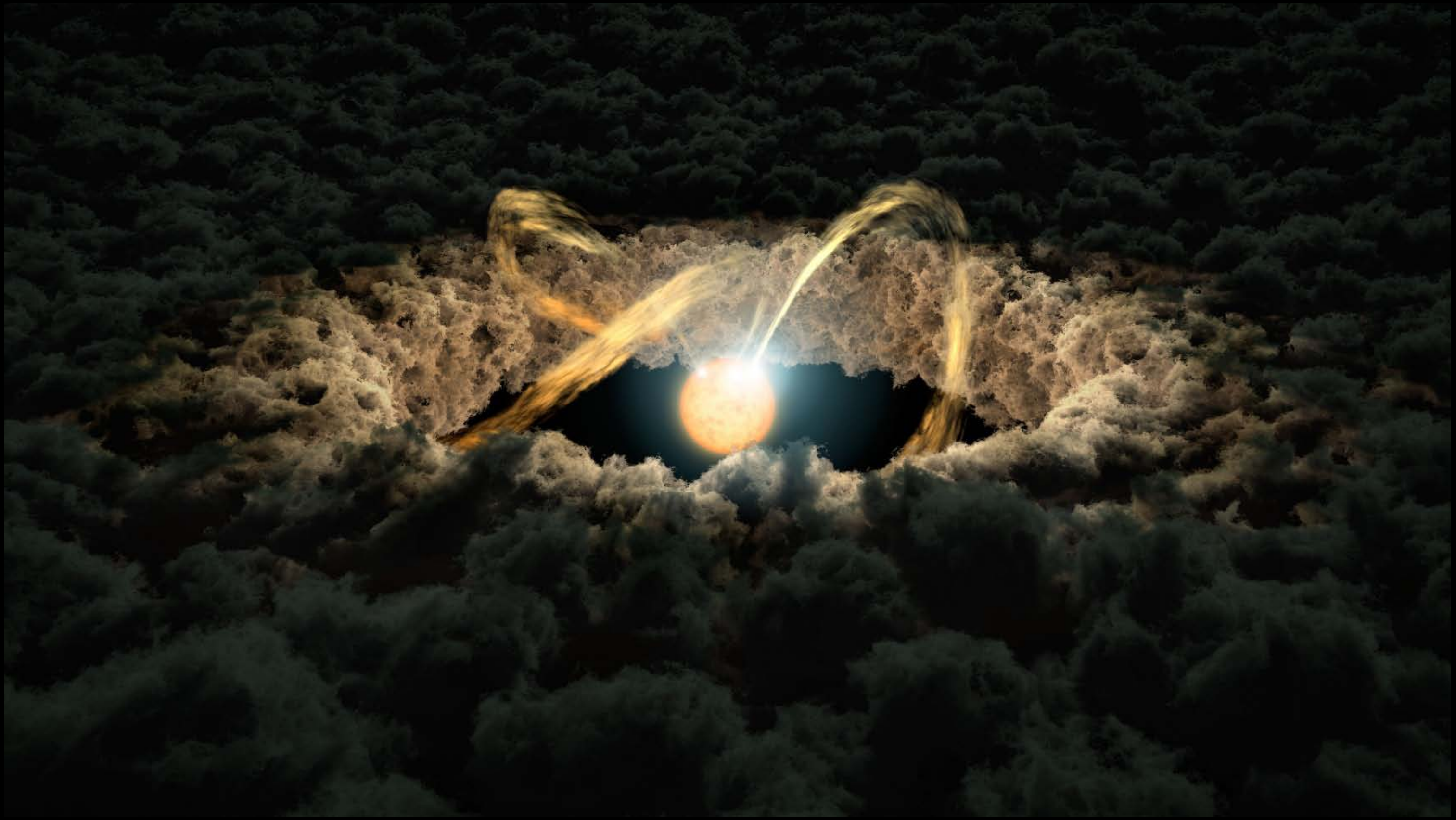
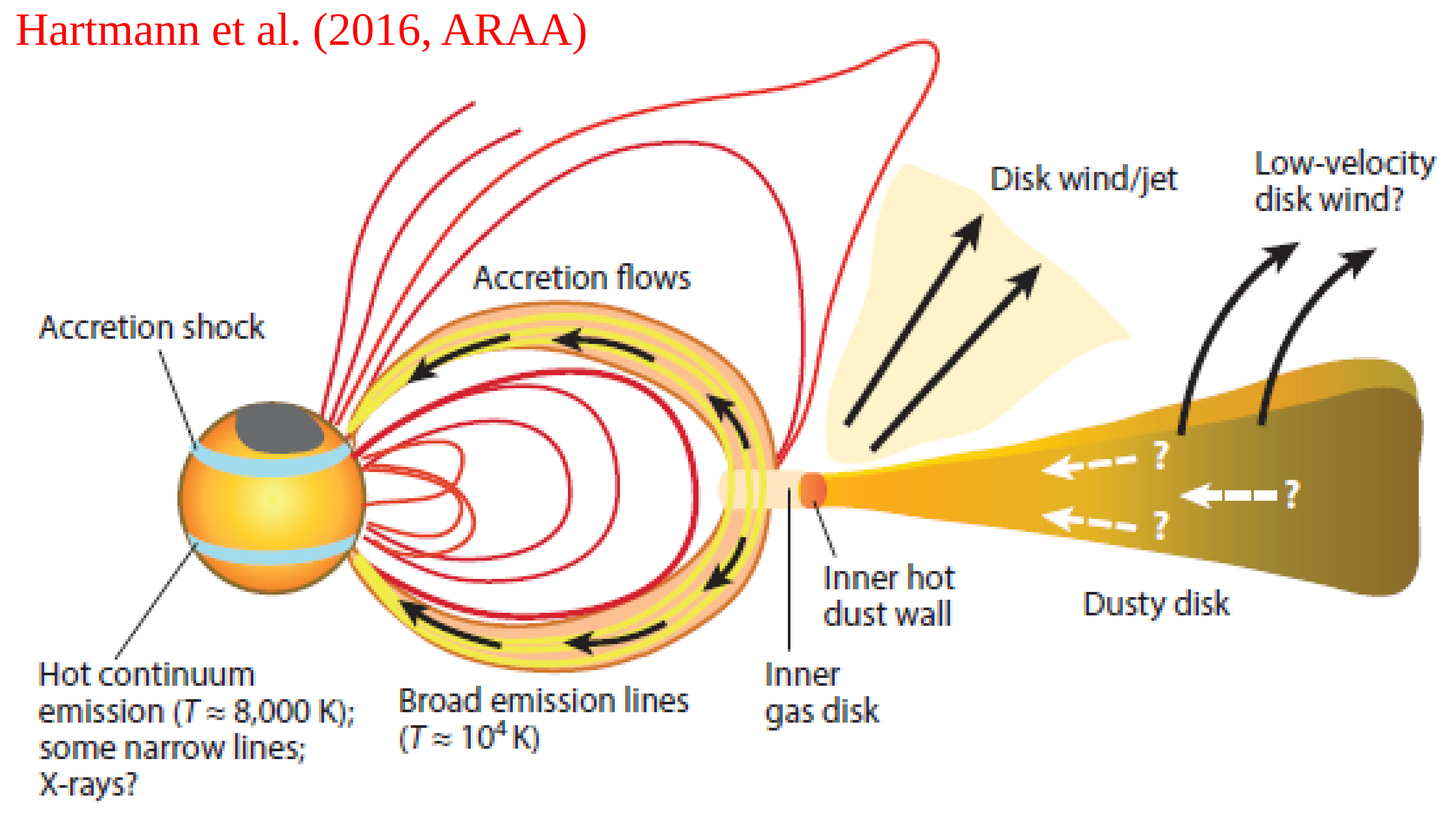
Magnetically Controlled Accretion onto Young Stars: Testing Current Models



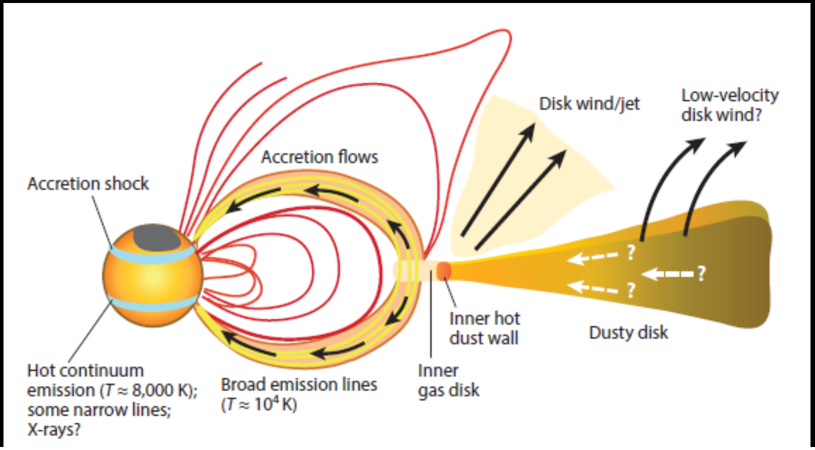
Christopher M. Johns-Krull (Rice University)

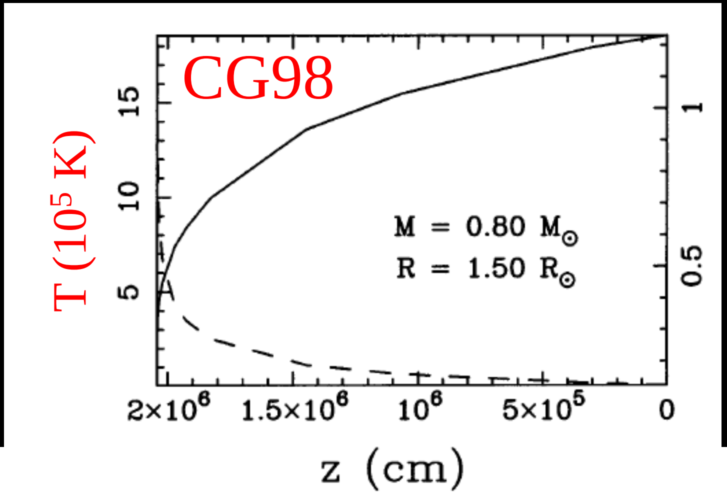
Disks, Dynamos, and Data Confronting MHD Accretion Theory with Observations: Feb. 6, 2017

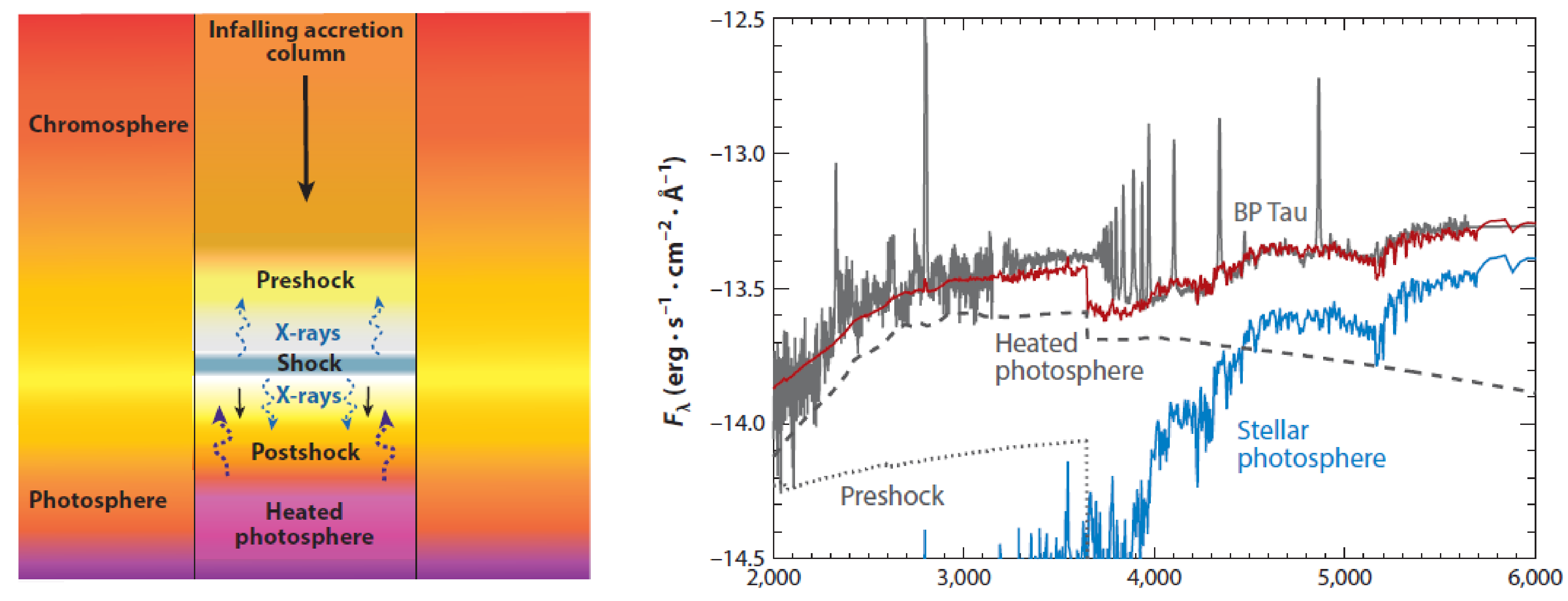
The Near Circumstellar Environment and Magnetospheric Accretion


Hartmann et al. (2016, ARAA)

Accretion Emission

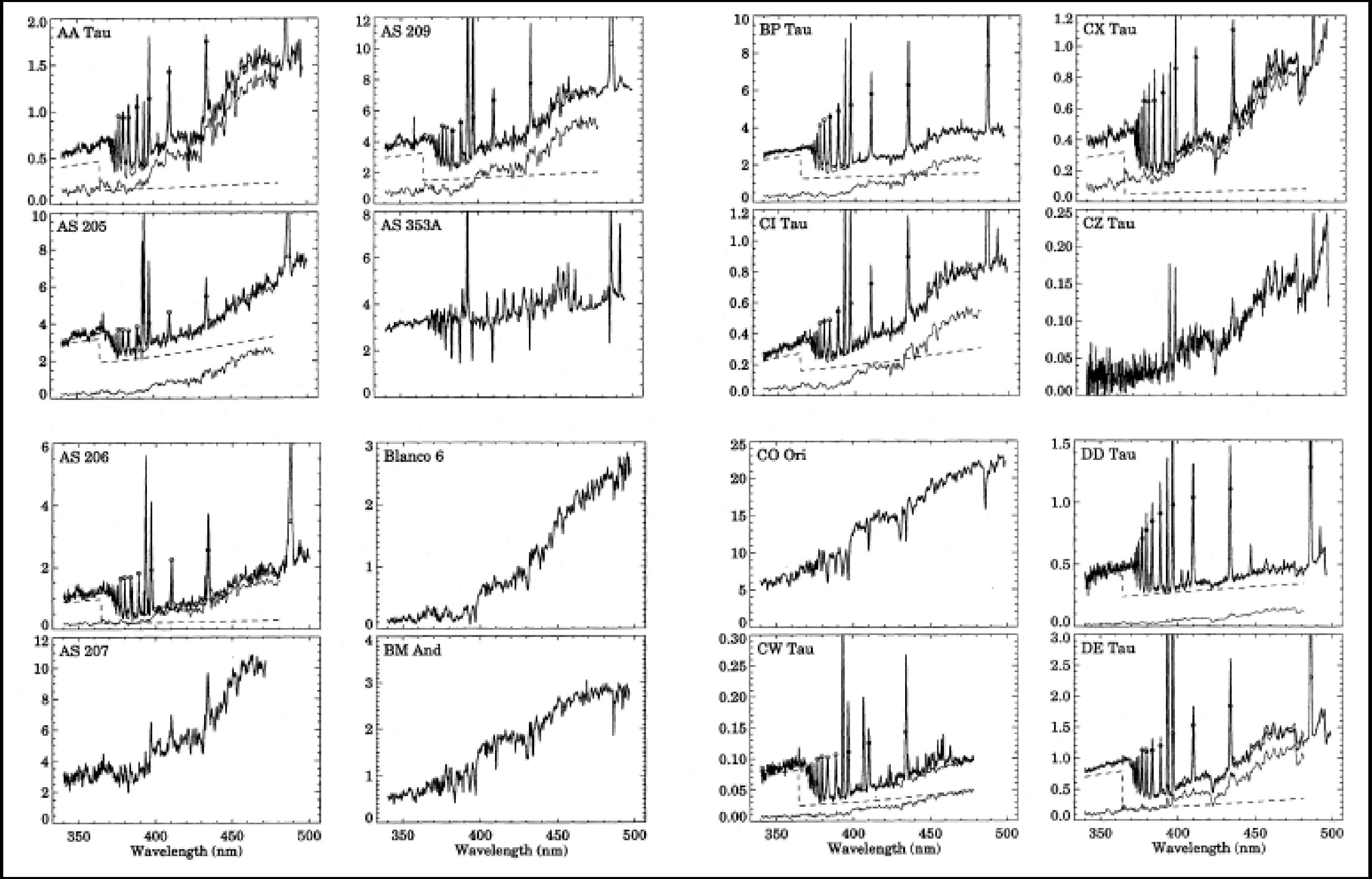






Hartmann et al. (2016, ARAA)

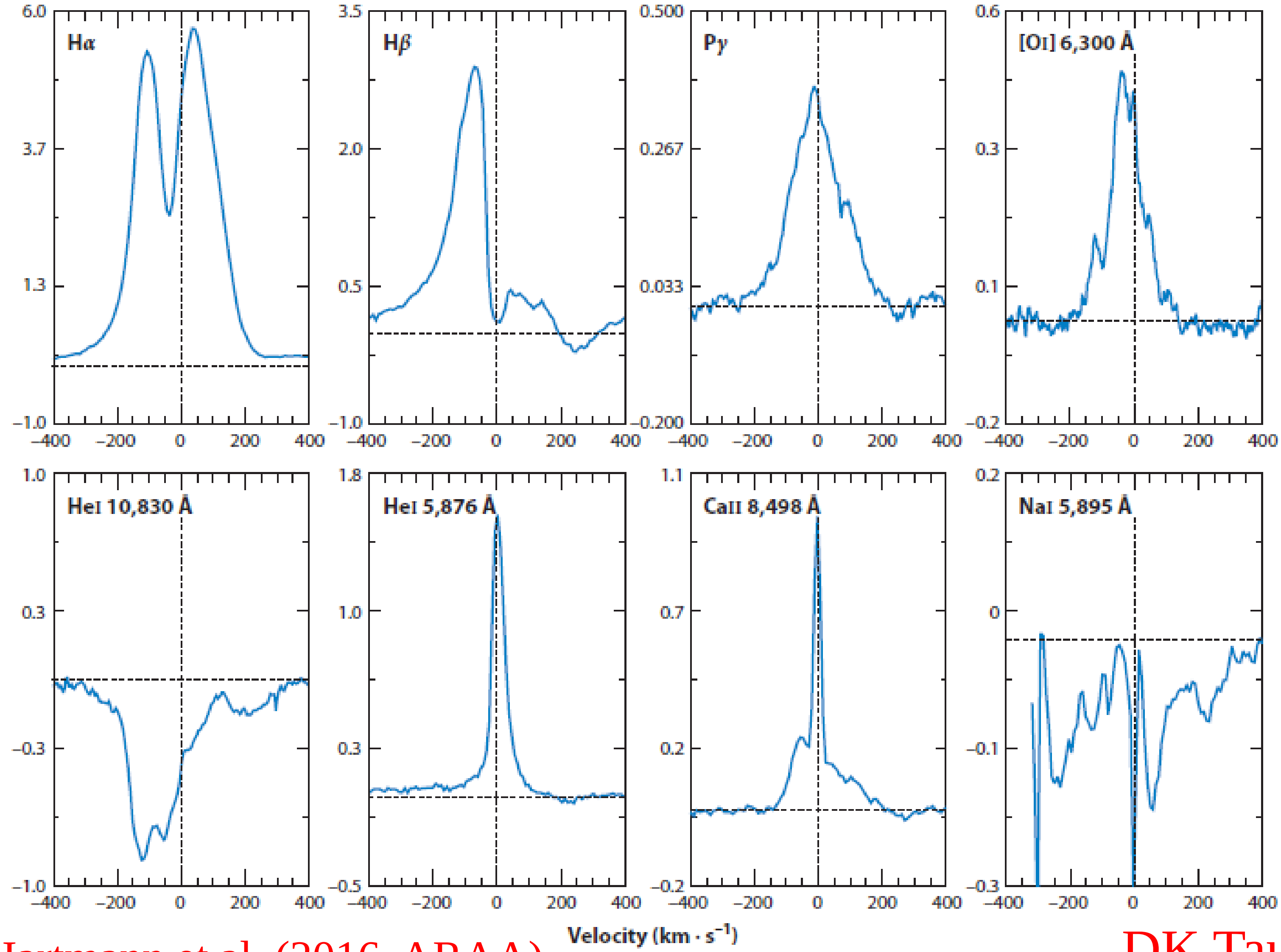
Accretion Emission



Valenti, Basri, & Johns (1993)

$$L_{\rm acc} \simeq \frac{GM_* \dot{M}}{R_*}\left(1 - \frac{R_*}{R_{\rm in}}\right)$$

