et al. (1994):

$$B_* = 3.38\left(\frac{\alpha_x}{0.923}\right)^{-7/4}\left(\frac{M_*}{1M_\odot}\right)^{5/6}\left(\frac{\dot{M}}{10^{-7}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{R_*}{1R_\odot}\right)^{-3}\left(\frac{P_*}{1\mathrm{d}}\right)^{7/6}\mathrm{kG}$$

Theoretical Predictions

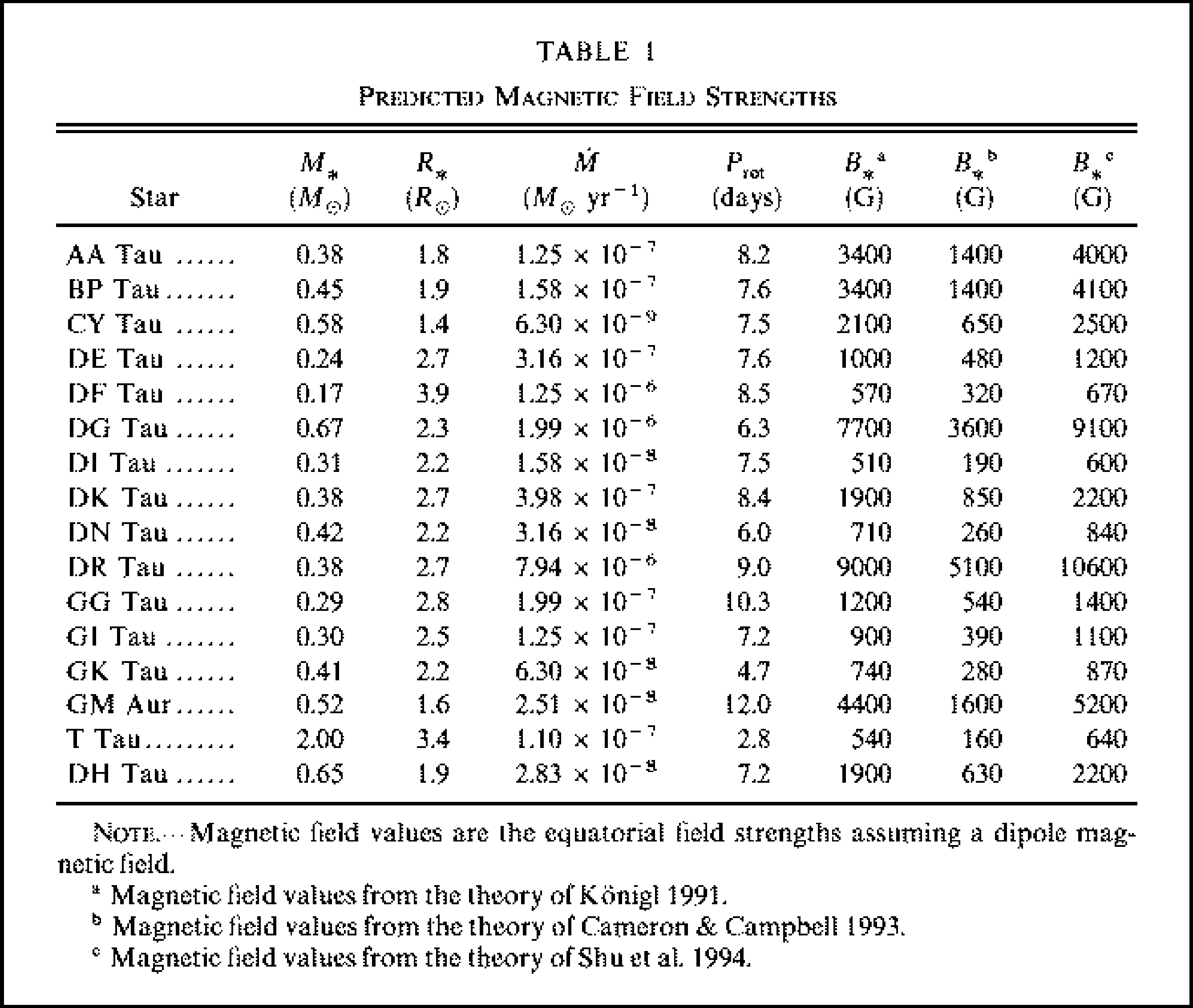


TABLE 1

PREDICTED MAGNETIC FIELD STRENGTHS

Star	M_* ($M_\odot$)	R_* ($R_\odot$)	$\dot{M}$ ($M_\odot$ yr^{-1})	$P_{\rm rot}$ (days)	$B_*{}^{\rm a}$ (G)	$B_*{}^{\rm b}$ (G)	$B_*{}^{\rm c}$ (G)
AA Tau	0.38	1.8	1.25×10^{-7}	8.2	3400	1400	4000
BP Tau	0.45	1.9	1.58×10^{-7}	7.6	3400	1400	4100
CY Tau	0.58	1.4	6.30×10^{-9}	7.5	2100	650	2500
DE Tau	0.24	2.7	3.16×10^{-7}	7.6	1000	480	1200
DF Tau	0.17	3.9	1.25×10^{-6}	8.5	570	320	670
DG Tau	0.67	2.3	1.99×10^{-6}	6.3	7700	3600	9100
DI Tau	0.31	2.2	1.58×10^{-8}	7.5	510	190	600
DK Tau	0.38	2.7	3.98×10^{-7}	8.4	1900	850	2200
DN Tau	0.42	2.2	3.16×10^{-8}	6.0	710	260	840
DR Tau	0.38	2.7	7.94×10^{-6}	9.0	9000	5100	10600
GG Tau	0.29	2.8	1.99×10^{-7}	10.3	1200	540	1400
GI Tau	0.30	2.5	1.25×10^{-7}	7.2	900	390	1100
GK Tau	0.41	2.2	6.30×10^{-8}	4.7	740	280	870
GM Aur	0.52	1.6	2.51×10^{-8}	12.0	4400	1600	5200
T Tau	2.00	3.4	1.10×10^{-7}	2.8	540	160	640
DH Tau	0.65	1.9	2.83×10^{-8}	7.2	1900	630	2200

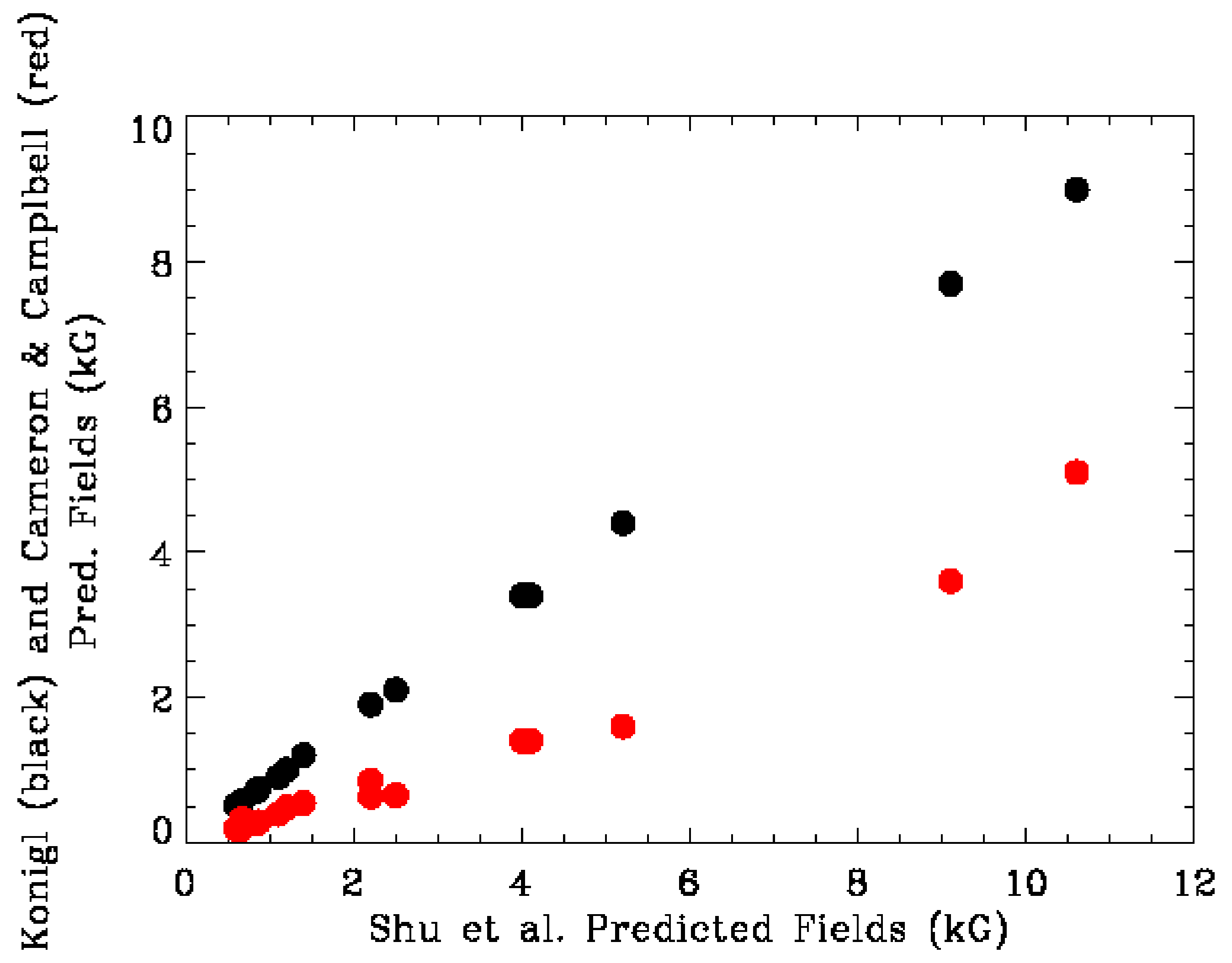
NOTE.—Magnetic field values are the equatorial field strengths assuming a dipole magnetic field.

[a] Magnetic field values from the theory of Königl 1991.

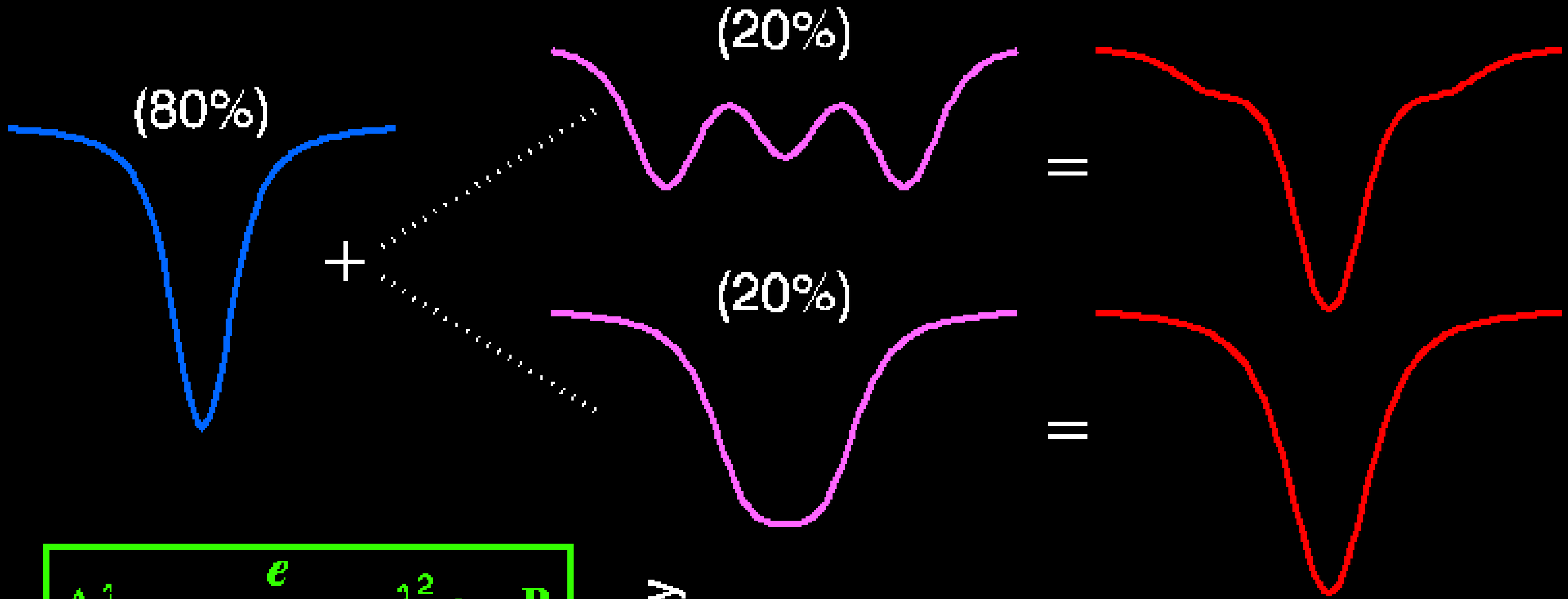
[b] Magnetic field values from the theory of Cameron & Campbell 1993.

[c] Magnetic field values from the theory of Shu et al. 1994.

Theoretical Predictions



Measuring Fields from Zeeman Broadening



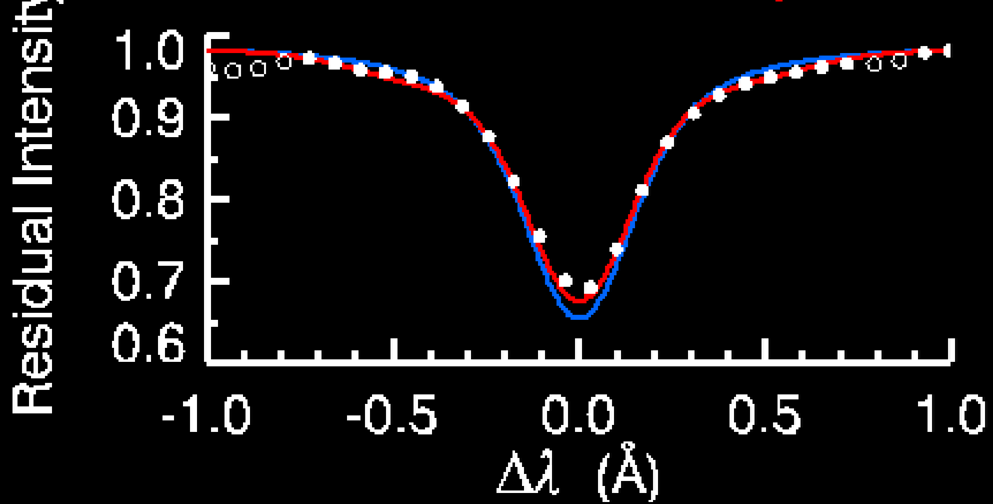
$$\boxed{\Delta\lambda = \frac{e}{4\pi\, mc^2}\,\lambda^2 g_{\rm eff}\, B}$$

ε Eri (K2 V)

