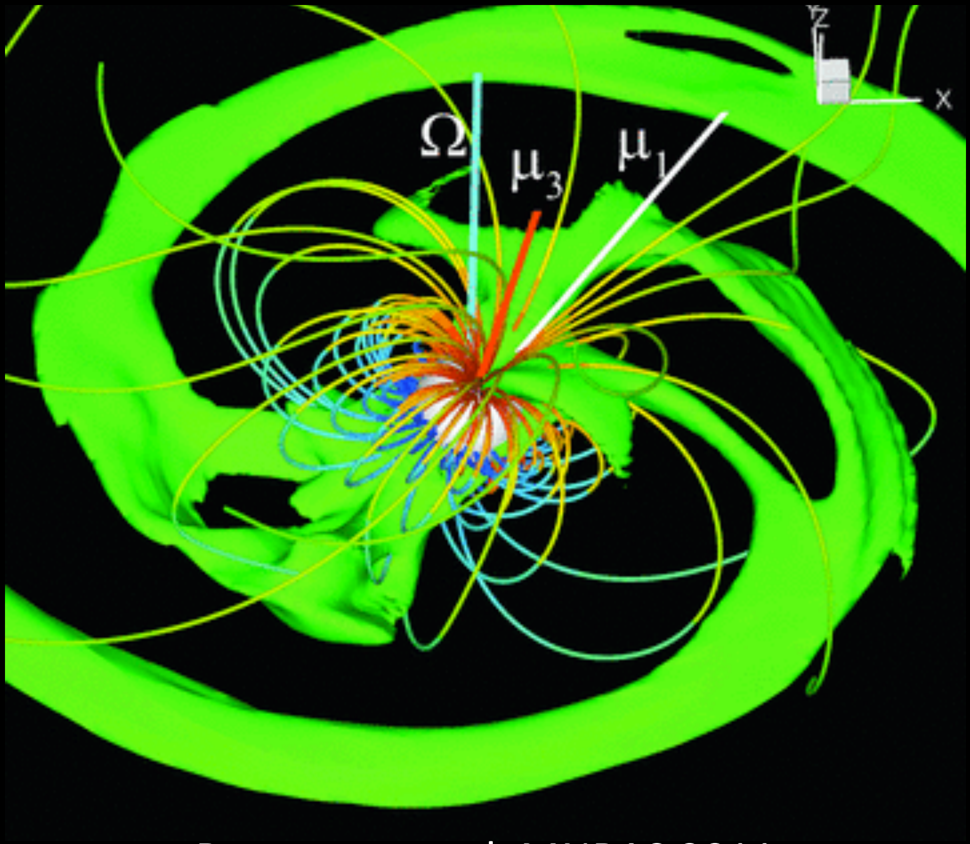


Romanova et al. MNRAS 2011

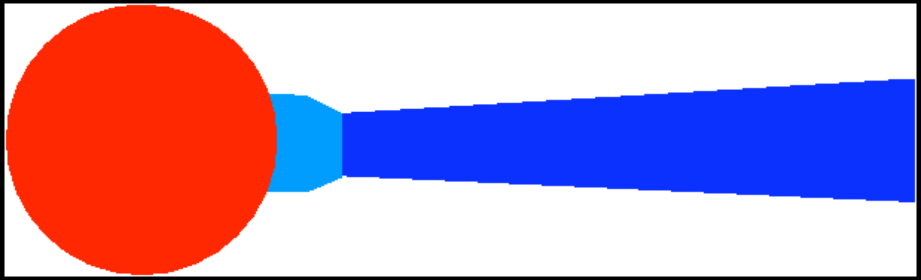
Magnetospheric Accretion:

How do young stars accrete from their disks?

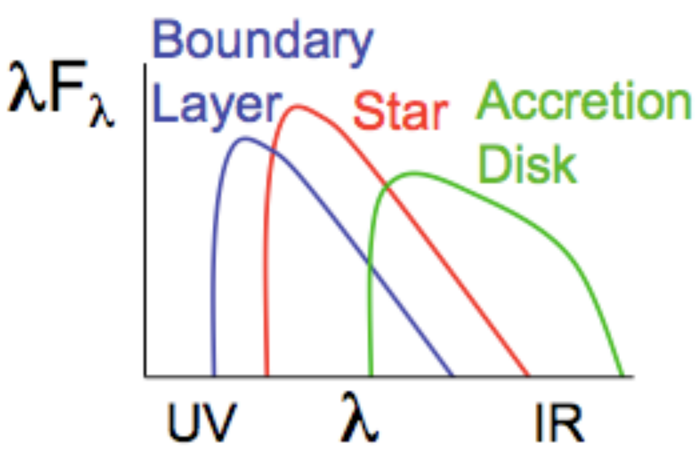
Will Fischer
PHYS 6820/7820
March 1, 2011

How do young stars accrete from disks? Early Model: Boundary Layer

- Lynden-Bell & Pringle 1974
- Assume disk extends to stellar surface



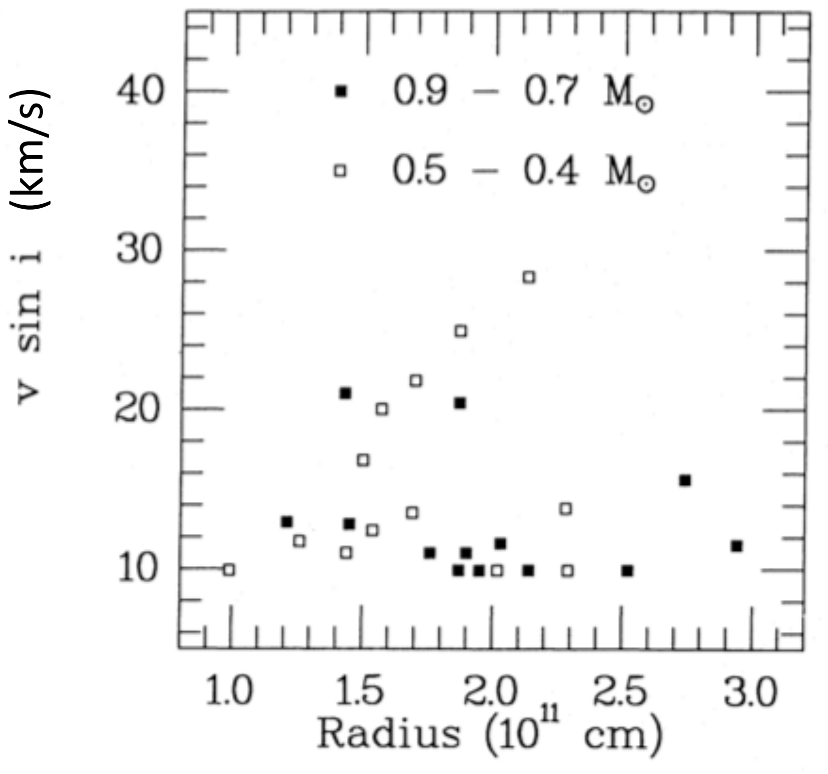
- Viscosity at the star/disk boundary layer accounts for the UV/optical excess of TTS



Boundary Layer

- At the stellar surface, disk Keplerian velocity is 220 km/s for a T Tauri star ($R=2R_\odot$, $M=0.5M_\odot$)
- Young stars should be spun up to rotational velocities of ~ few hundred km/s
- But TTS rotate at a fraction of this speed

$$v_{\text{disk}} = \sqrt{\frac{GM}{R_*}}$$



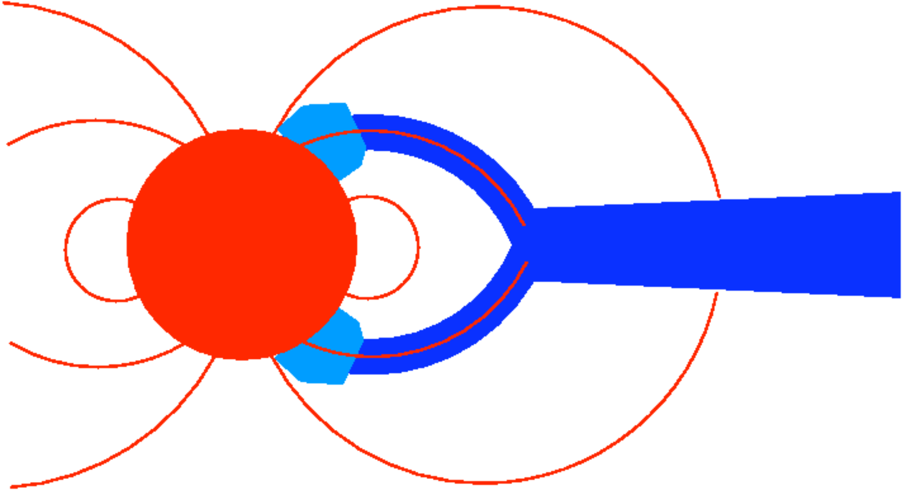
(Hartmann et al. 1986)

Magnetospheric Accretion

- Ghosh & Lamb (1978) for neutron stars
- Camenzind (1990), Königl (1991), Shu et al. (1994), Wang (1995) for TT stars

- Avoid the spin-up problem: At several stellar radii, disk Keplerian velocity is similar to observed stellar rotation velocities (tens, not hundreds, of km/s)

- A stellar magnetic field can truncate the disk at the required radius



Magnetic pressure (assumed dipolar)

$$P_{\mathrm{mag}} \propto |\mathbf{B}|^2 = B_*^{\,2}\left(\frac{R_*}{r}\right)^6$$

Accretion pressure

$$P_{\mathrm{acc}} = \dot{M}\frac{v_{in}}{r^2} = \dot{M}\frac{\sqrt{2GM_*/r}}{r^2}$$

Magnetospheric Accretion

Magnetic pressure

$$P_{\mathrm{mag}} \propto |\mathbf{B}|^2 = B_*^{\,2}\left(\frac{R_*}{r}\right)^6$$

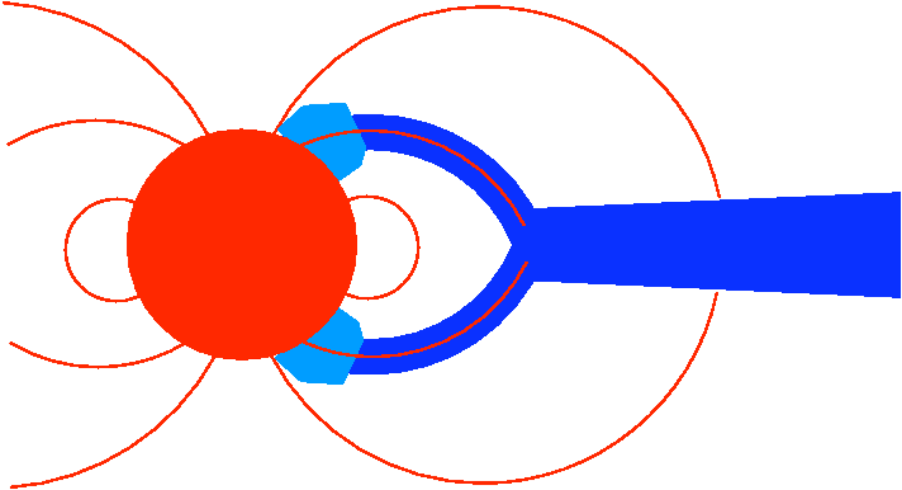
Accretion pressure

$$P_{\mathrm{acc}} = \dot{M}\frac{v_{in}}{r^2} = \dot{M}\frac{\sqrt{2GM_*/r}}{r^2}$$

- These are equal at the truncation radius r_T

$$r_T/R_* \propto B_0^{\,4/7}\dot{M}^{-2/7}M_*^{\,-1/7}R_*^{\,5/7}$$

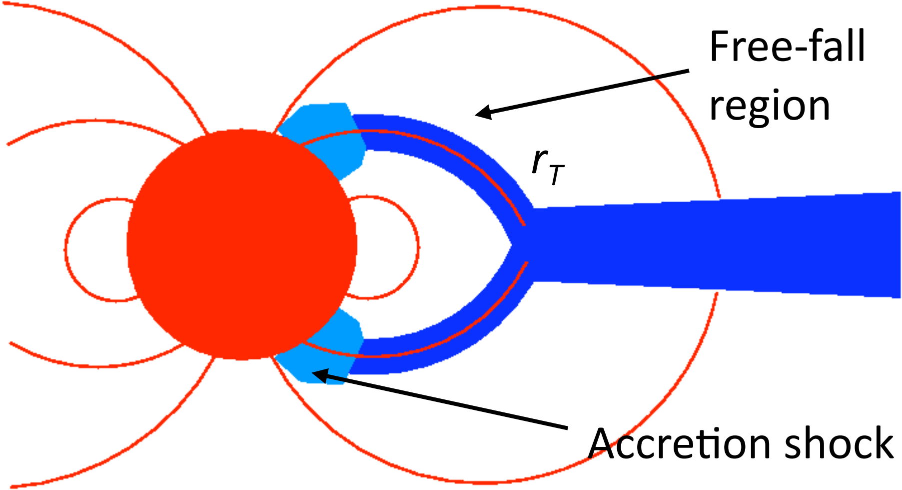
- For a 1 kG field, an accretion rate of 10^{-7} $M_\odot$/yr, a mass of 0.5 $M_\odot$, and a radius of 2 $R_\odot$, $r_T = 7.2\ R_*$



Truncation radii are expected to be a bit less than this; the accretion pressure above is for spherical infall and is a lower limit to the case of a rotating, equatorial disk.