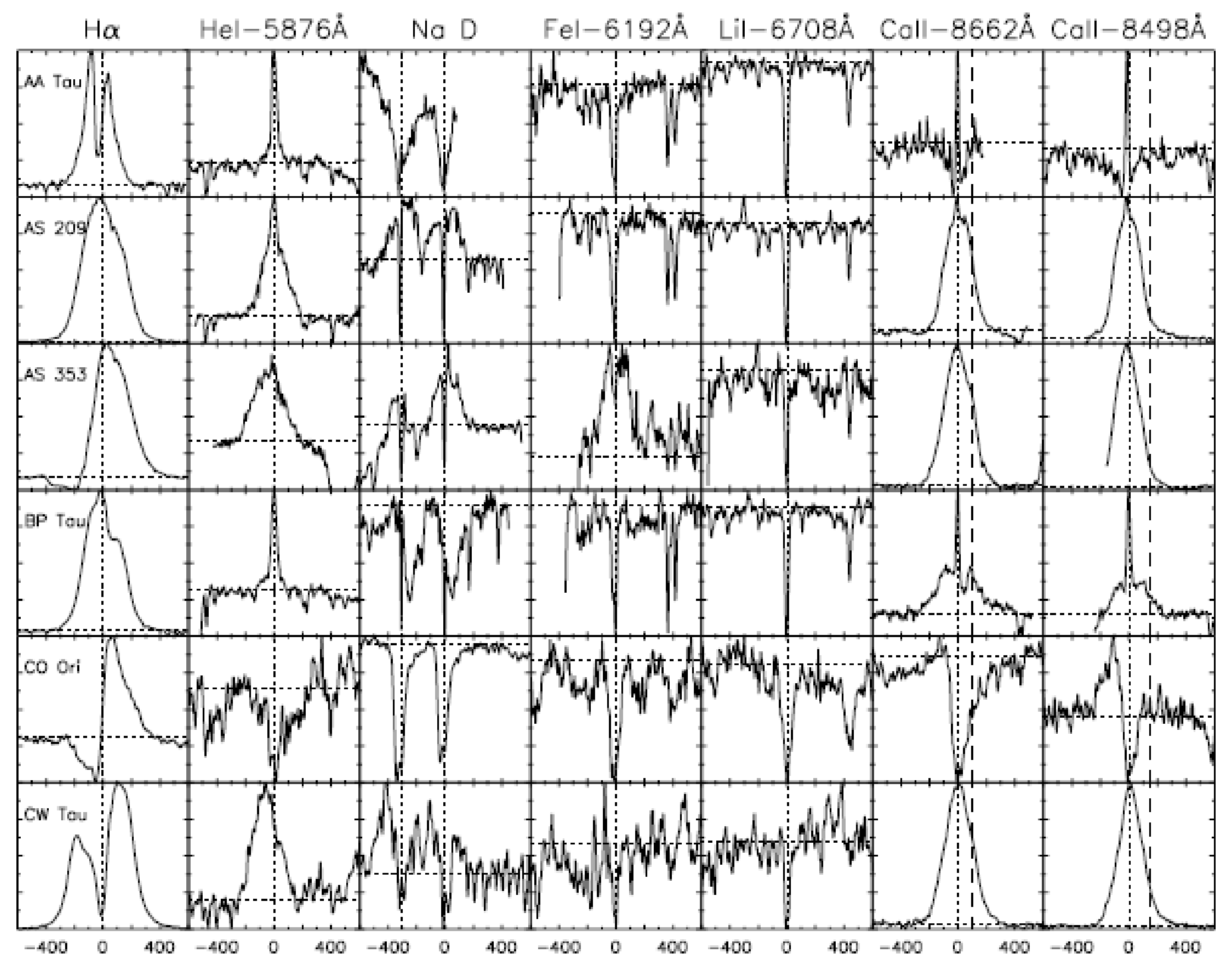
High Resolution Line Profiles



Hartmann et al. (2016, ARAA)

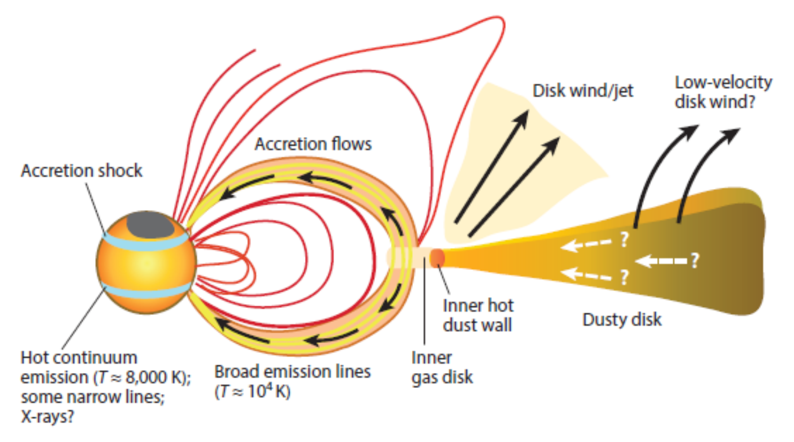
DK Tau

High Resolution Line Profiles

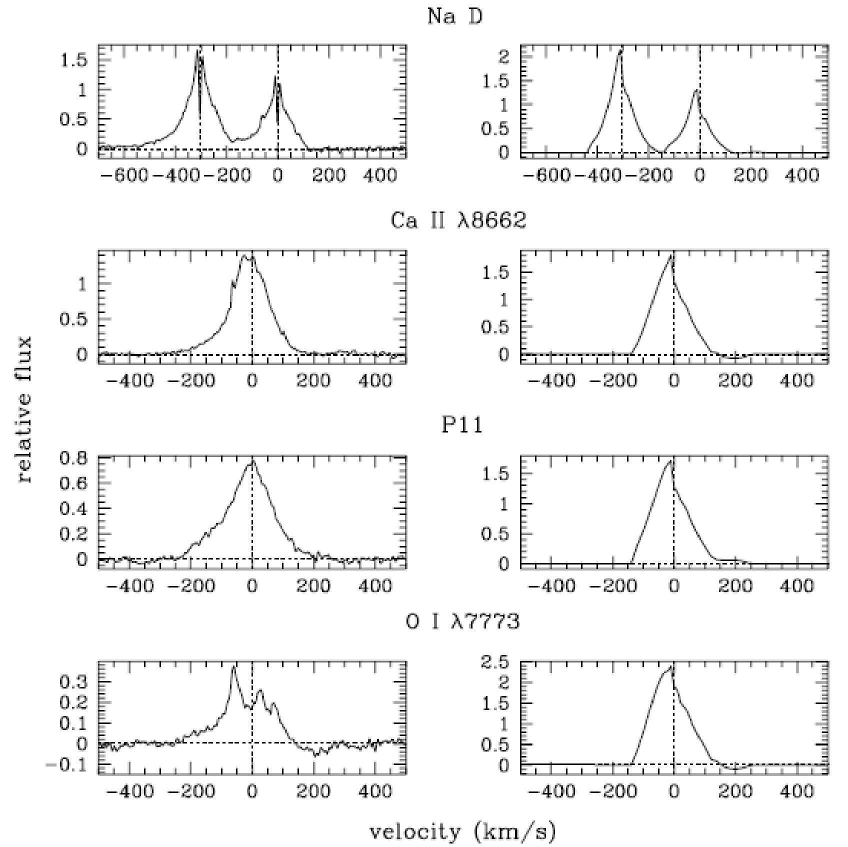


Alencar & Basri (2000)

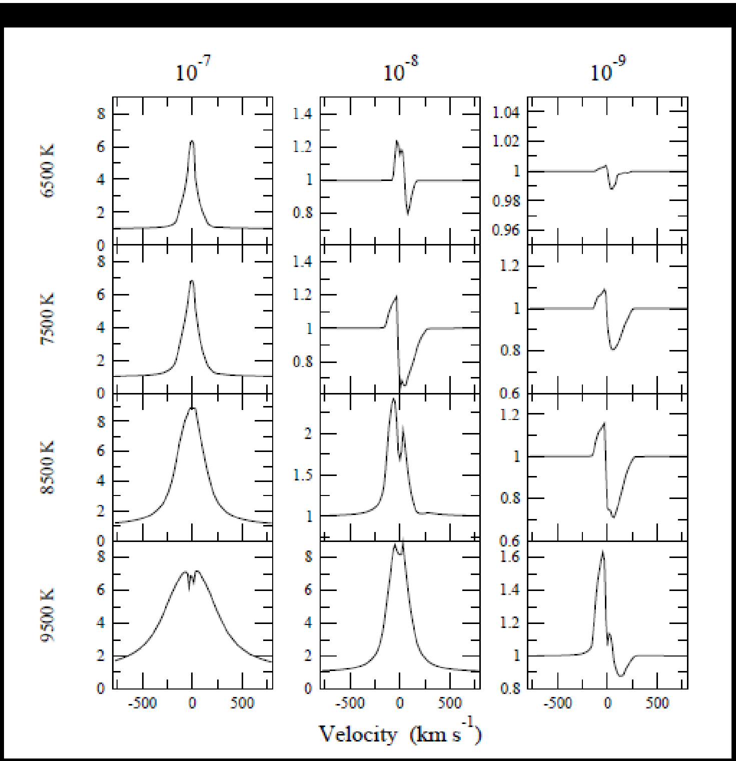
High Resolution Line Profiles



Muzerolle et al. (1998)

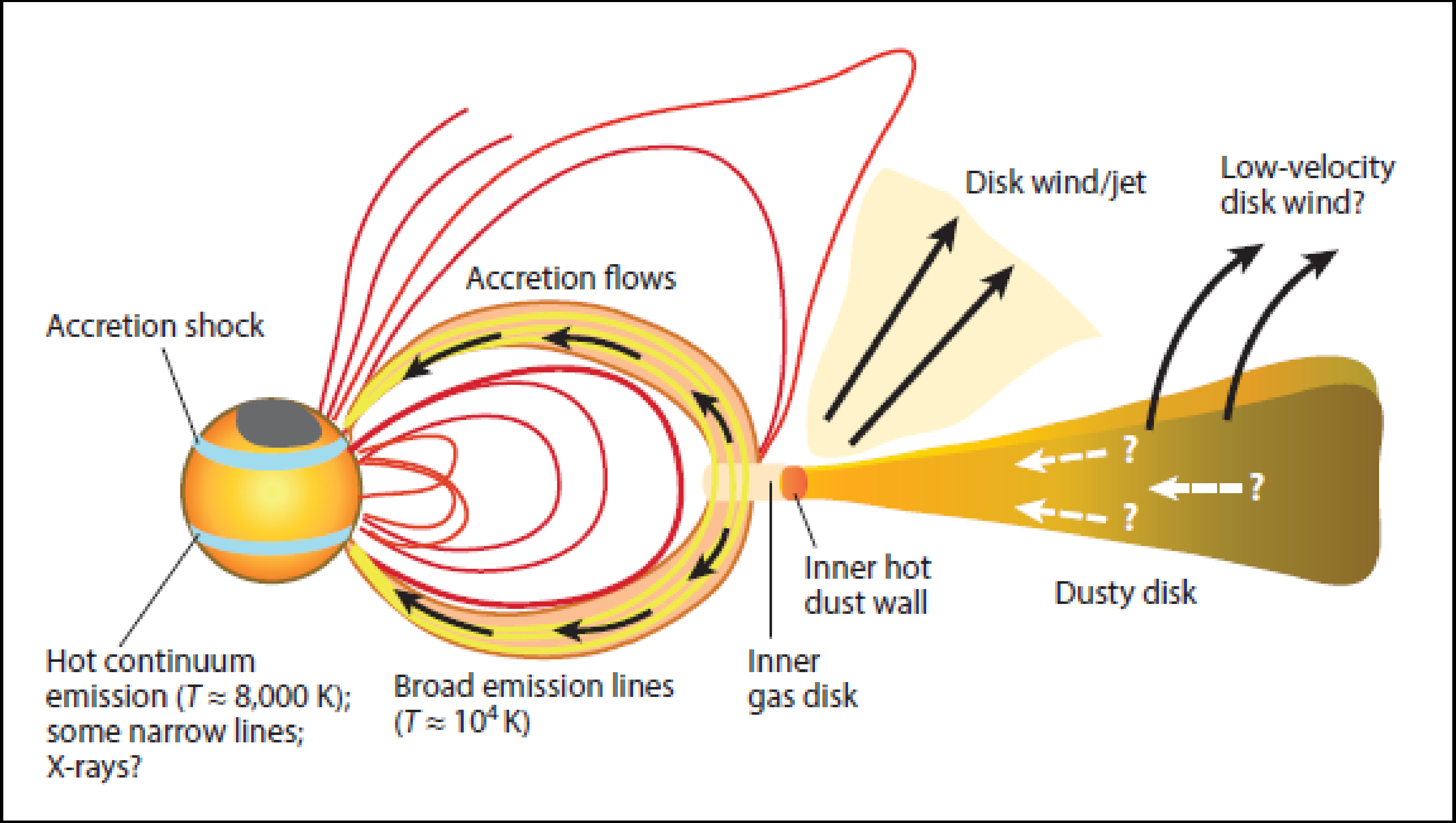


BP Tau



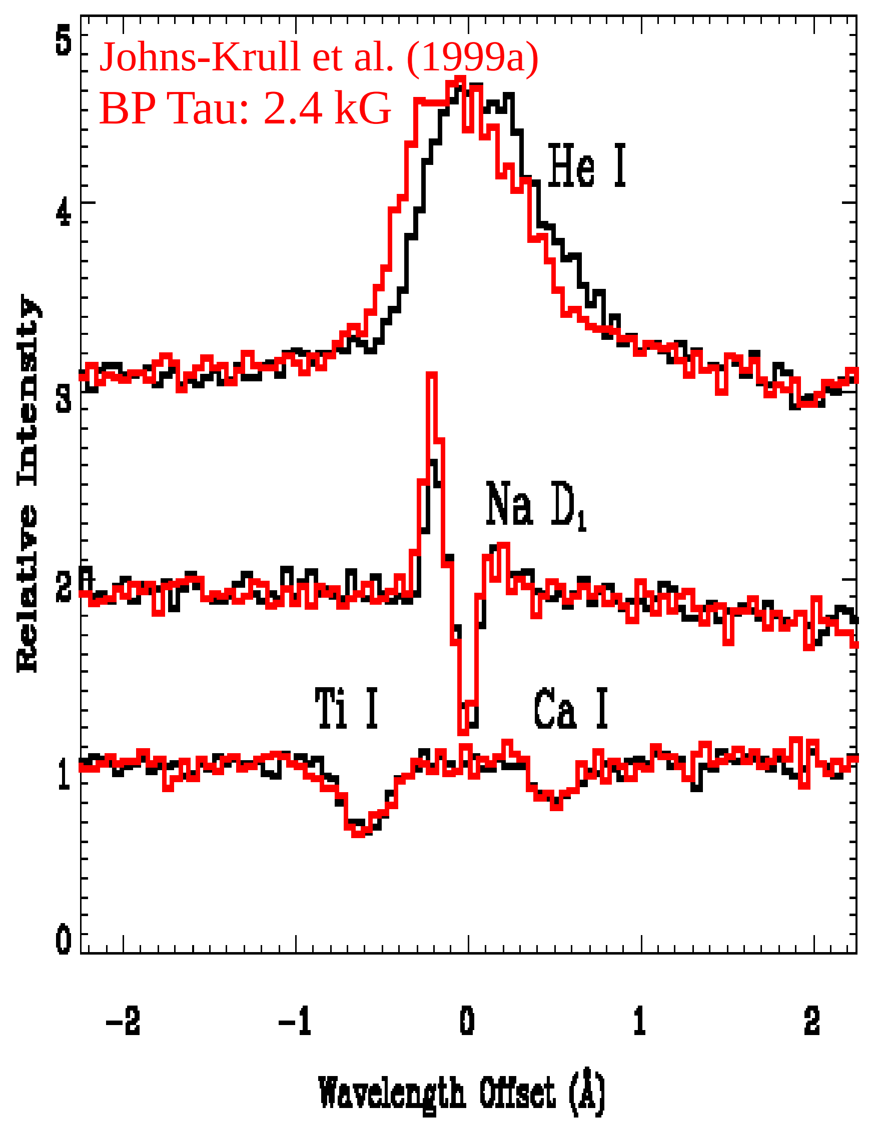
Kurosawa et al. (2006)

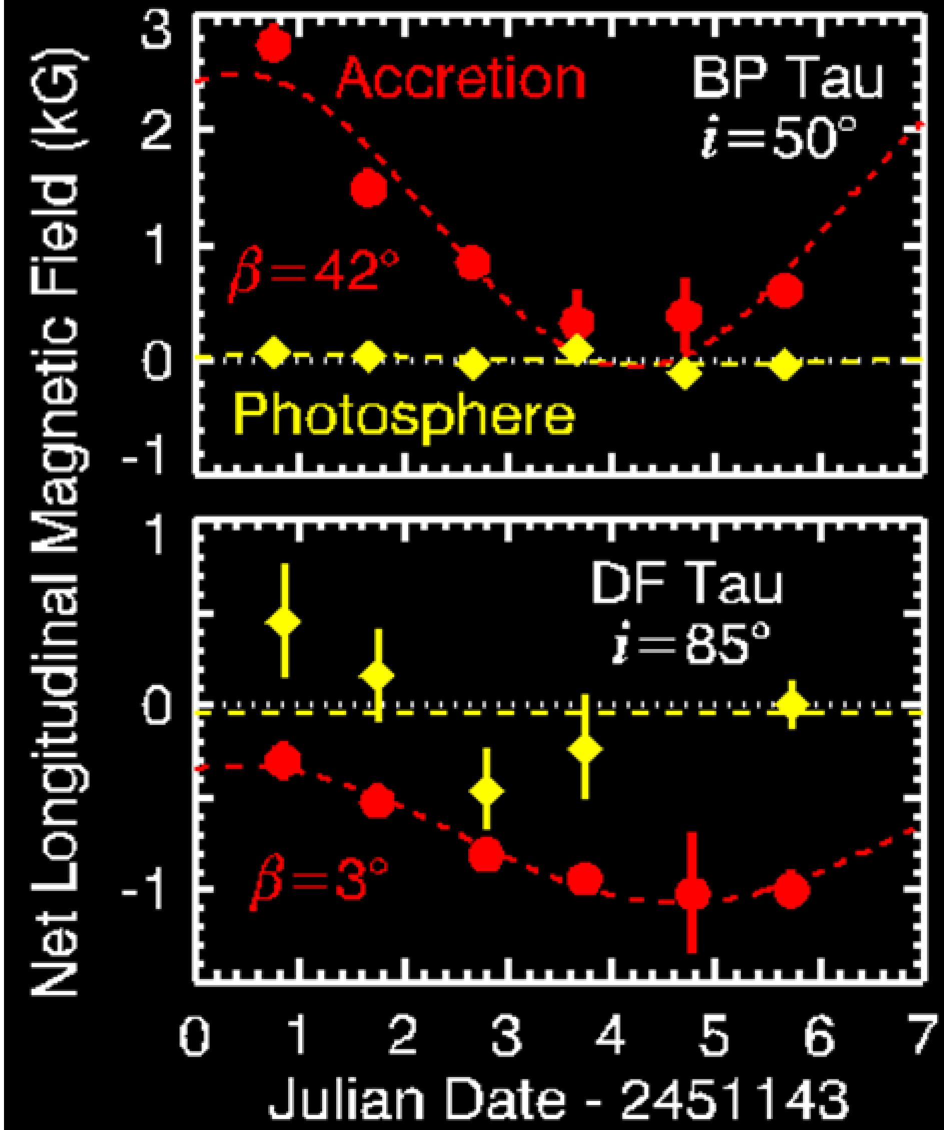
Polarization of Accretion Shock Material



Polarization of Accretion Shock Material

Valenti & Johns-Krull (2004)

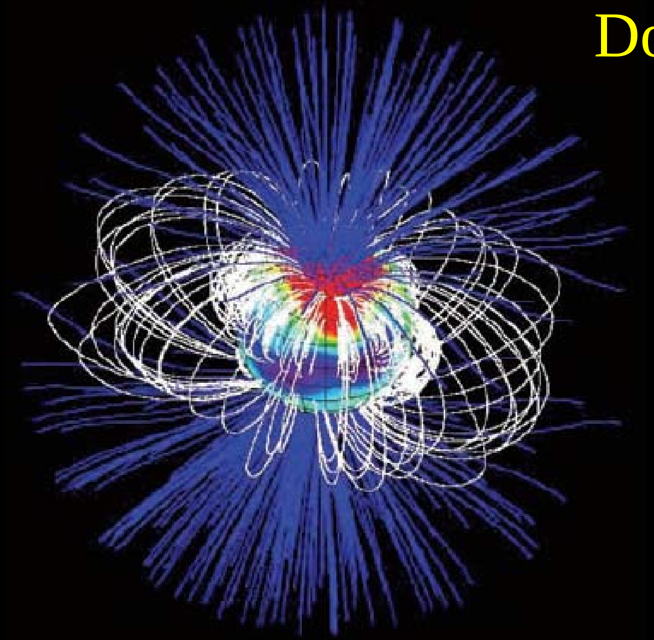


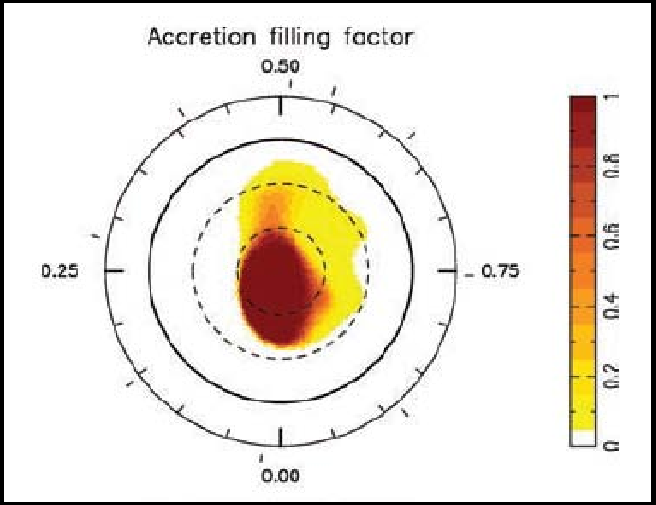


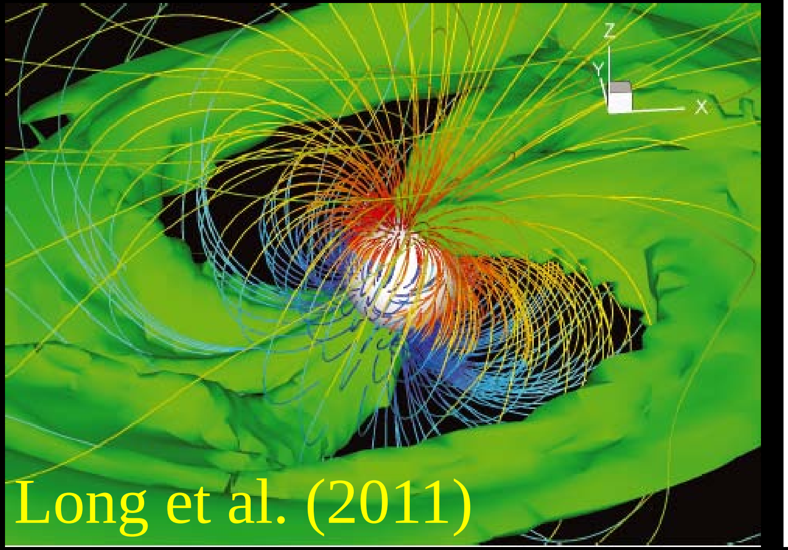
Field Mapping & Accretion Simulations

Donati et al. (2008)