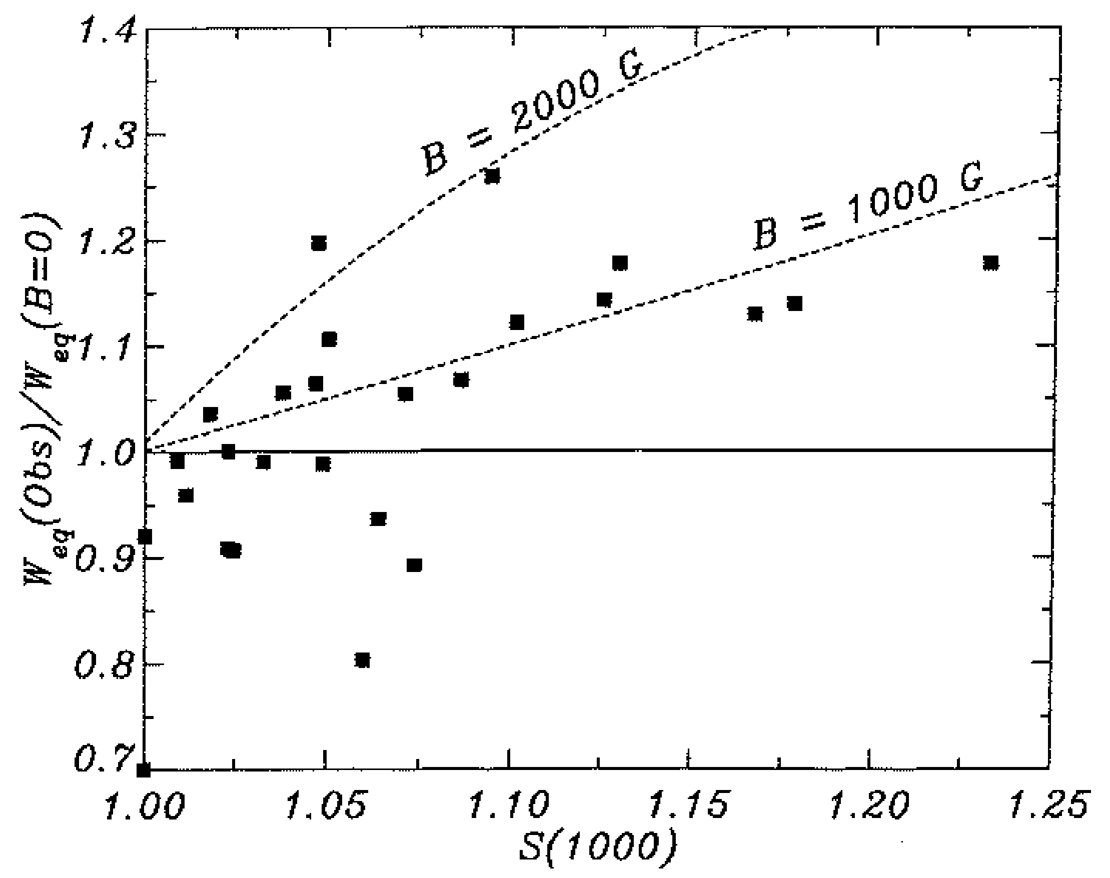
B = 1.44 kG, f = 9%

λ = 1.56485 μm

$g_{\rm eff}$ = 3.0



Early Measures of TTS Magnetic Fields

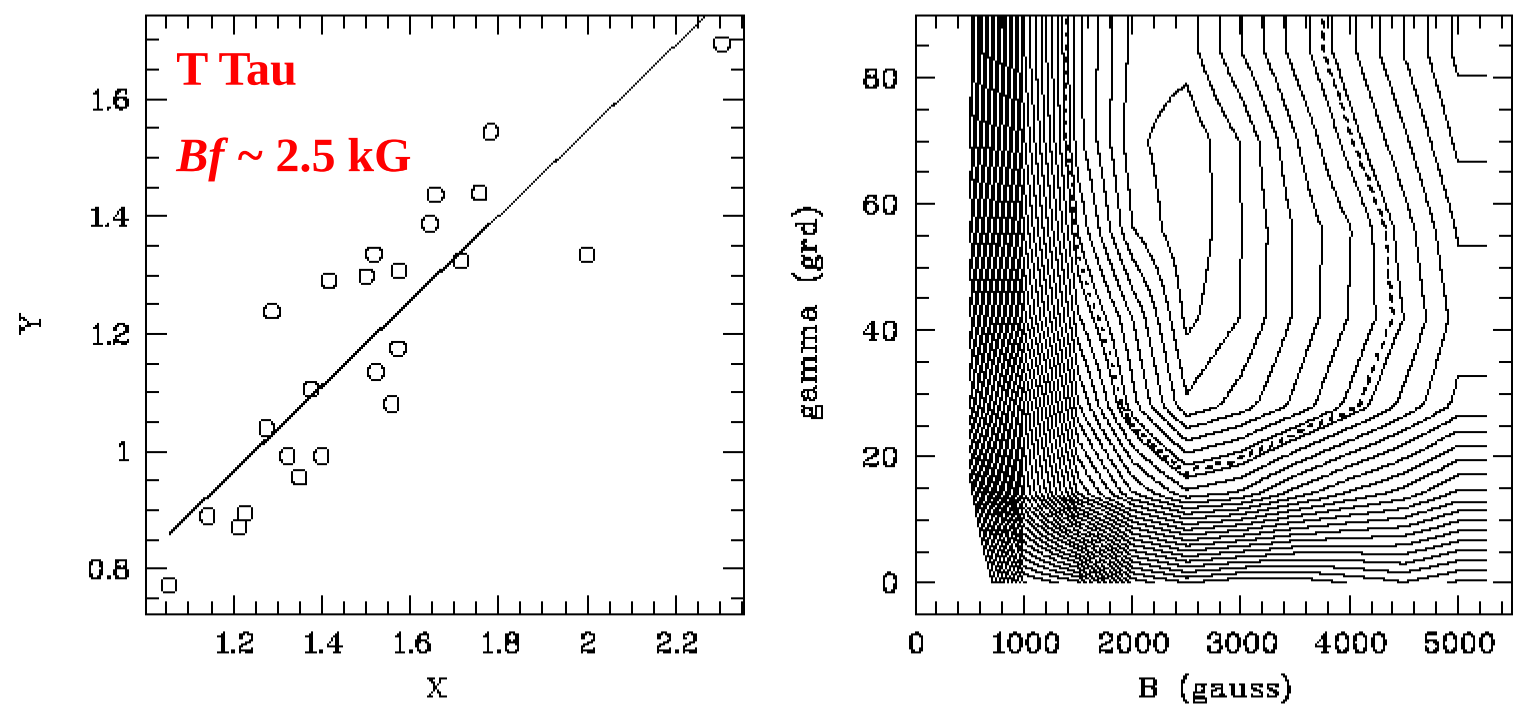


Model with B/Model Without B

- **Basri et al. (1992)**
- **Zeeman desaturation of optical line**
- ***R* = 60,000 spectra**
- **NTTS Tap 35 *Bf* ~ 1000 G**
- **NTTS Tap 10 *Bf* < 1500 G**

More Recent Field Measurements

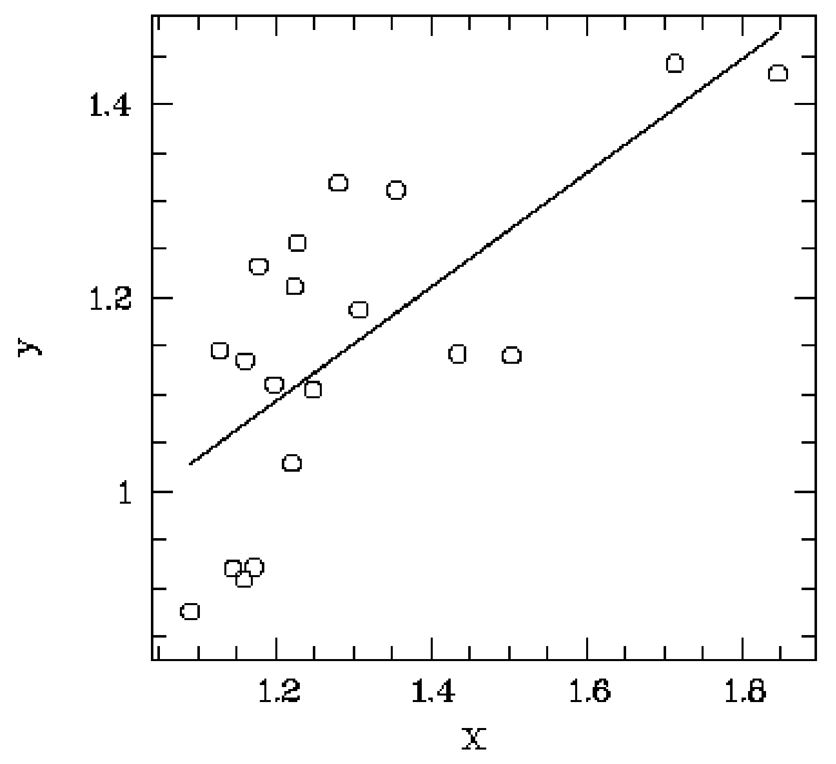
- **Guenther et al. (1999)**
- **Zeeman desaturation of optical lines**
- **Possibly detected fields on 4 stars: CTTS and NTTS**

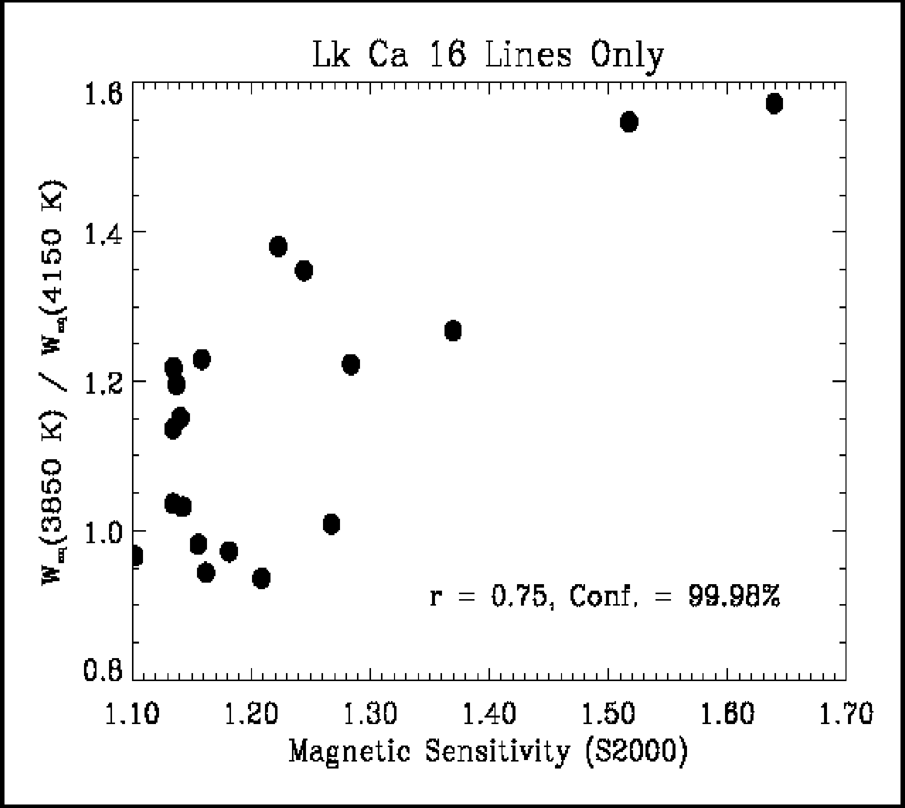


What Can Go Wrong

- Guenther et al. (1999)
- LkCa 16, r_{max} = 0.71, *Bf* ~ 2 kG

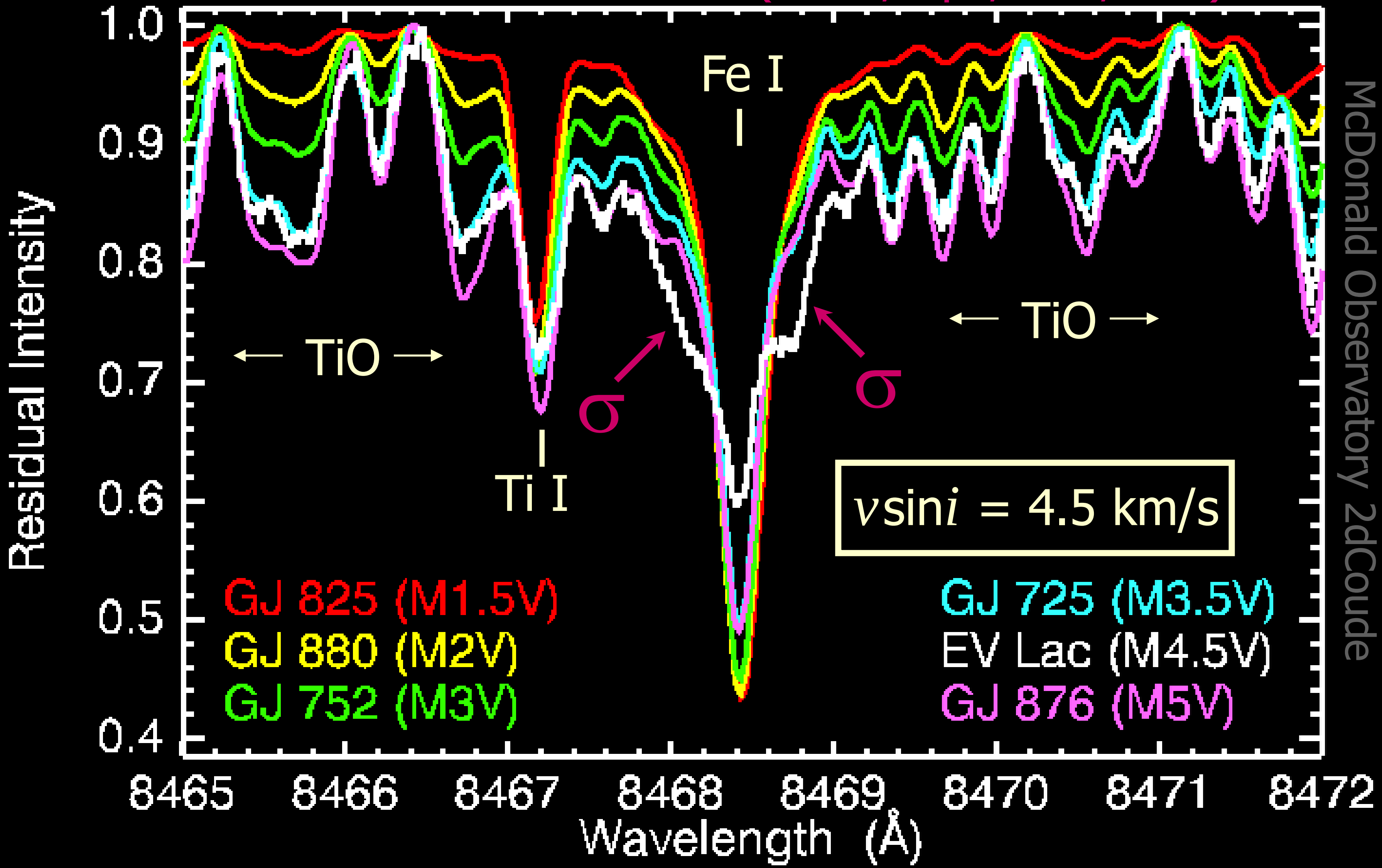
- Same Fe I lines used
- No Magnetic Field
- Temperature Error of 300 K





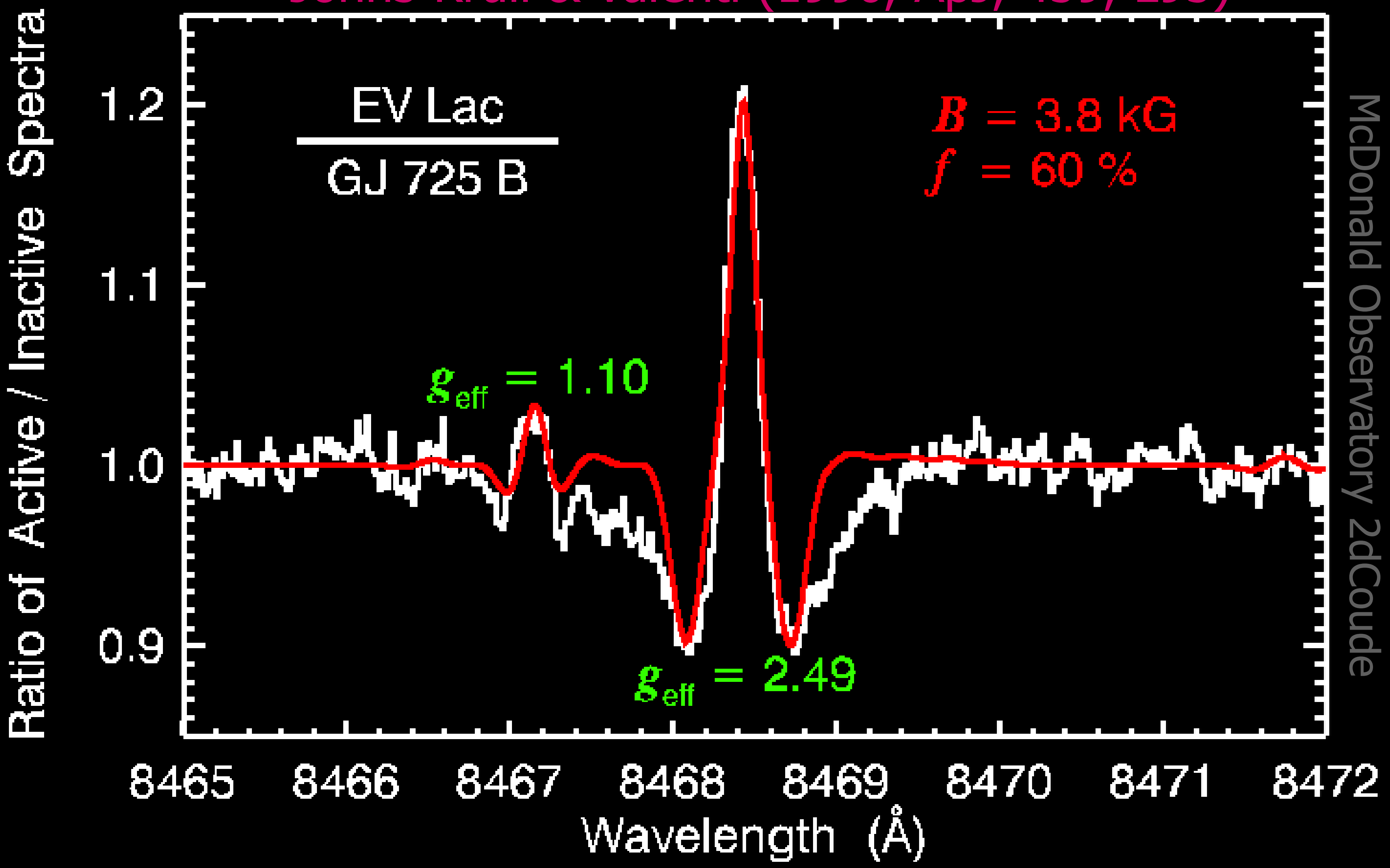
A Good Example

Johns-Krull & Valenti (1996, ApJ, 459, L95)