Magnetospheric Accretion

$$r_T / R_* \propto B_0^{4/7} \dot{M}^{-2/7} M_*^{-1/7} R_*^{5/7}$$



- At r_T, the (ionized) gas stops flowing radially inward and follows magnetic field lines to the stellar surface
- Matter is in free-fall
- Shock velocity →
- Dissipated energy (Accretion luminosity) →

$$v_s = \sqrt{\frac{2GM_*}{R_*}} \sqrt{1 - \frac{R_*}{r_T}}$$

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

Magnetospheric Accretion: Regulation of Stellar Rotation

- The corotation radius is where the Keplerian angular velocity of the disk equals the angular velocity of the star:

$$\Omega_{disk} = \Omega_*$$

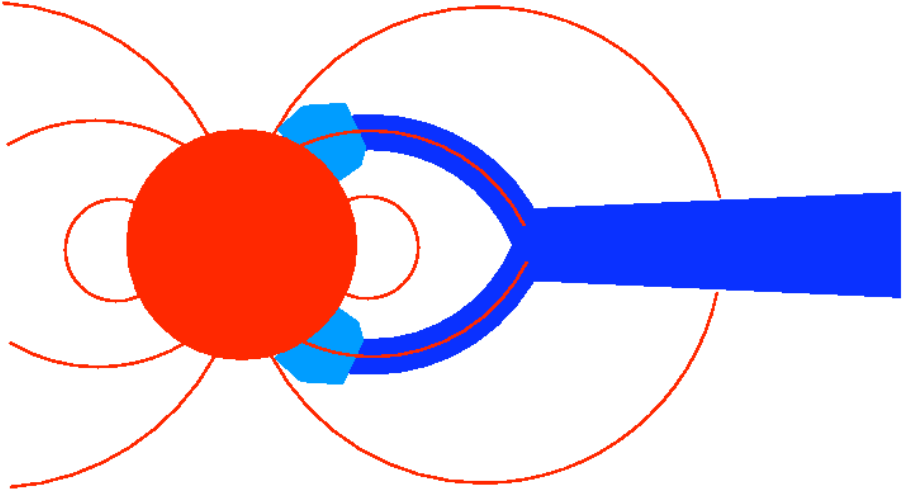
$$\sqrt{GM/r_{co}^{\;3}} = \Omega_*$$

$$r_{co} = \left(GM/\Omega_*^{\;2}\right)^{1/3}$$

- For a stellar rotation period of 7 days and the usual stellar parameters, $r_{co} = 6.1\ R_*$

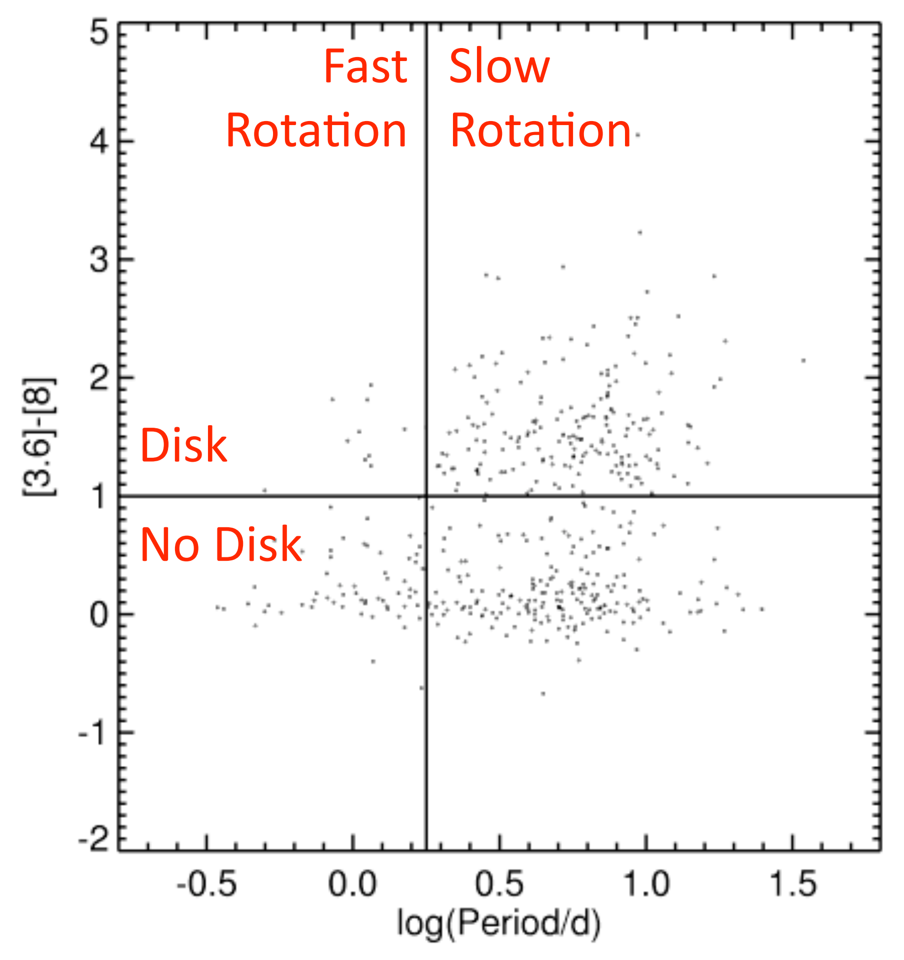
$r > r_{co}$: Angular momentum flows from the star to the disk

$r < r_{co}$: Angular momentum & mass flow from the disk to the star (accretion)



Magnetospheric Accretion: Regulation of Stellar Rotation

- Accretion clearly affects stellar rotation
- Slowly rotating stars are more likely to have disks

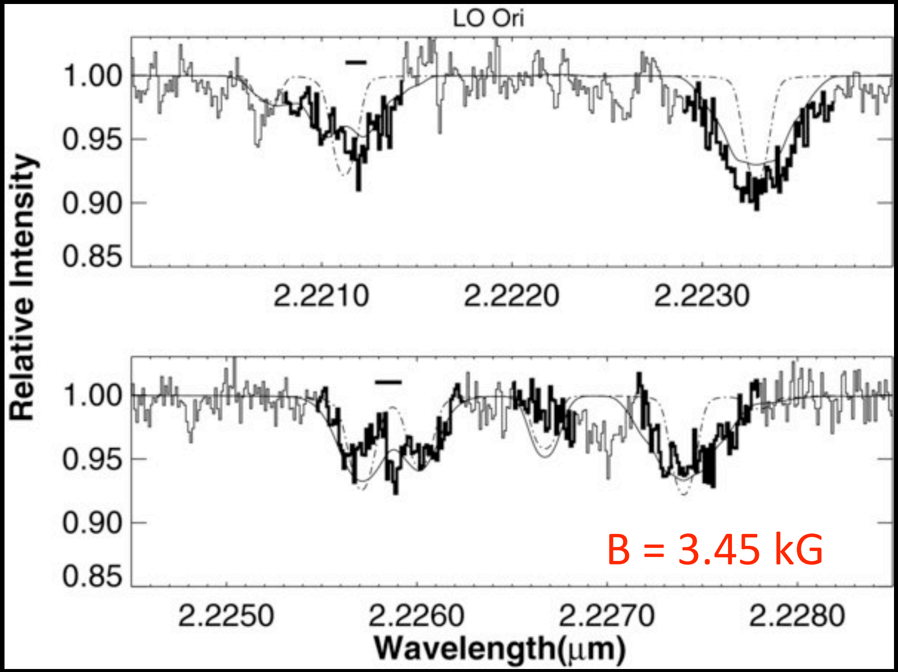


Rebull et al. 2008: Orion

Magnetospheric Accretion: The Evidence

I. Stellar magnetic fields

- Magnetically-sensitive lines (e.g., Ti I in the K band) are Zeeman-broadened
- Easier in the IR due to λ^2 dependence (vs λ dependence of rotational broadening)
- Average field strength is 1-2 kG, implying disk disruption at several R_*



B = 3.45 kG

Yang & Johns-Krull 2011
(also many earlier works
by Johns-Krull et al.)

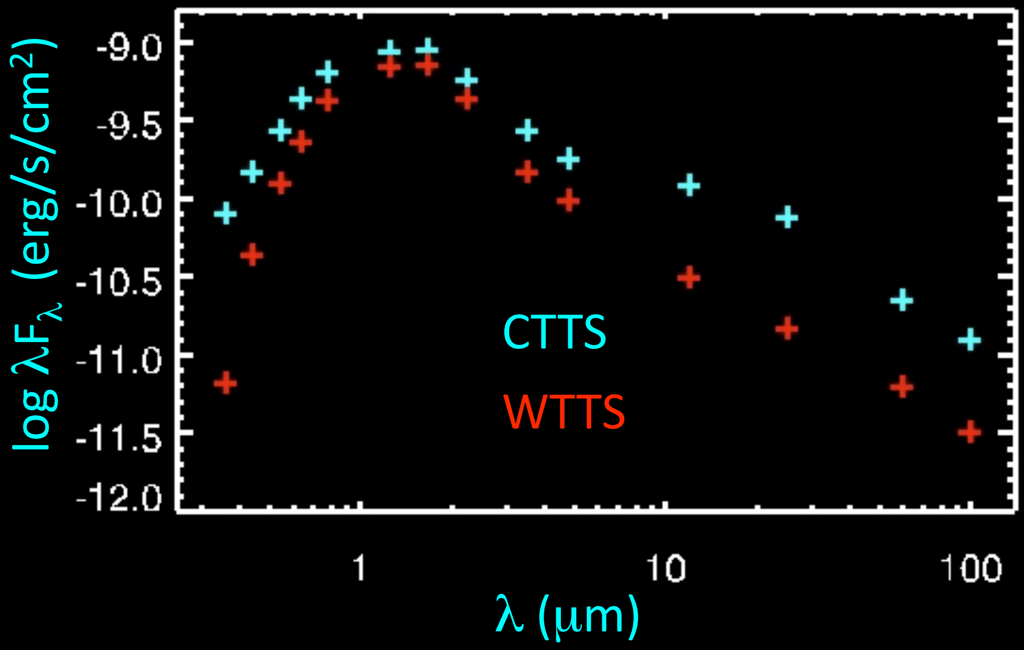
$$\Delta\lambda\ [\mathrm{m\mathring{A}}] = \frac{e}{4\pi m_e c^2}\lambda^2 g B = 4.67\times 10^{-7}\lambda^2 g B$$

Magnetospheric Accretion: The Evidence

II. Optical/UV excess continuum

- CTTS show more emission at all wavelengths than expected from a young, cool star
- This can be studied in detail with measurements of *line veiling*