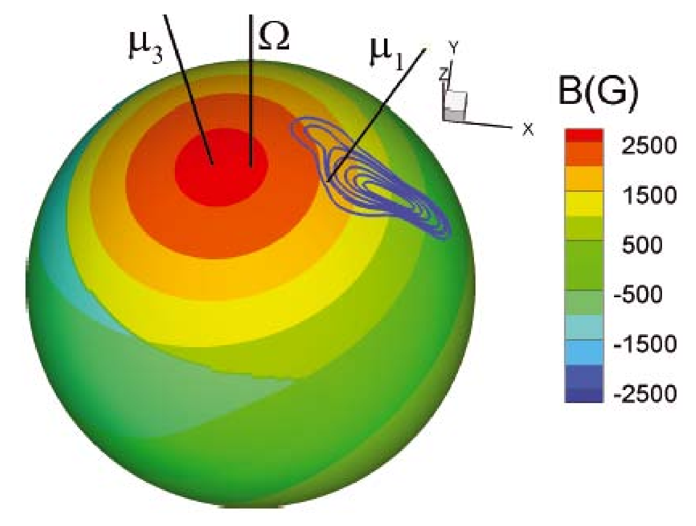
BP Tau



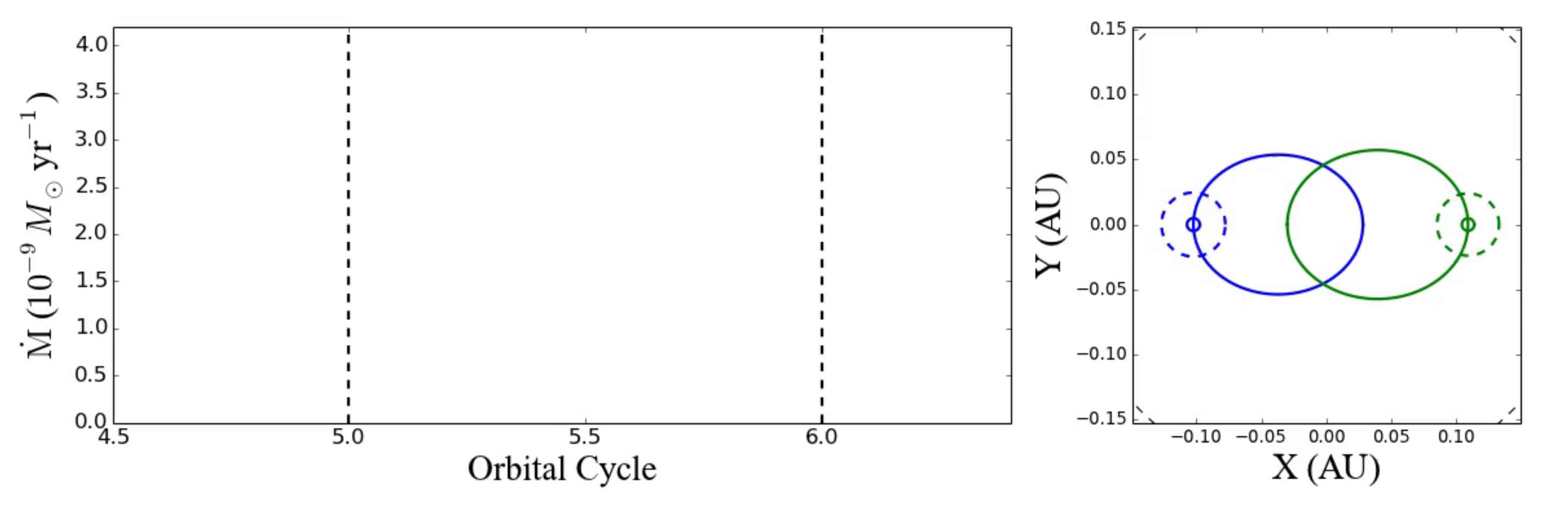




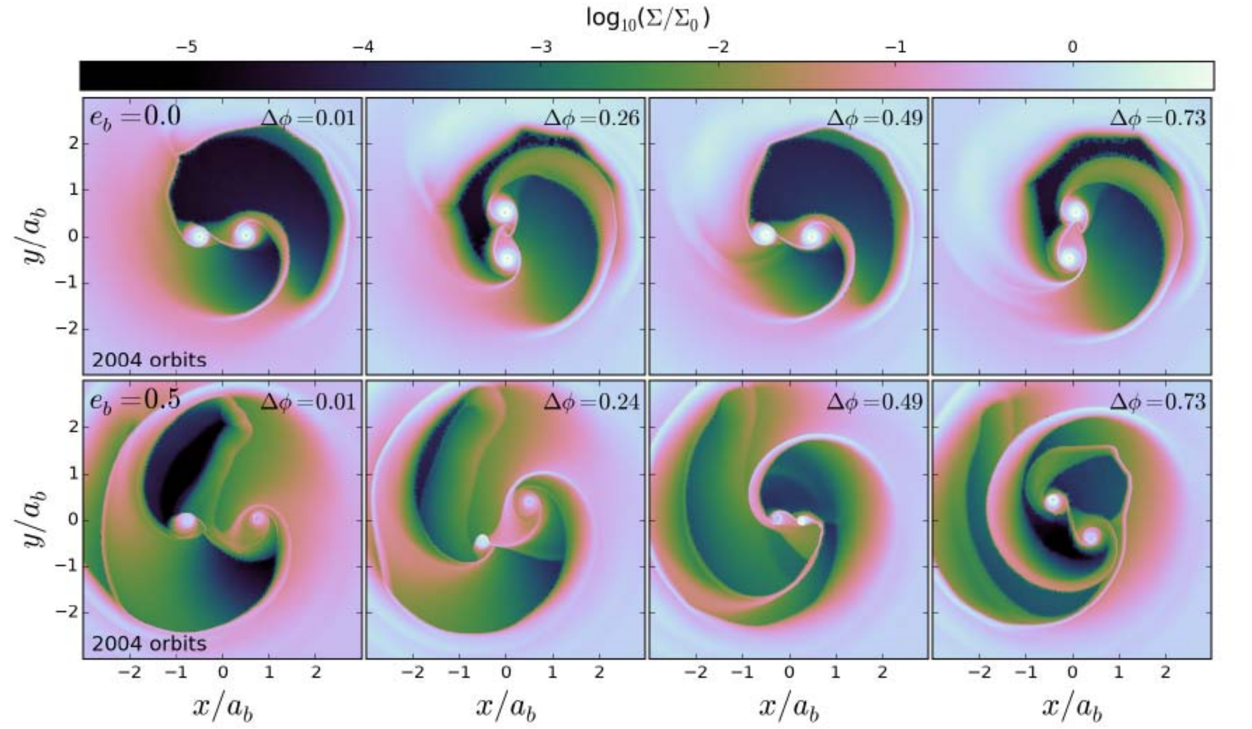
Long et al. (2011)



Accretion in Binaries



DQ Tau
Tofflemire et al.
(2017)



Muñoz & Lai
(2016)

Can You Tell?

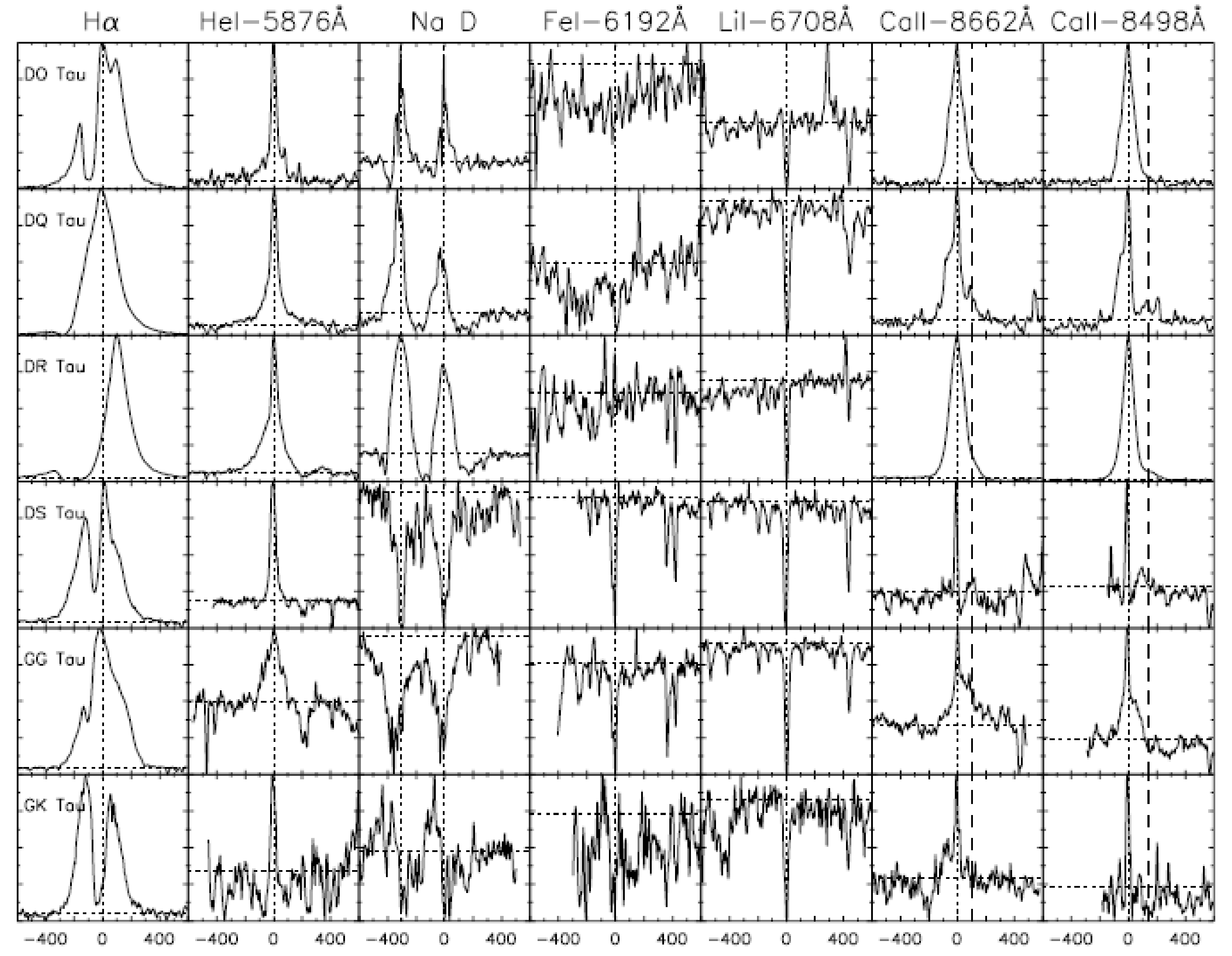
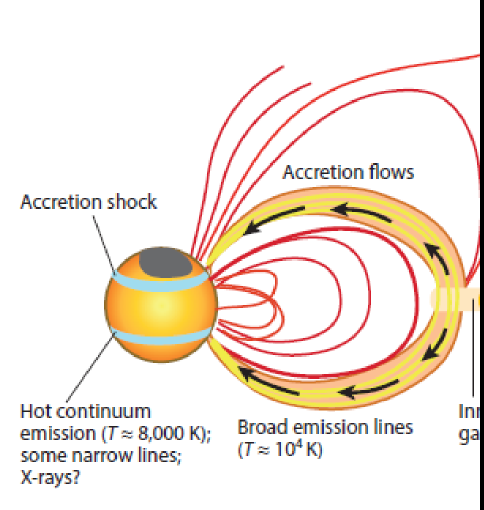


FIG. 1.—*Continued*

Alencar & Basri (2000)

There Are Clues but Geometry Uncertain



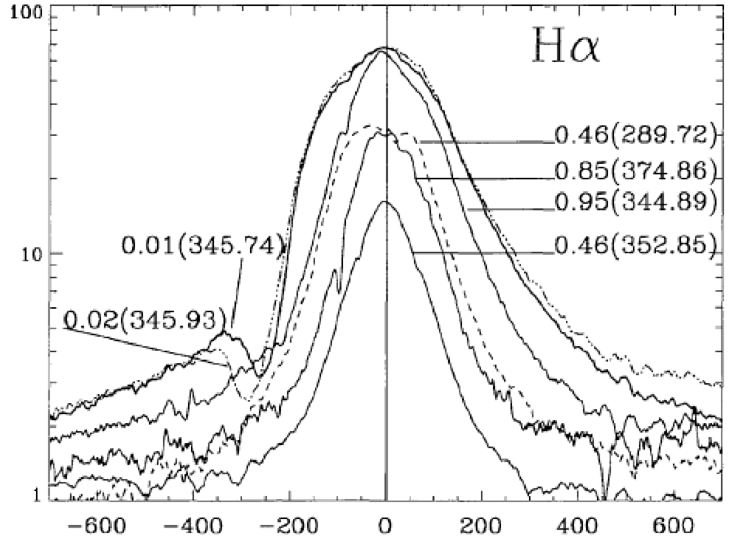
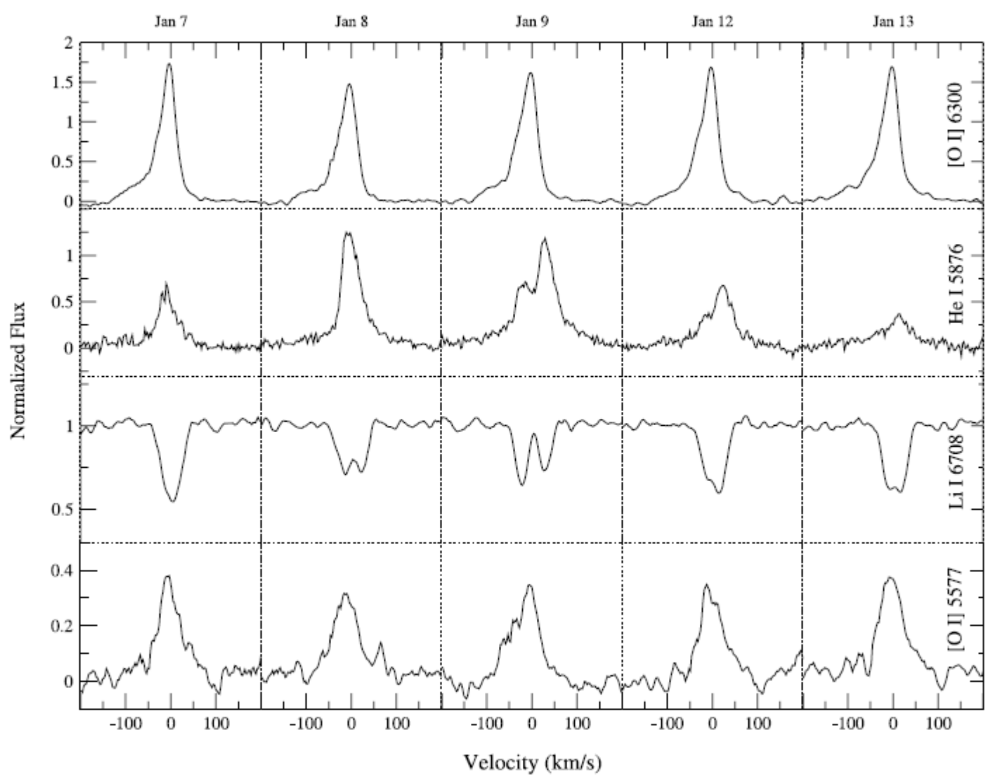


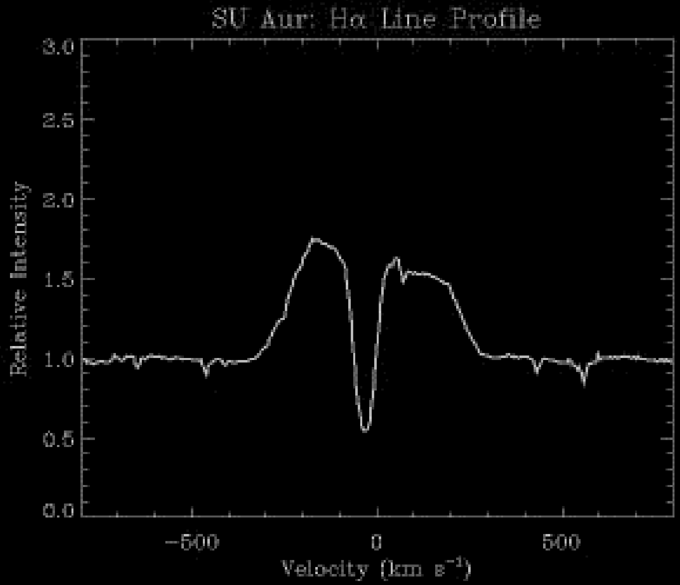
FIG. 5. Same as Fig. 1 but for the Hα line at 656.3 nm. Note that the intensity scale is logarithmic.

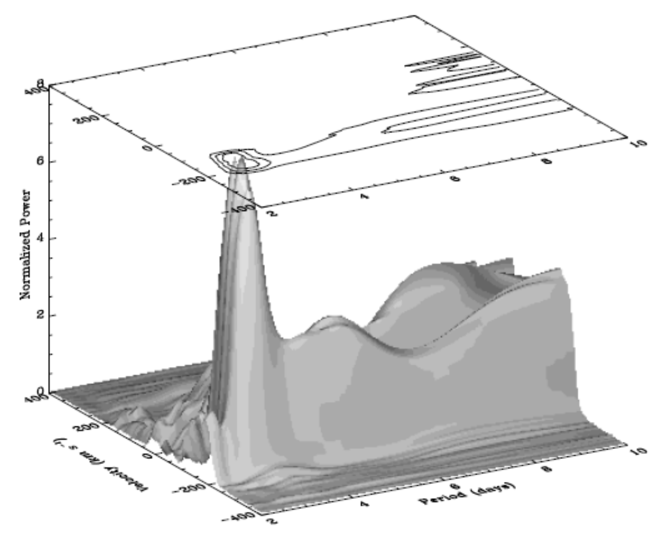
Basri et al, (1997)



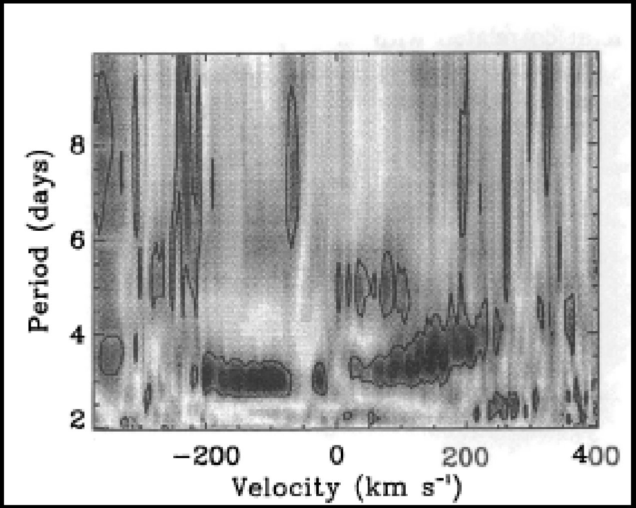
Huerta et al, (2005)