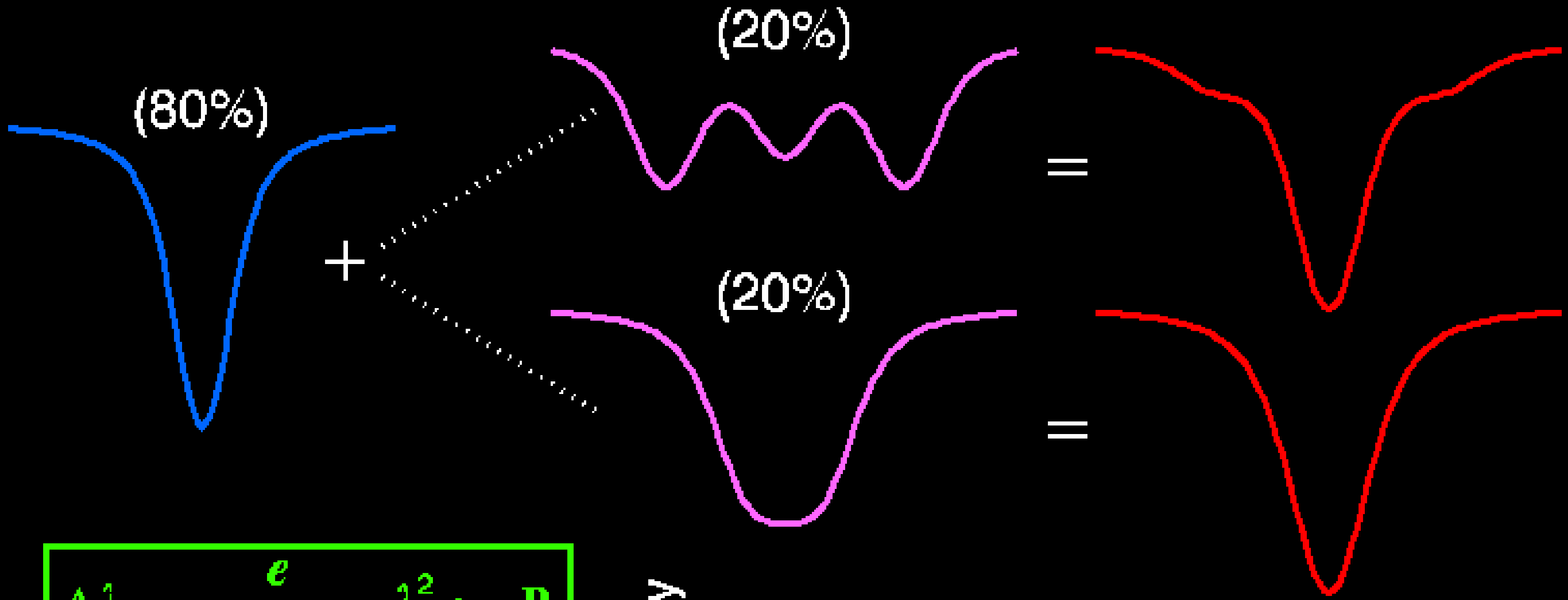


Getting Rid of the TiO

Johns-Krull & Valenti (1996, ApJ, 459, L95)



Going to the Infrared



$$\Delta\lambda = \frac{e}{4\pi mc^2}\lambda^2 g_{\mathrm{eff}} B$$

ε Eri (K2 V)

B = 1.44 kG, f = 9%

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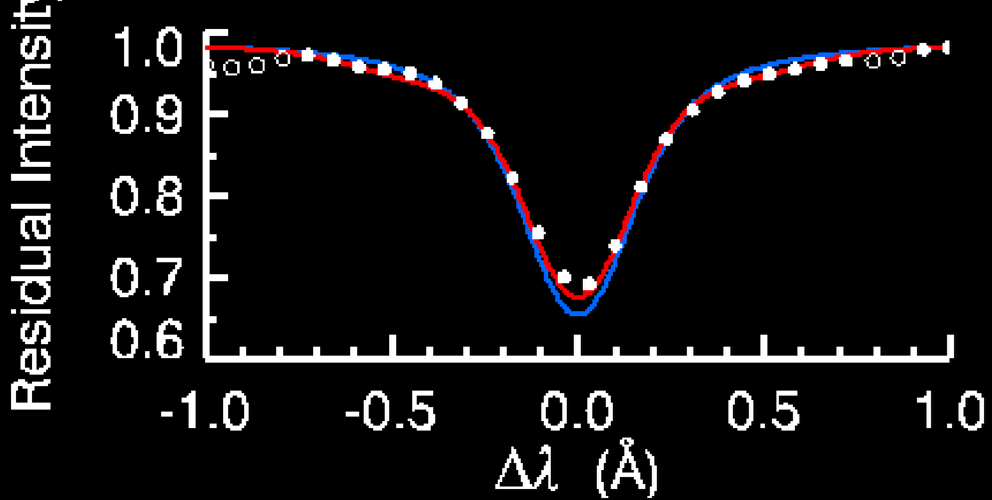
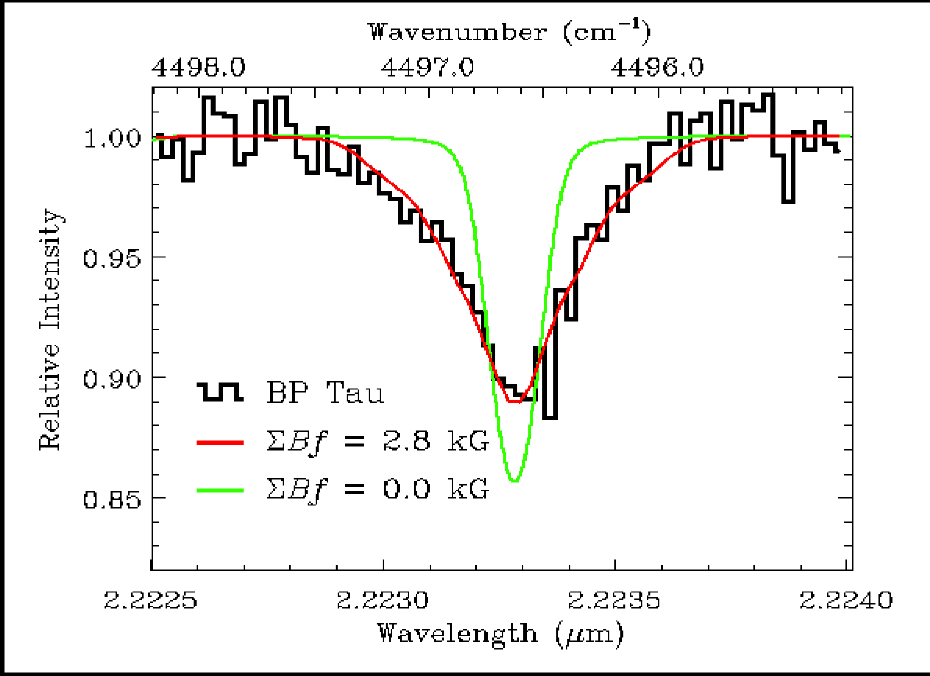
g_{eff} = 3.0



Going to the Infrared

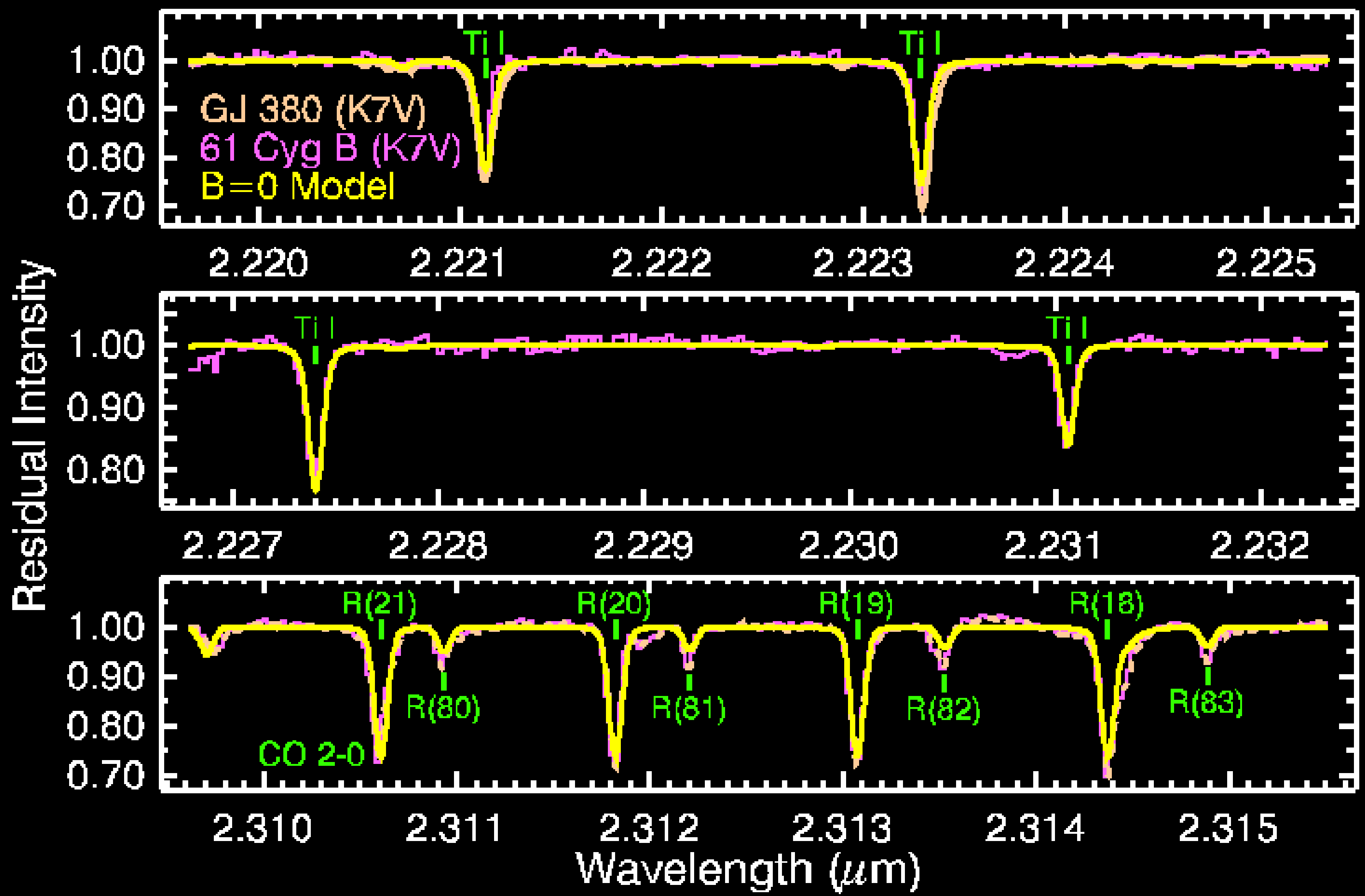
- Johns-Krull, Valenti, & Koresko (1999)
- NASA IRTF (3m) + CSHELL spectrometer
- *R* ~ 35,000 spectra
- Excess Broadening Clearly Seen in the Ti I line



Spectrum Synthesis

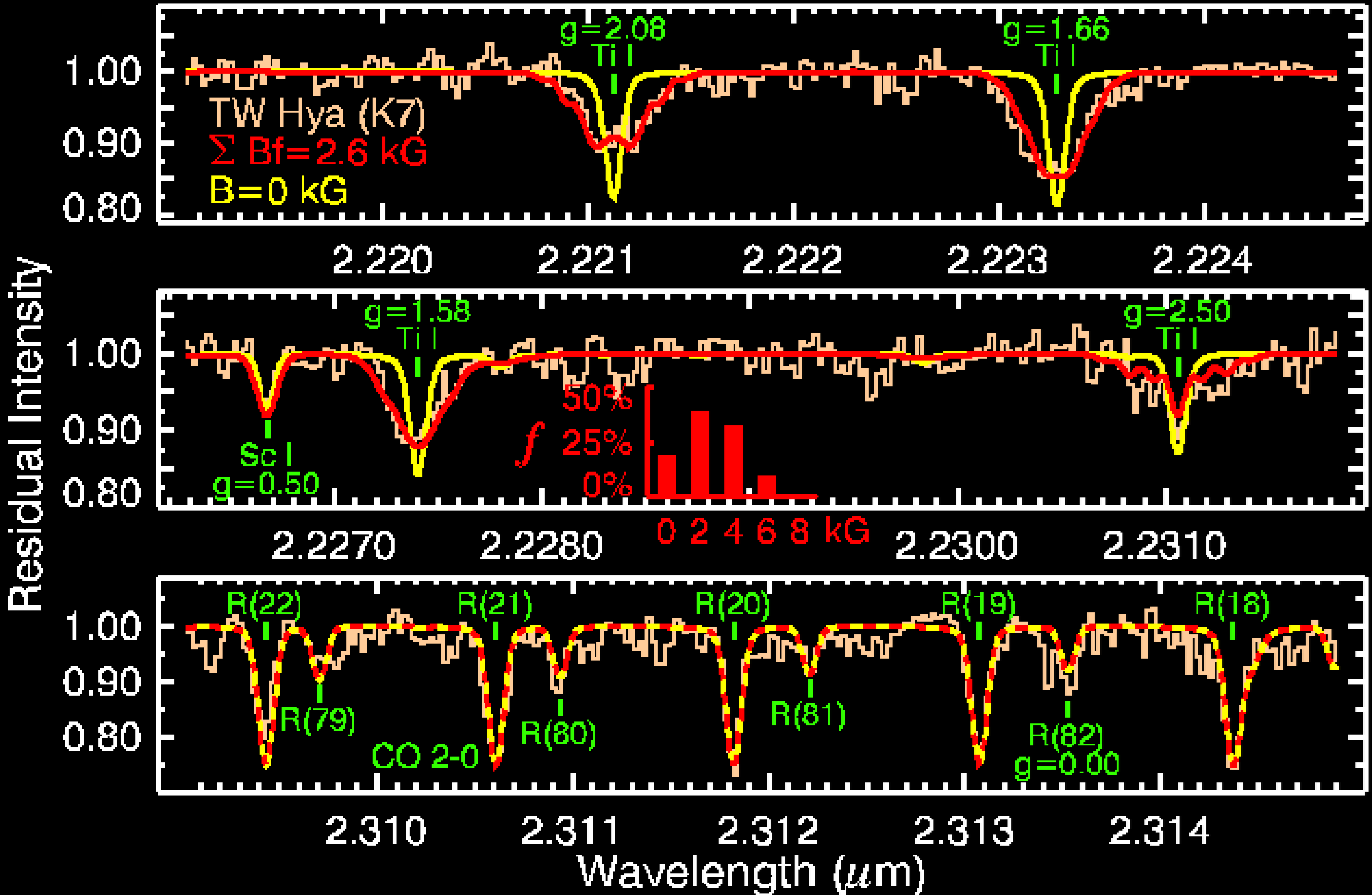
- **Full Stokes radiative transfer (Valenti & Piskunov 1998)**
- **Line data checked against solar models/observations**
- **NextGen model atmospheres (Allard & Hauschildt 1995)**
- **Magnetic field lines assumed radial at the stellar surface**
- **Distribution of field strengths allowed**
- **Magnetic 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



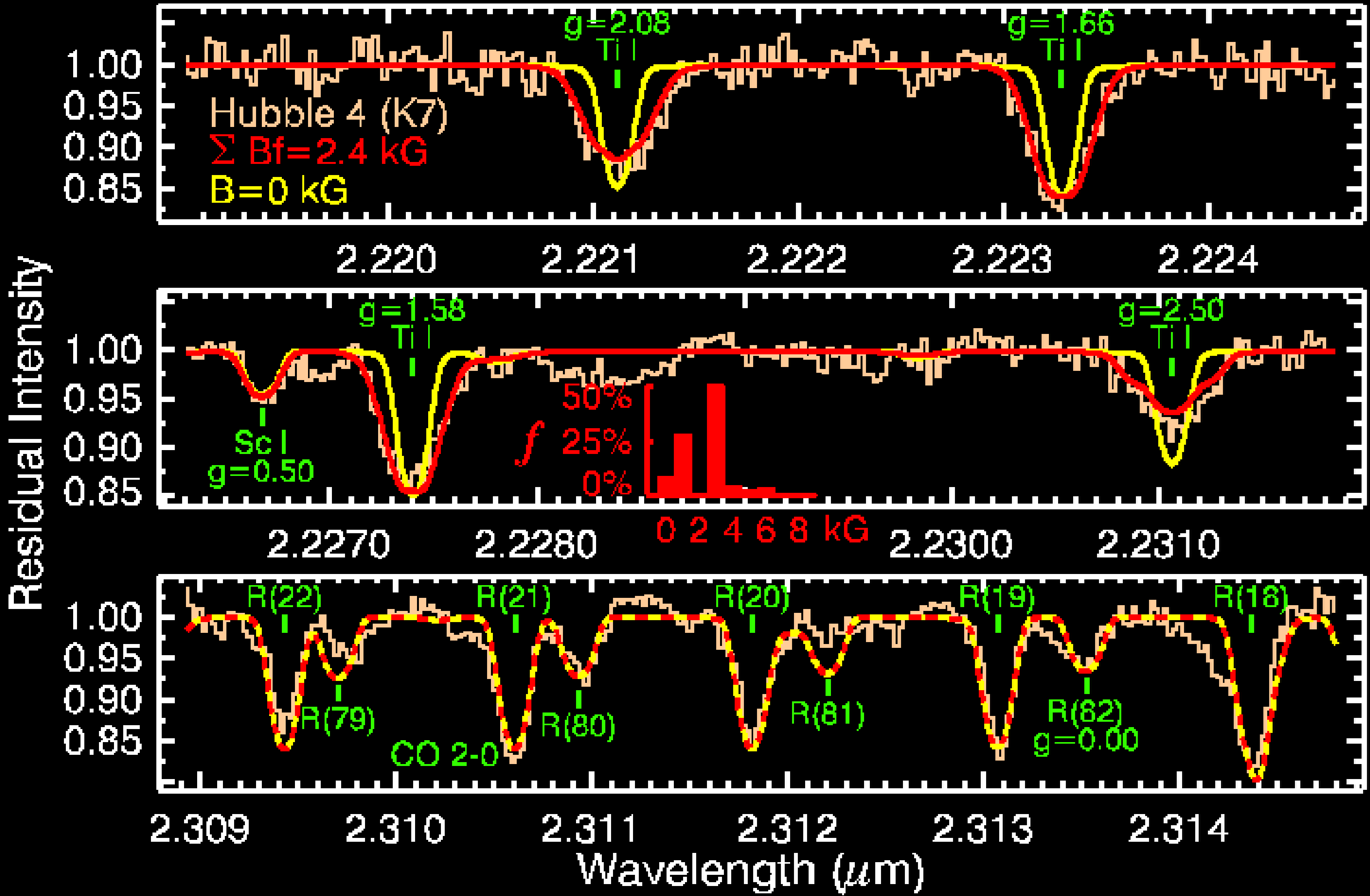
TW Hya: CTTS

Yang, Johns-Krull, & Valenti (2005)