SED: spectral energy distribution

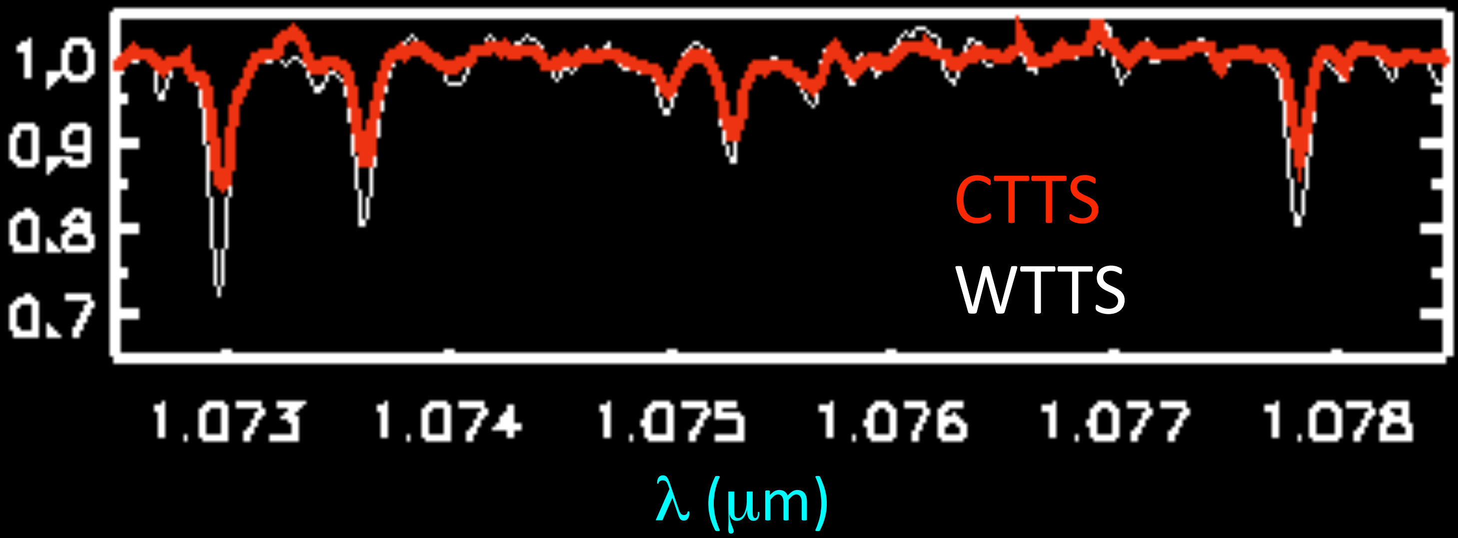


Magnetospheric Accretion: The Evidence

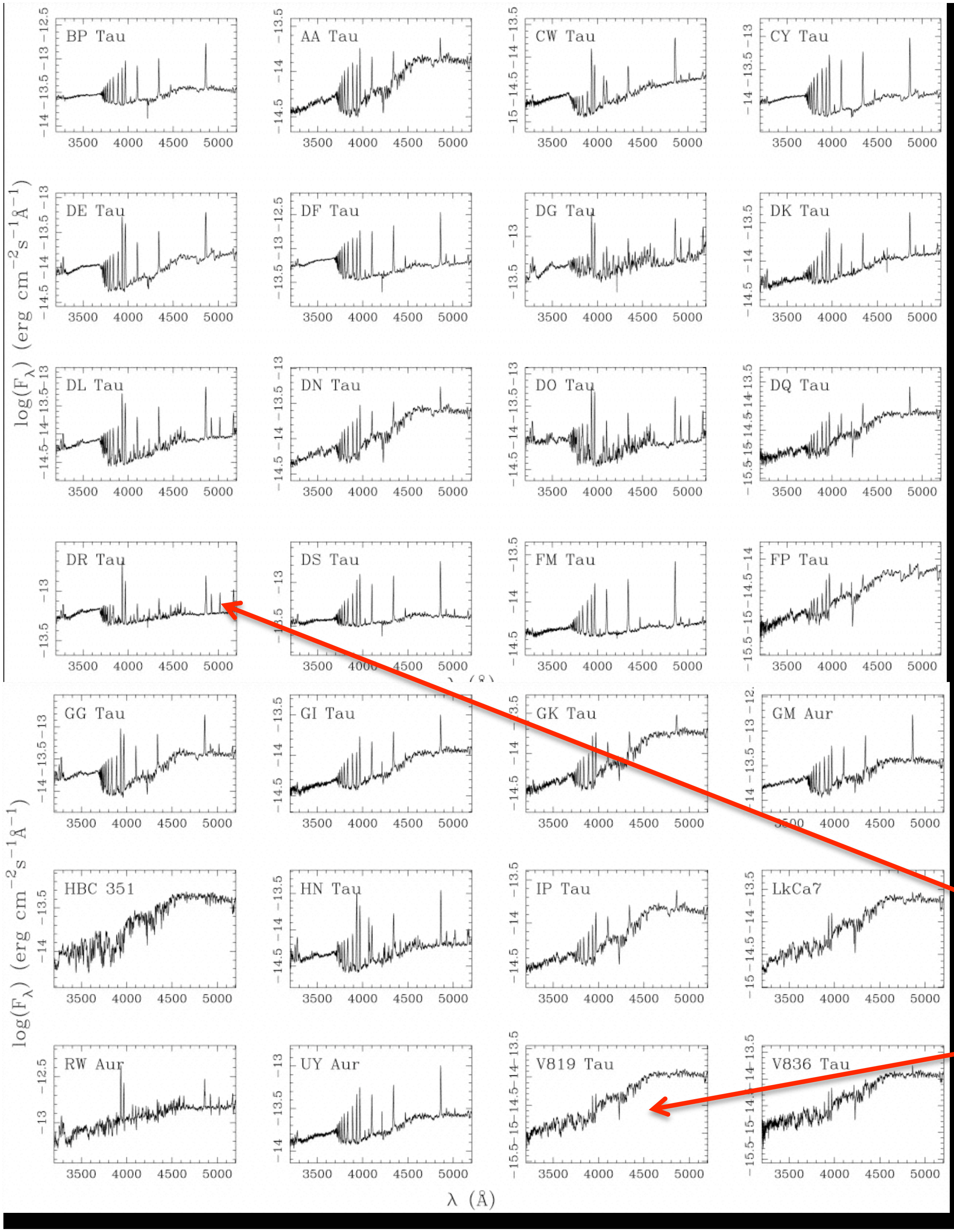
II. Optical/UV excess continuum

$r_\lambda = F_{excess} / F_{photosphere}$

	Range	Median
r_B (0.48 μm)	0.1-6.3	1.0
r_Y (1.08 μm)	0-3.5	0.4
r_K (2.2 μm)	0.3-10	1.9



Observed Spectra of TTS



From Gullbring et al. ApJ 1998

Sum of stellar and excess components

Note

- Continuum shape
- Balmer series

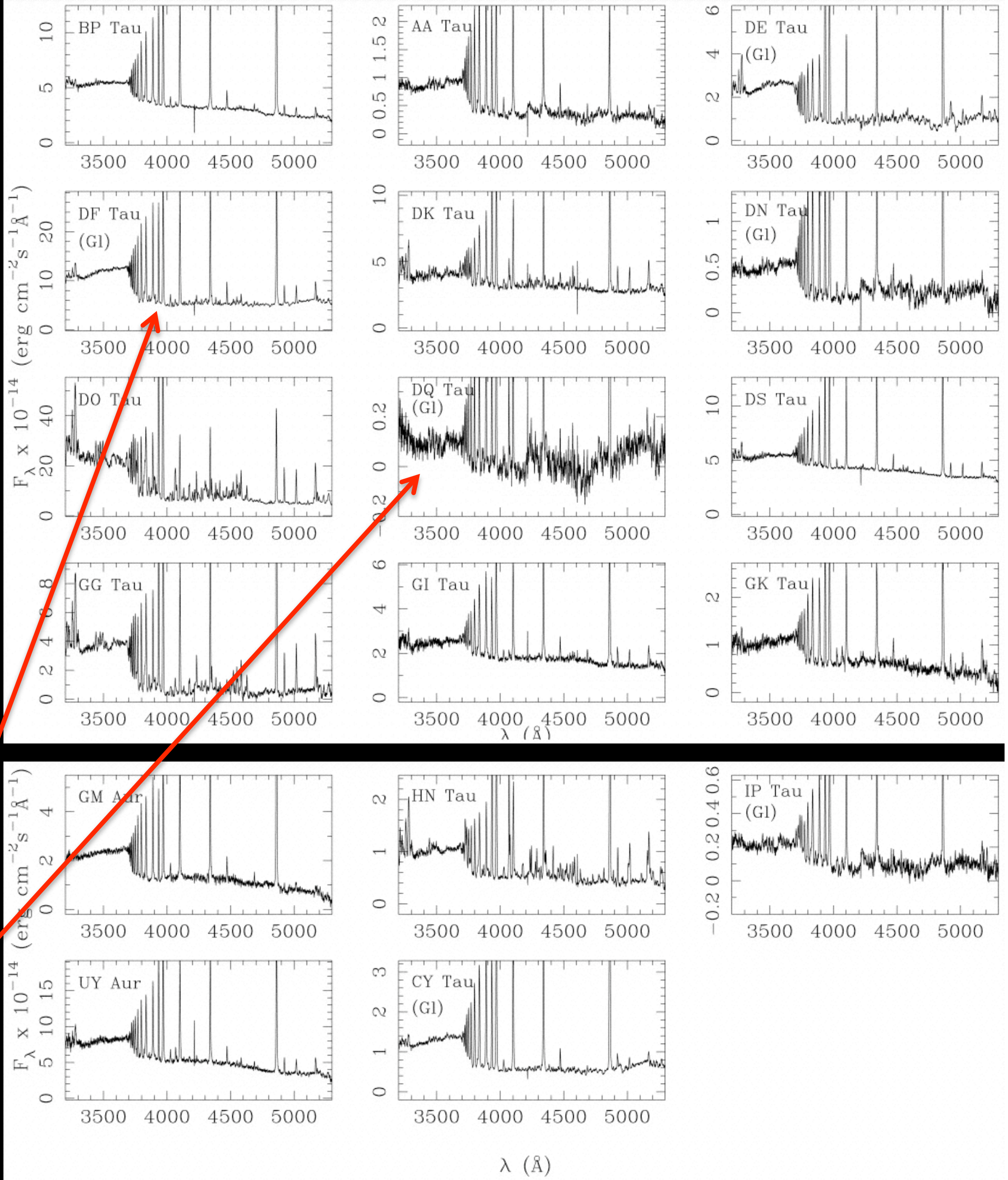
Heavily accreting CTTS

Non-accreting WTTS

Excess Spectra of TTS

From Gullbring et al. ApJ 1998

The stellar component has been subtracted after measuring the veiling



Heavily accreting CTTS

Mildly accreting CTTS

Magnetospheric Accretion: The Evidence

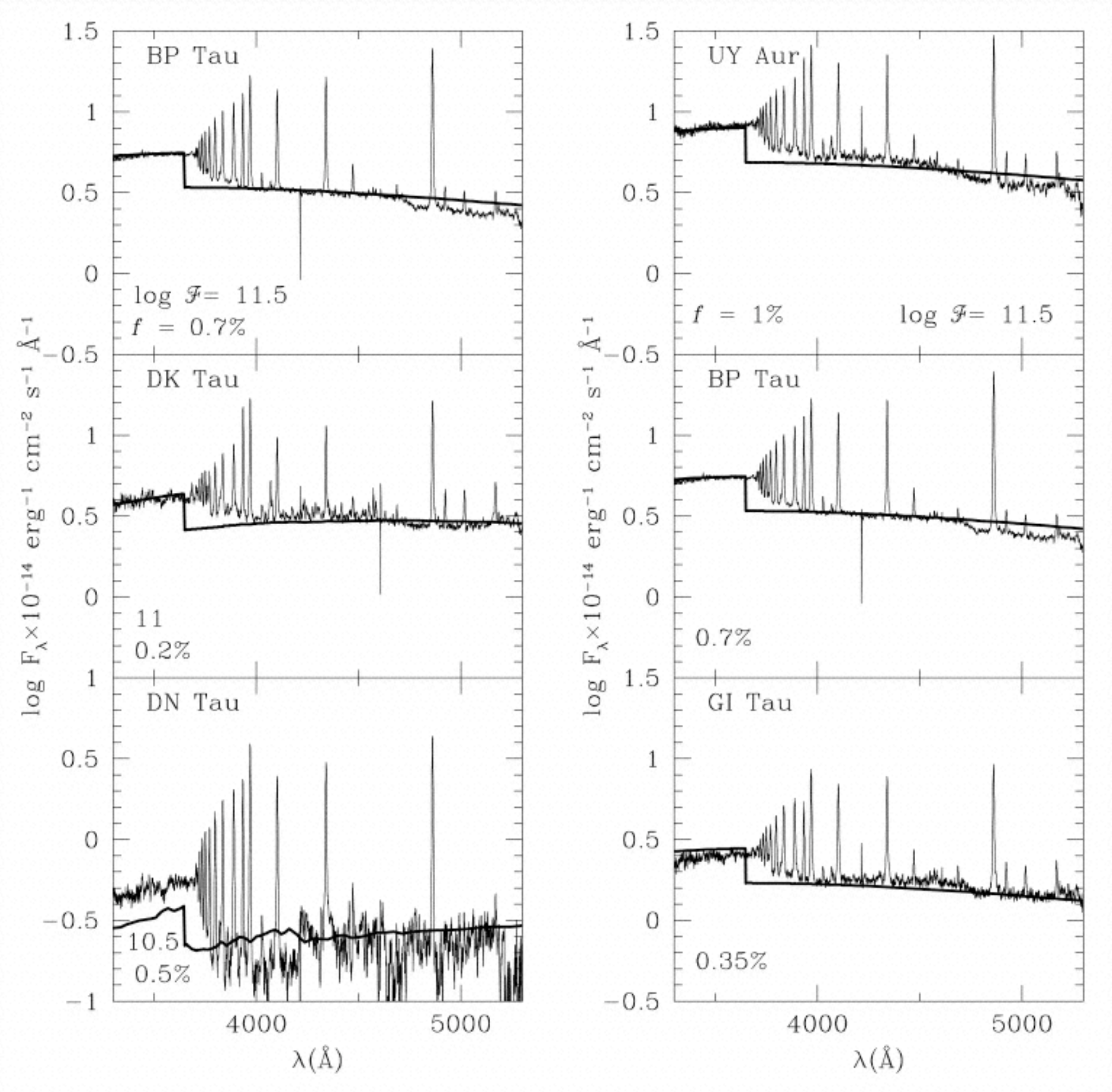
II. Optical/UV excess continuum

Conclusions from Gullbring et al. 1998

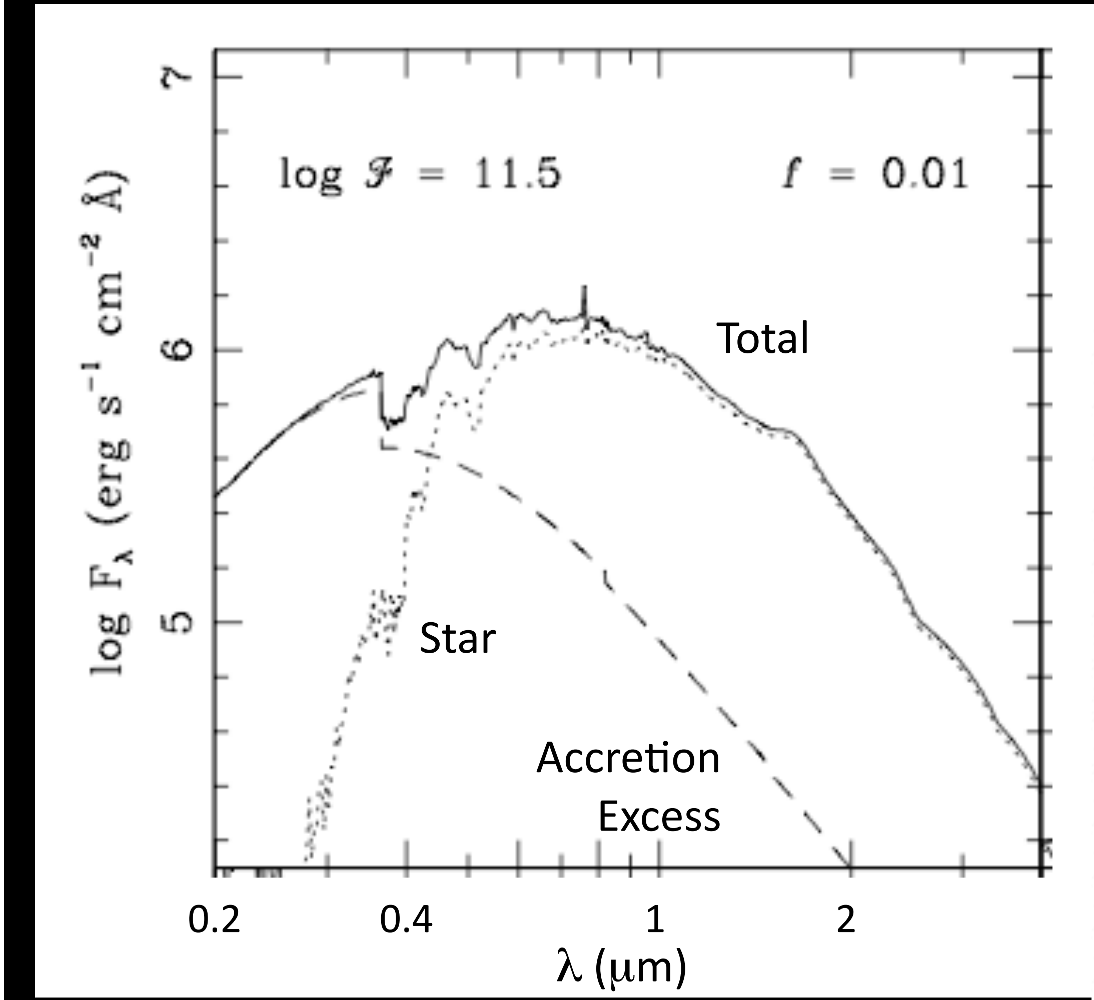
- Accretion rates range from 10^{-9} to 10^{-7} $M_{\odot}$ / yr
- Balmer continuum ($\lambda < 0.3647$ μm) is optically thin
  - *The boundary-layer model predicts this part of the continuum to be optically thick*

Calvet & Gullbring (1998) modeled the spectra as arising in hot accretion shocks covering 0.1-1% of the star