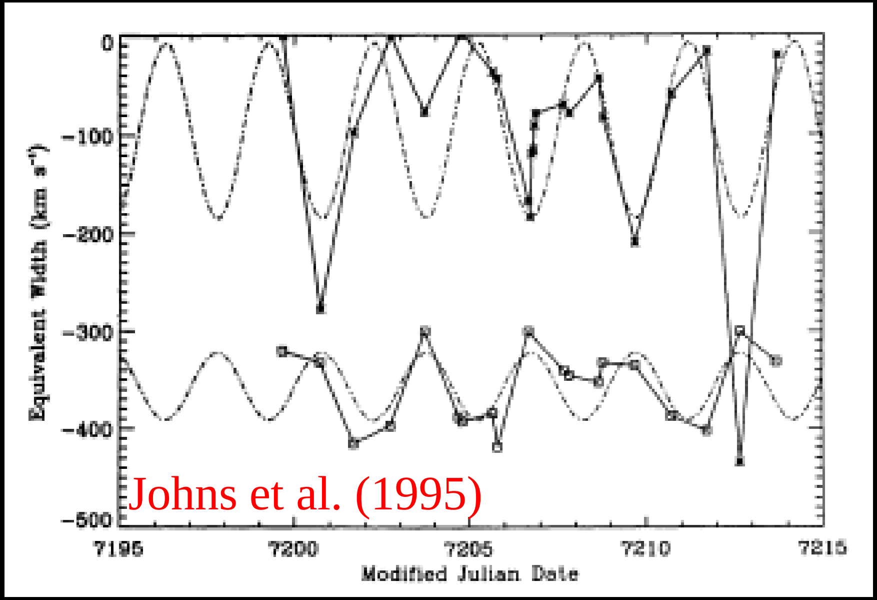
Strong Variability is a Hallmark





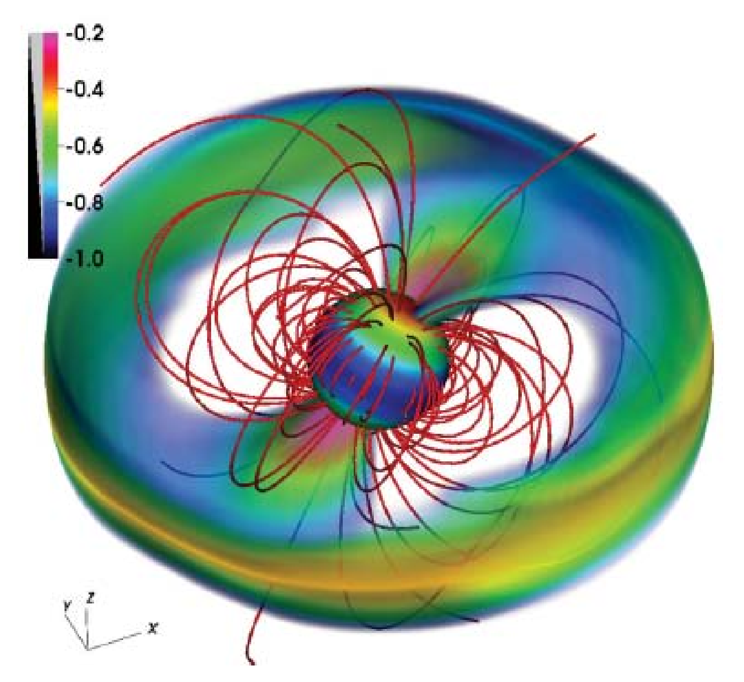
Johns & Basri (1995)

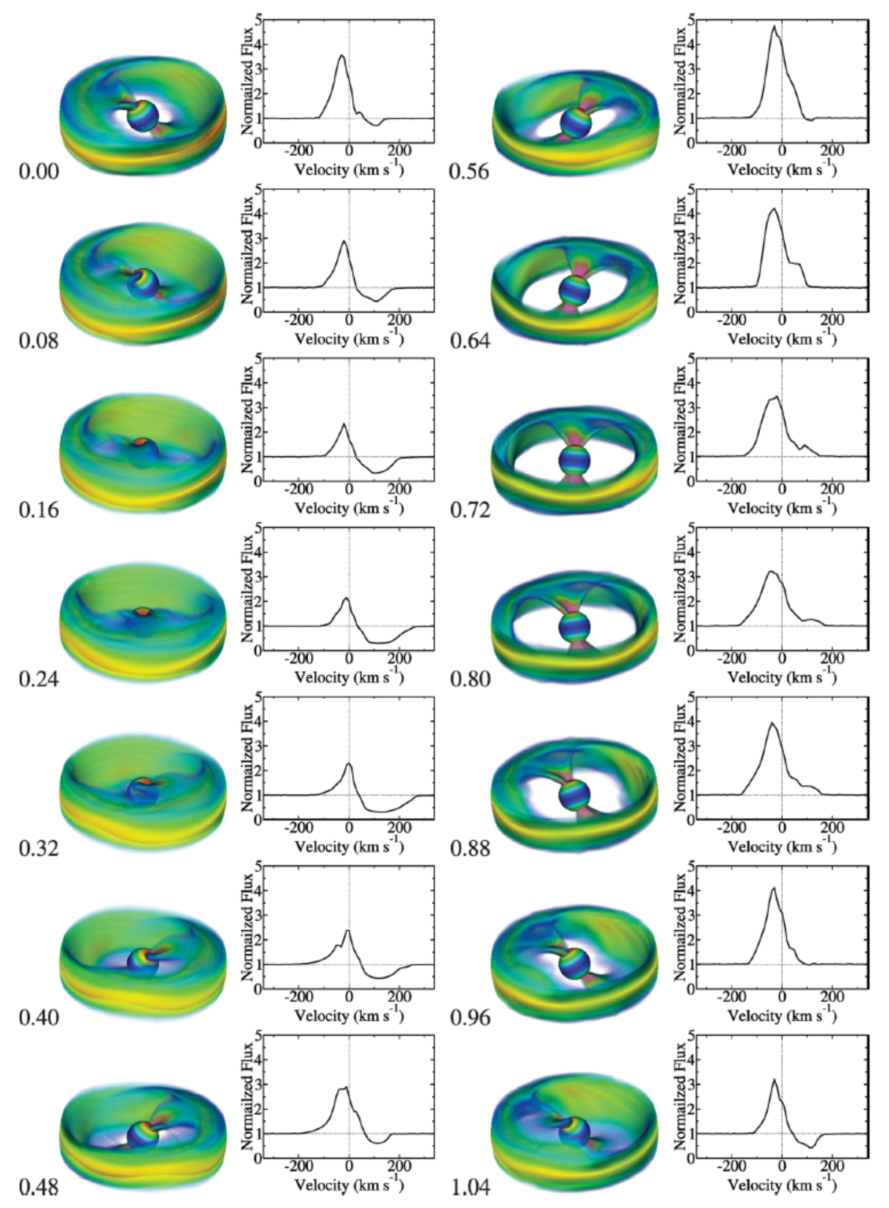




Johns et al. (1995)

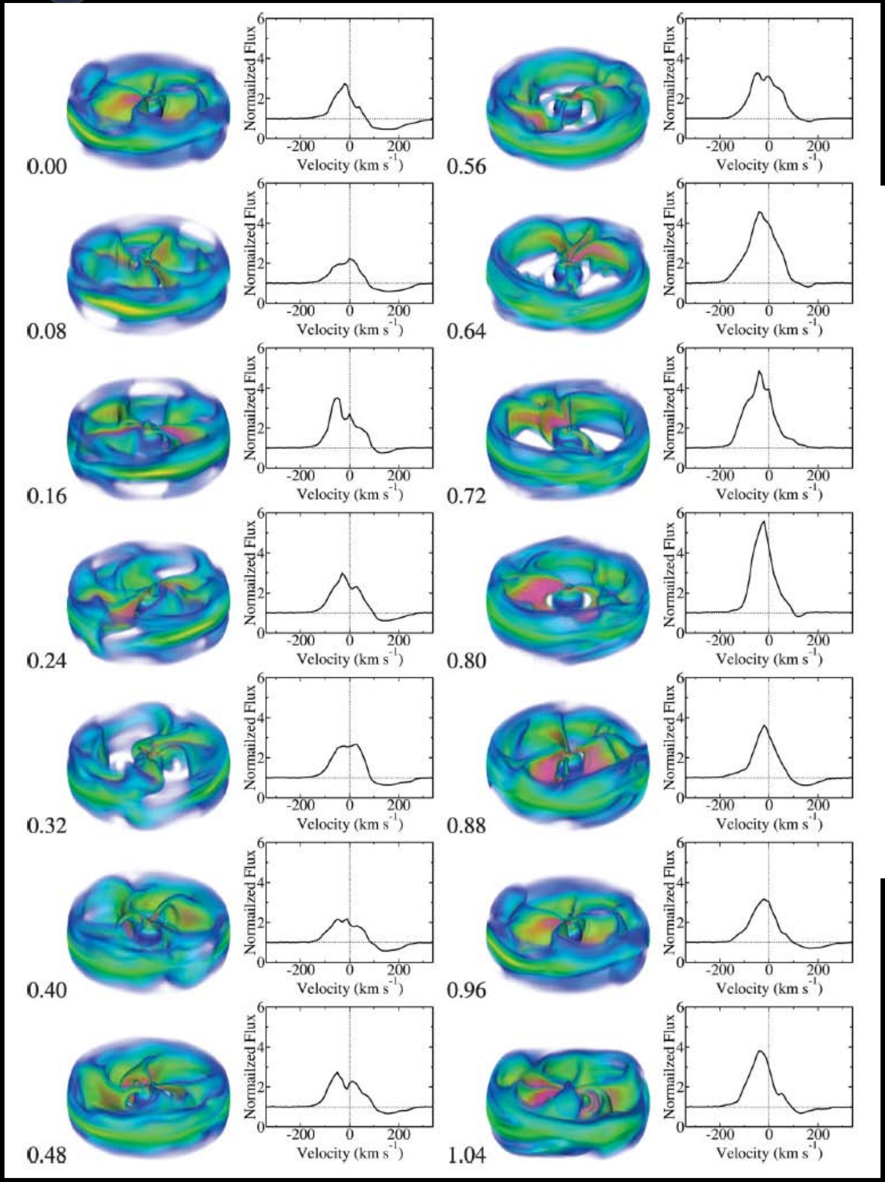
Modeling the Variability

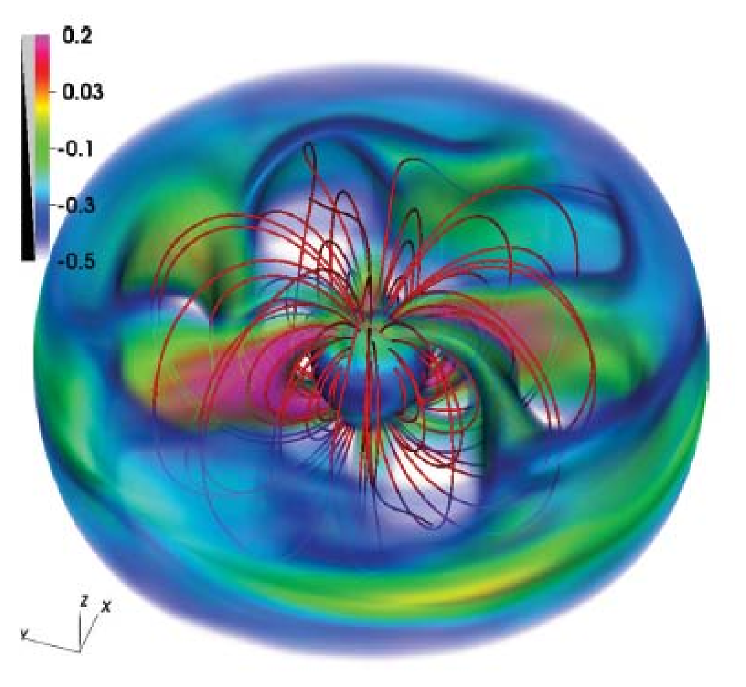




Kurosawa & Romanova (2013)

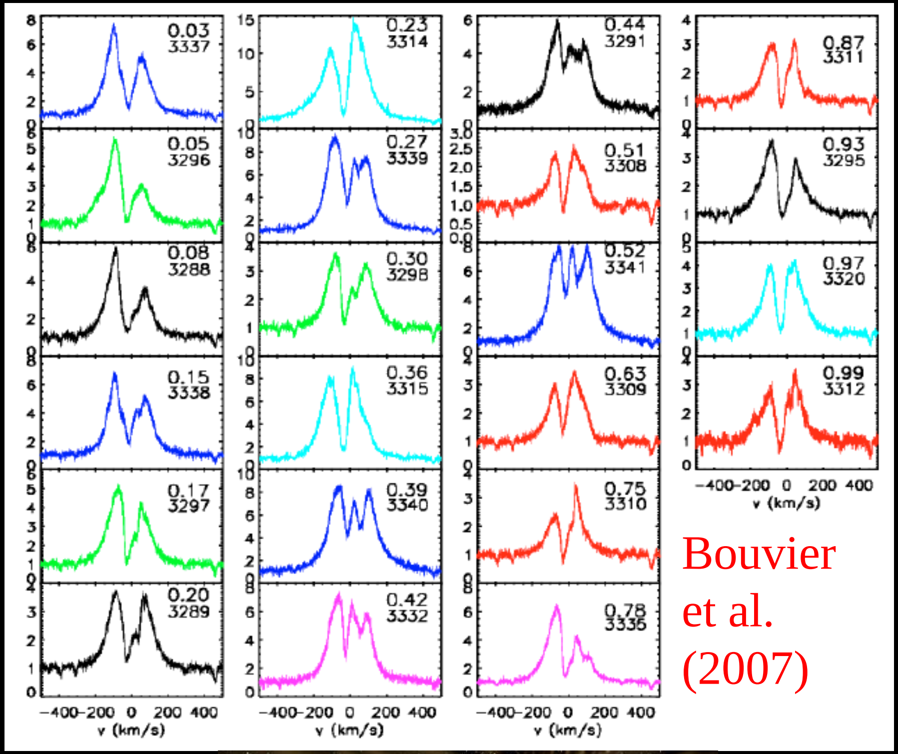
Modeling the Variability





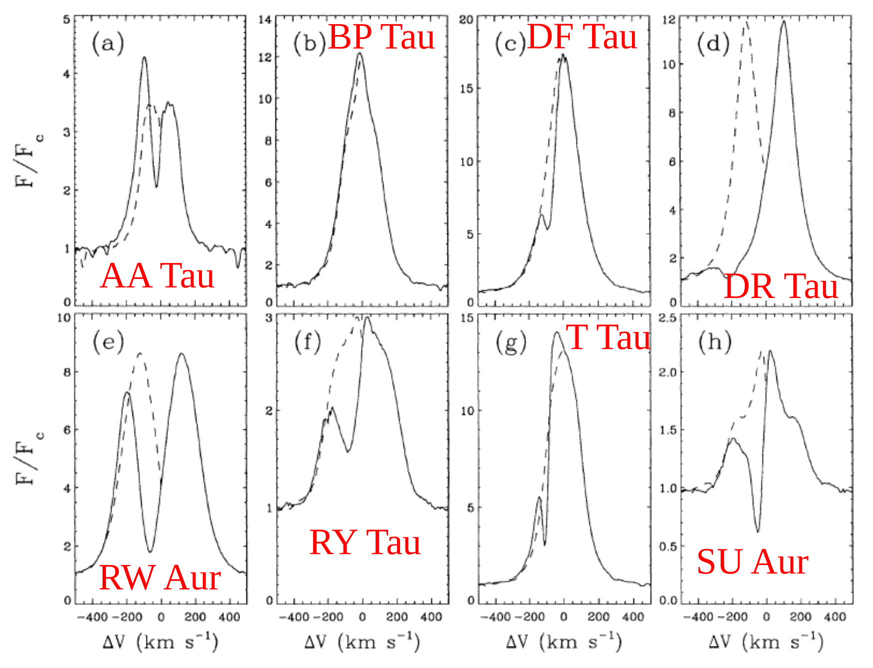
Observing the Variability

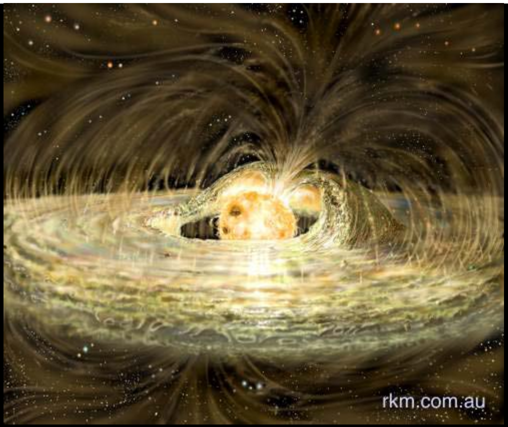
AA Tau

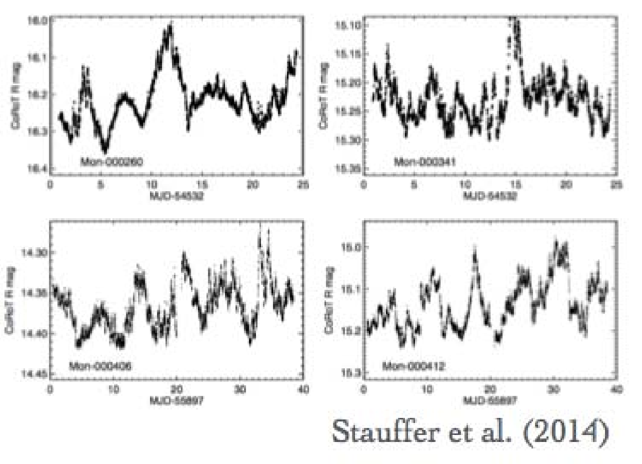


Bouvier et al. (2007)

Johns & Basri (1995)



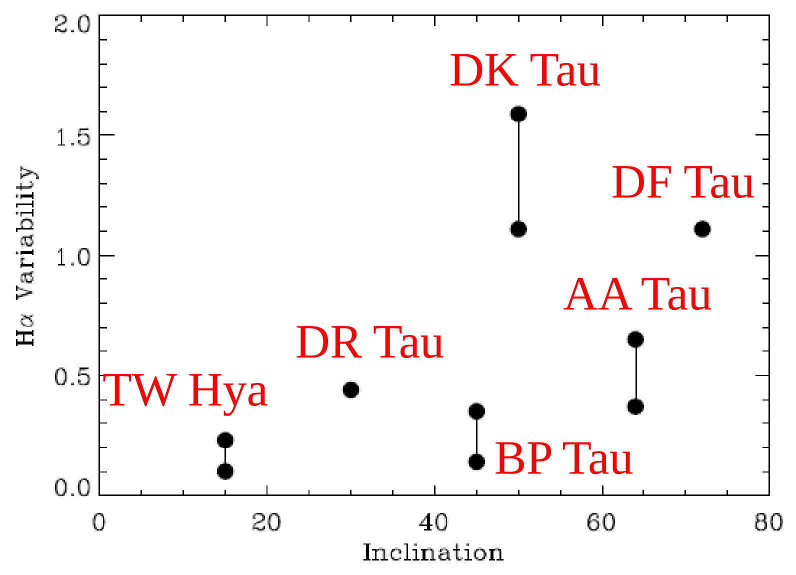


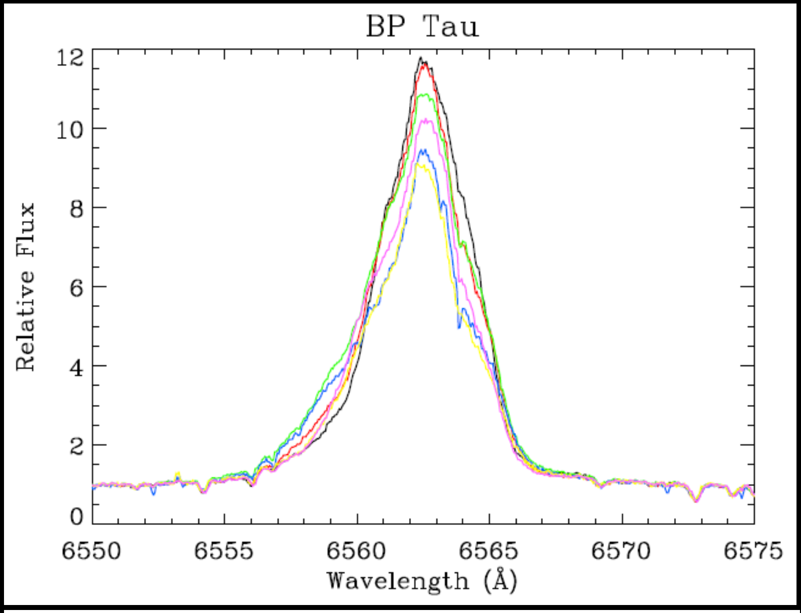


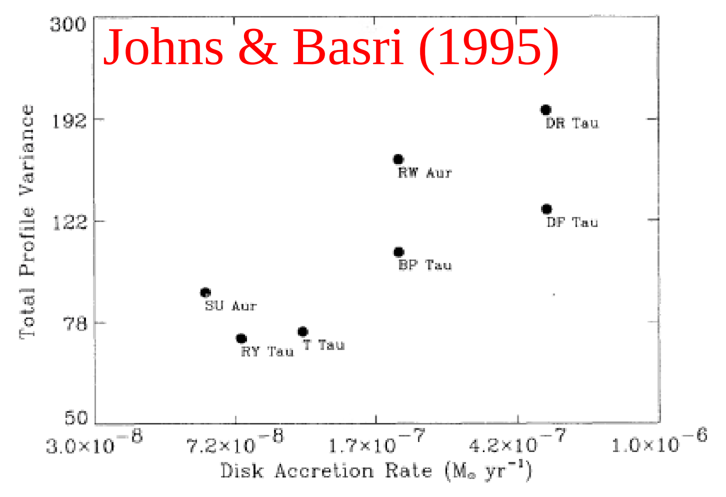
Stauffer et al. (2014)

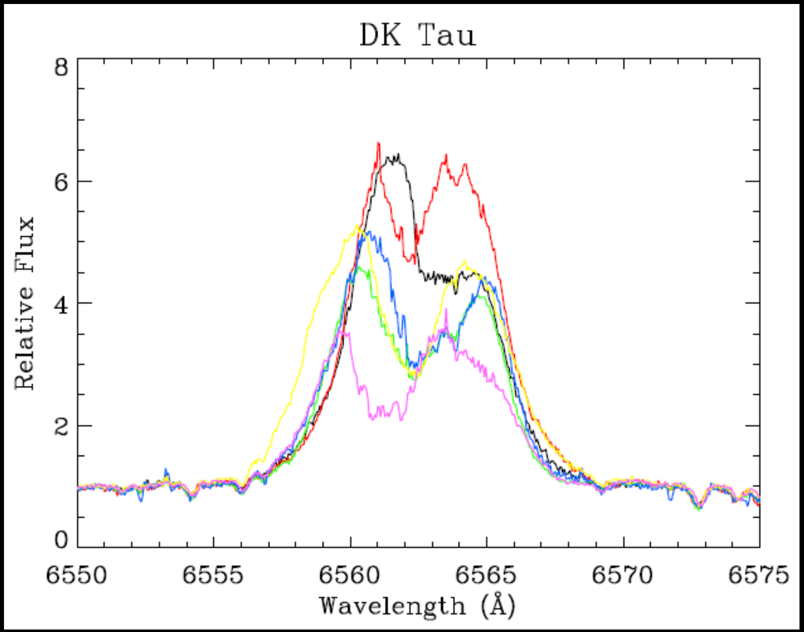
Correlations of Hα Variability

Chen & Johns-Krull (2017)