Hubble 4: NTTS

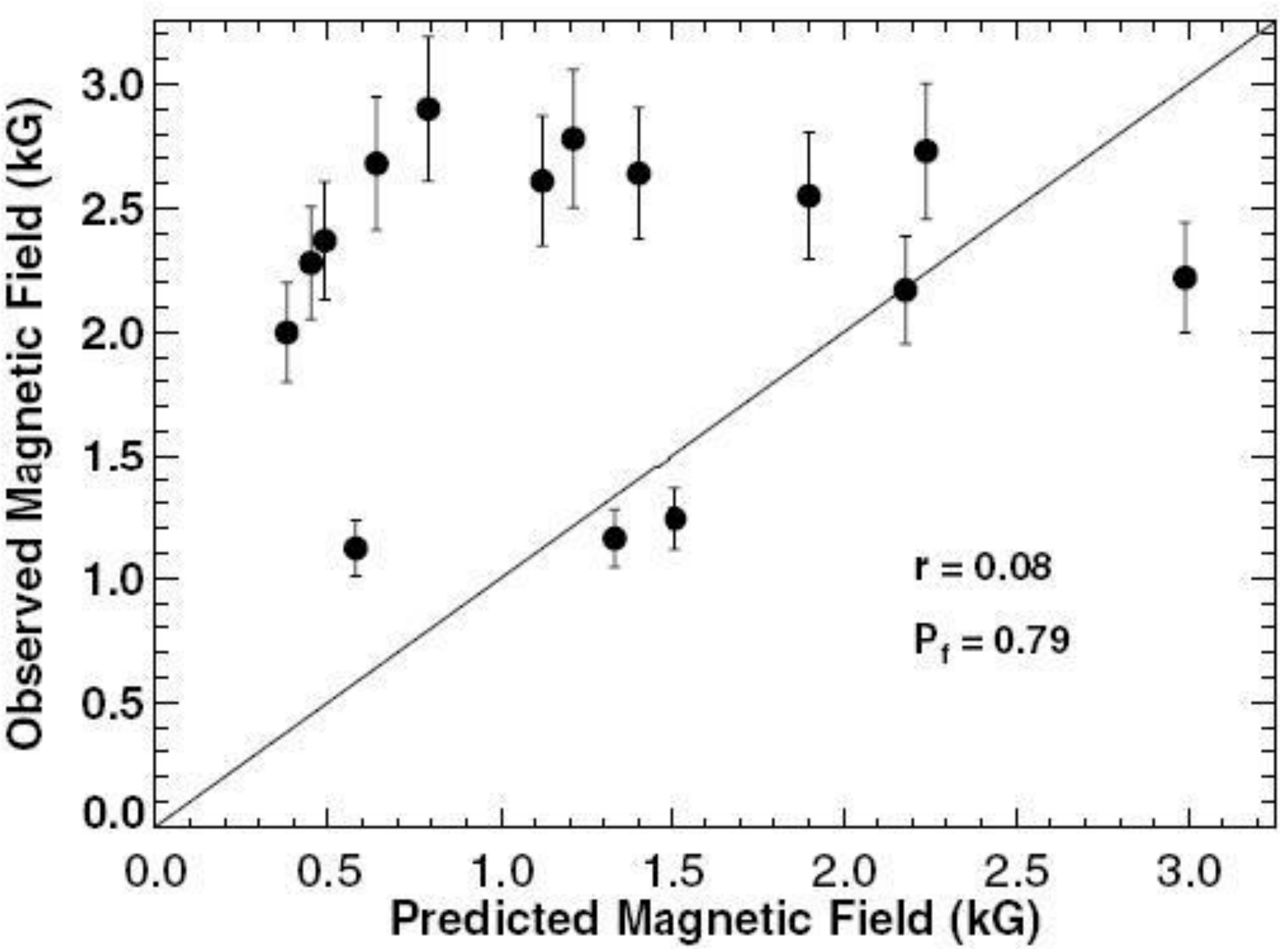
Johns-Krull, Valenti, & Saar (2004)



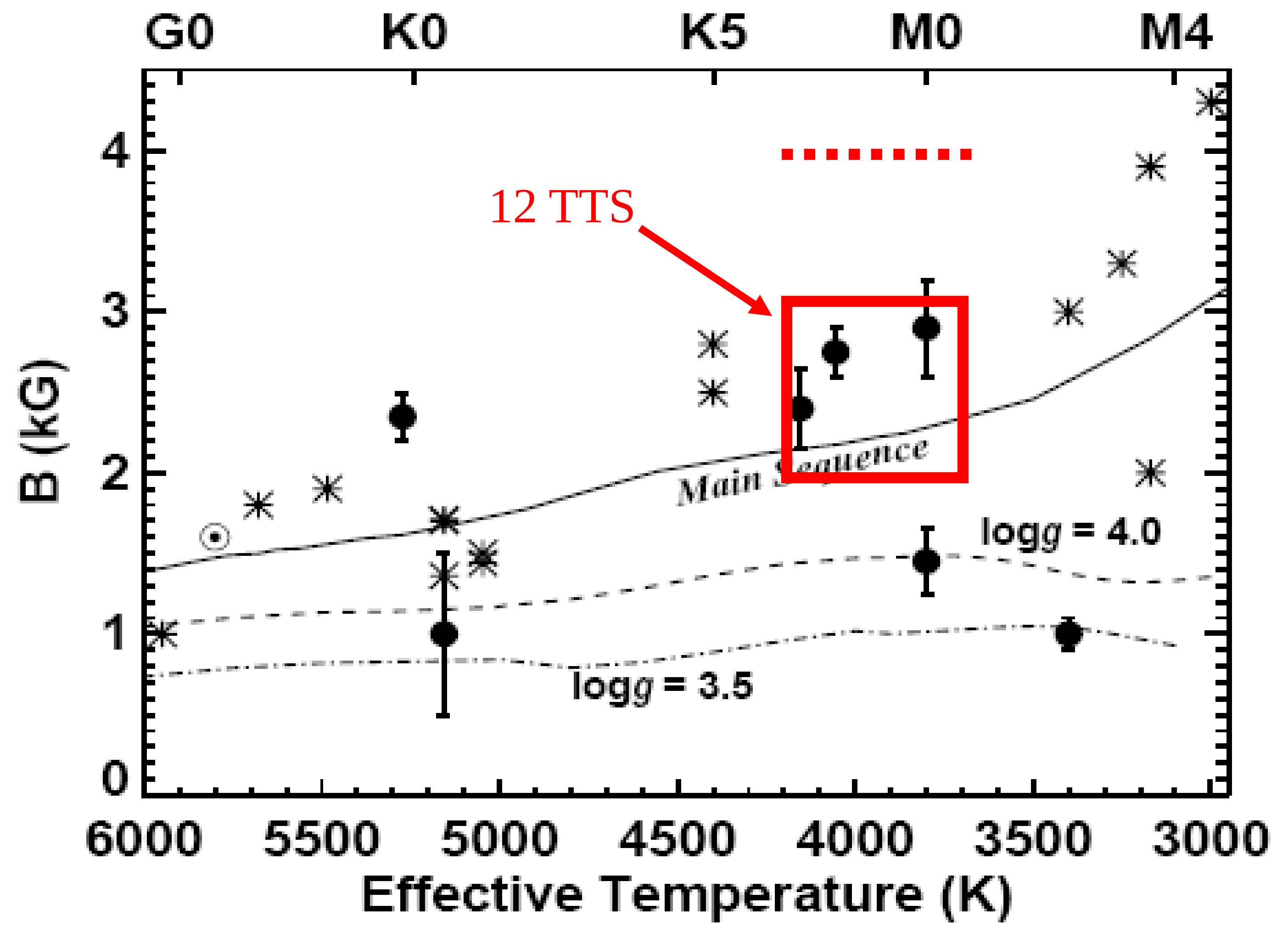
Predicted vs. Observed Mean Fields

Star	M_* ($M_\odot$)	R_* ($R_\odot$)	M x 10^8 ($M_\odot yr^{-1}$)	P_{rot} (days)	B_{Kon} (kG)	B_{Cam} (kG)	B_{Shu} (kG)	B_{obs} (kG)
AA Tau	0.53	1.74	0.33	8.20	0.81	0.24	0.96	2.57
BP Tau	0.49	1.99	2.88	7.60	1.37	0.49	1.62	2.17
CY Tau	0.42	1.63	0.75	7.90	1.17	0.39	1.38	
DE Tau	0.26	2.45	2.64	7.60	0.42	0.16	0.49	1.35
DF Tau	0.27	3.37	17.7	8.50	0.49	0.22	0.57	2.98
DK Tau	0.43	2.49	3.79	8.40	0.81	0.30	0.95	2.58
DN Tau	0.38	2.09	0.35	6.00	0.25	0.08	0.30	2.14
GG Tau A	0.44	2.31	1.75	10.30	0.89	0.32	1.05	1.57
GI Tau	0.67	1.74	0.96	7.20	1.45	0.45	1.70	2.69
GK Tau	0.46	2.15	0.64	4.65	0.27	0.09	0.32	2.13
GM Aur	0.52	1.78	0.96	12.00	1.99	0.66	2.34	
IP Tau	0.52	1.44	0.08	3.25	0.24	0.06	0.28	
T Tau	2.11	3.31	4.40	2.80	0.39	0.11	0.46	2.39
TW Hya	0.70	1.00	0.20	2.20	0.90	0.24	1.06	2.61

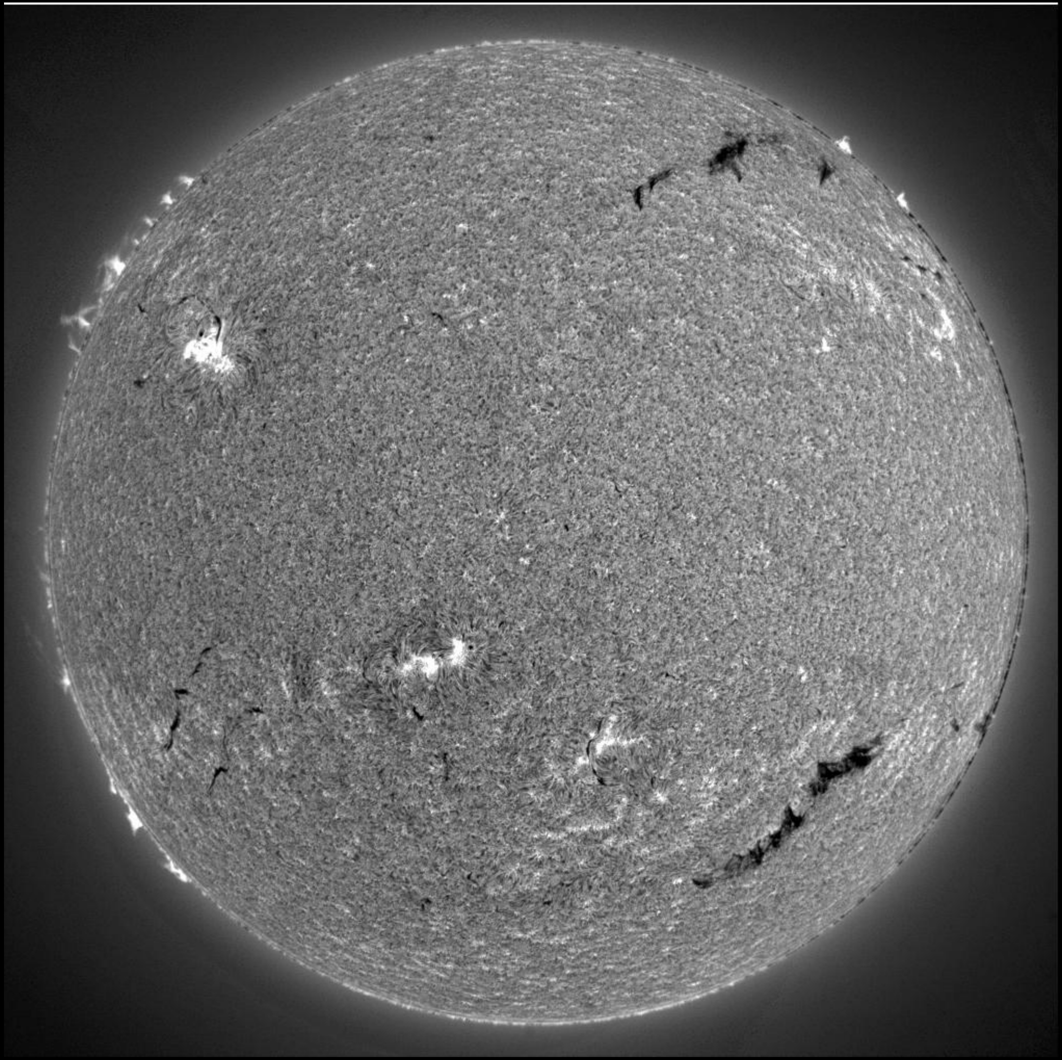
Predicted vs. Observed Mean Fields



Pressure Equilibrium Fields


12 TTS

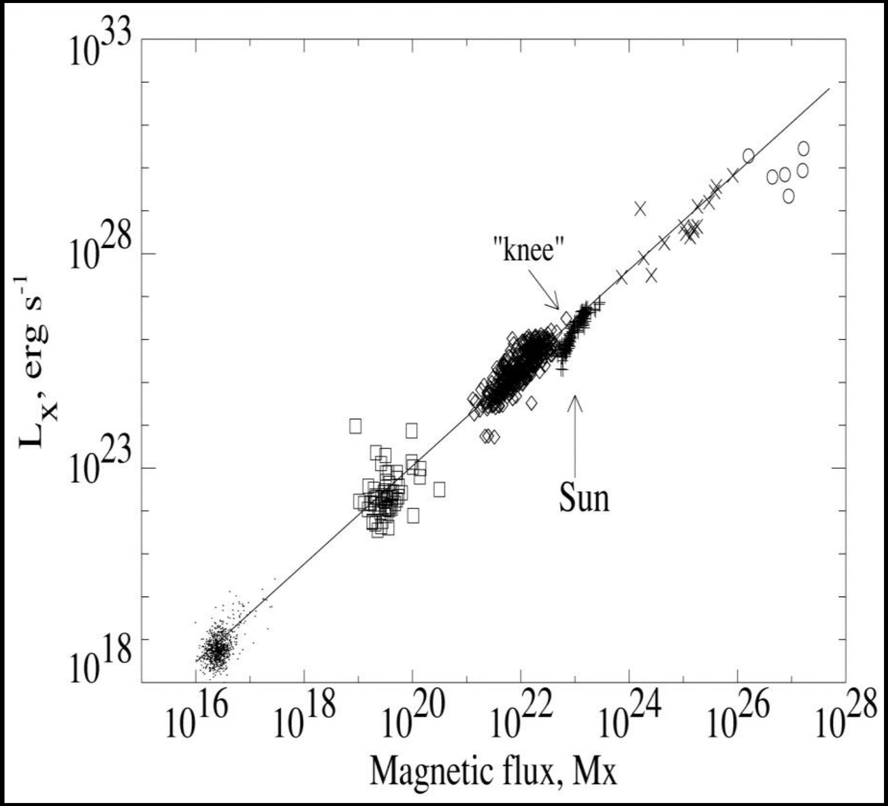
The Surface of a T Tauri Star?