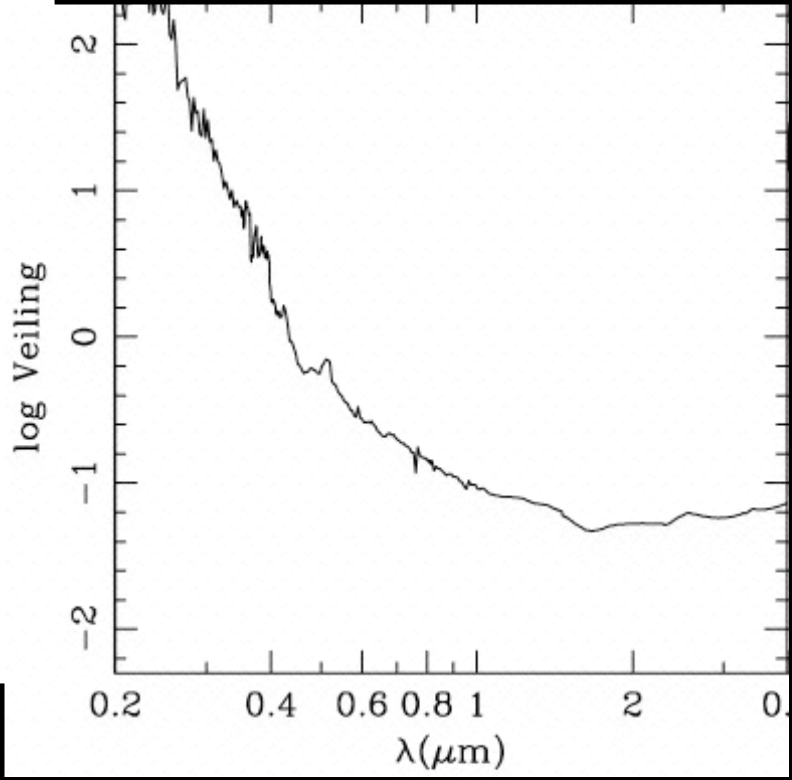
- Optically thin short-wavelength emission from the pre-shock and attenuated post-shock regions
- Optically thick long-wavelength emission from the shock-heated photosphere



Combined Stellar and Excess Continuum (Calvet & Gullbring 1998)



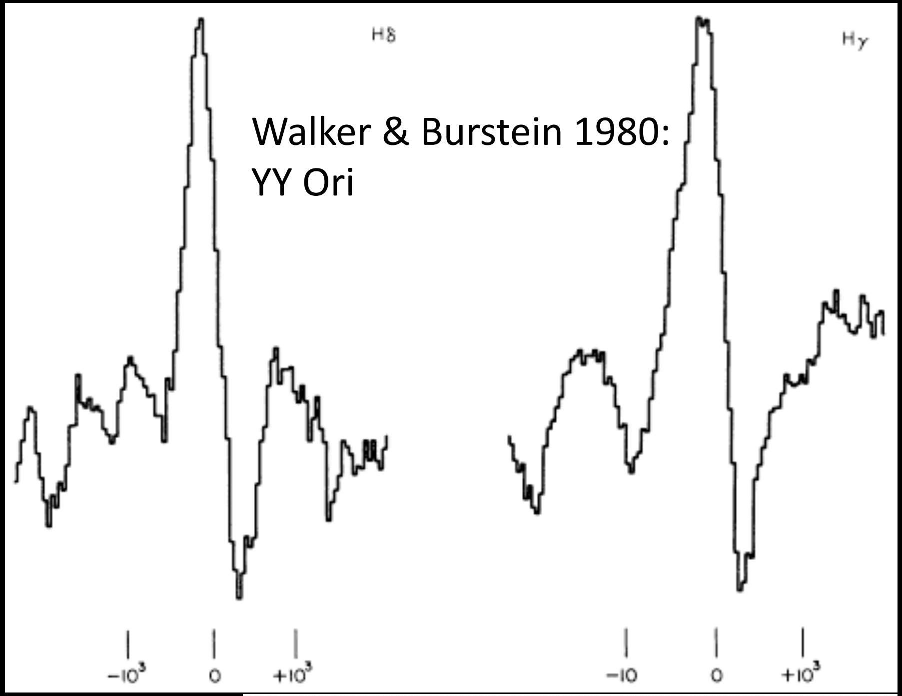
- F is the energy flux of the accretion flow (cgs)
- f is the fraction of the star covered by shocks



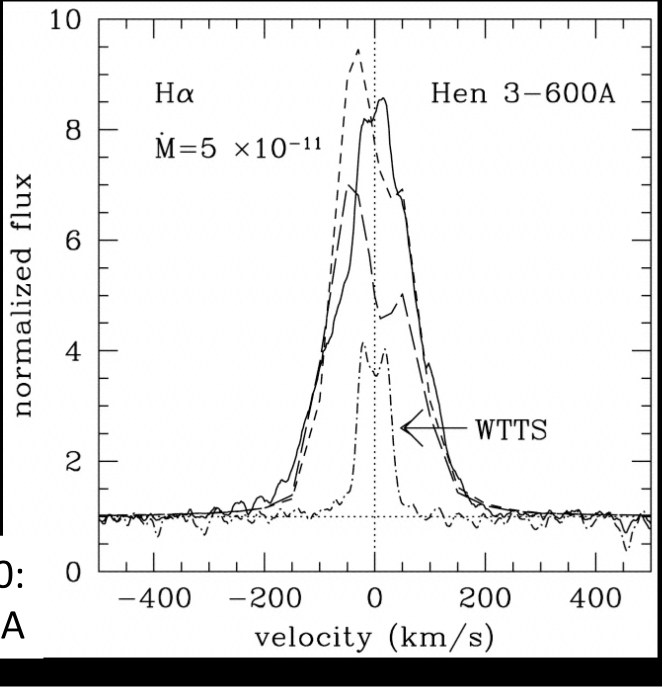
Magnetospheric Accretion: The Evidence

III. Line Profiles

- Line morphologies suggest free-fall, not low velocities expected from boundary-layer accretion
  - Redshifted absorption (v_{red} > 300 km/s)
  - Broad emission (FWHM > 200 km/s)



Walker & Burstein 1980: YY Ori

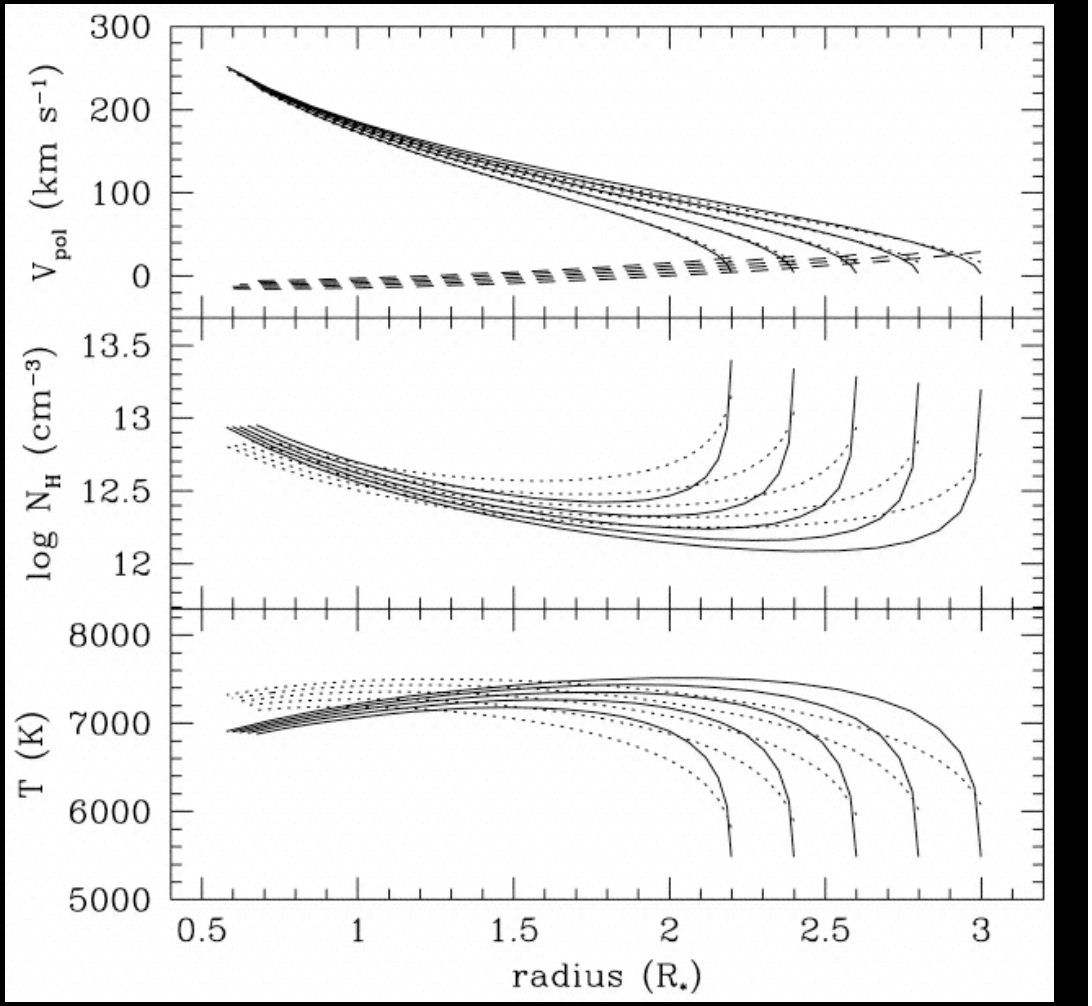


Muzerolle et al. 2000: TWA 3A

Magnetospheric Accretion: The Evidence

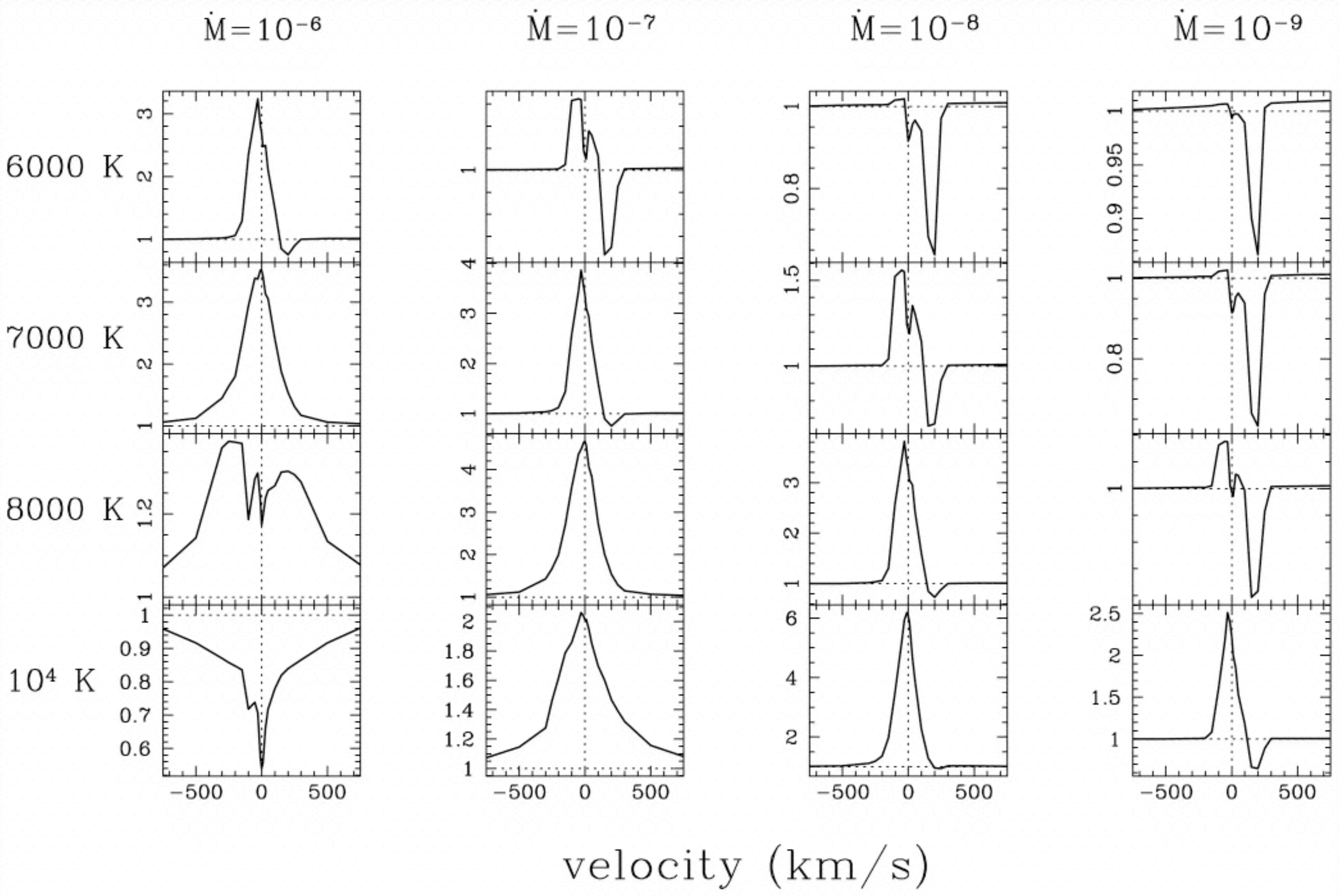
III. Line Profiles

- Canonical RT models (Muzerolle et al. 2001) include
  - ballistic infall
  - axisymmetric dipolar flow
  - “highly schematic” temperature structure
- H I and Na I profiles are produced