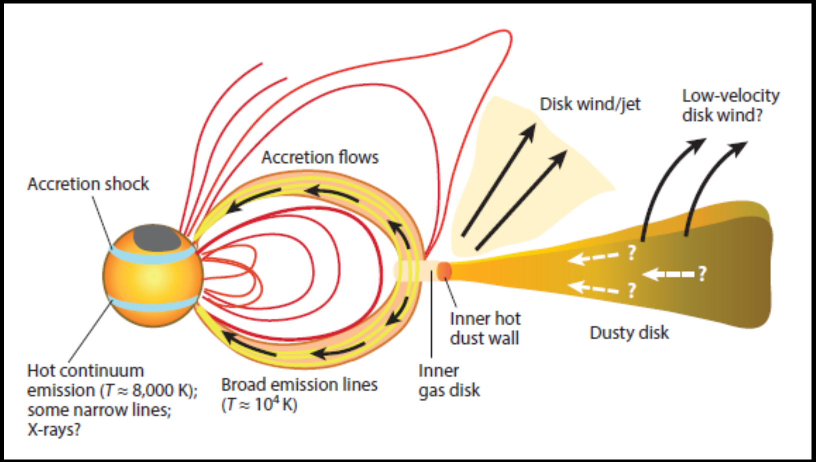




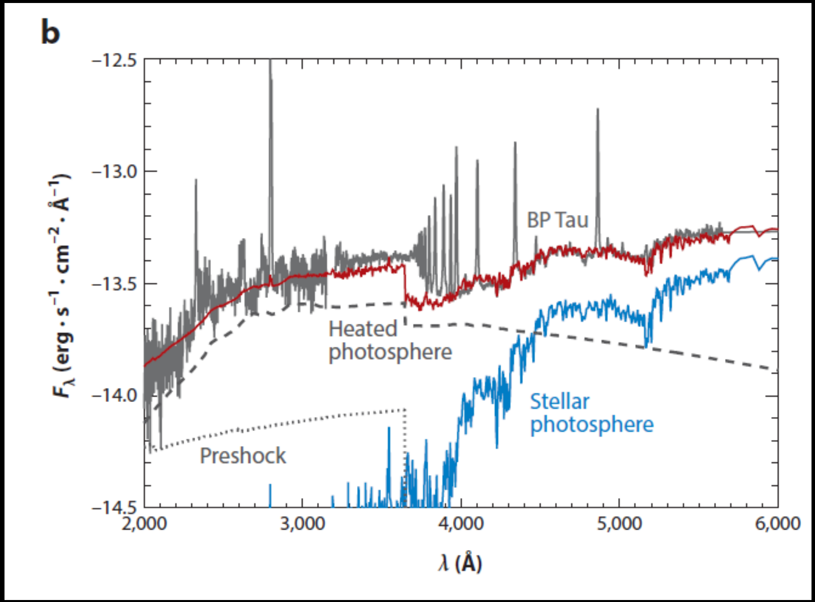

Johns & Basri (1995)

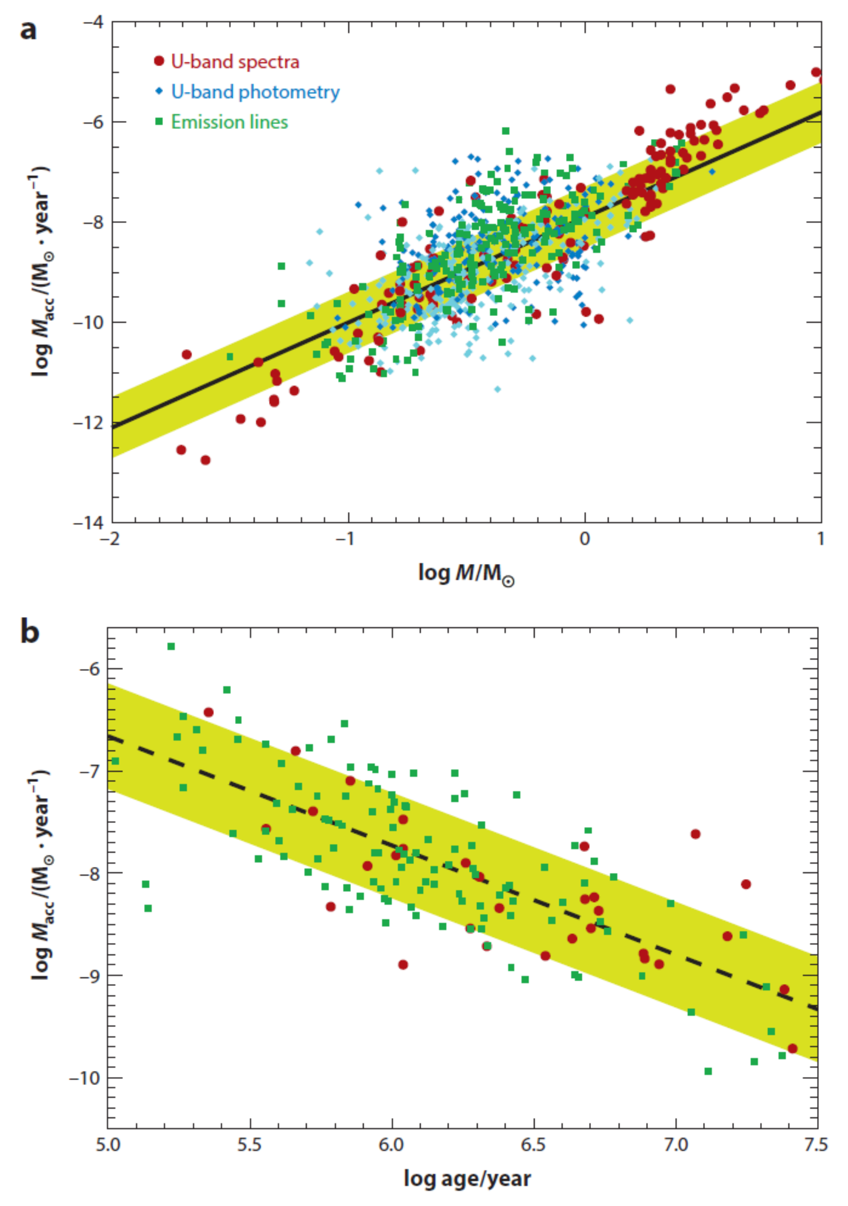


Some Observed Trends

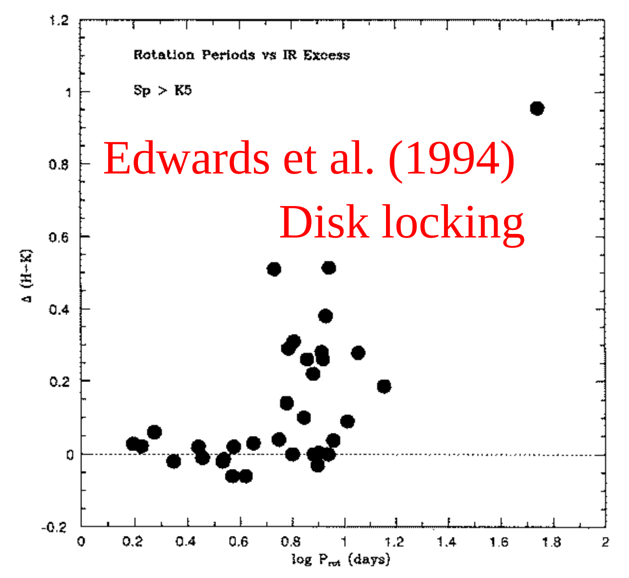


Hartmann et al. (2016, ARAA)



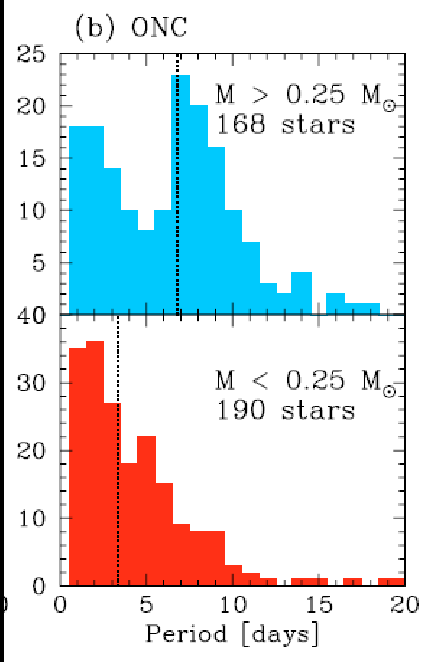


Magnetospheric Accretion and Disk Locking



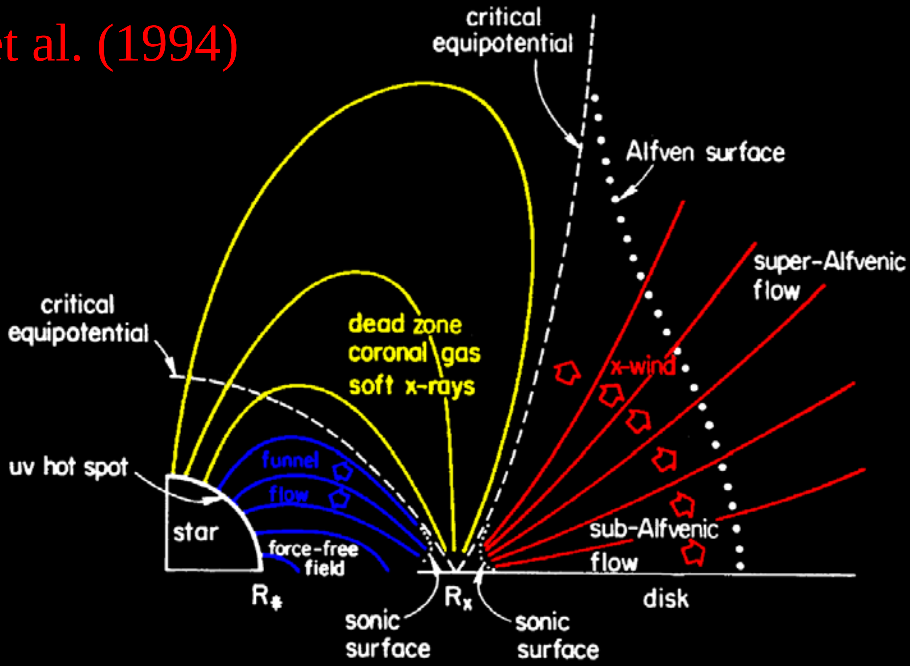
Edwards et al. (1994)

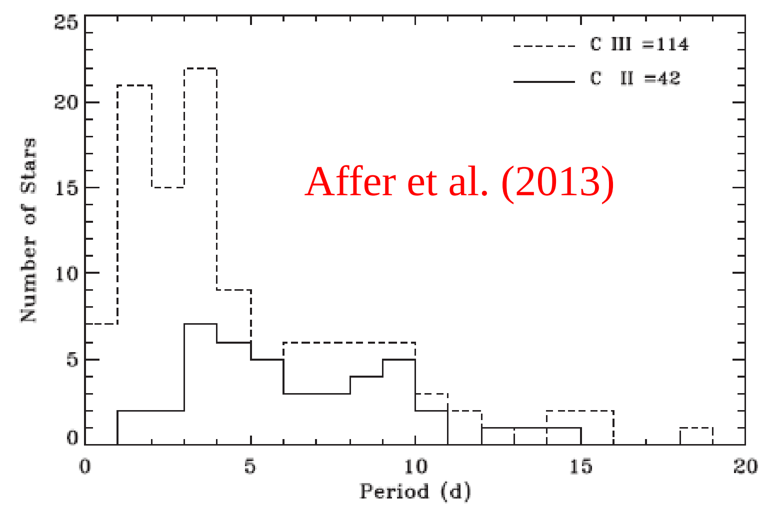
Disk locking



Herbst et al. (2002)

Shu et al. (1994)





Affer et al. (2013)

Disk Locking Predictions

Konigl

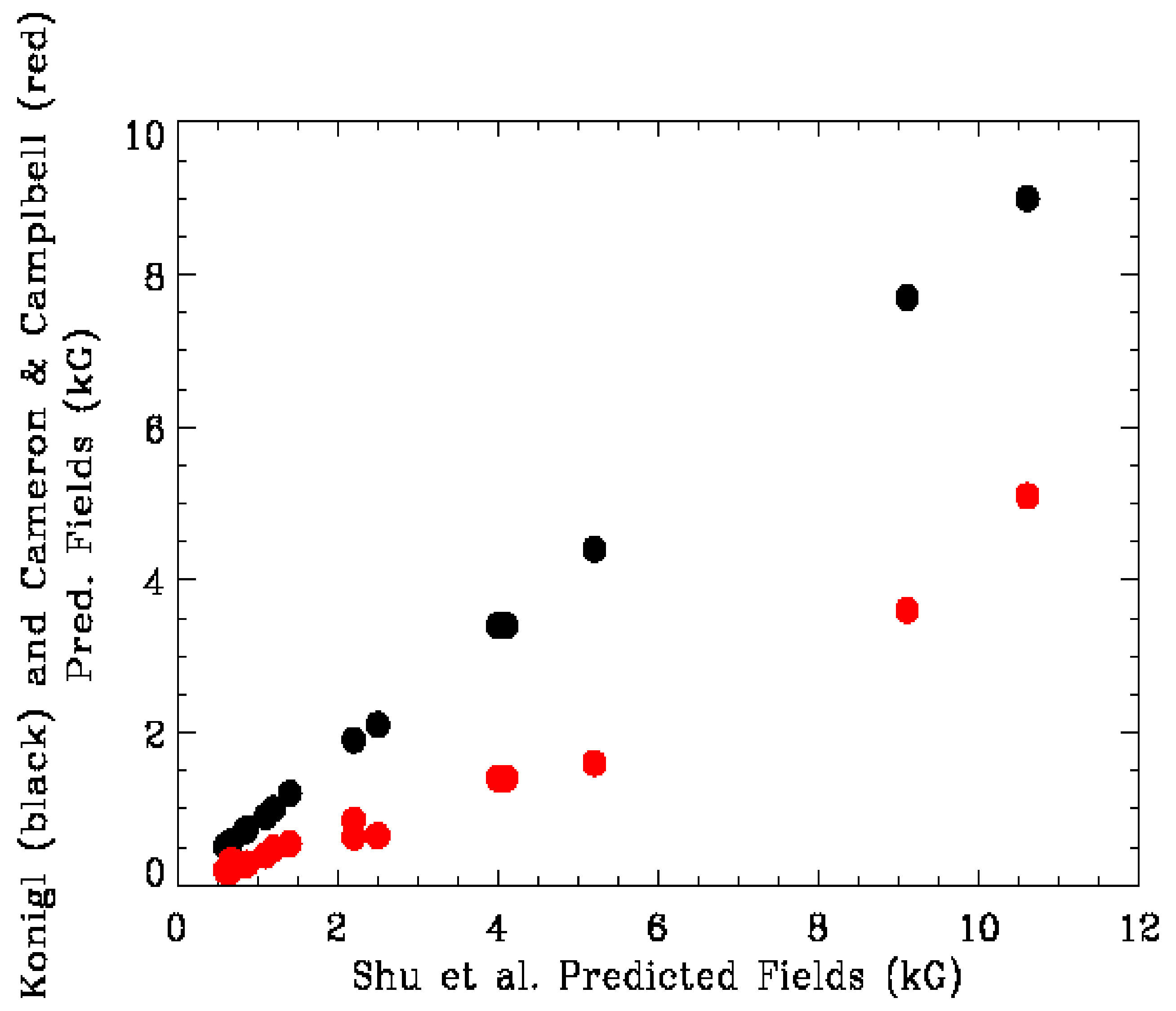
$B_* = 3$ … $\Big)^{7/6}$ kG

Camero

B

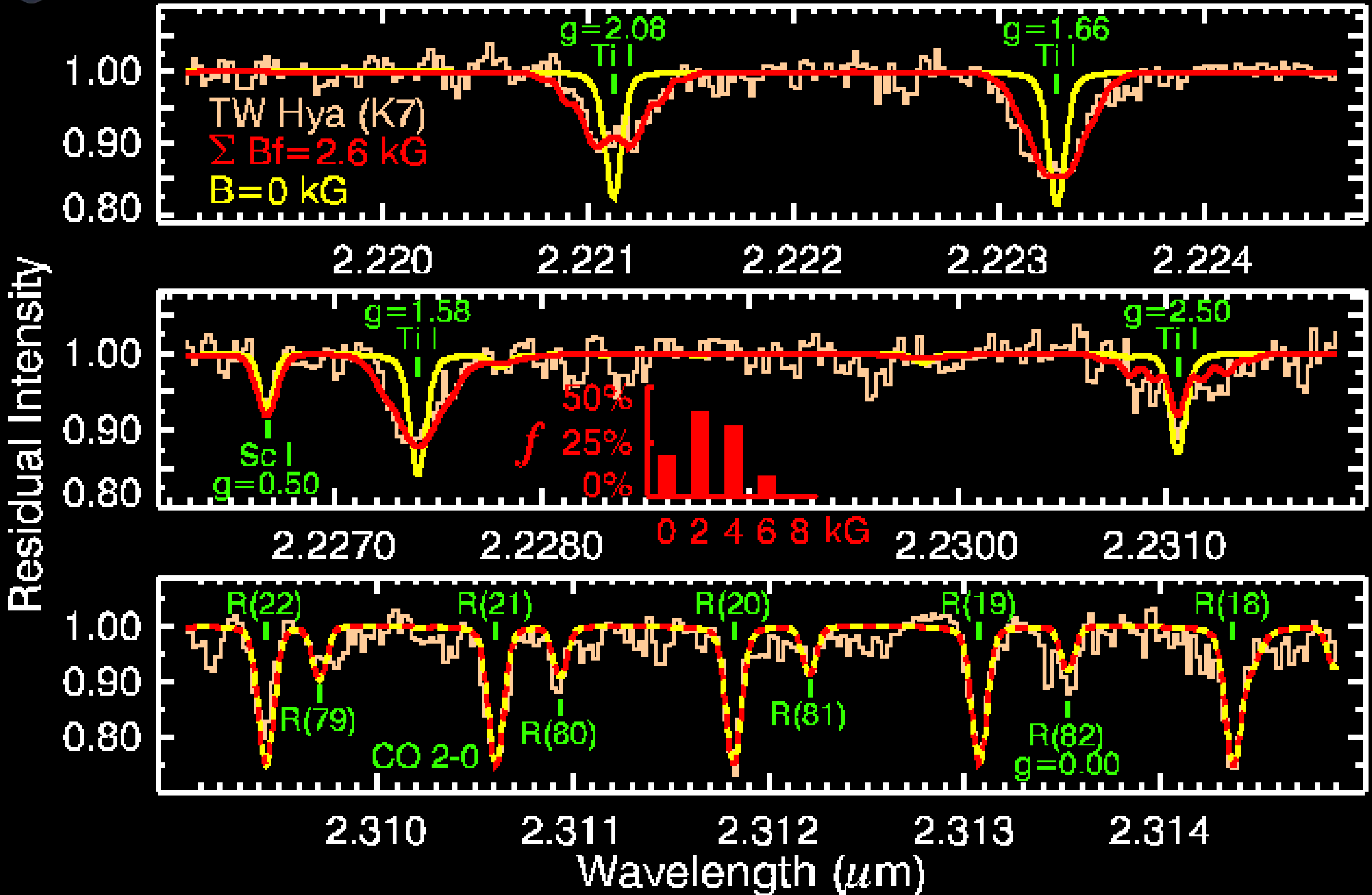
Shu et

B_* … kG



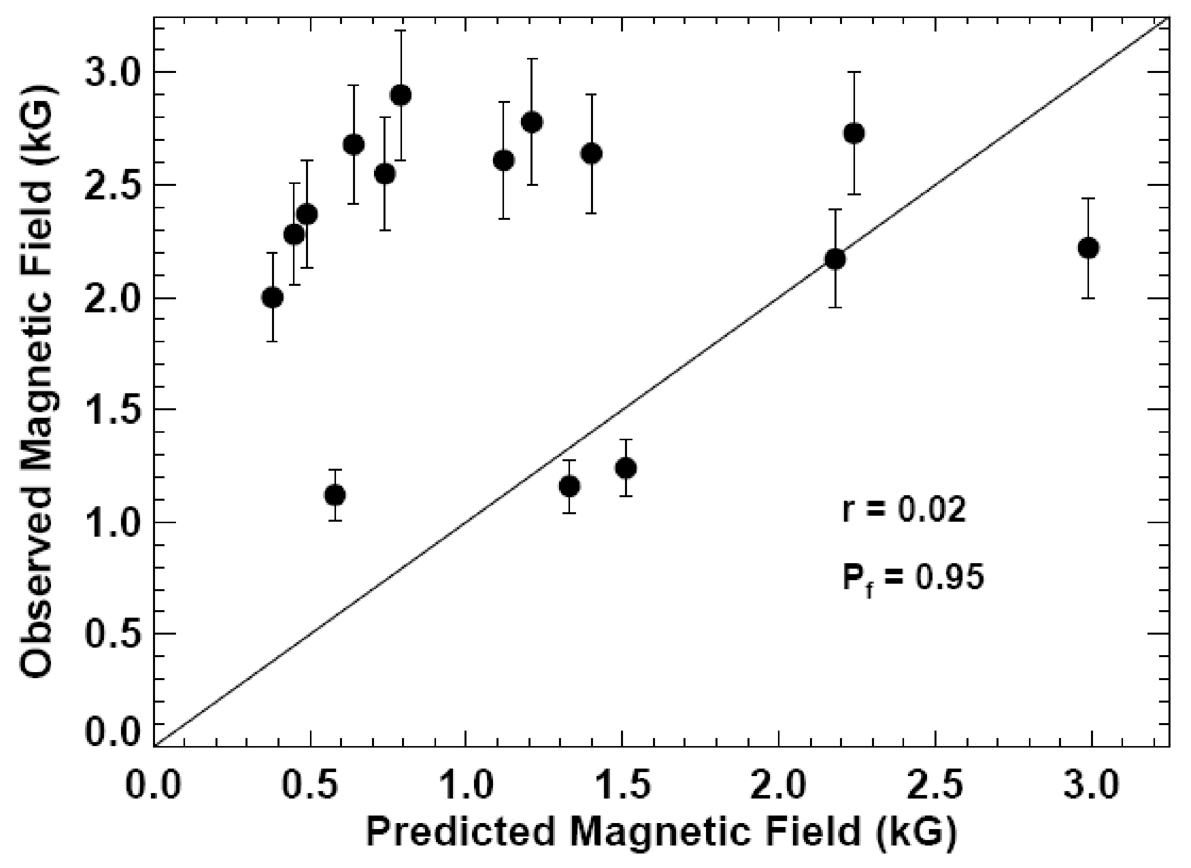
TW Hya: CTTS

Yang, Johns-Krull, & Valenti (2005)