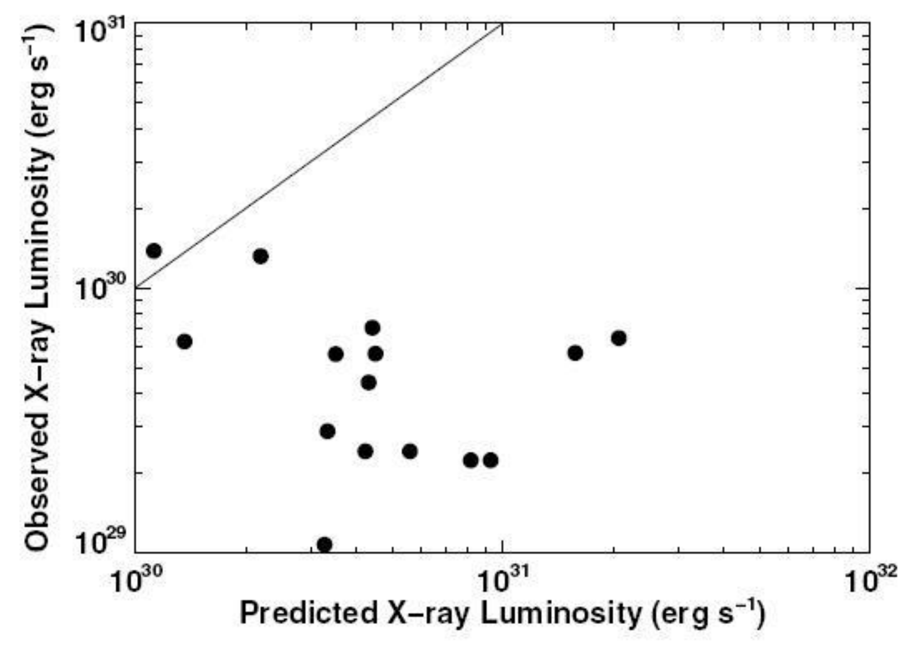
- The optical continuum forms in something like the solar chromosphere
- Polytropic models of TTS structure indicate that *B* field dominates only in outer 0.5-1.0%

Observed Fields & X-ray Emission

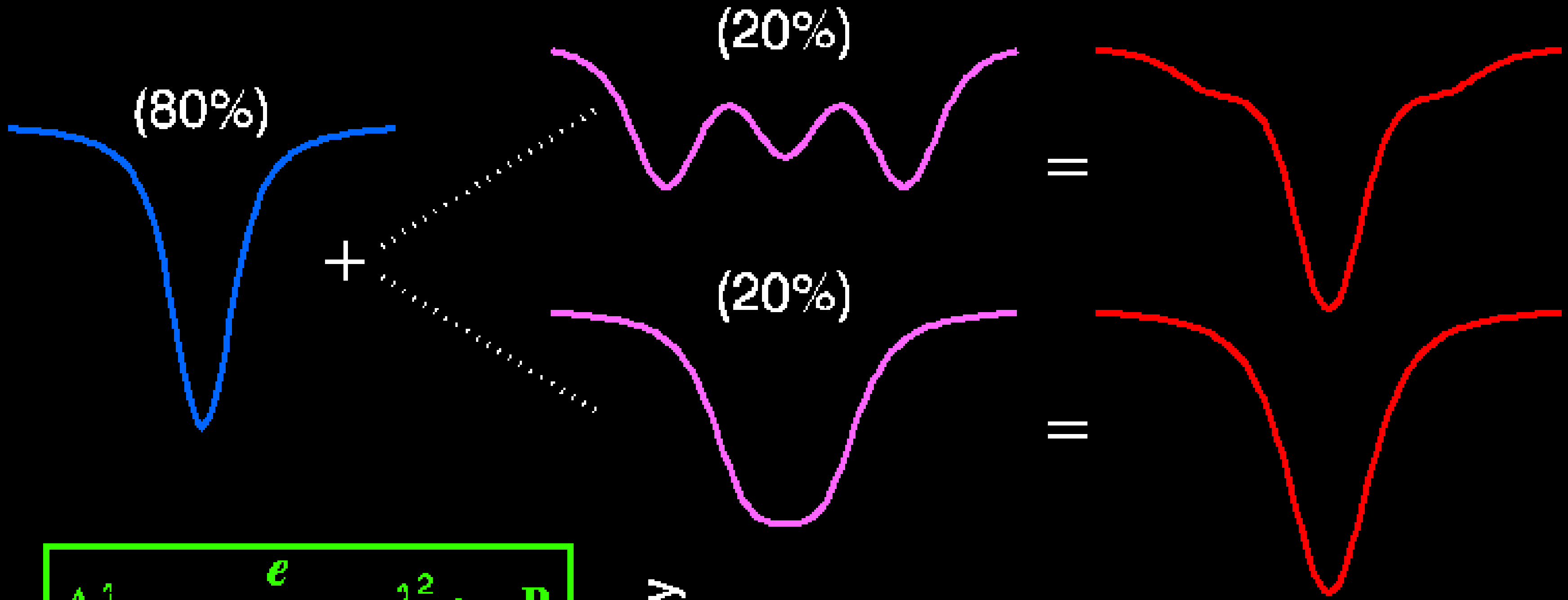
Pevtsov et al. (2003)



Johns-Krull (2007)



Circular Polarization



$$\boxed{\Delta\lambda = \frac{e}{4\pi\, mc^2}\,\lambda^2\, g_{\rm eff}\, B}$$

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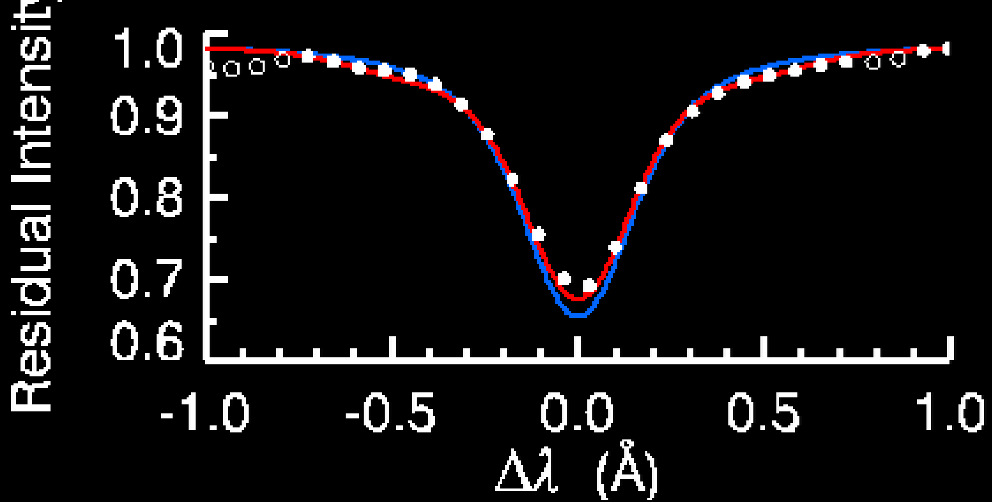
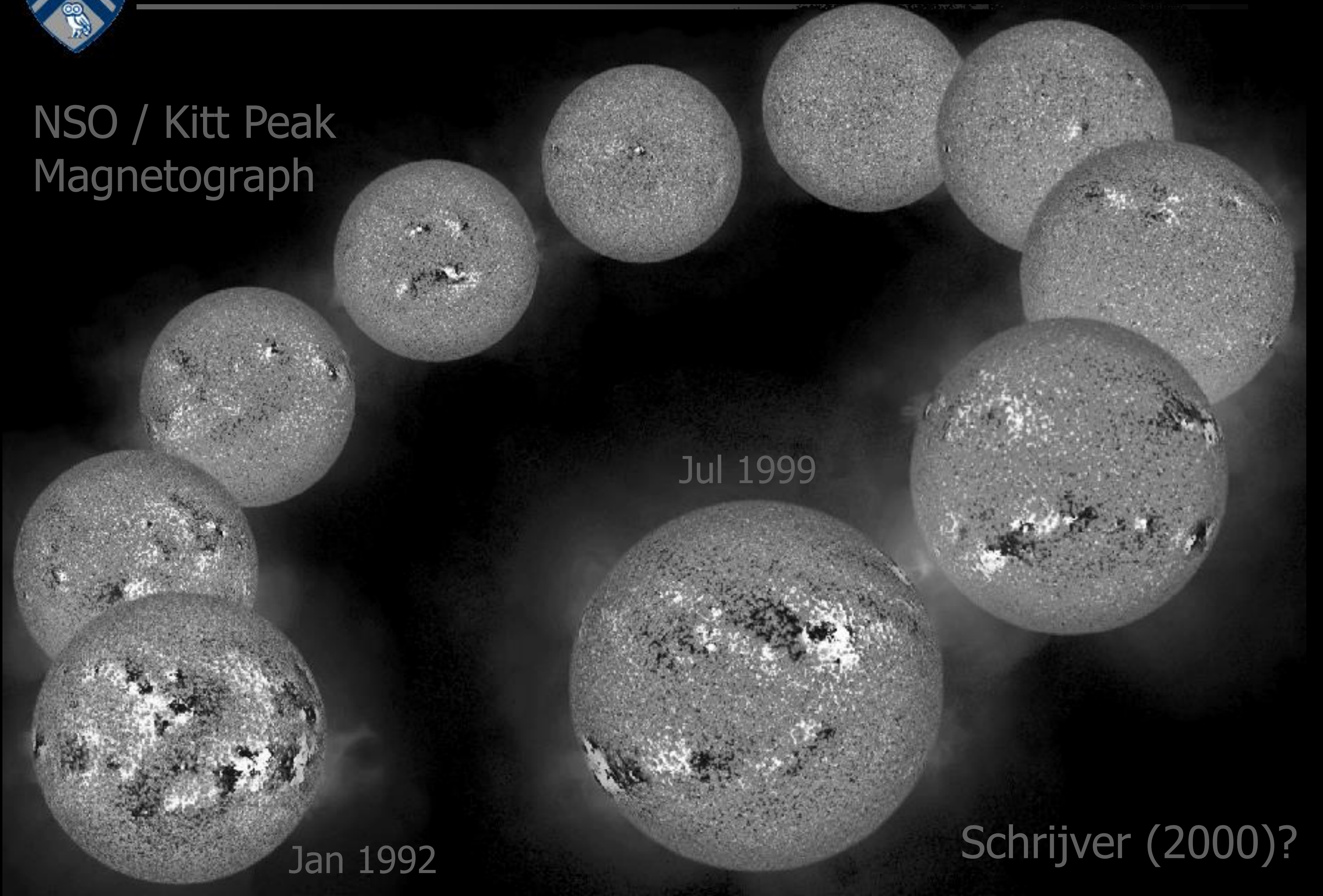


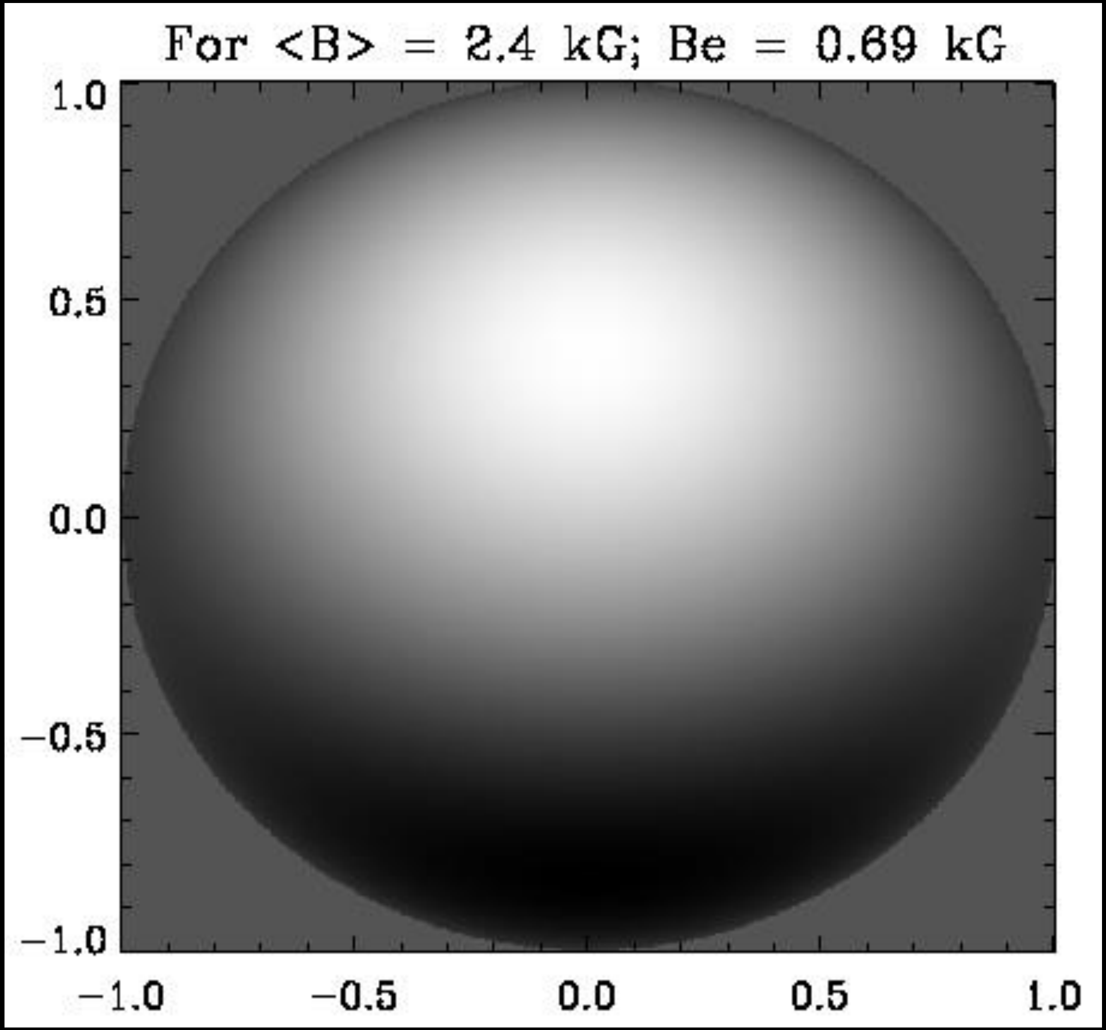
Field Geometry: Polarization



NSO / Kitt Peak
Magnetograph

Schrijver (2000)?

Field Geometry: Polarization from a Dipole

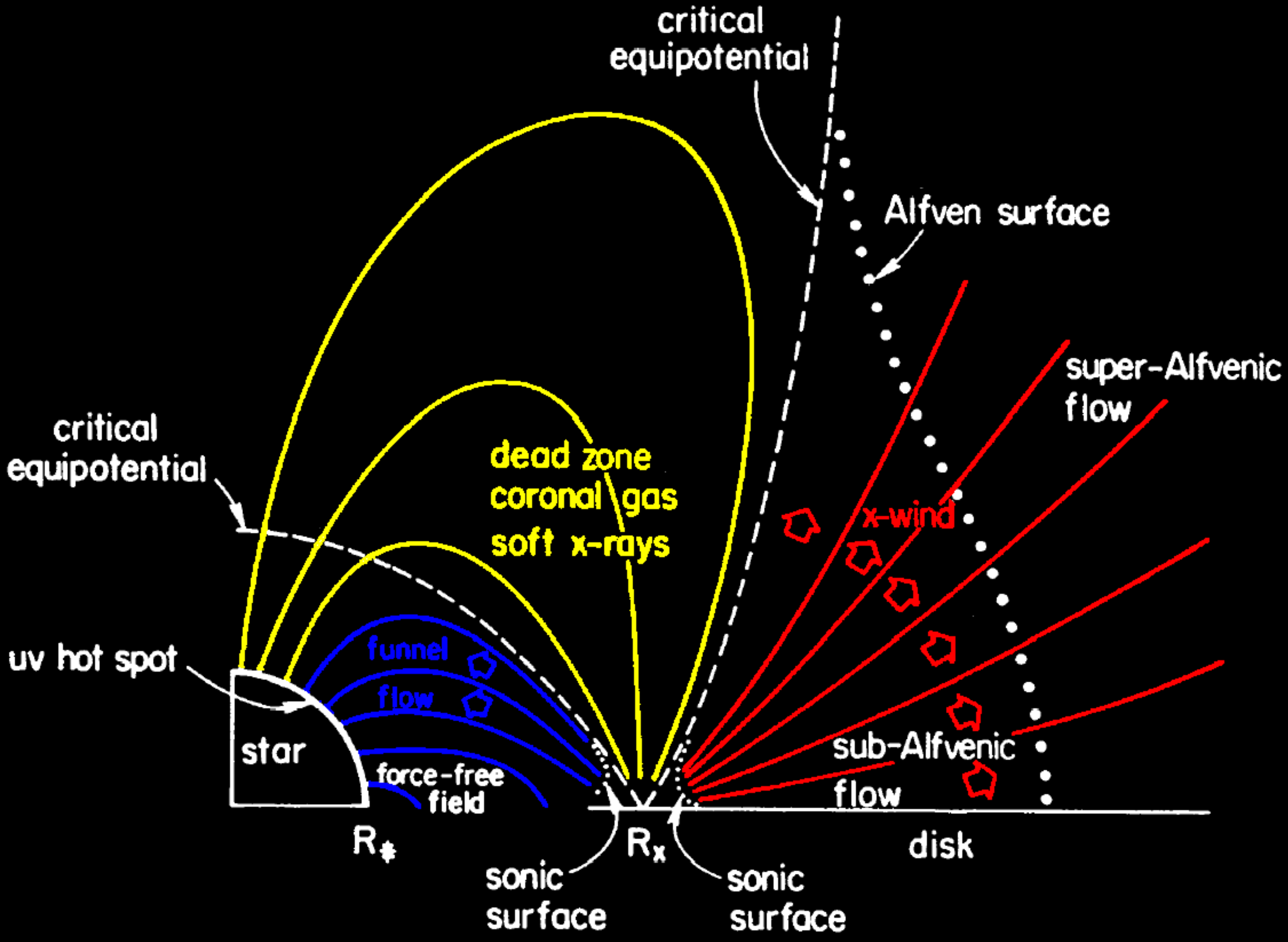


- **Brown & Landstreet (1981)**
- **T Tau B_Z < 816 G**
- **Predicted 320-1280 G x 0.31 = 99-400 G**
- **<B> = 2.4 kG gives B_Z = 950 G**

- **Johnstone & Penston (1986, 1987)**
- **RU Lup: B_Z< 494 G, B_p< 1400 G**
- **GW Ori: B_Z< 1.1 kG, B_p< 3.2 kG**
- **CoD-34 7151: B_Z< 2.0 kG, B_p< 5.8 kG, B_{pred}< 0.4 kG**