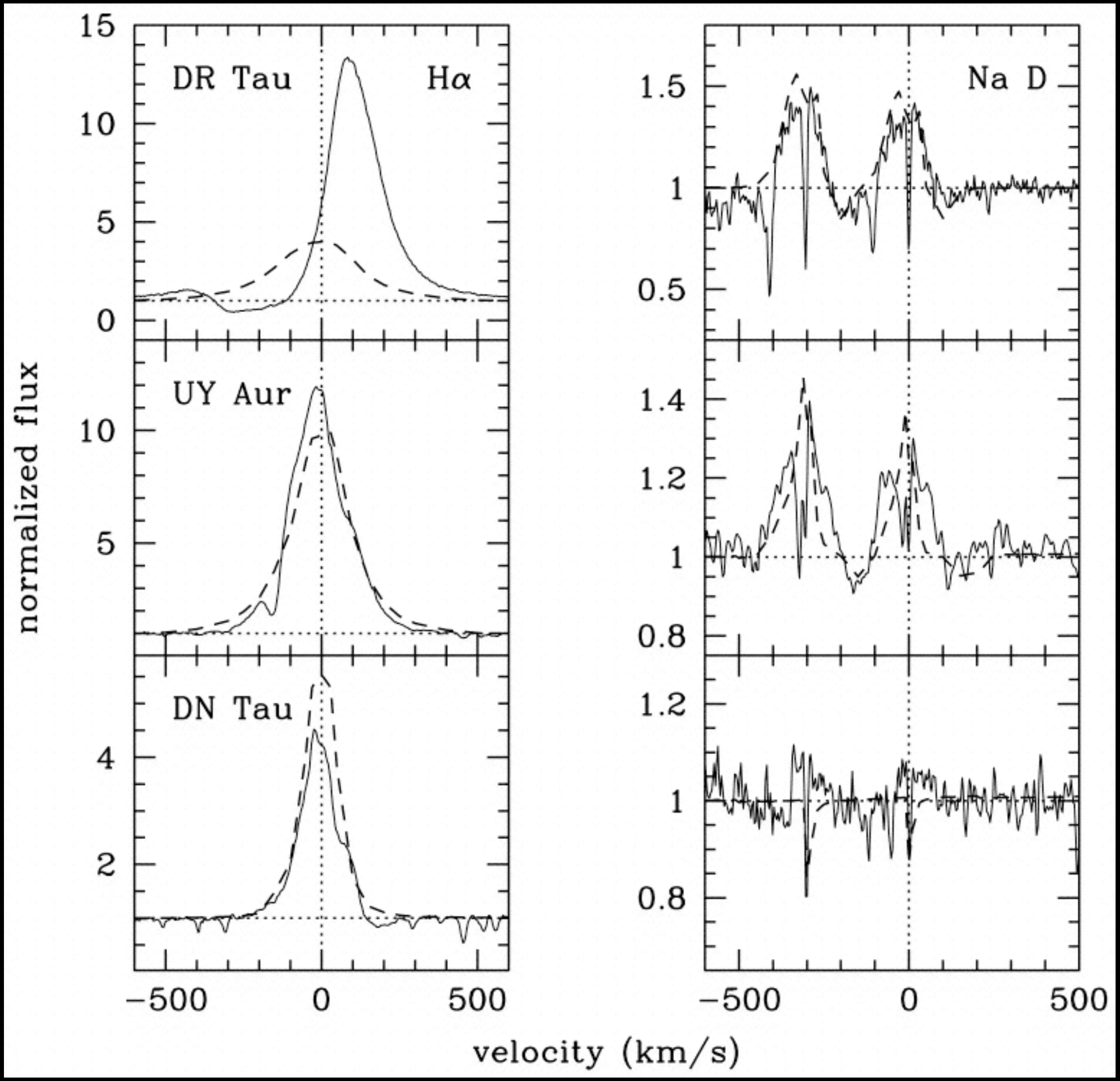
Physical Properties

Hβ, $i = 60^{o}$, $R_m = 2.2 - 3\ R_*$



Muzerolle et al. 2001

Comparison to observations

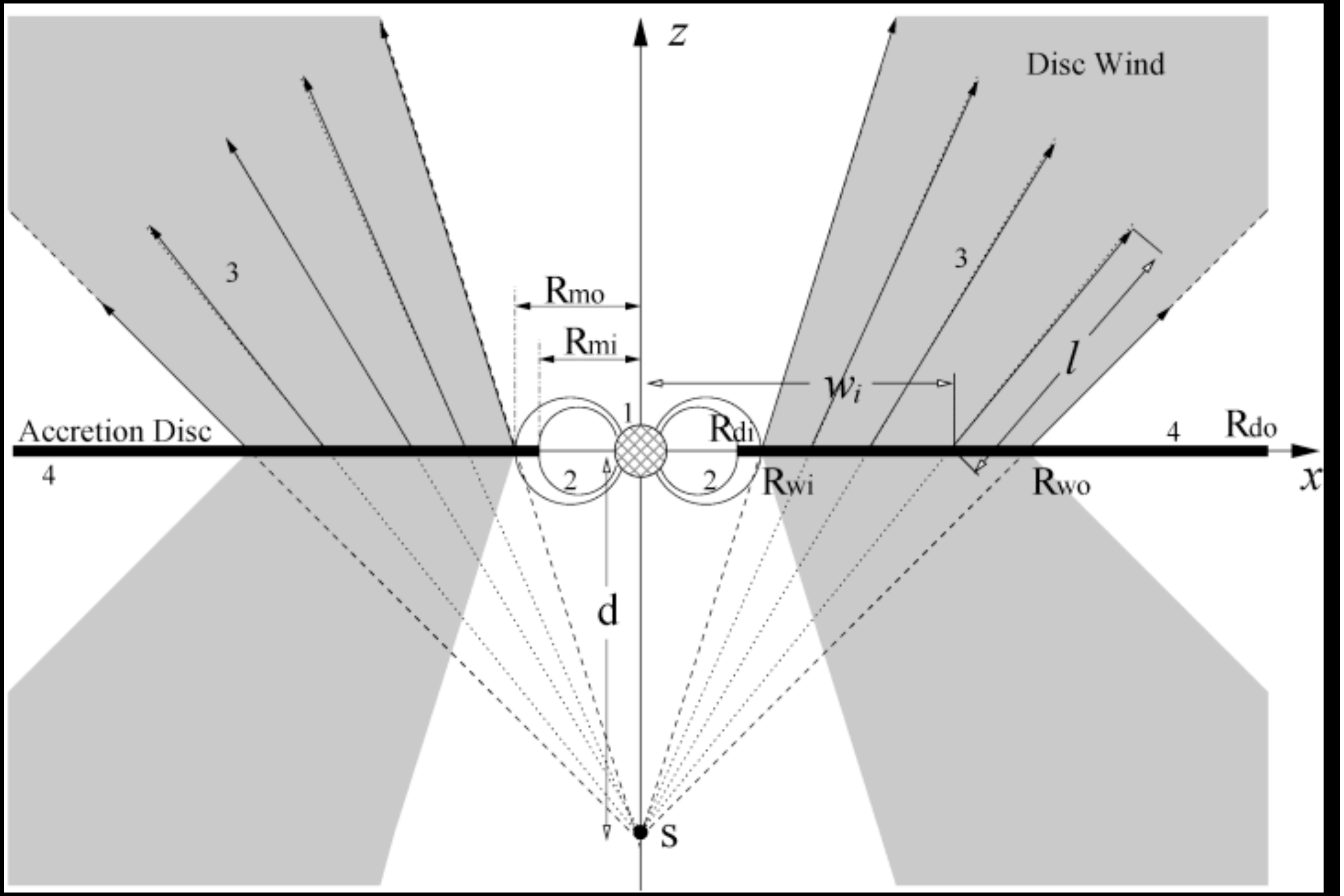


- Reasonably good matches at low (DN Tau) & intermediate (UY Aur) accretion rates
- Poor match at high accretion rates (DR Tau)
  - Probably a contribution from a wind

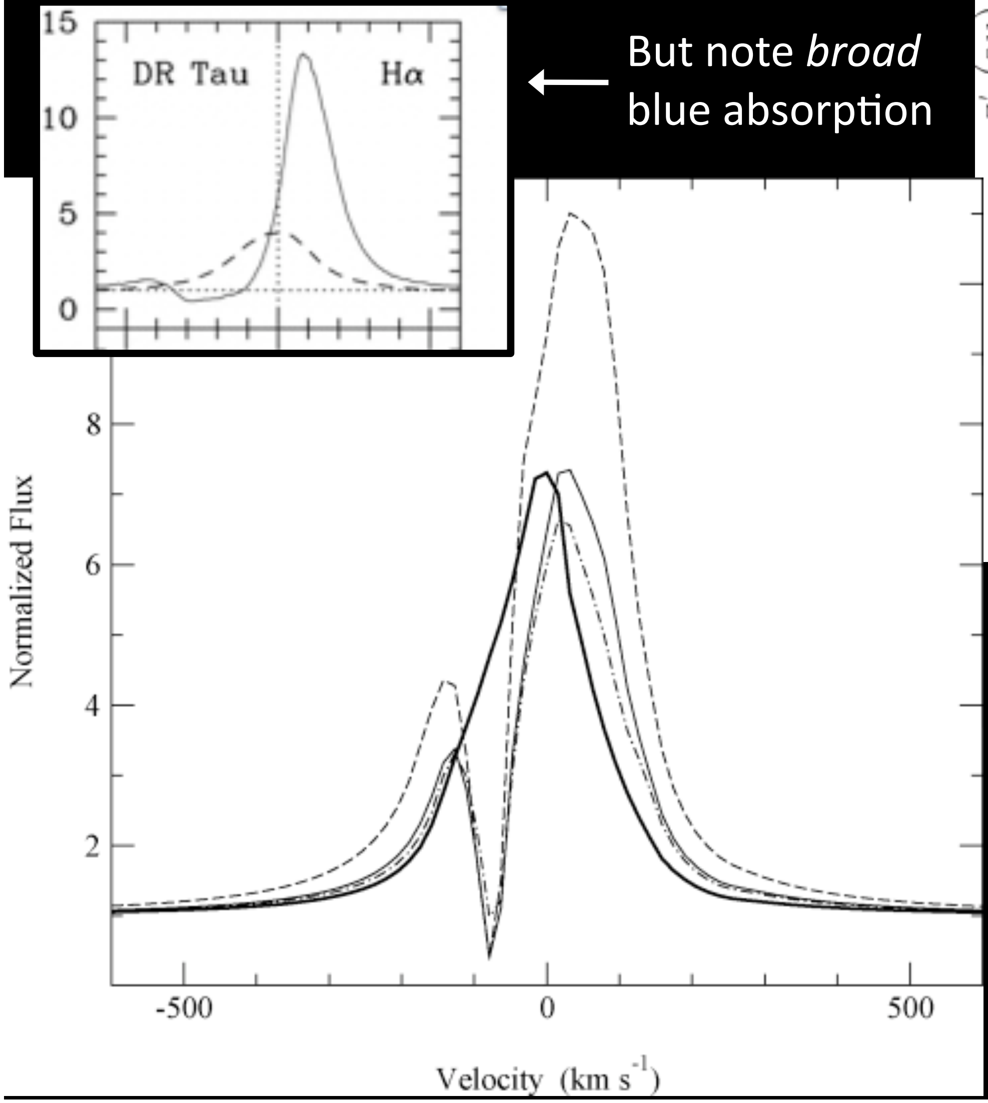
Muzerolle et al. 2001

Improved Hα models

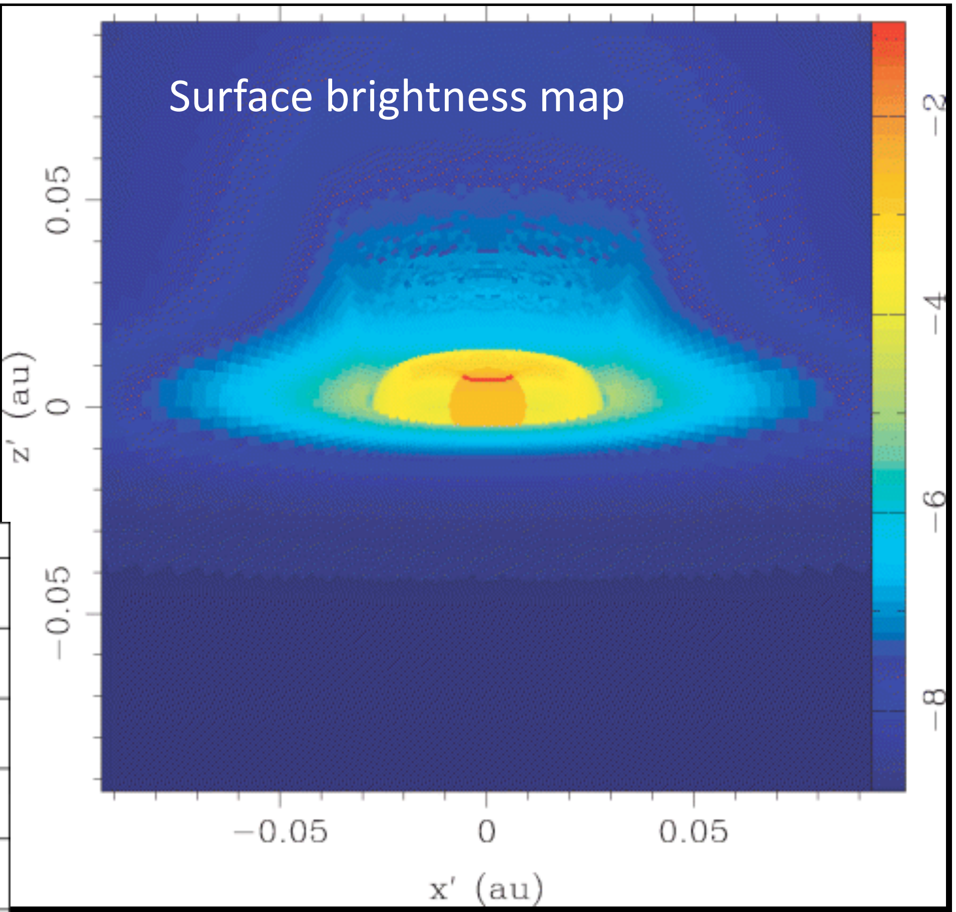
- Hybrid disk wind + accretion flow: Kurosawa et al. 2006