Predicted vs. Observed Mean Fields

Johns-Krull (2007)



Also Yang et al. (2008), Yang & Johns-Krull (2011)

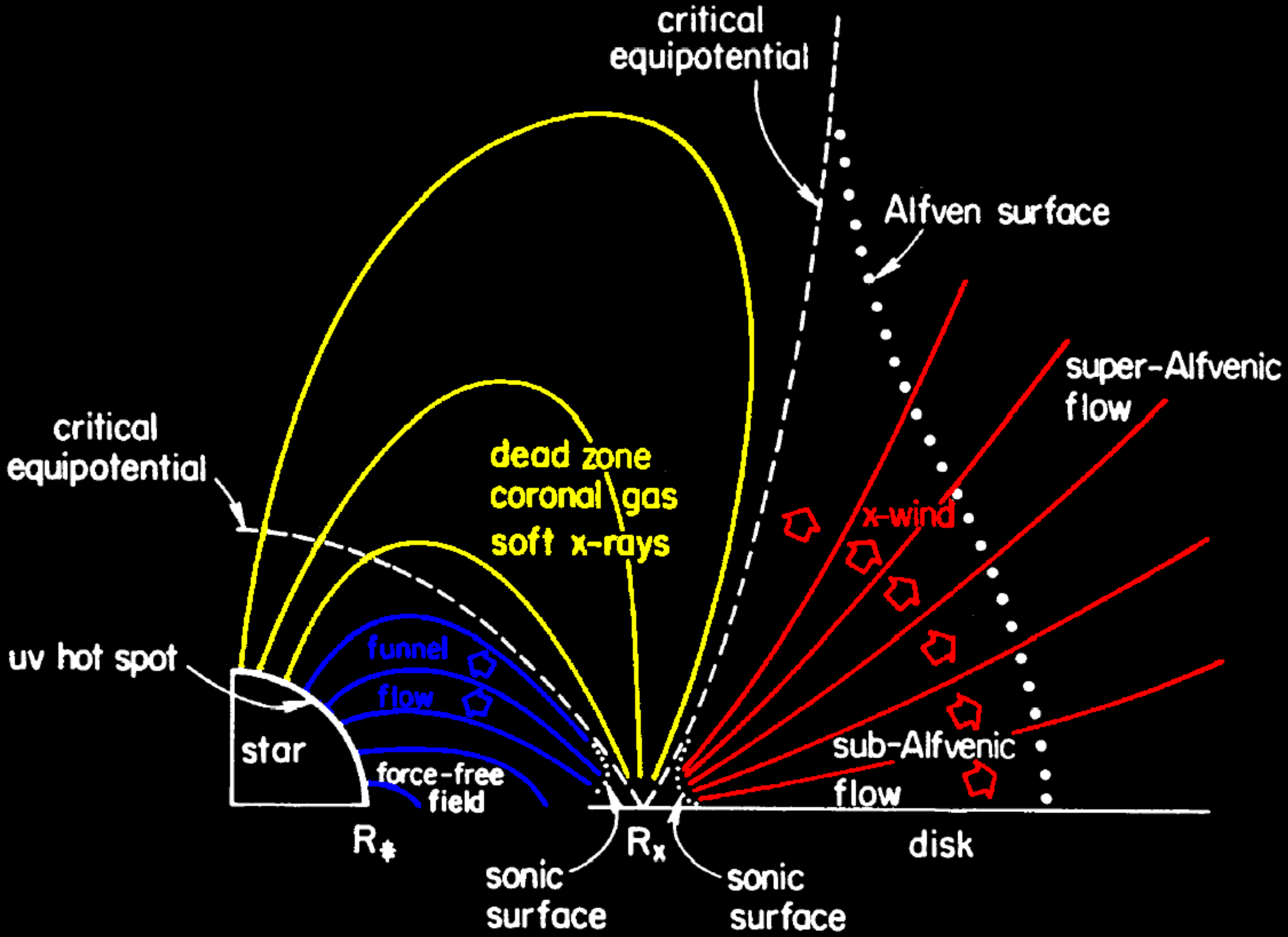
Caveats:

- Theory assumes dipole
- We measure mean field
- Uncertainty on x-axis difficult to quantify

Additionally: no correlation with rotation rate, Rossby number, etc.

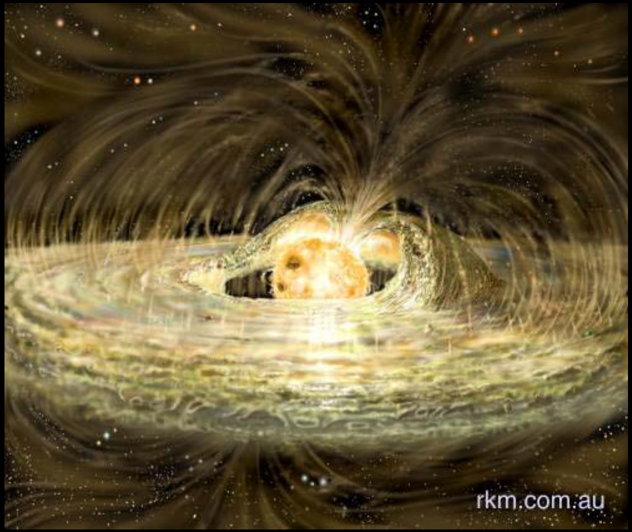
Trapped Flux in the Shu et al. Model

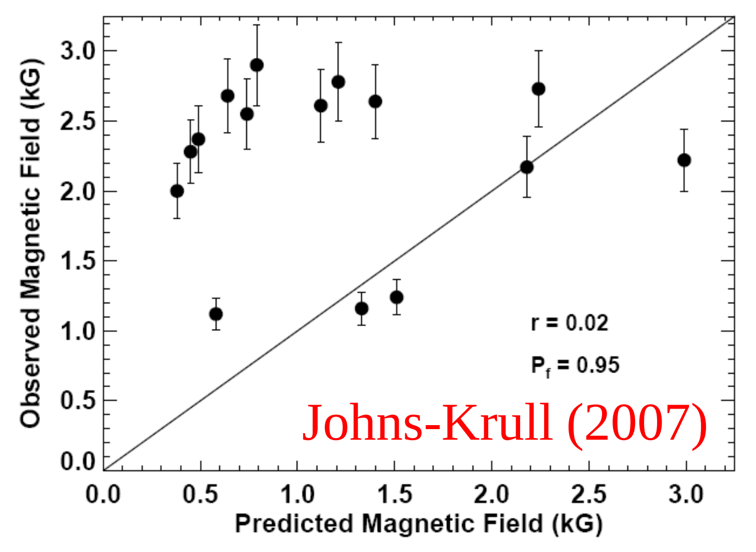
Shu et al. (1994)



Theory gives field at some point in the disk

Assuming *B* Constant





Johns-Krull (2007)

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

Johns-Krull & Gafford (2002):

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

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

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

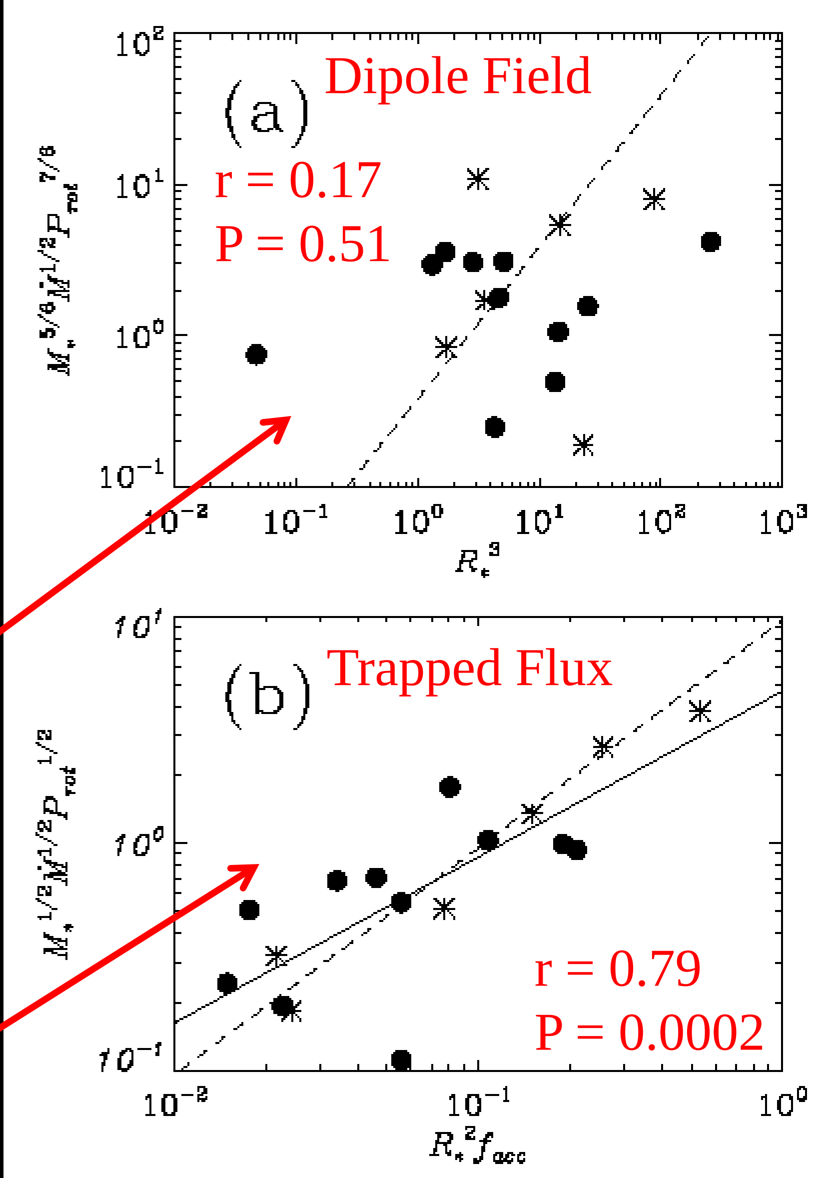
$$R_*^2 f_{acc} \propto M_*^{1/2}\dot{M}^{1/2}P_{rot}^{1/2}$$

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

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

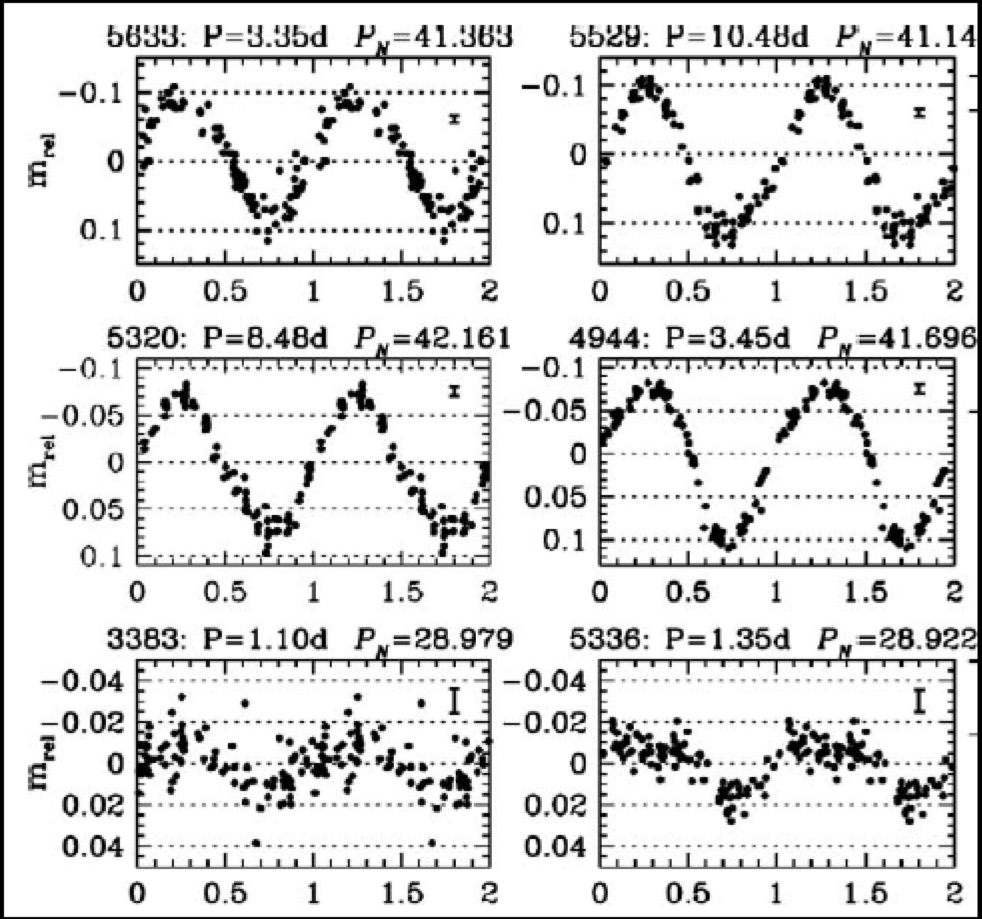
$$R_*^2 f_{acc} \propto M_*^{1/2}\dot{M}^{1/2}P_{rot}^{1/2}$$



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

Moving to NGC 2264

Lamm et al. (2004, 2005)



Age ~3 Myr
Distance ~760 pc

$$R_*^2 f_{acc} \propto M_*^{1/2} \dot{M}^{1/2} P_{rot}^{1/2}$$

New NGC 2264 Observations

Cauley et al. (2012)

- Low resolution, flux calibrated, blue spectra of a large sample of TTS
- Fit Template + LTE Hydrogen slab models to spectra of CTTS
- Give mass accretion rate and filling factor of slab emission

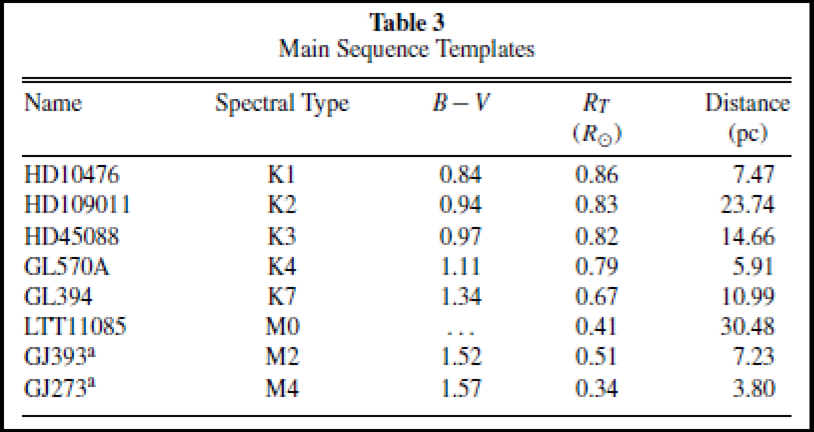
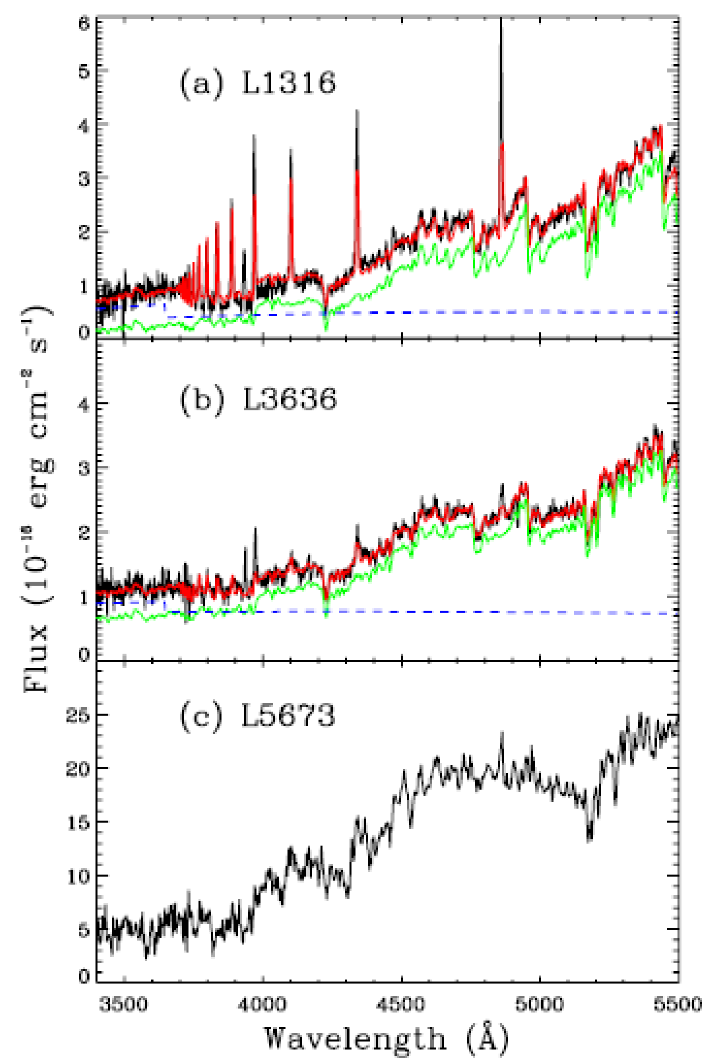


Table 3
Main Sequence Templates

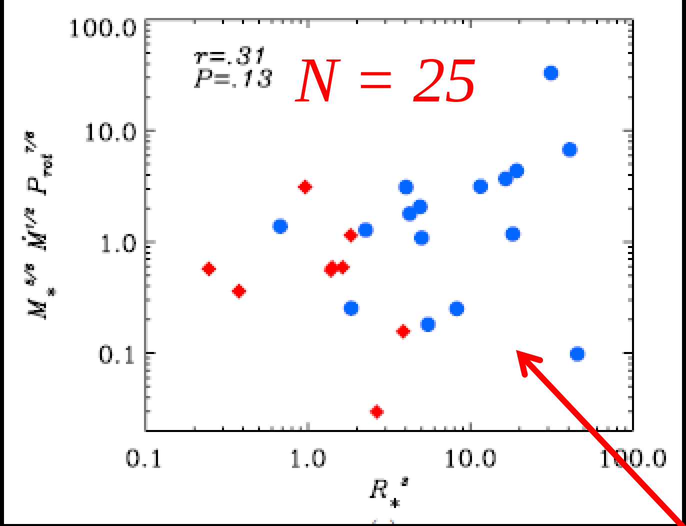
Name	Spectral Type	$B-V$	R_T ($R_\odot$)	Distance (pc)
HD10476	K1	0.84	0.86	7.47
HD109011	K2	0.94	0.83	23.74
HD45088	K3	0.97	0.82	14.66
GL570A	K4	1.11	0.79	5.91
GL394	K7	1.34	0.67	10.99
LTT11085	M0	…	0.41	30.48
GJ393[a]	M2	1.52	0.51	7.23
GJ273[a]	M4	1.57	0.34	3.80

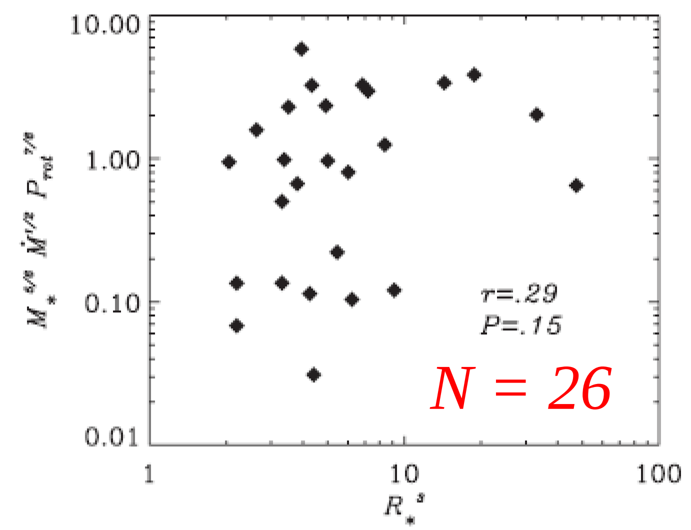
$$\dot{M} = \frac{L_{\mathrm{acc}} R_*}{G M_*}\left(1 - \frac{R_*}{R_{\mathrm{Tr}}}\right)^{-1}$$