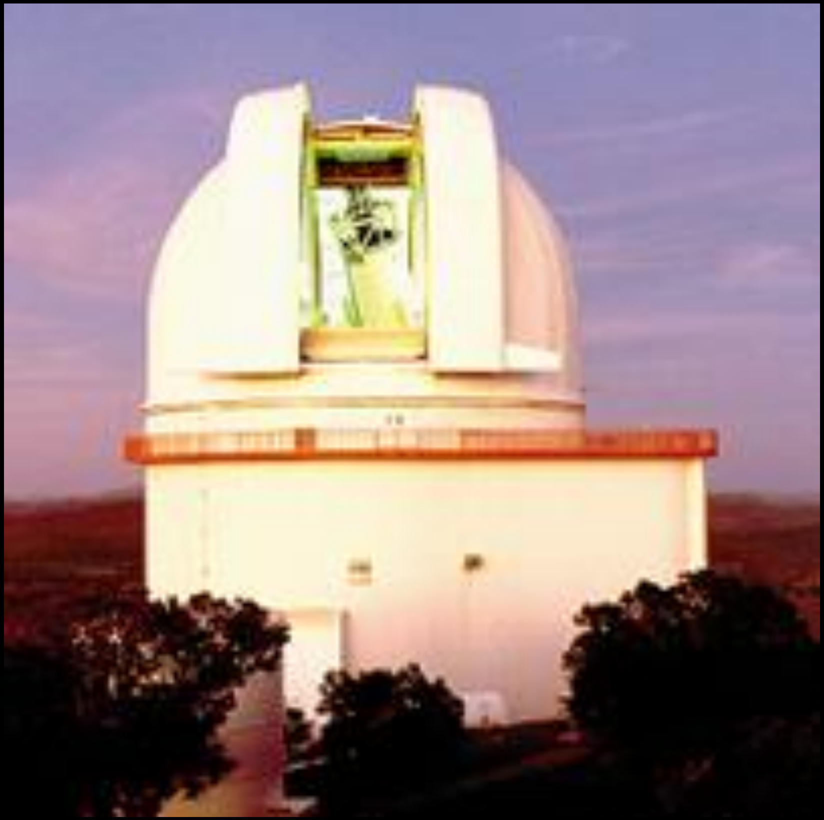
The Close Circumstellar Environment

Shu et al. (1994)

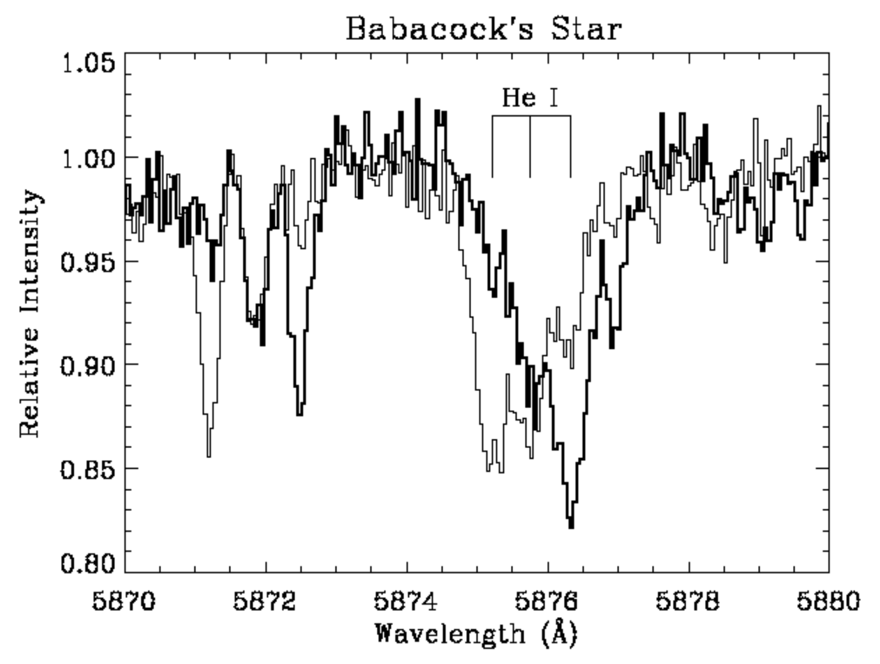


Theory gives field at some point in the disk

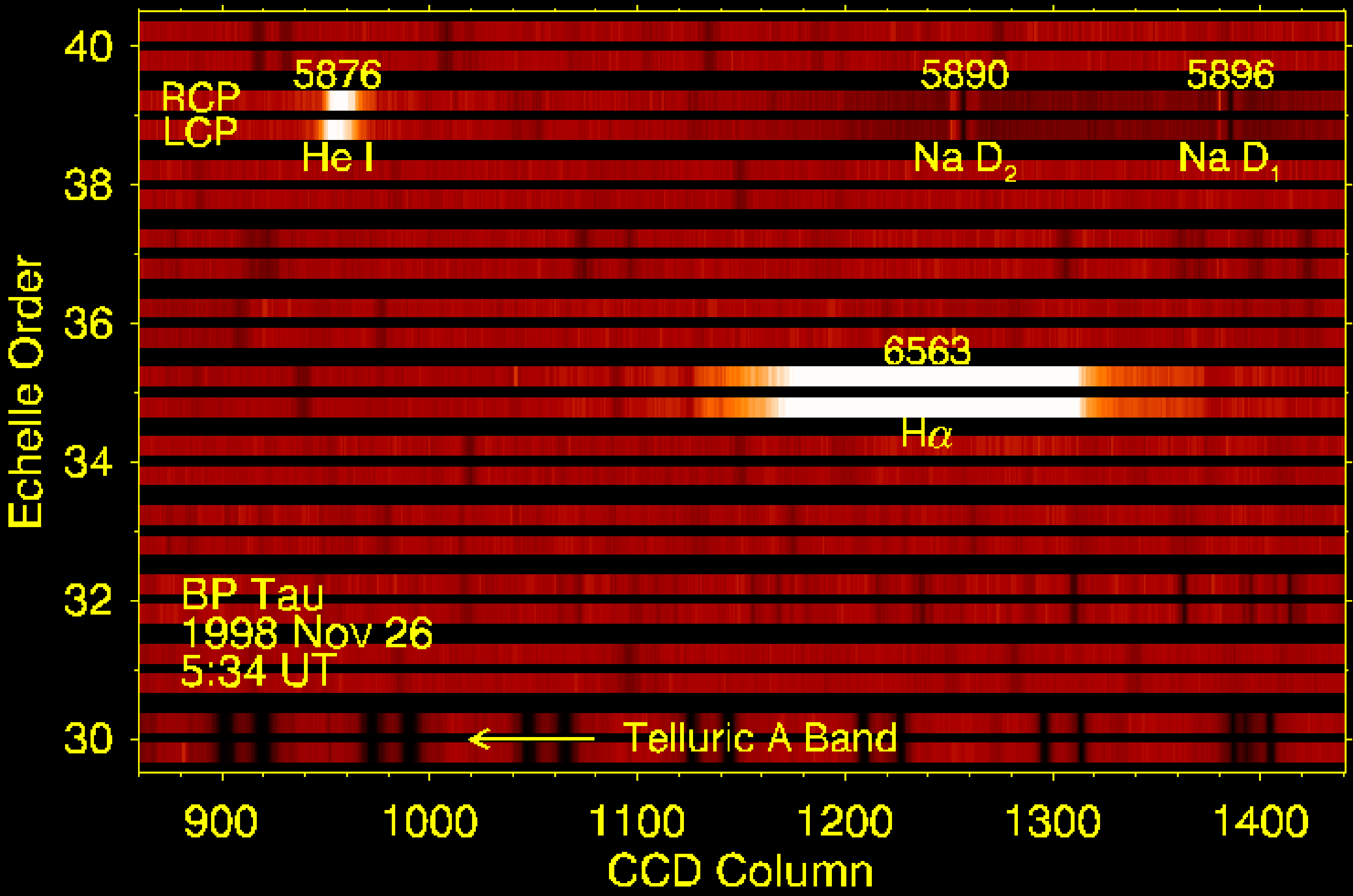
New Polarization Observations of TTS



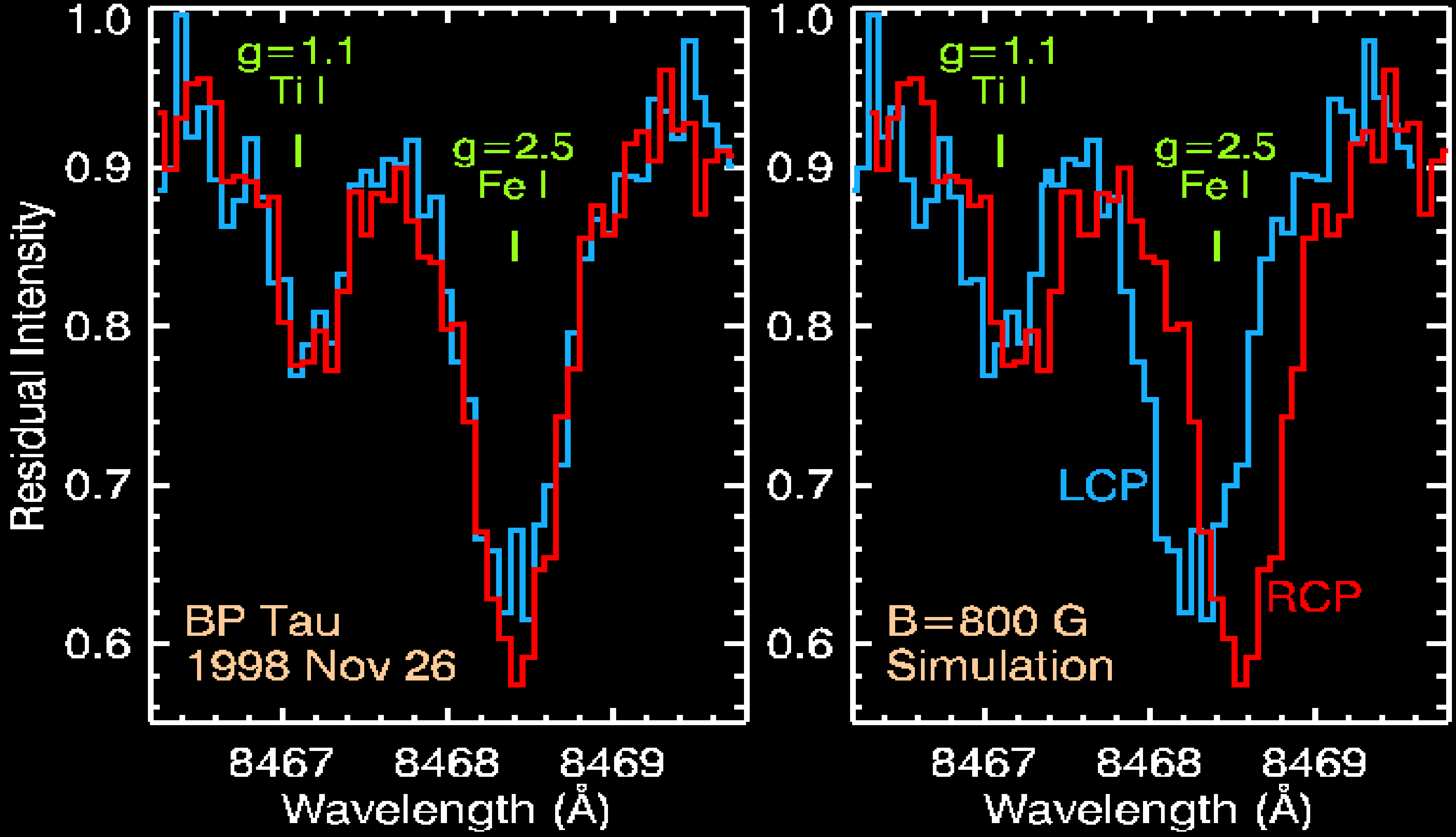
- **Johns-Krull et al. (1999a)**
- **McDonald Observatory 2.7m**
- **R = 60,000 echelle spectrometer**
- **Zeeman Analyzer (Vogt 1980)**



TTS Spectrapolarimetry



The Photospheric Field of BP Tau



The Photospheric Field of BP Tau

Johns-Krull et al. (1999a)

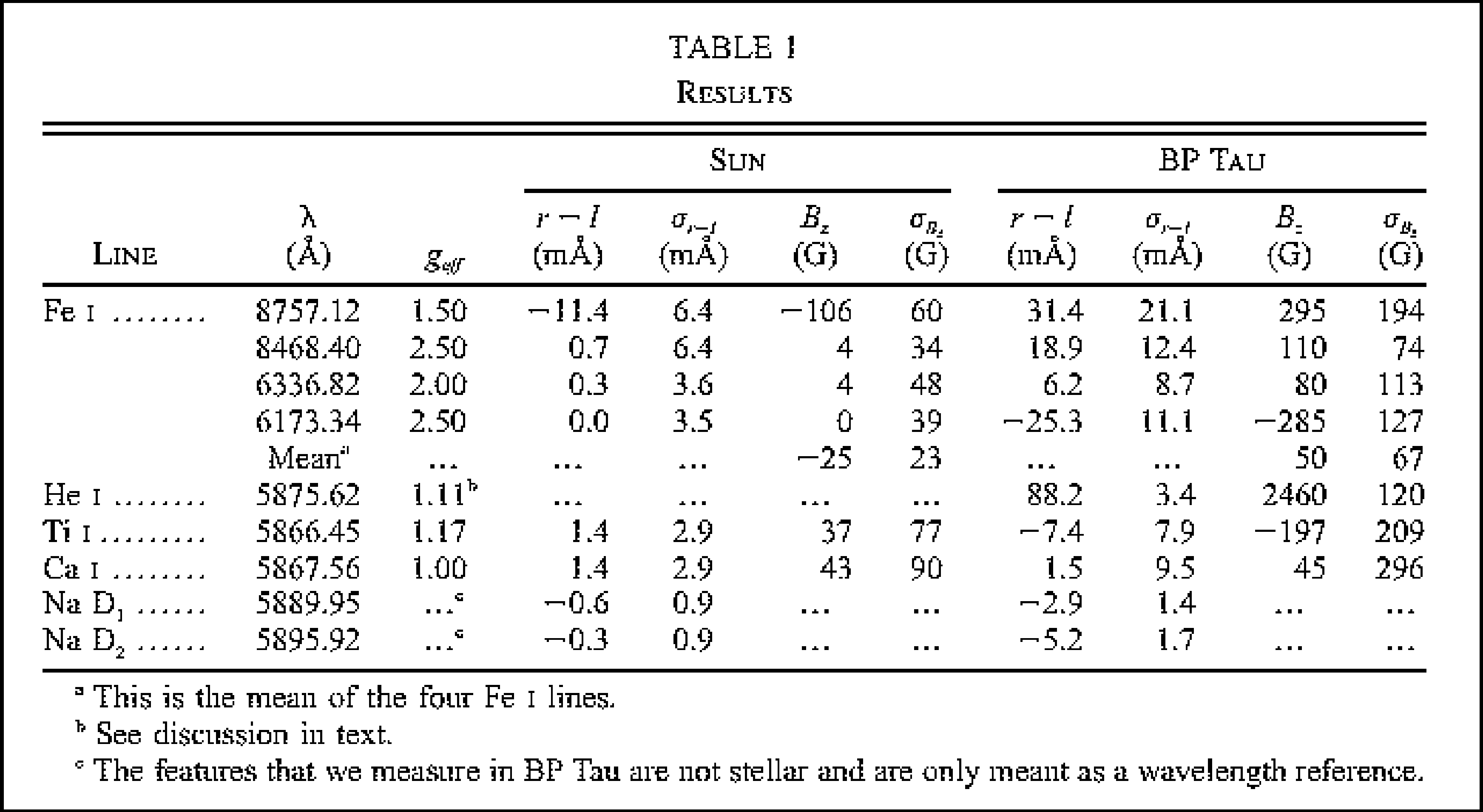


TABLE 1

RESULTS

LINE	λ (Å)	g_{eff}	SUN $r-l$ (mÅ)	SUN σ_{r-l} (mÅ)	SUN B_z (G)	SUN σ_{B_z} (G)	BP TAU $r-l$ (mÅ)	BP TAU σ_{r-l} (mÅ)	BP TAU B_z (G)	BP TAU σ_{B_z} (G)
Fe I	8757.12	1.50	−11.4	6.4	−106	60	31.4	21.1	295	194
	8468.40	2.50	0.7	6.4	4	34	18.9	12.4	110	74
	6336.82	2.00	0.3	3.6	4	48	6.2	8.7	80	113
	6173.34	2.50	0.0	3.5	0	39	−25.3	11.1	−285	127
	Mean[a]	...	...	...	−25	23	...	...	50	67
He I	5875.62	1.11[b]	...	...	...	...	88.2	3.4	2460	120
Ti I	5866.45	1.17	1.4	2.9	37	77	−7.4	7.9	−197	209
Ca I	5867.56	1.00	1.4	2.9	43	90	1.5	9.5	45	296
Na D_1	5889.95	...[c]	−0.6	0.9	...	...	−2.9	1.4	...	...
Na D_2	5895.92	...[c]	−0.3	0.9	...	...	−5.2	1.7	...	...

[a] This is the mean of the four Fe I lines.

[b] See discussion in text.