Kurosawa et al. 2006



← But note *broad* blue absorption



Hα model with

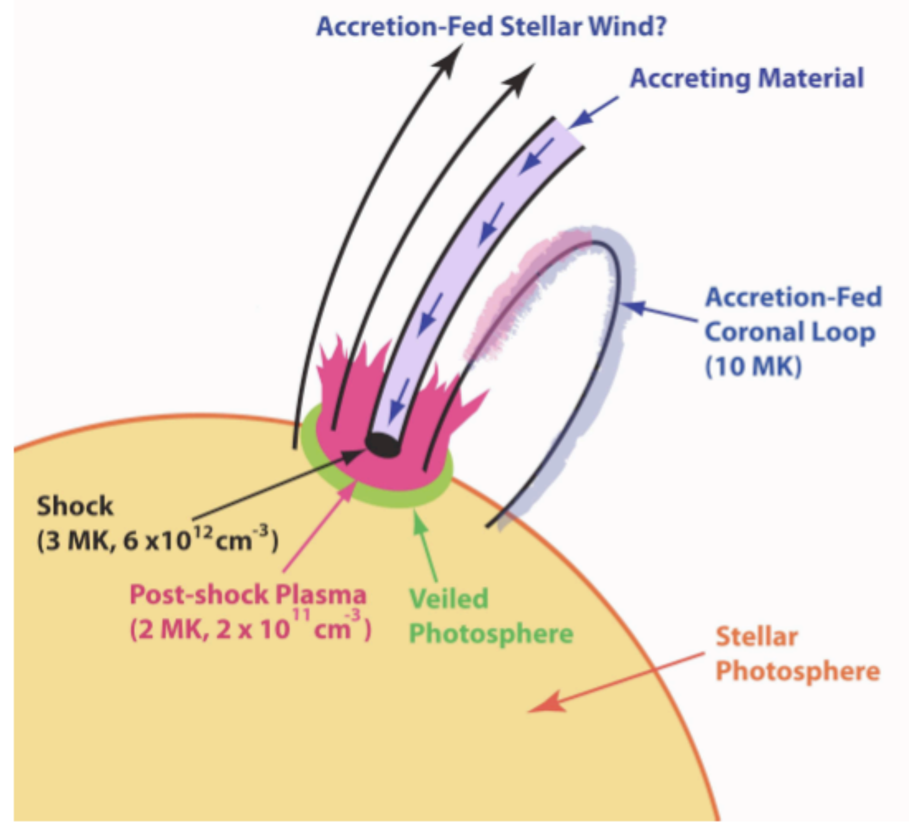
$\dot{M}_{acc} = 10^{-7}\ M_{\odot}/yr$,

$\dot{M}_{wind} / \dot{M}_{acc}$ =

- 0.05 (dash-dot)
- 0.10 (solid)
- 0.20 (dash)

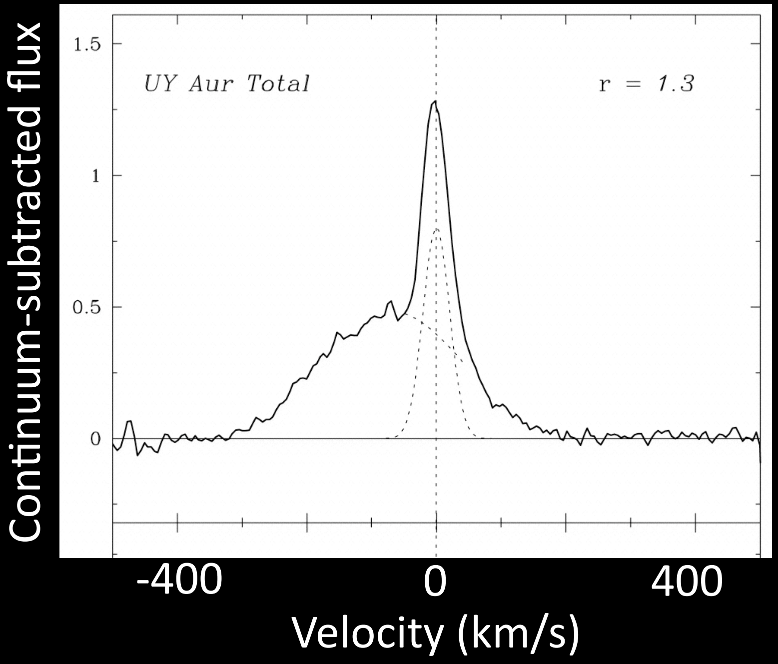
Clues from Helium

- High excitation potential (20 eV) restricts formation to regions of high temperature (> 20,000 K) or high ionizing photon flux
  - Accretion shocks generate X-rays that can ionize the helium
  - Restricted formation region reduces influence from a wind that complicates Hα



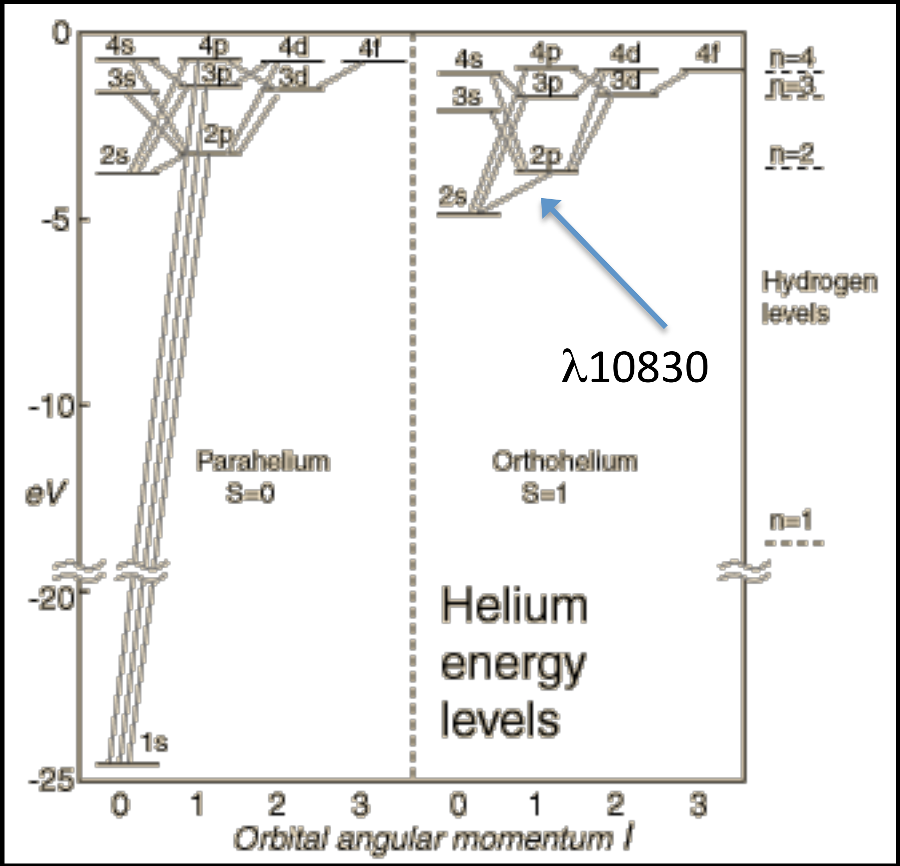
Clues from Helium

- He I 5876: two components (Beristain et al. 2001)
  - Narrow, centered component (NC) forms at the accretion shock
  - Broad, blueshifted component (BC) forms in a wind
- Correlation between veiling and NC strengths
  - Tight if no BC
  - Weak if BC
- Presence of a wind alters the magnetospheric flow



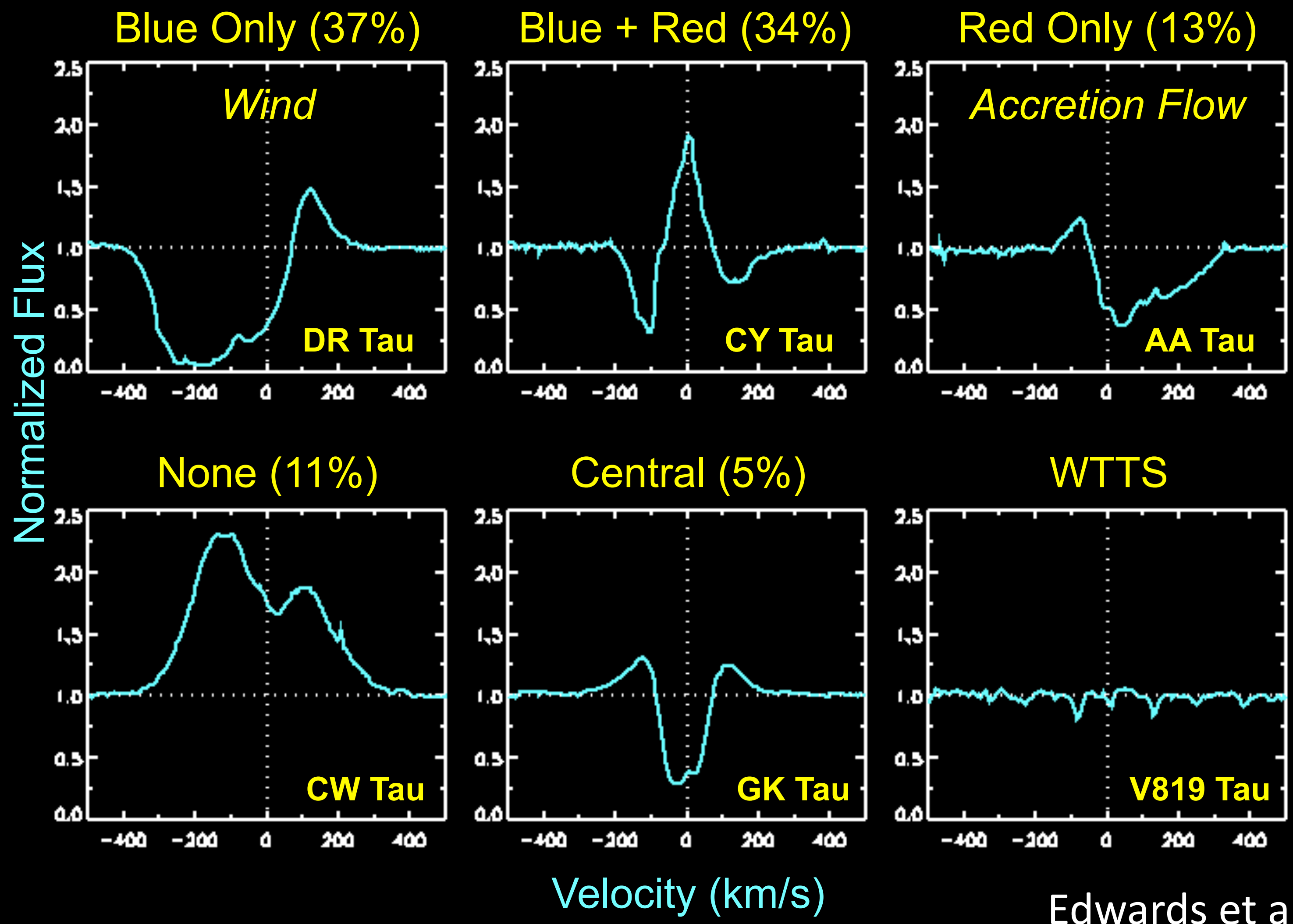
Clues from Helium

- He I 10830: Subcontinuum absorption
- Its lower level is *metastable* – it acts like a ground state – so absorption profiles are common



He 10830 Profiles

(Sorted by morphology of subcontinuum absorption)



Blue Only (37%)

Blue + Red (34%)

Red Only (13%)

None (11%)

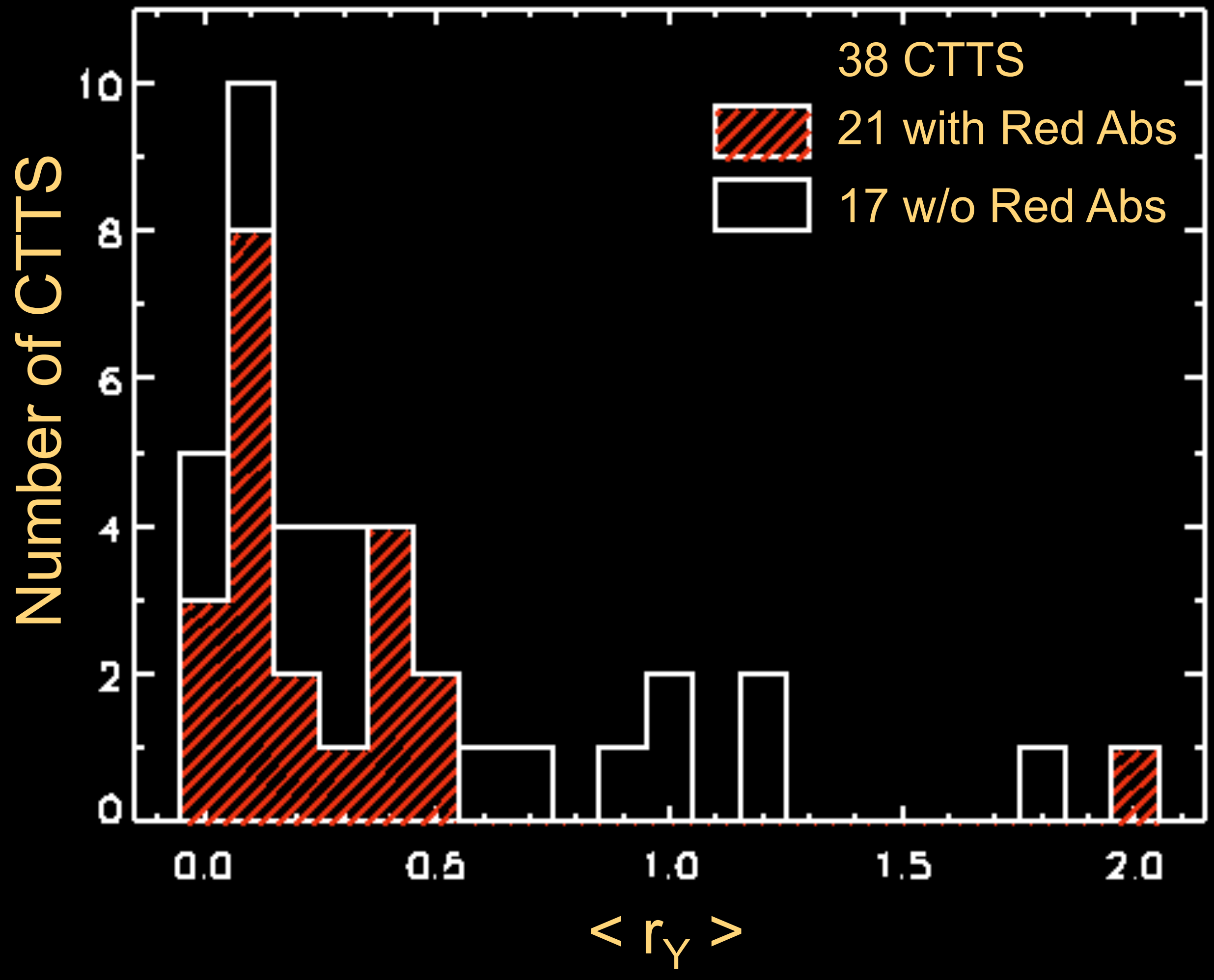
Central (5%)