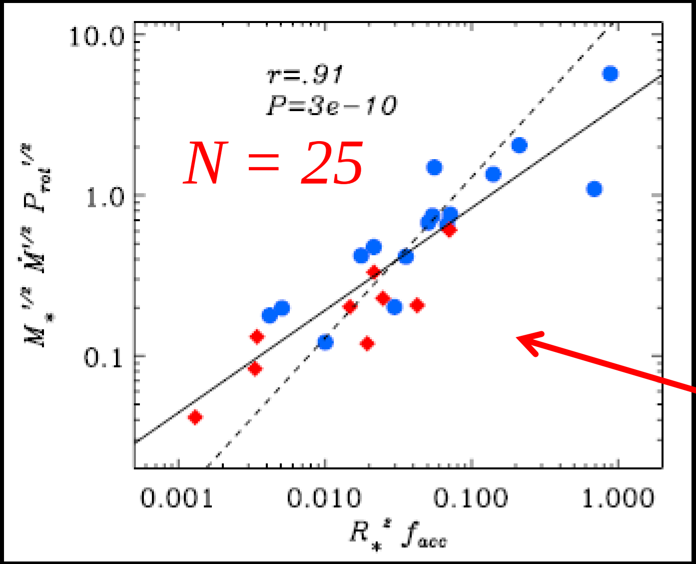


Testing Disk Locking

Cauley et al. (2012)





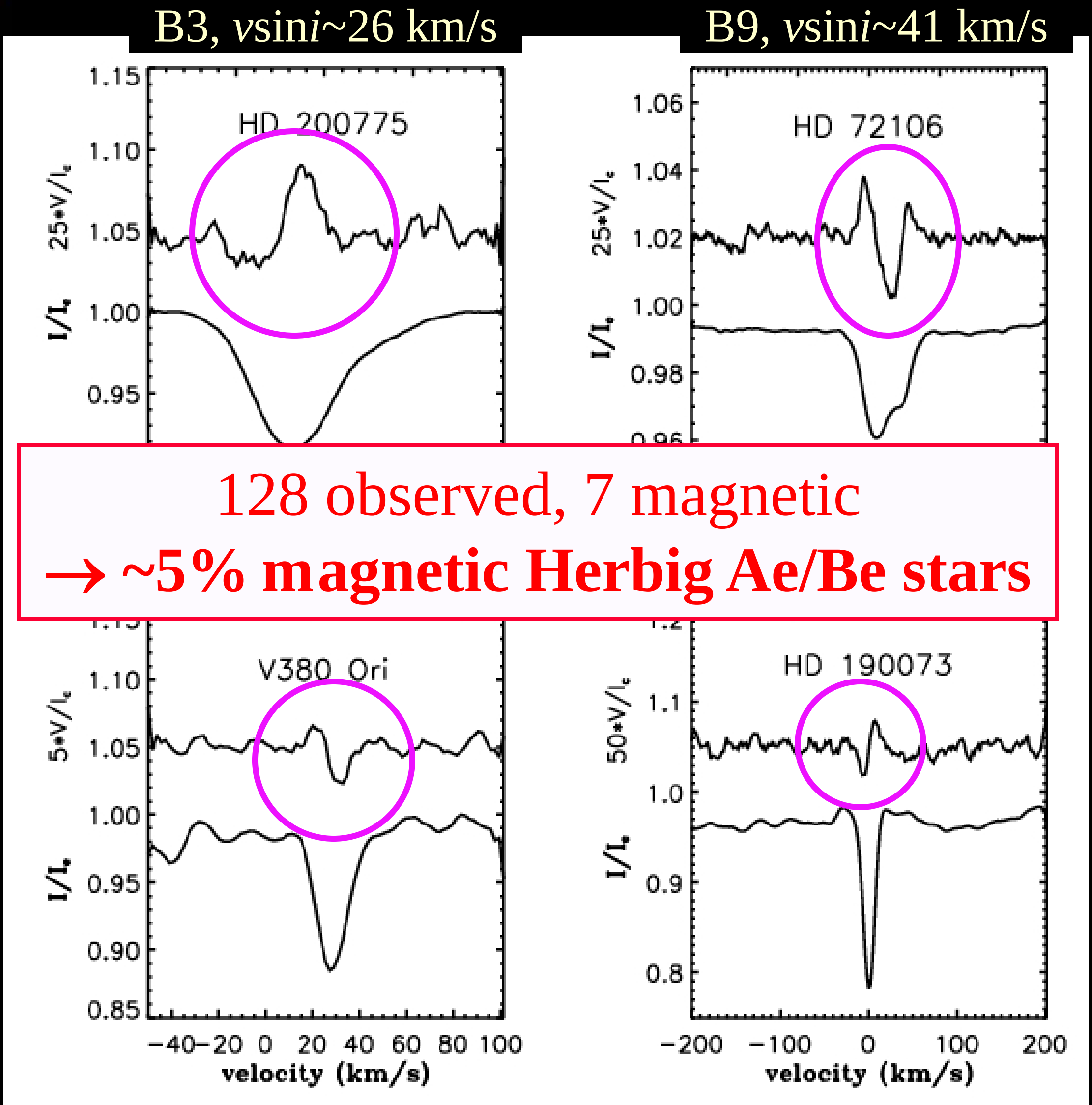


$$\left(\frac{R_*}{R_\odot}\right)^3 \propto \left(\frac{M_*}{1M_\odot}\right)^{5/6}\left(\frac{\dot{M}}{10^{-7}M_\odot yr^{-1}}\right)^{1/2}\left(\frac{P_*}{1\,day}\right)^{7/6}$$

$$R_*^2 f_{acc} \propto M_*^{1/2}\dot{M}^{1/2}P_{rot}^{1/2}$$

Herbig Ae/Be Magnetic Fields

Alecian 2010: CC2YSO

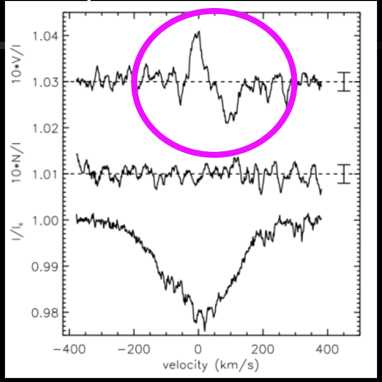

B3, *v*sini~26 km/s

B9, *v*sini~41 km/s

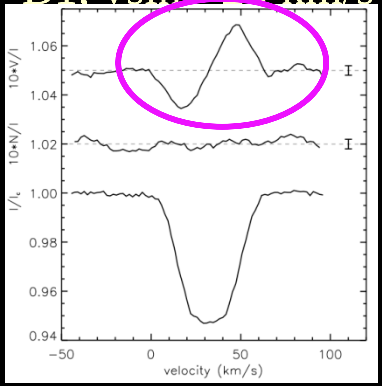
128 observed, 7 magnetic

→ ~5% magnetic Herbig Ae/Be stars

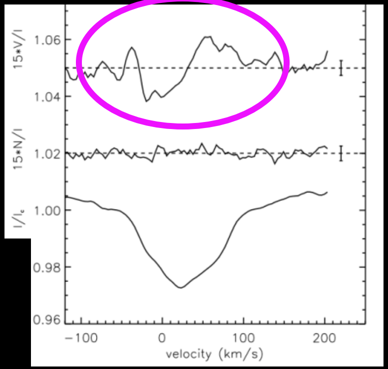
NGC 6611 601
B1.5, vsini~180 km/s



NGC 2244 201
B1, vsini~25 km/s



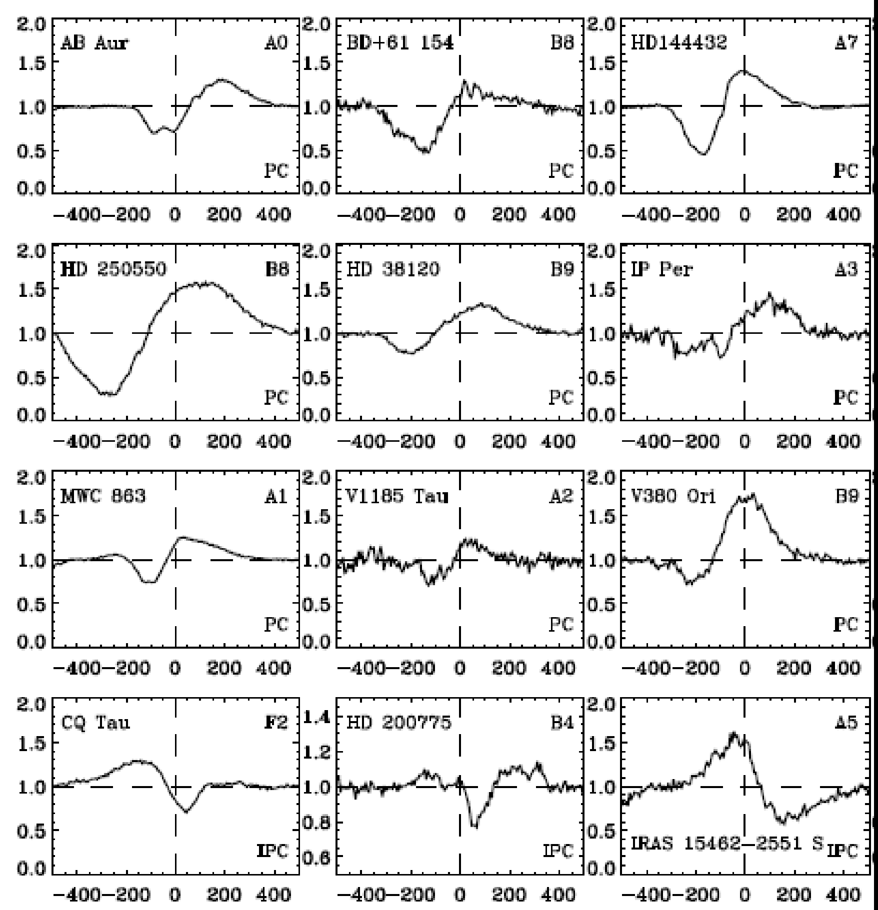
NGC 2264 83
B3, vsini~65 km/s

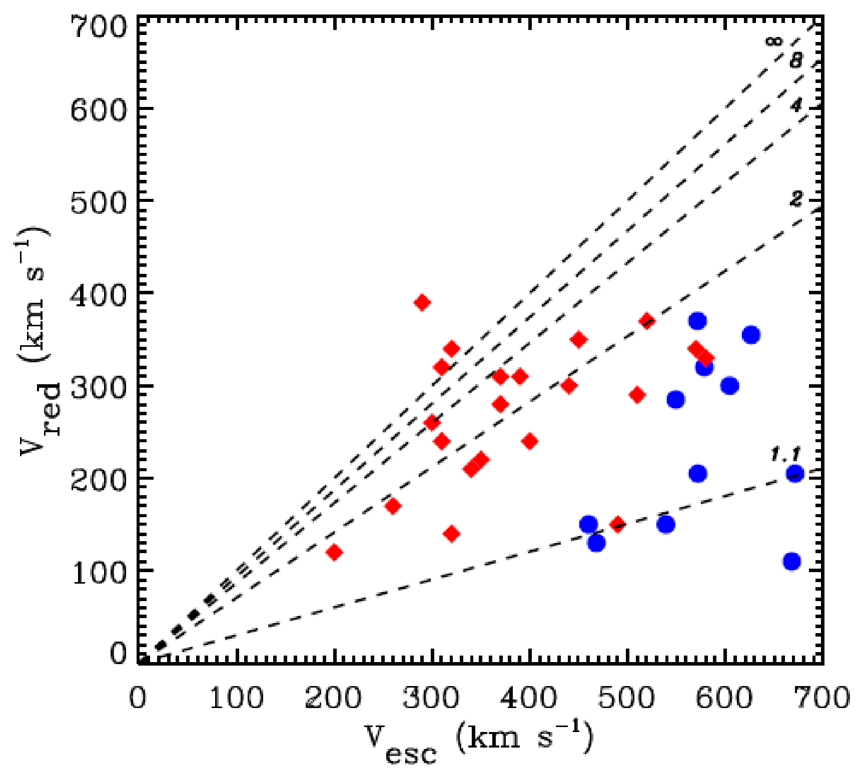


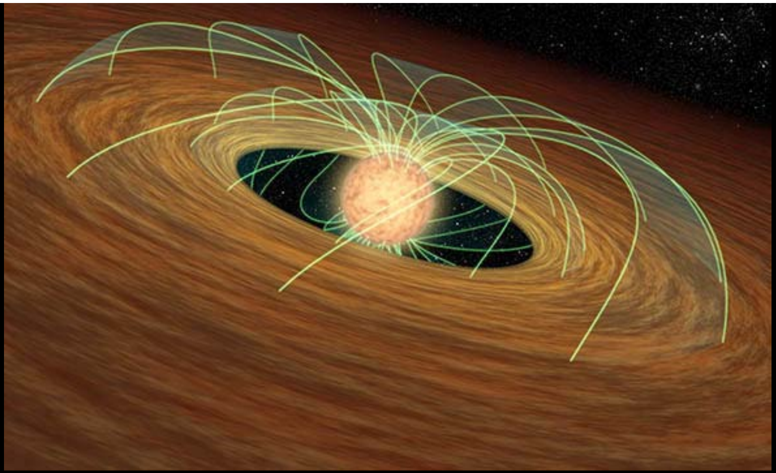
Catala et al. 2007, Alecian et al. 2008a, Alecian et al. 2008b, Folsom et al. 2008, Alecian et al. 2009, Alecian et al. (2013)

Smaller Magnetospheres for Herbig Ae/Be Stars

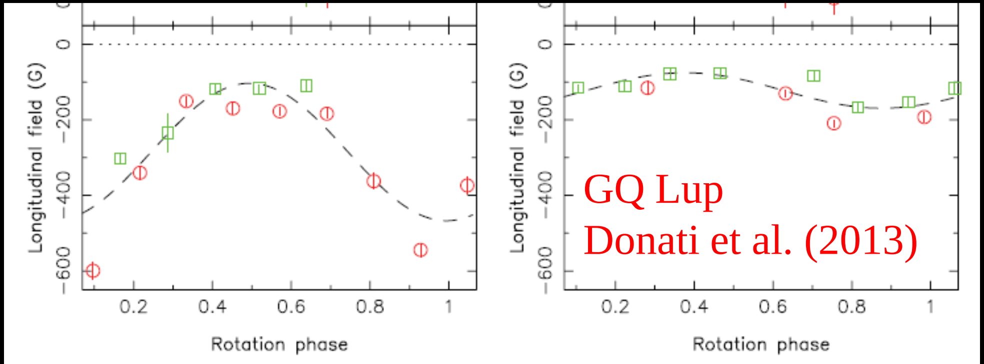
Cauley & Johns-Krull (2014, 2015)



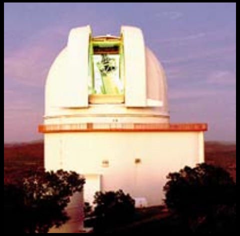


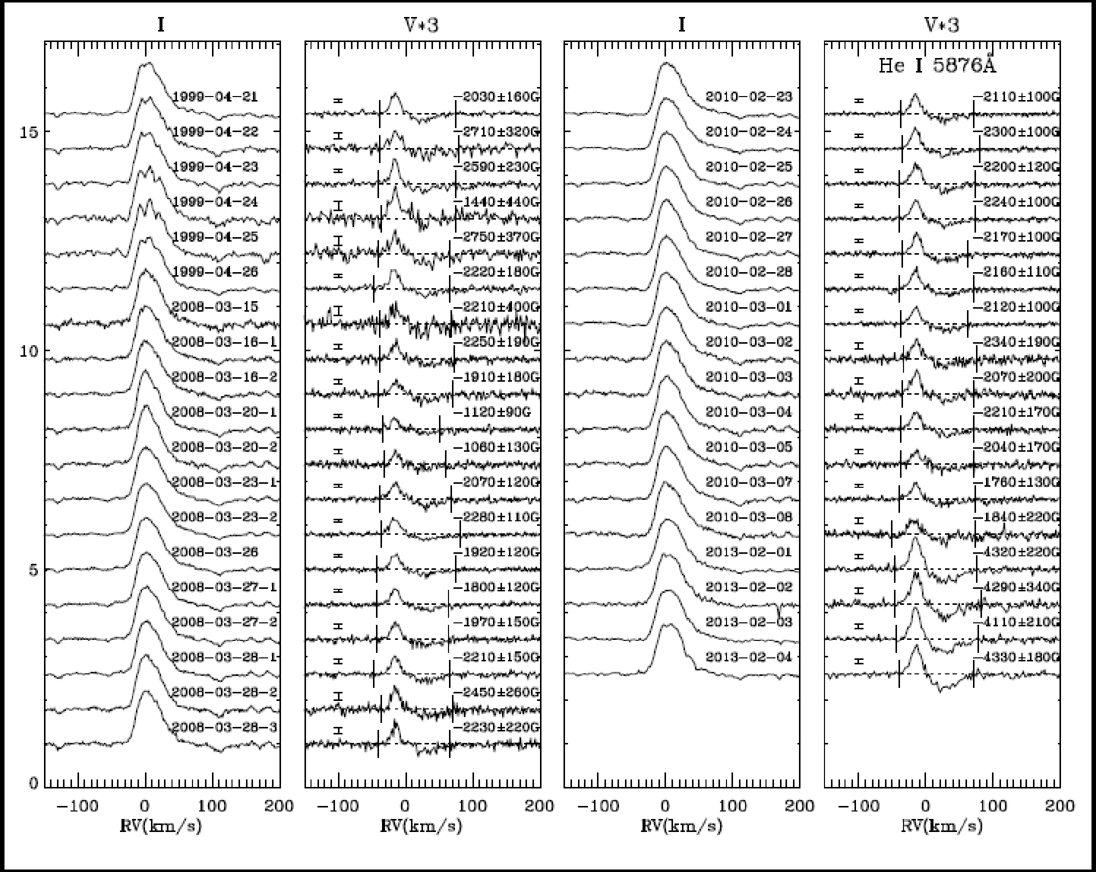


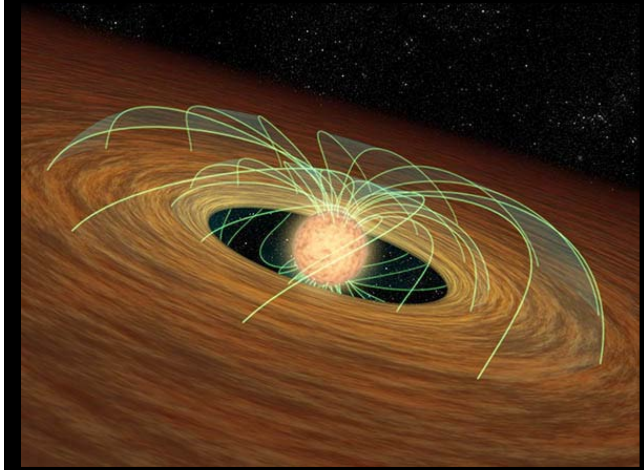
Dynamo Origin of the Stellar Field?