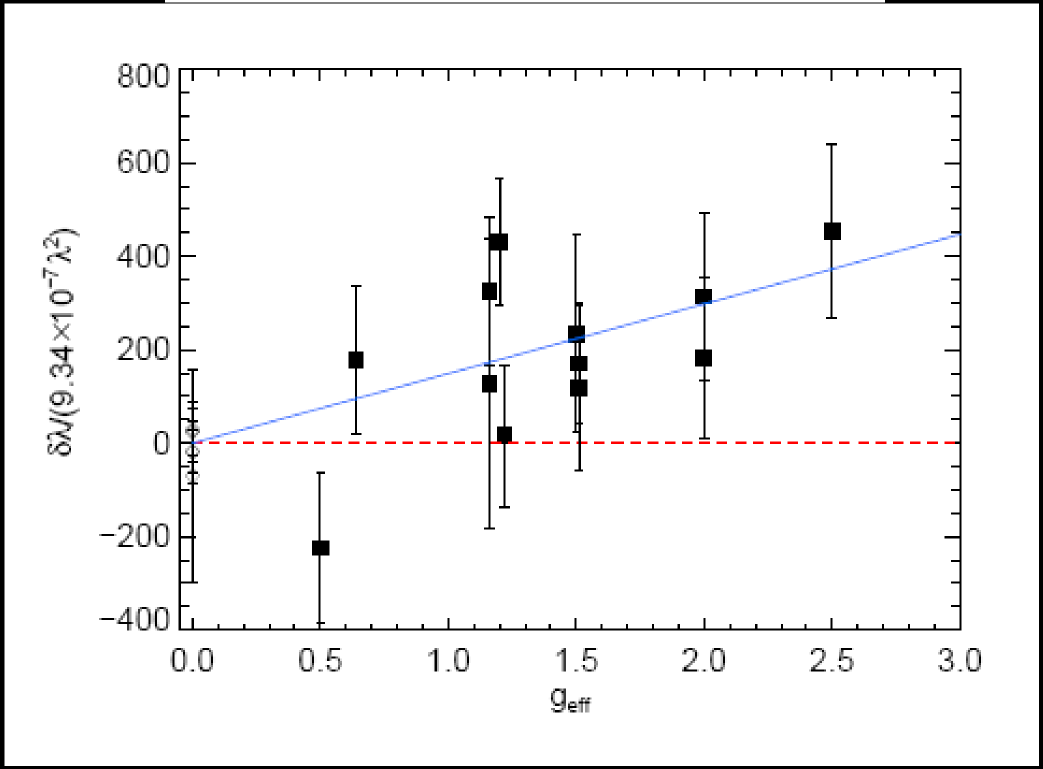
[c] The features that we measure in BP Tau are not stellar and are only meant as a wavelength reference.

Additional Spectropolarimetry

TW Hya

- Recall, |B| = 2.6 kG → B_Z = 1040 G
- Yang, Johns-Krull, & Valenti (2006) find $B_Z < 150$ G

$$\Delta\lambda = 2\frac{e}{4\pi m_e c^2}\lambda^2 g_{\rm eff} B_z = 9.34\times10^{-7}\lambda^2 g_{\rm eff} B_z \quad \text{mÅ}$$

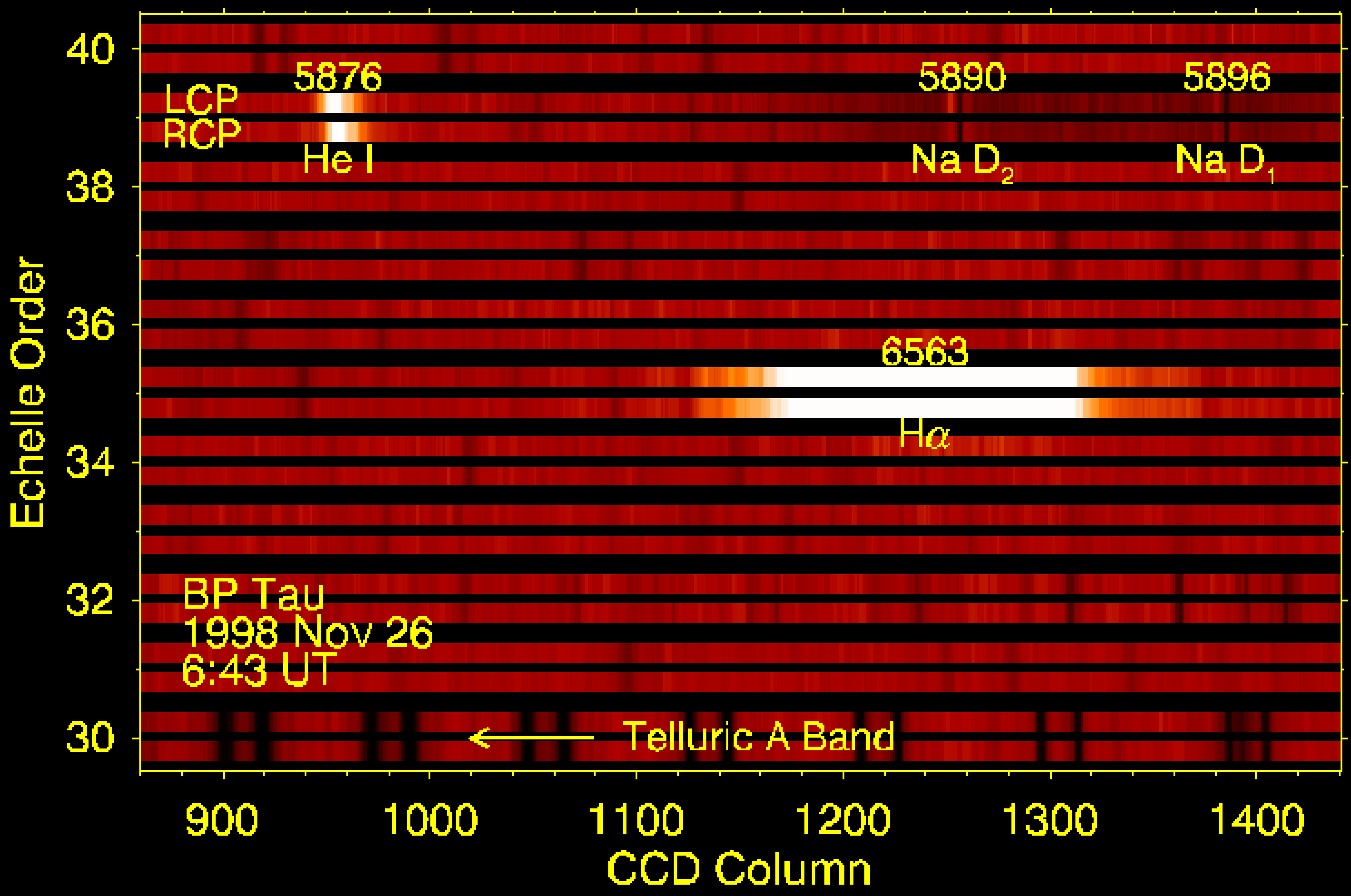


T Tau

- Recall, |B| = 2.4 kG → *BZ* = 950 G
- Smirnov et al. (2003): *BZ* = 160 +/- 40 G
- Not confirmed by Smirnov et al. (2004)
- Daou, Johns-Krull, & Valenti (2006) find $B_Z < 105$ G (3σ)

- Multiple observations rule out misaligned dipole at 97%

Polarization of Accretion Shock Material

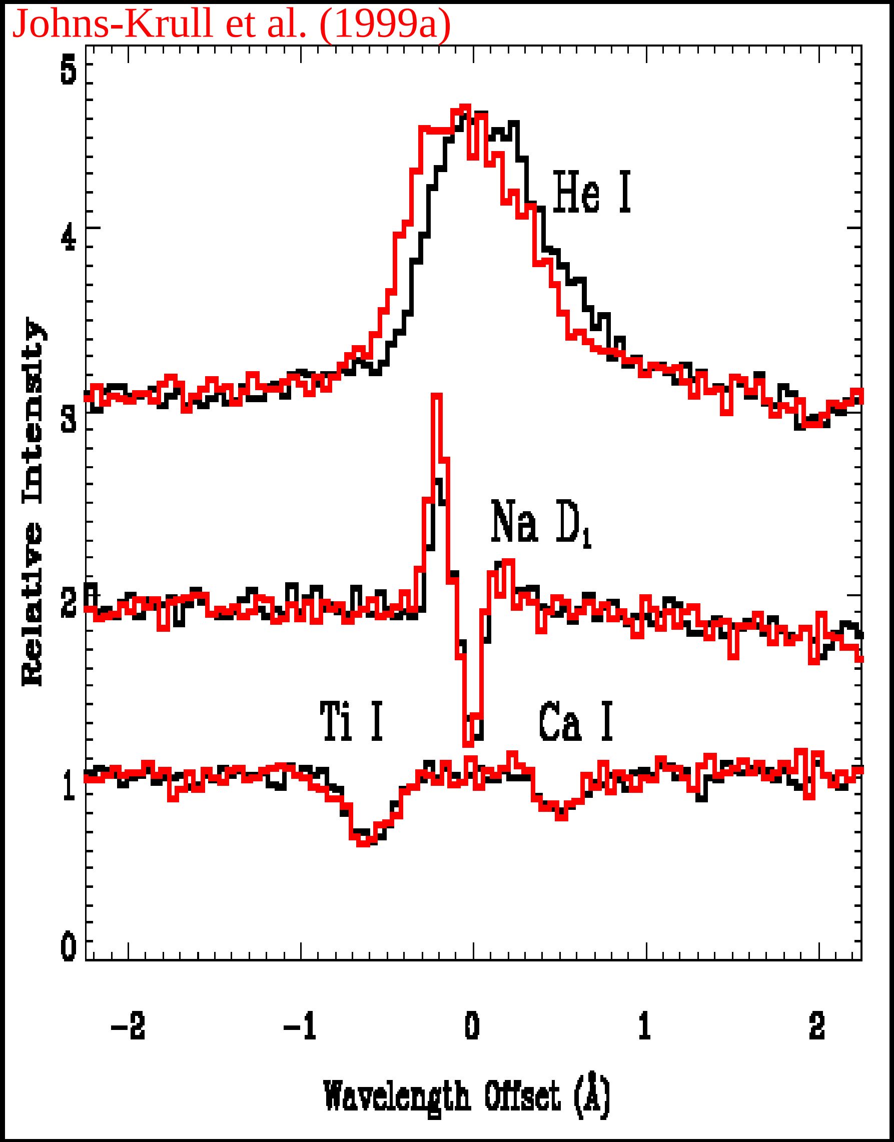


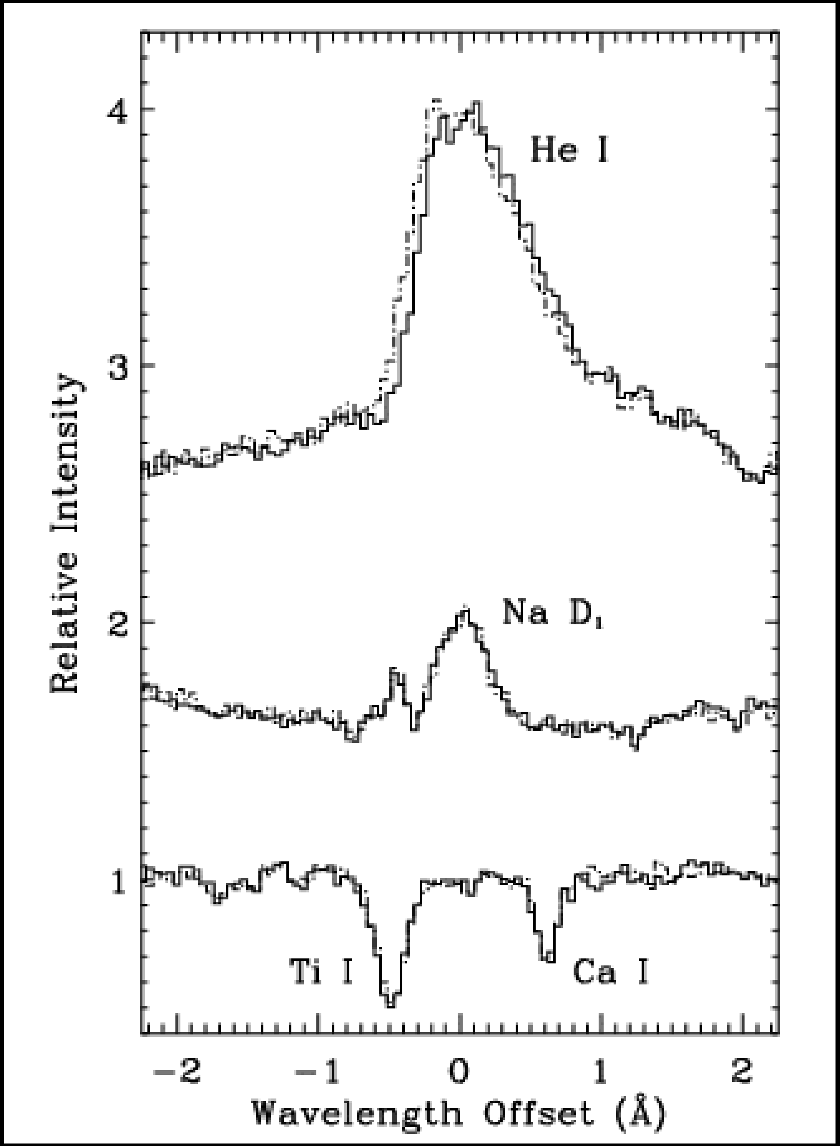
Polarization of Accretion Shock Material

BP Tau: 2.4 kG

TW Hya: 1.8 kG

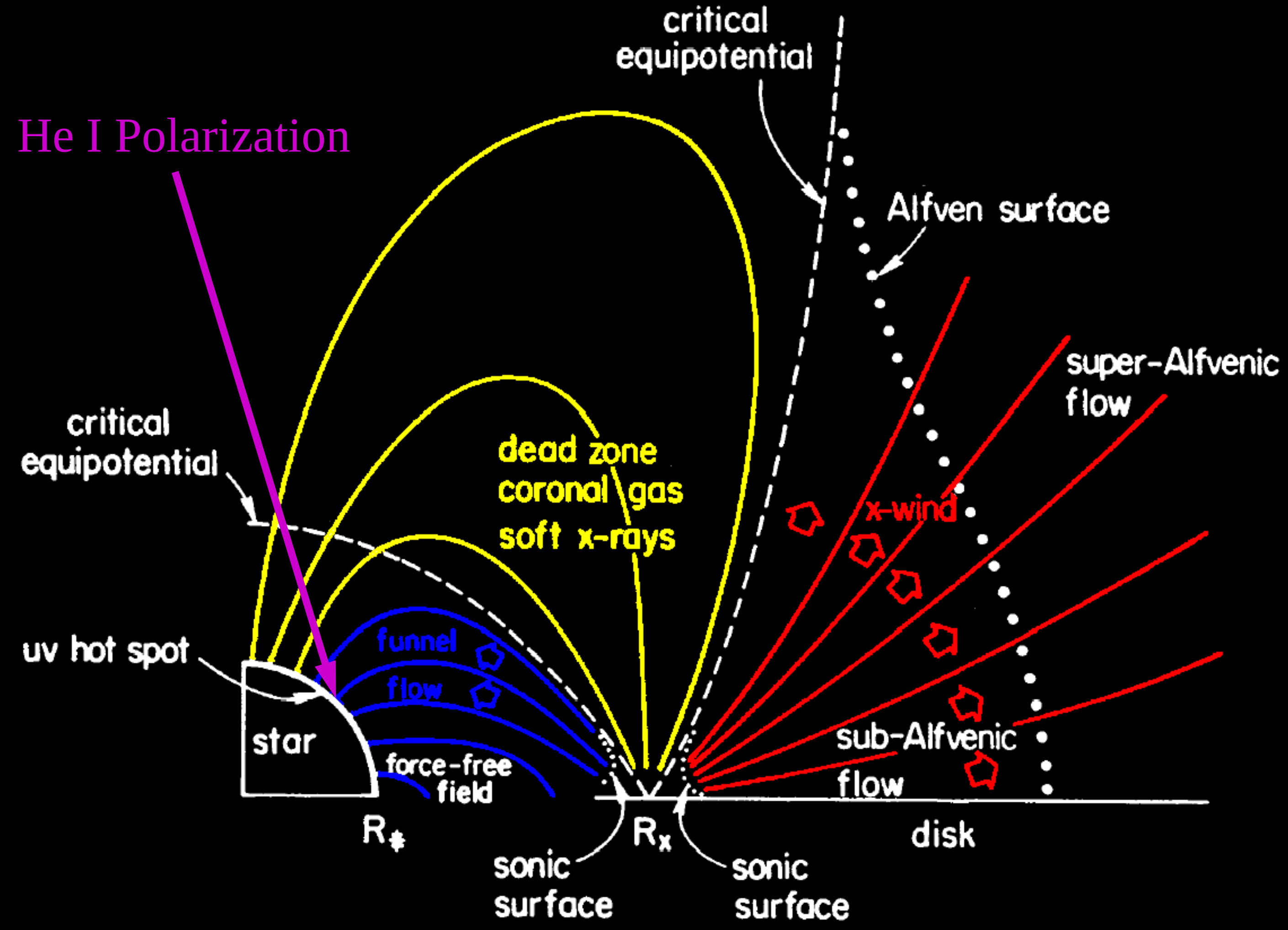
Johns-Krull et al. (1999a)