WTTS

Edwards et al. 2006

He 10830 Red Absorption and Veiling

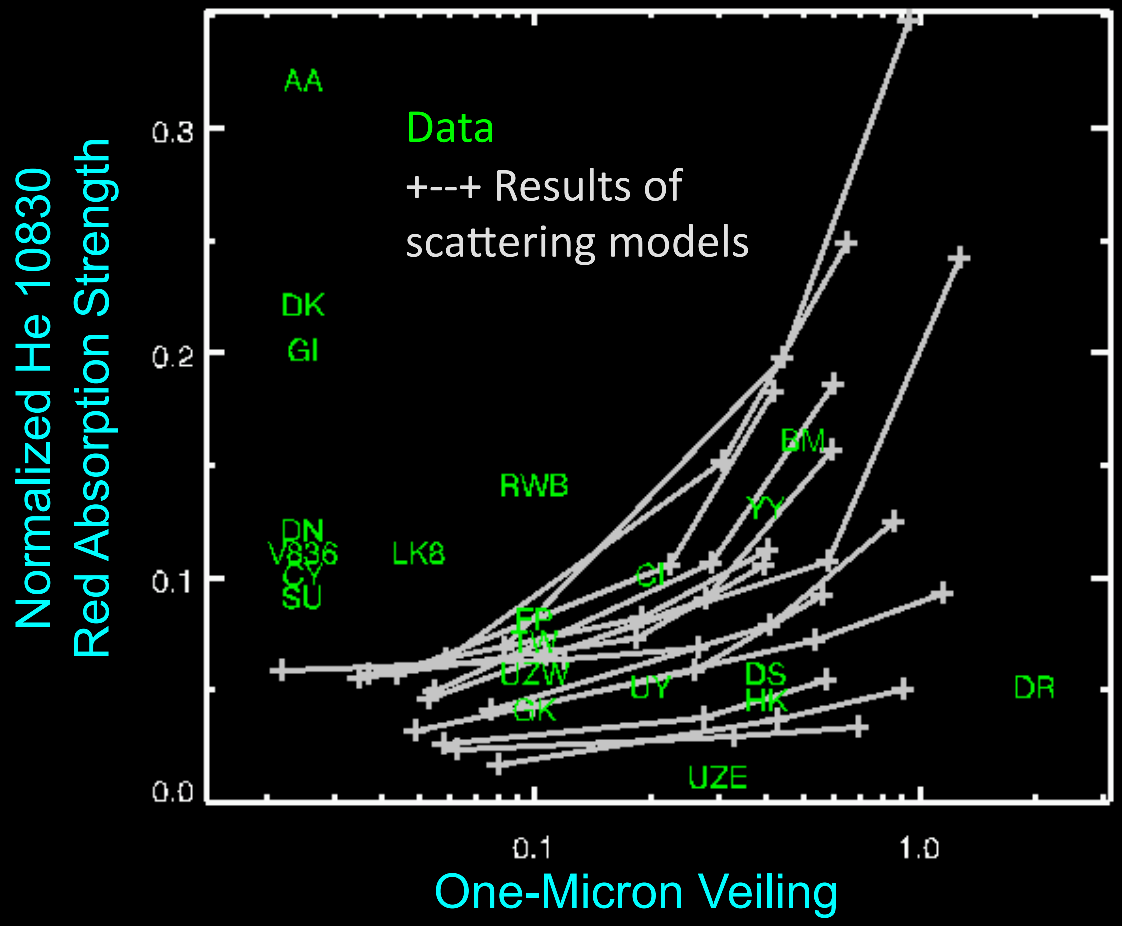
Fischer et al. 2008

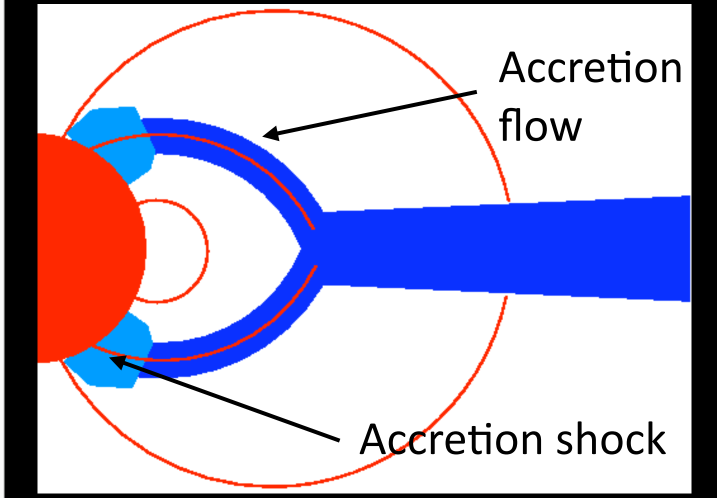


Red absorption is strongest when the veiling is low

Comparison to Observations

Fischer et al. 2008

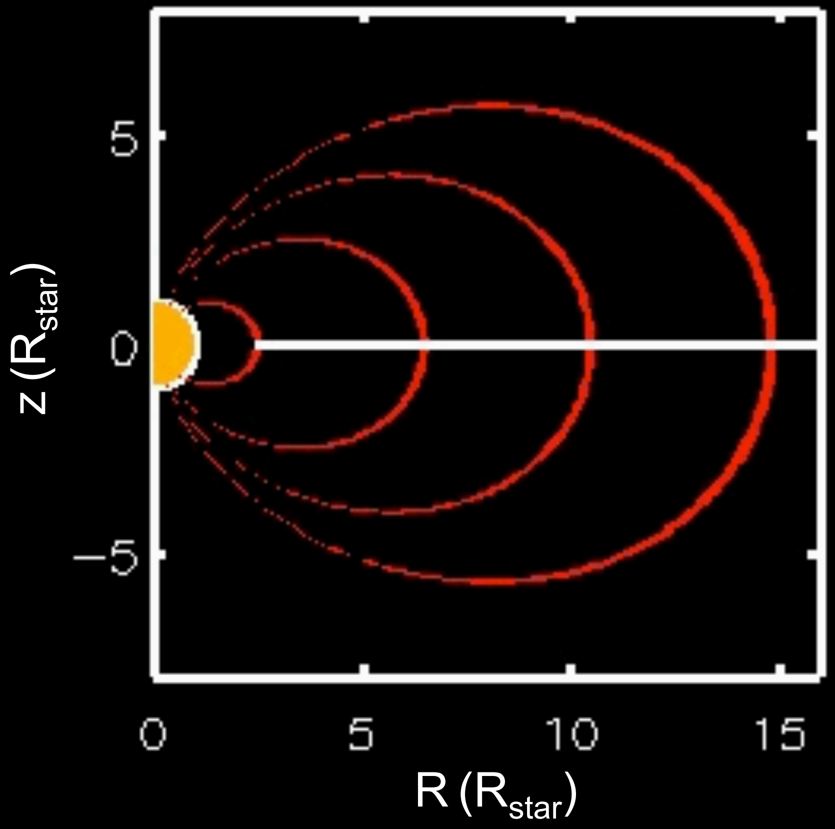




If the accretion flow is large enough for strong absorption, the resulting shocks generate large veiling

Flow Dilution

Fischer et al. 2008



Many narrow streamlets

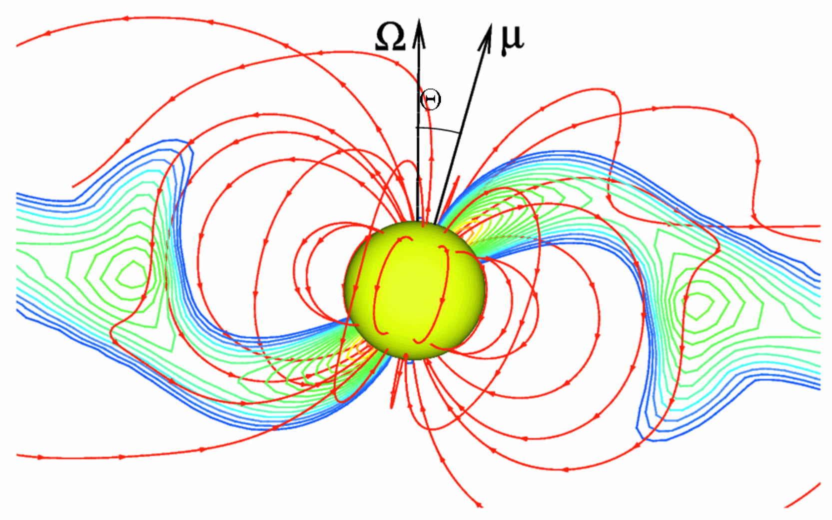
- Total coverage of shocks on the star is ~ 1% as predicted from veiling studies
- Broadly distributed streamlets (with some turbulence) present the range of velocities needed for the observed absorptions

Numerical Methods

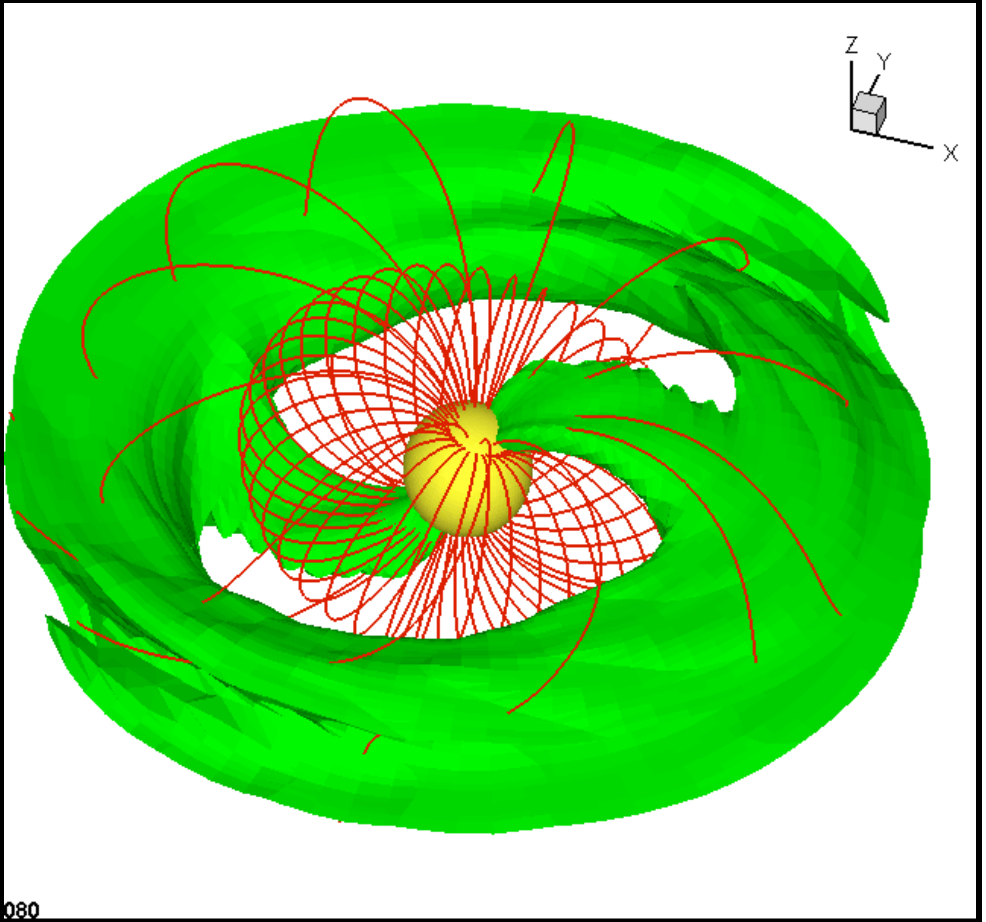
- Most treatments of magnetospheric accretion through mid-2000s used analytic flow solutions
  - Velocity: ballistic infall
  - Temperature: simple heating / cooling parameterization
  - Density: ideal magnetohydrodynamic (MHD) result
  - Geometry: axisymmetric dipole, magnetic axis aligned with rotation axis
- For more complexity, need numerical MHD codes