GQ Lup
Donati et al. (2013)



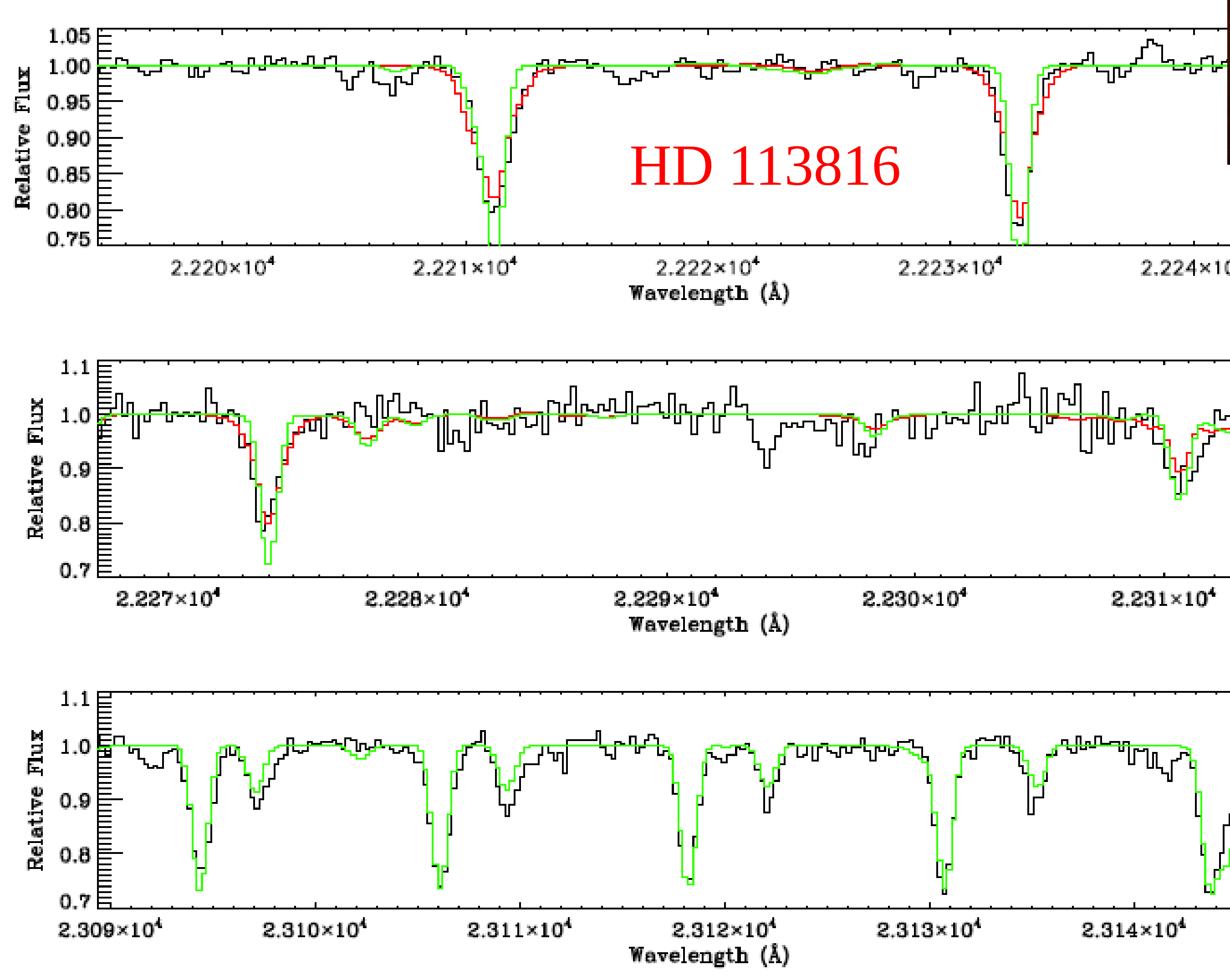


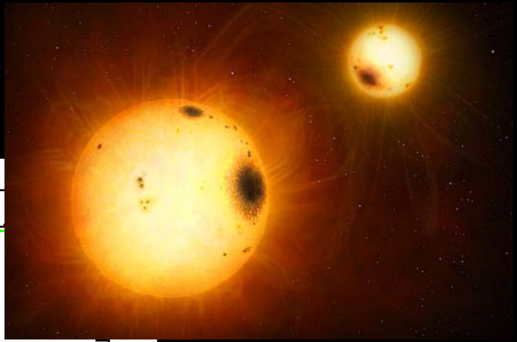


Chen & Johns-Krull (2017)

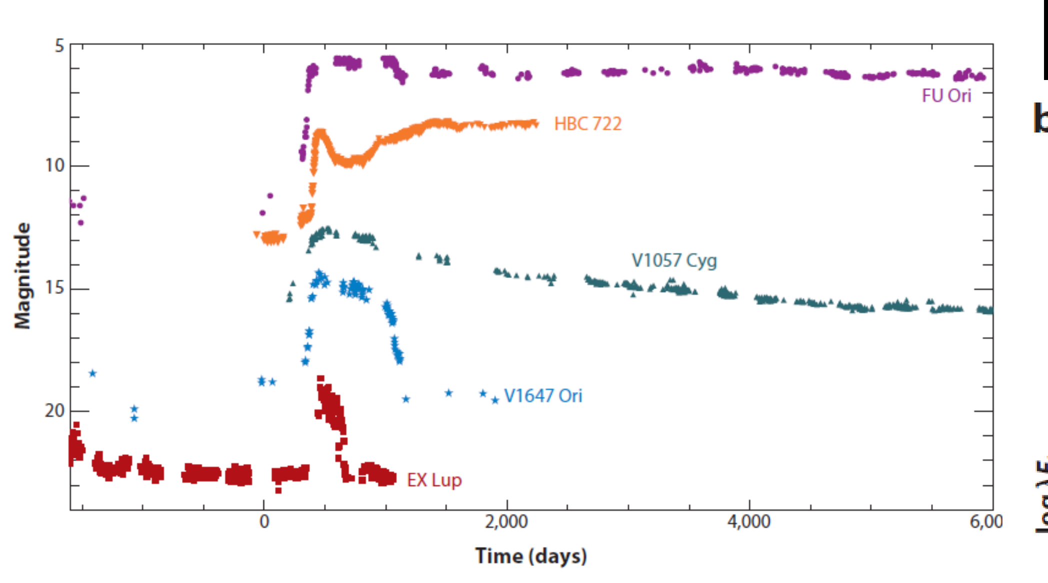
Dynamo Origin of the Stellar Field?

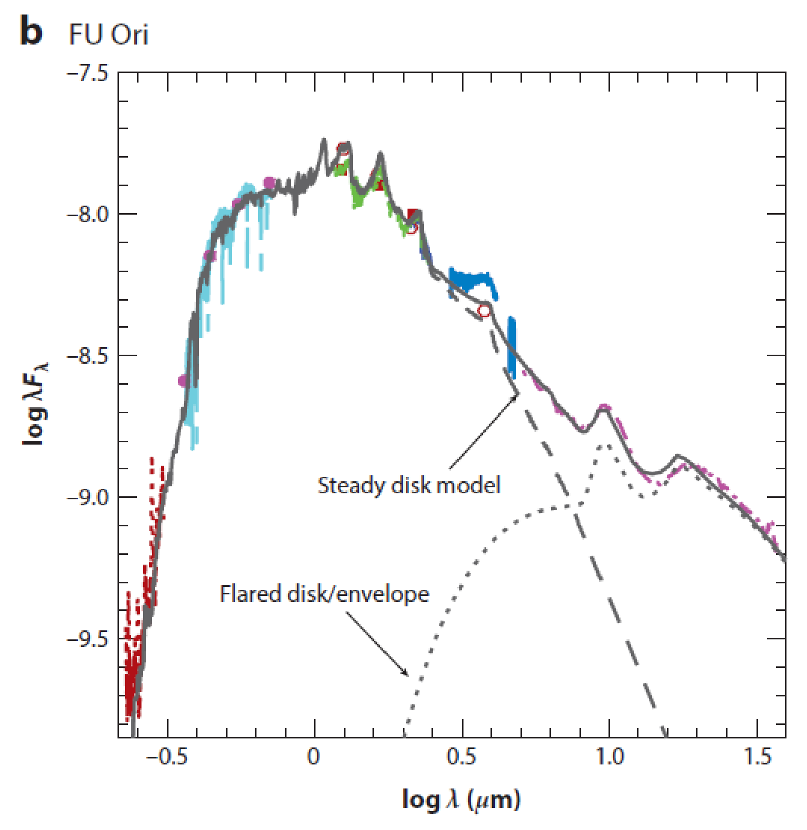
Johns-Krull (2017)

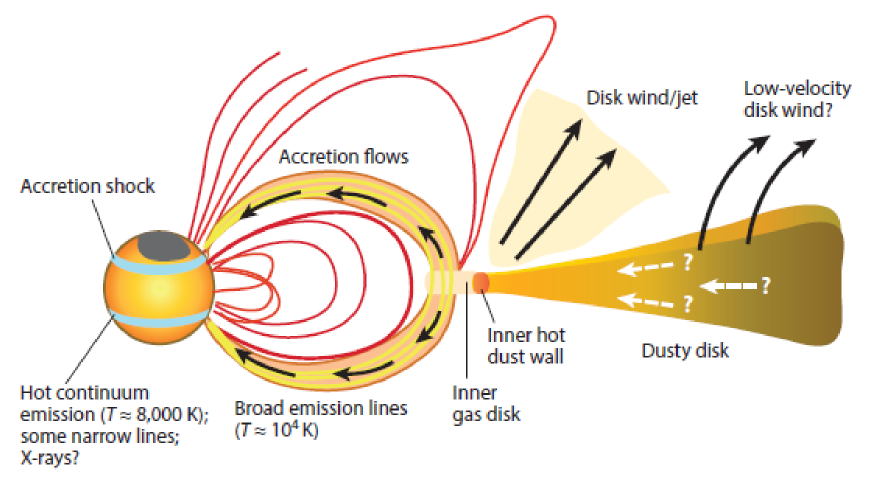




Fields in the Disk: The FU Ori Stars

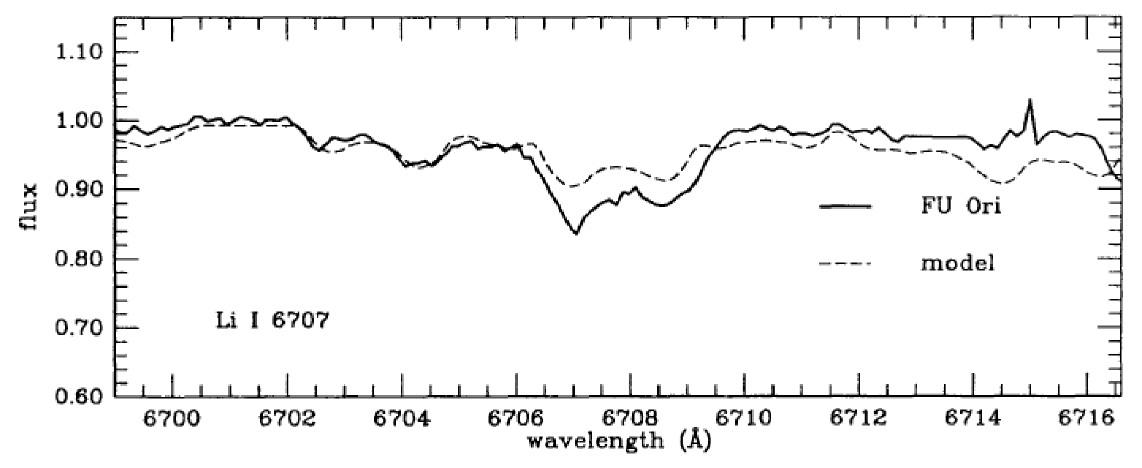




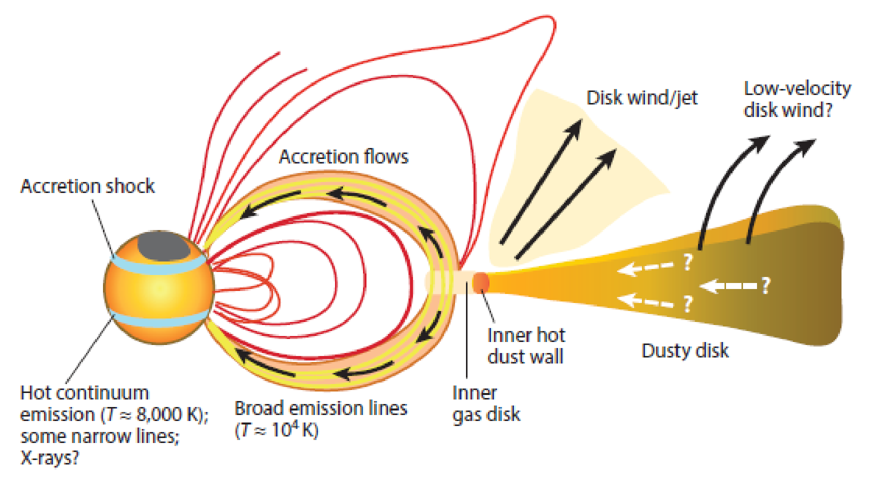


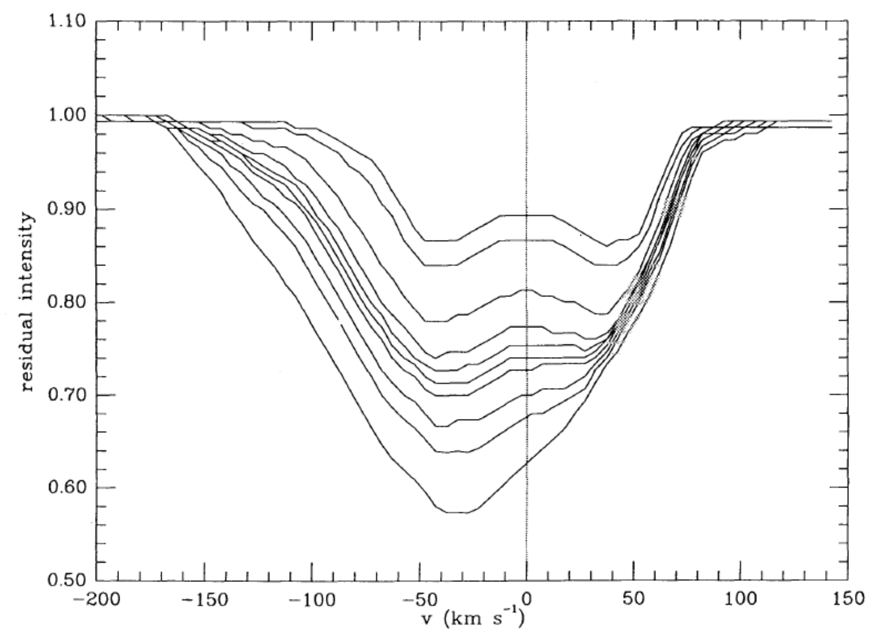
Hartmann et al. (2016, ARAA)

Fields in the Disk: The FU Ori Stars

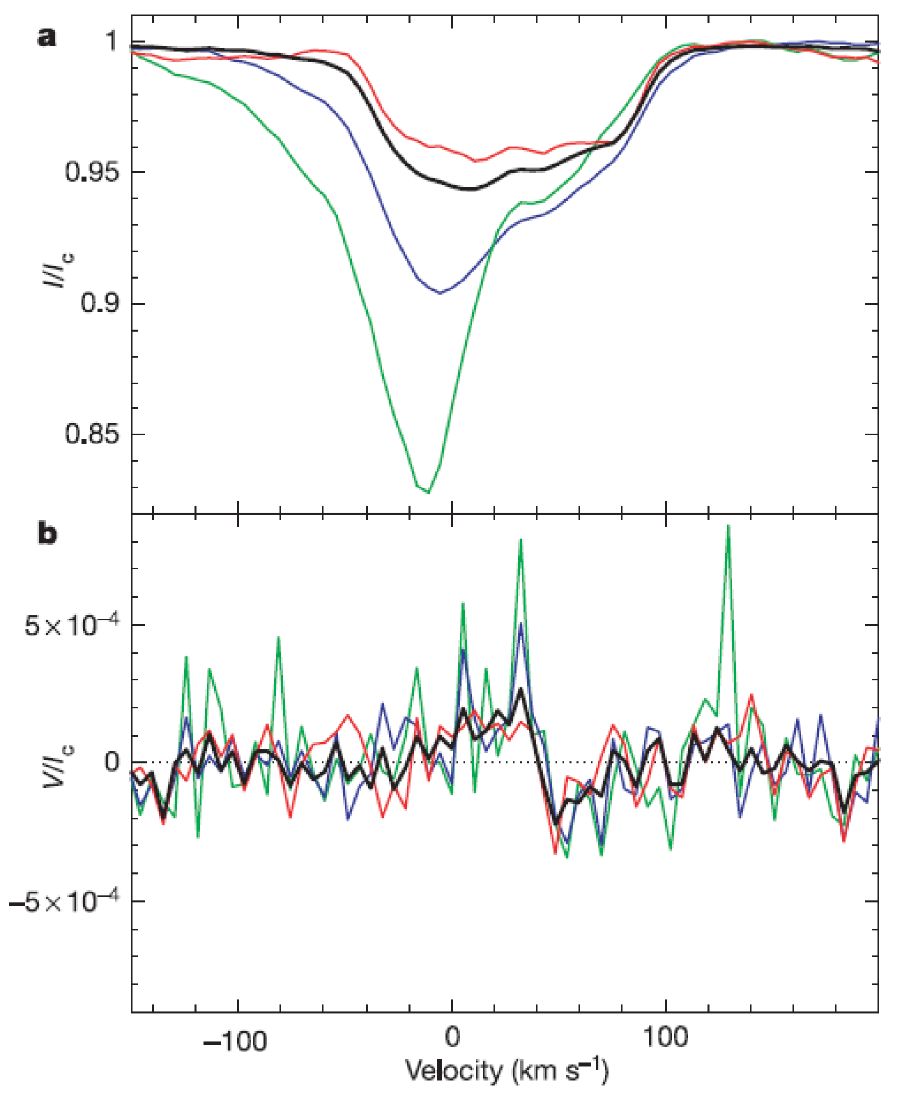


Calvet et al. (1993)



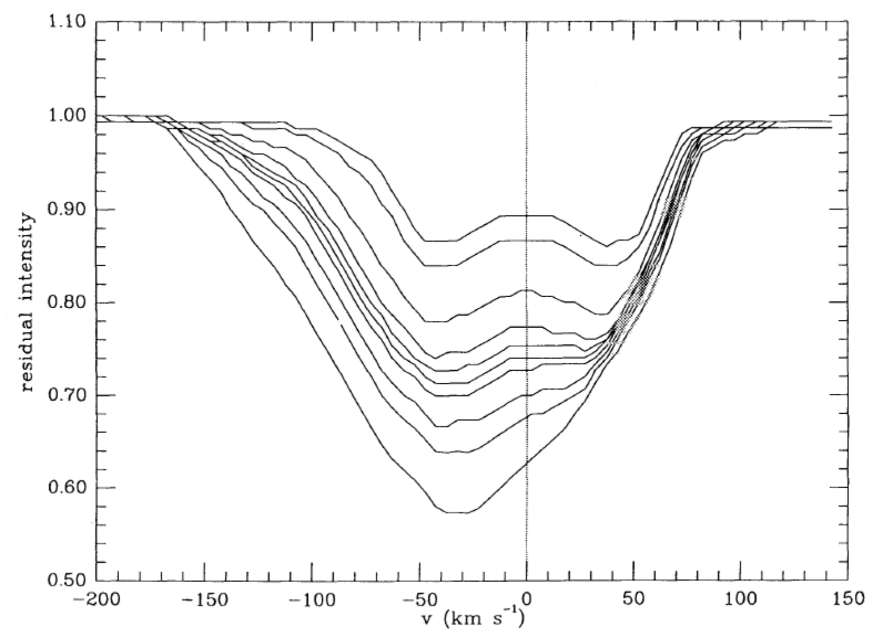


Fields in the Disk: The FU Ori Stars



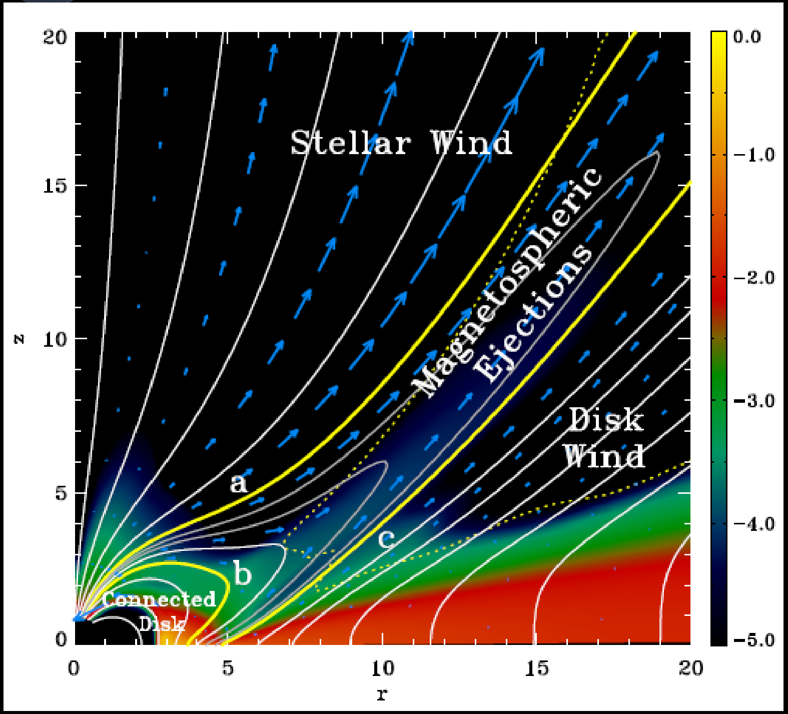
Donati et al. (2005)

Calvet et al. (1993)

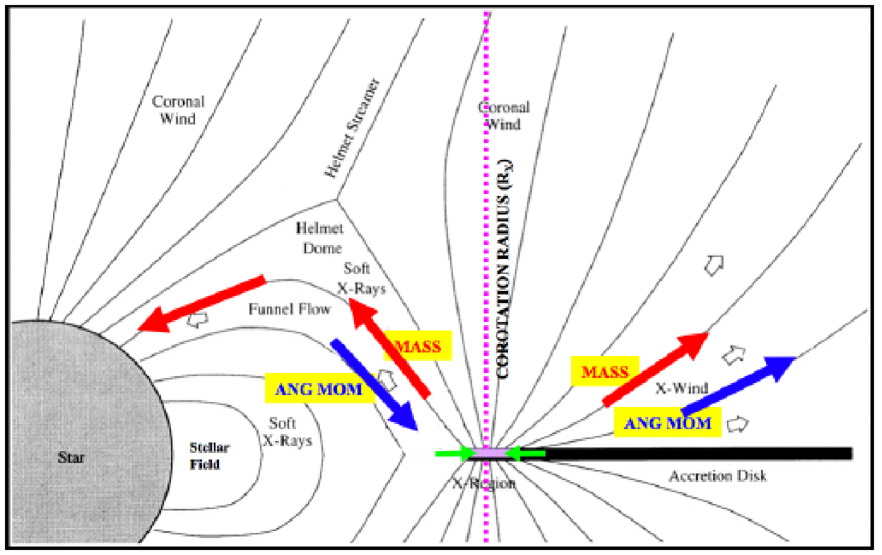


Outstanding Theoretical Issues

Zanni & Ferreira (2012)



Shu et al. (1994)



Weakness of the Dipole

Star	Total Field Johns-Krull (2007)	Large Scale Field Vidotto et al. (2014)
AA Tau	2.78 kG	0.92 kG
BP Tau	2.17 kG	0.69 kG
DN Tau	2.00 kG	0.32 kG
TW Hya	2.61 kG	1.12 kG

Summary and Implications

- Magnetospheric Accretion
  - Accretion onto the star controlled by the stellar field
  - Behavior characterized by variability with little clear periodicity
  - Accretion rate correlated with mass but with large scatter
  - Accretion rate inversely correlated with age but with large scatter
- Comparison of Accretion & Field Properties with Disk Locking
  - Mean fields show no correlation
  - Specific geometry of the fields likely the key
  - Disk locking relations show better correlation using trapped flux
  - Still many open theory questions related to disk locking, e.g. is the large scale field really strong enough?
  - Finally, we would like to explore the disk field more….stay tuned