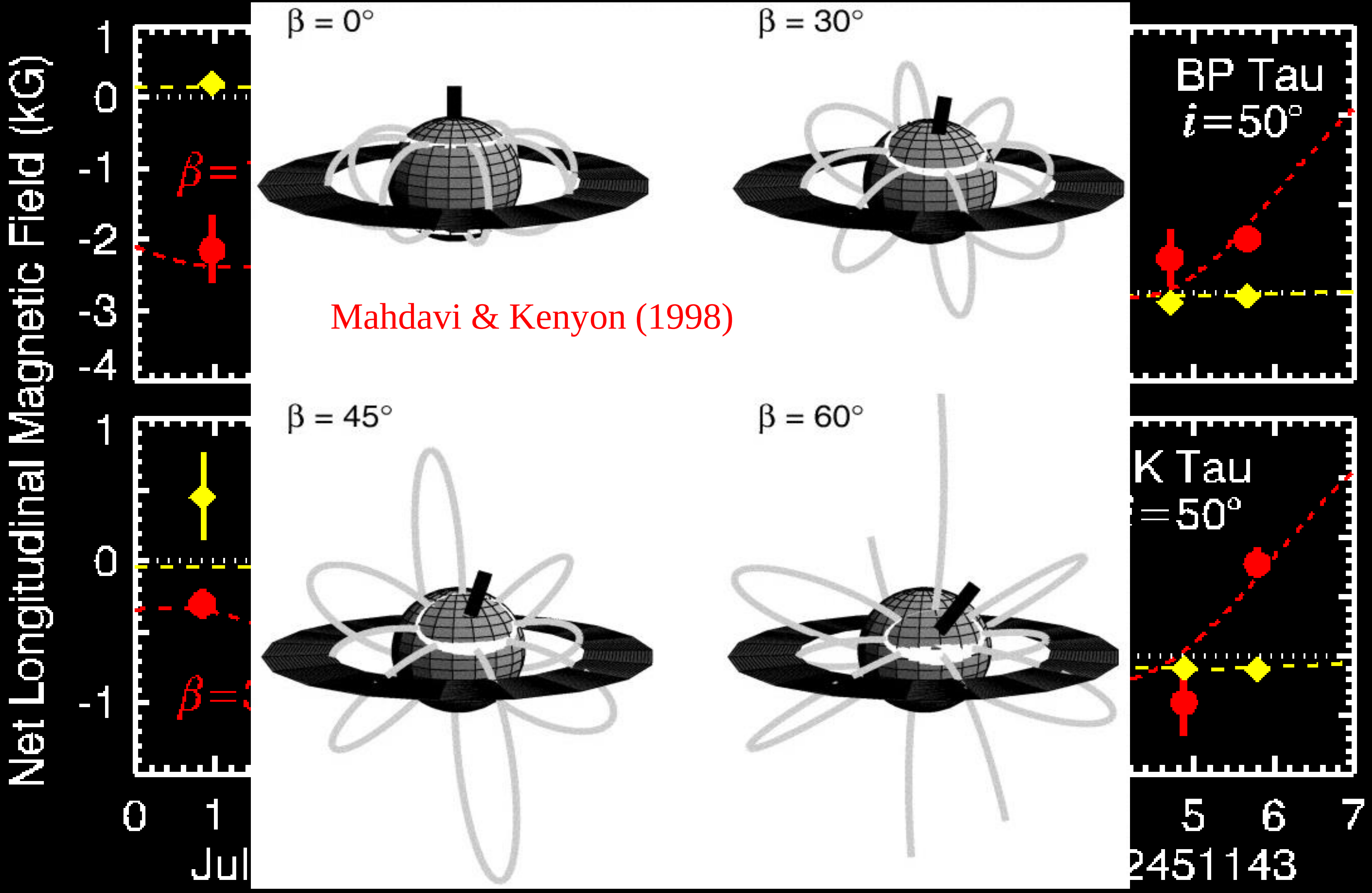
The Large Scale Field Likely Dipolar

Shu et al. (1994)



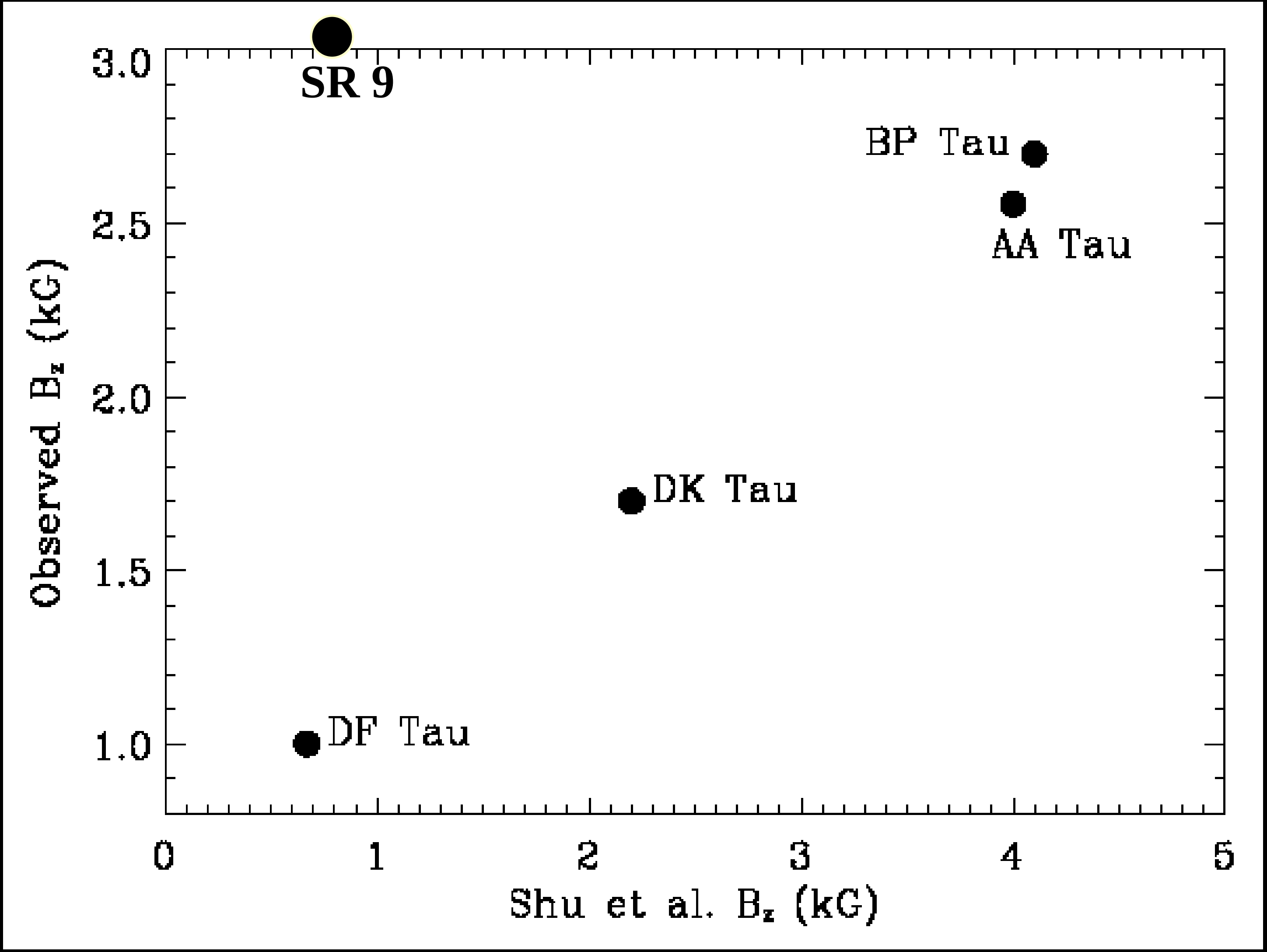
Theory gives field at some point in the disk

Polarization of Accretion Shock Material: Time Series

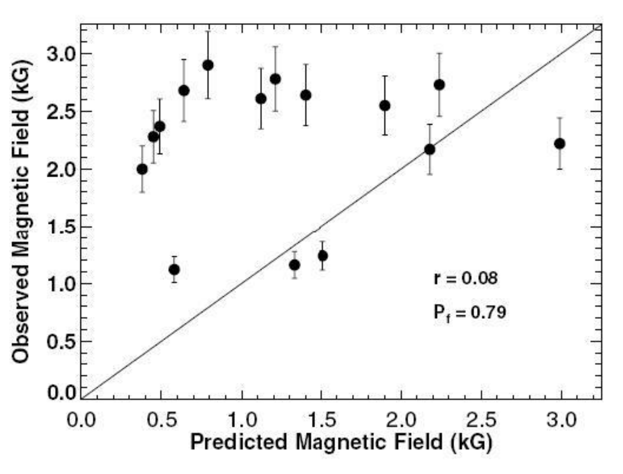


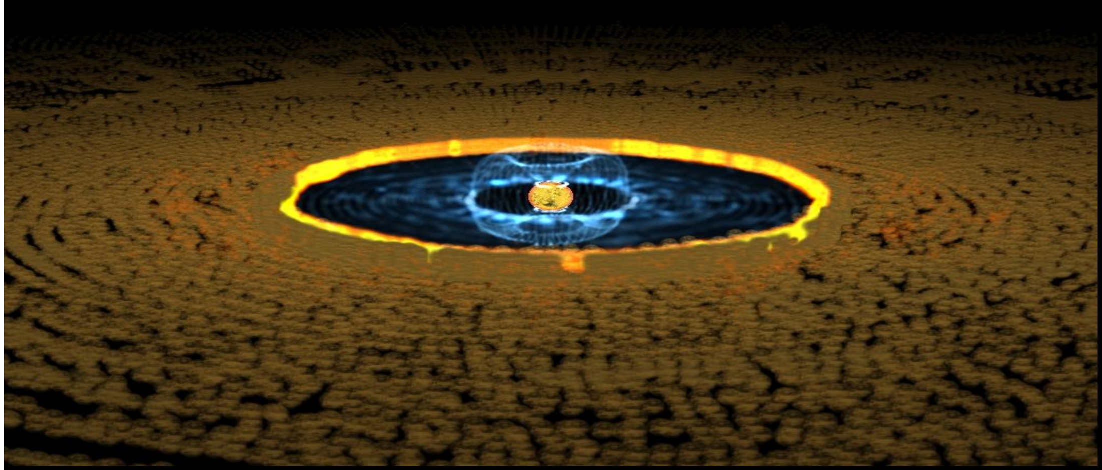
Mahdavi & Kenyon (1998)

Predicted vs. Observed Polarization



Assuming *B* Constant





Konigl (1991) & Shu et al. (1994):

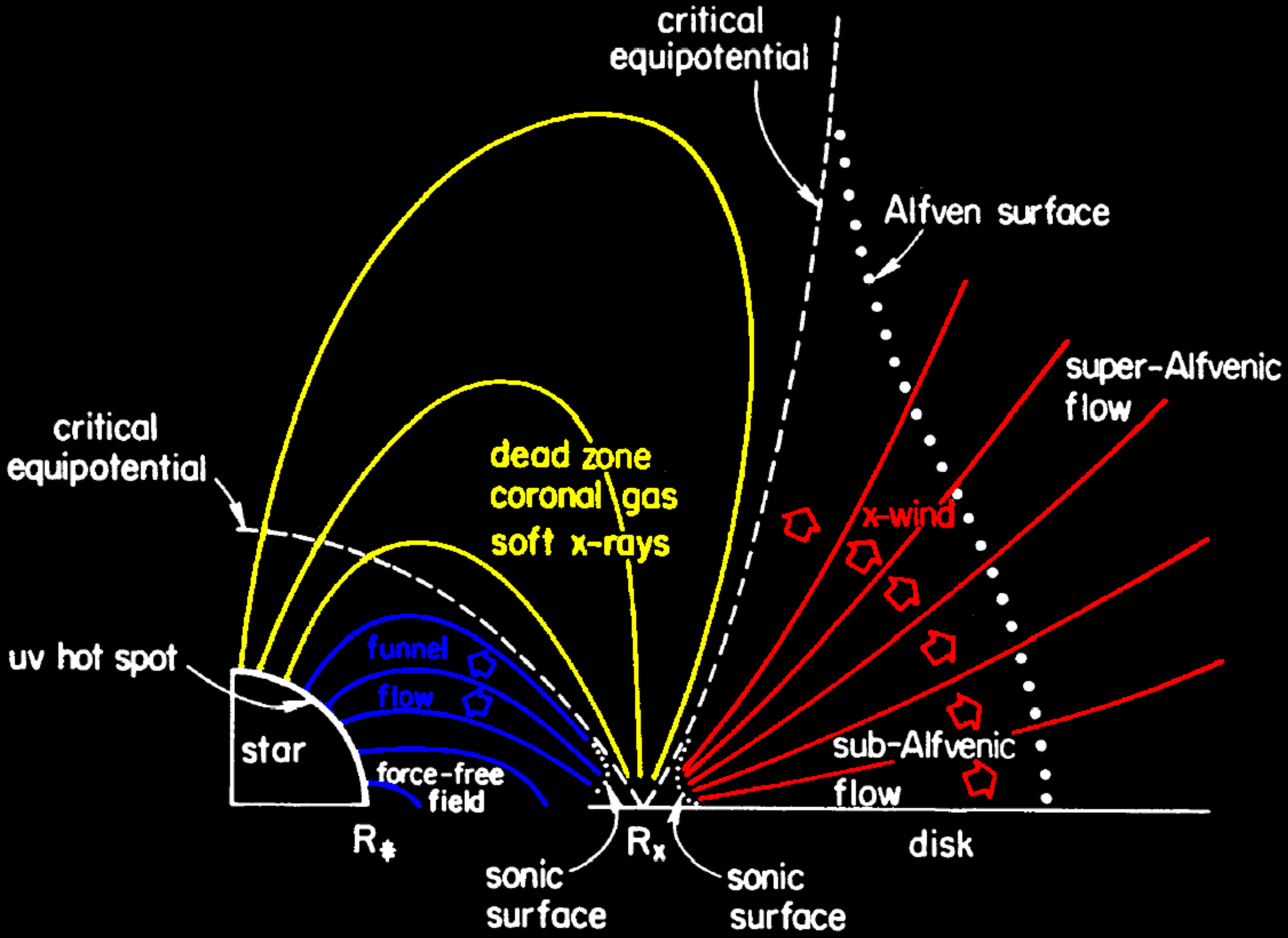
$$\left(\frac{R_*}{R_\odot}\right)^3 \propto \left(\frac{M_*}{1M_\odot}\right)^{5/6}\left(\frac{\dot{M}}{10^{-7}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{P_*}{1\,\mathrm{day}}\right)^{7/6}$$

Cameron & Campbell (1993):

$$\left(\frac{R_*}{1R_\odot}\right)^3 \propto \left(\frac{M_*}{1M_\odot}\right)^{2/3}\left(\frac{\dot{M}}{10^{-7}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{23/40}\left(\frac{P_*}{1\,\mathrm{day}}\right)^{29/24}$$

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, μ_*, should not enter *per se*
- The only combination which give units of magnetic flux is:

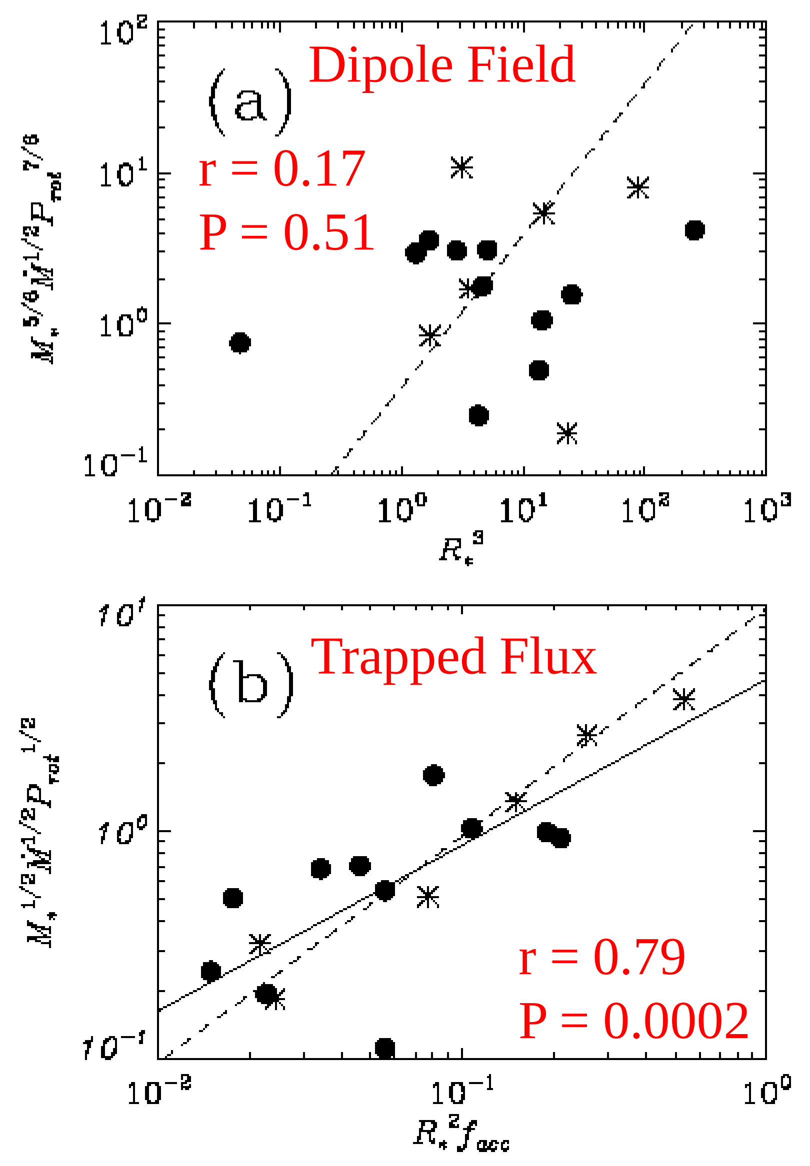
$$\Phi = \alpha\left(G M_* \dot{M}_D P_{rot}\right)^{1/2}$$

- 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



Johns-Krull & Gafford 2002, ApJ, 573, 685

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**