MHD Results

- Complex Fields: Tilted dipole
  - Two funnel streams
  - High-latitude spots

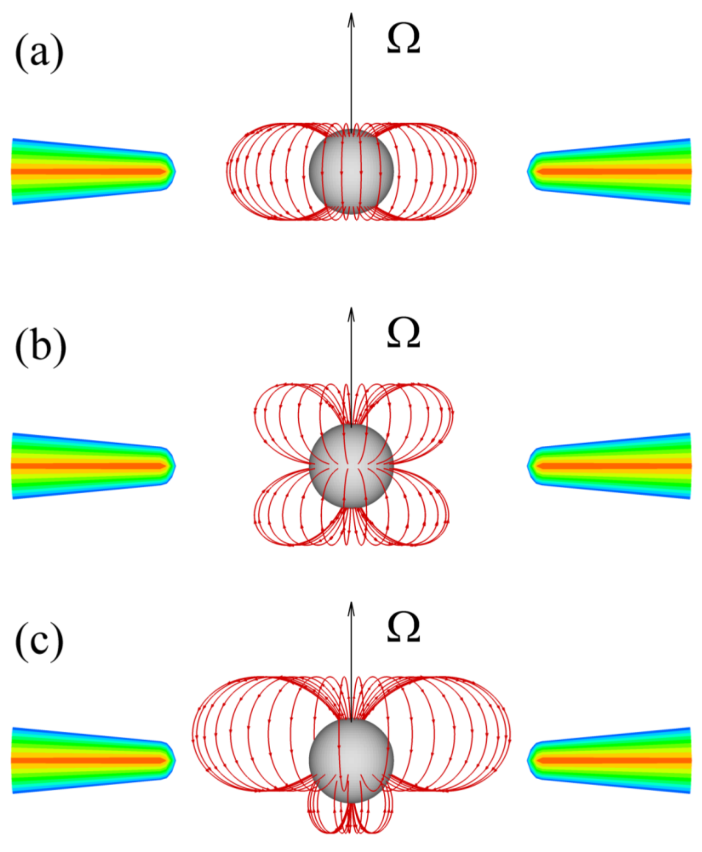


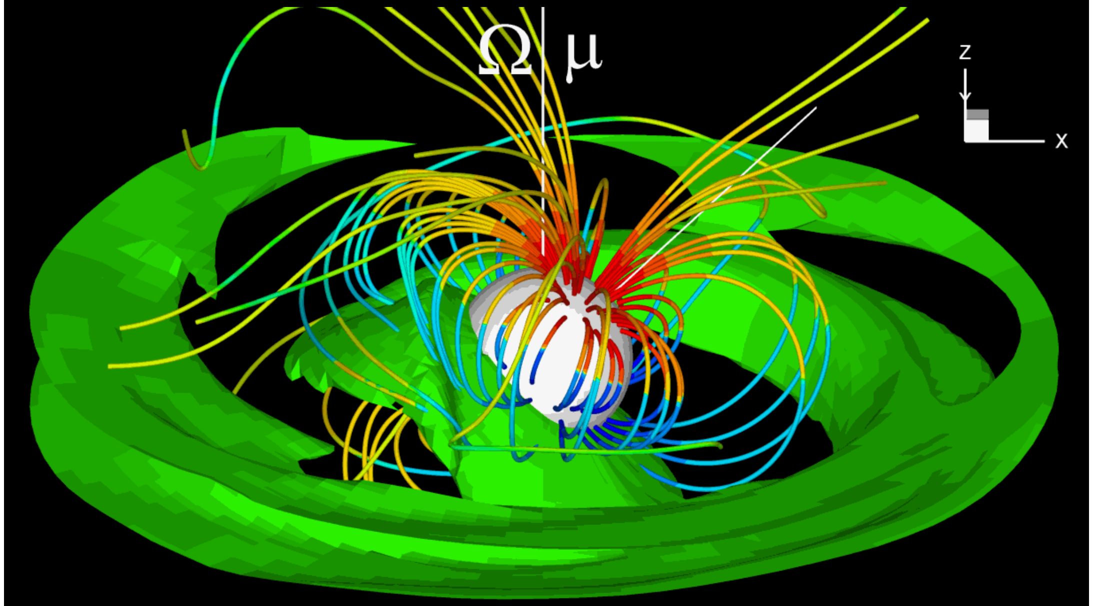
Romanova, Ustyugova, Koldoba, & Lovelace 2003, 2004



MHD Results

- Complex Fields: Tilted dipole + quadrupole

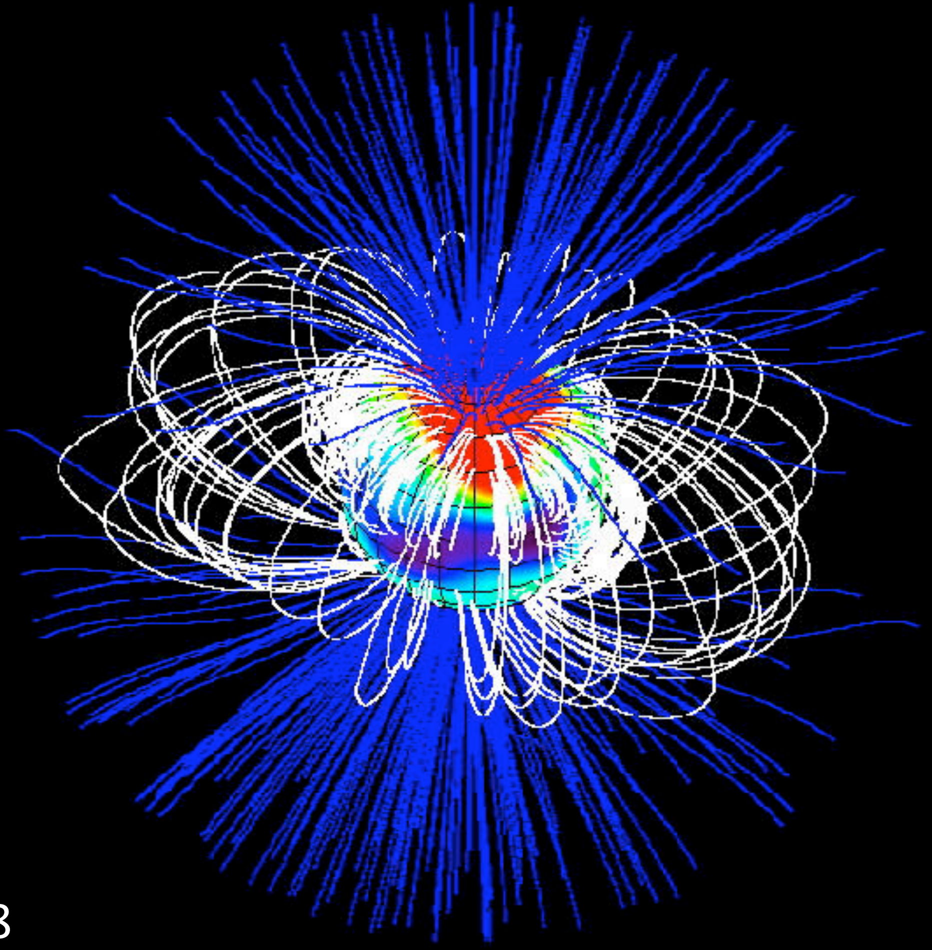




Long, Romanova, & Lovelace 2007

MHD Results

- Complex Fields: Use real magnetic field measurements

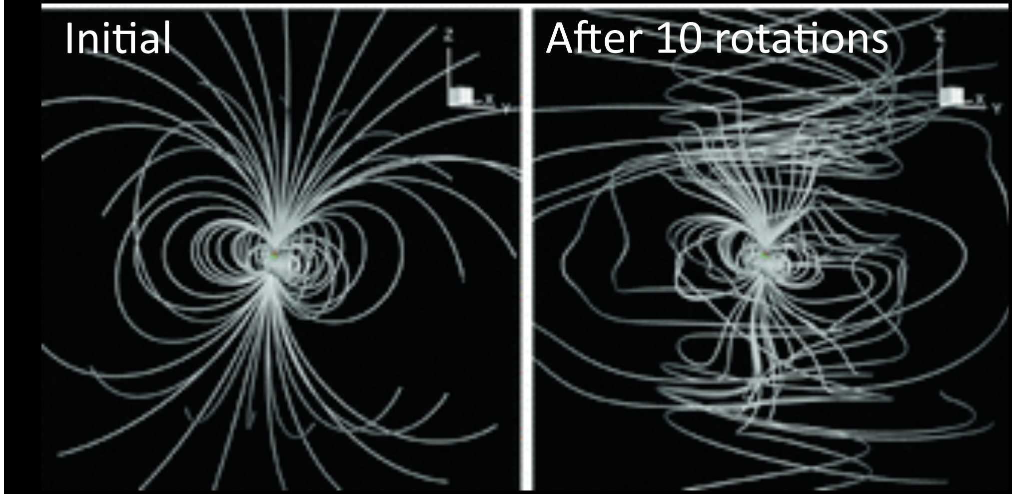


BP Tau
Dipole: 1.2 kG
Octupole: 1.6 kG

Donati, Jardine, Gregory et al. 2008

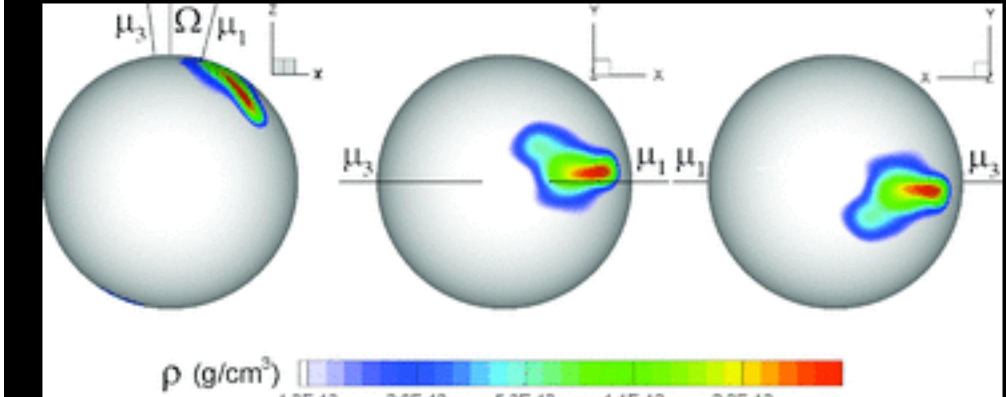
MHD Results: Observables

BP Tau: Long et al. 2011



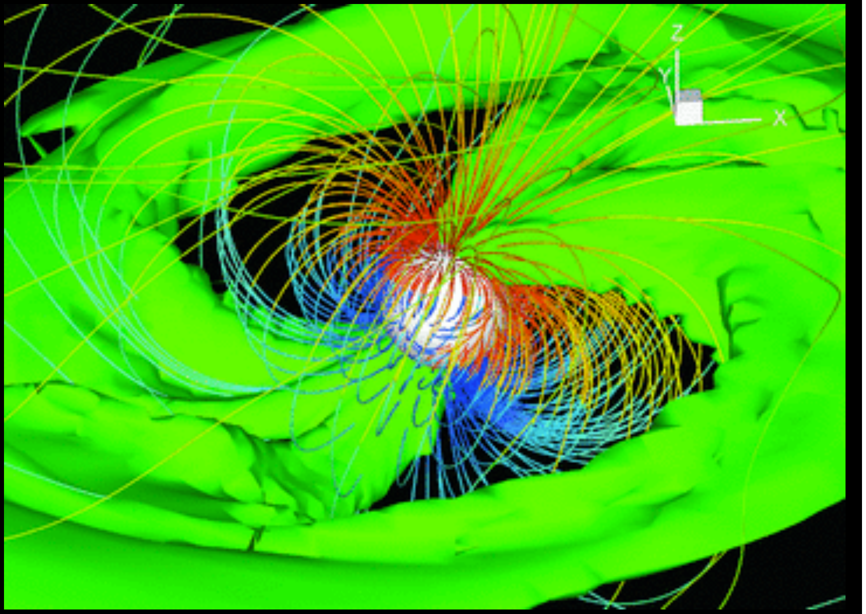
Magnetic field

Stellar hot spots



Time-dependent:
after 10 rotations

Density



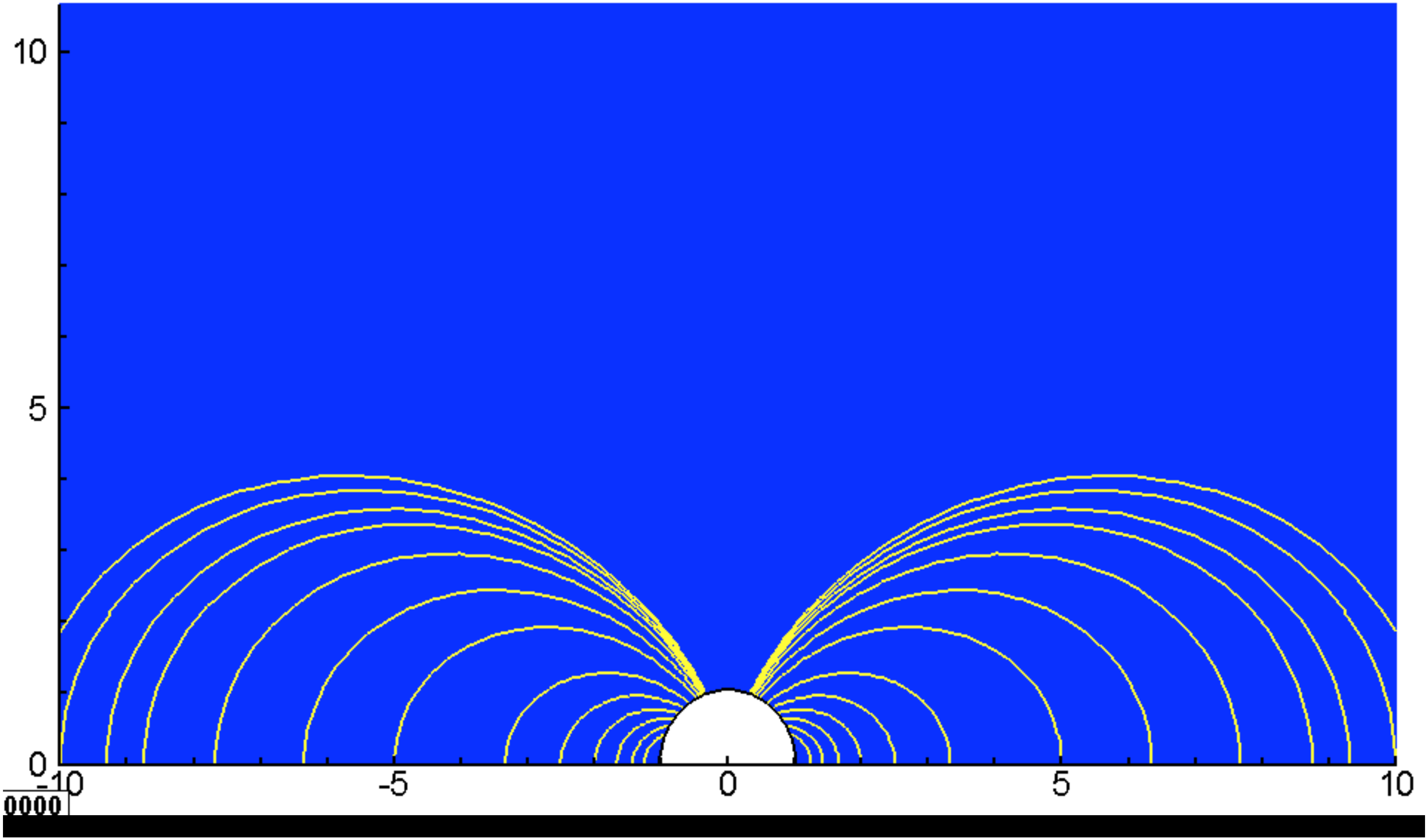
Line profiles?

Accretion / Outflow Connection

- Accretion must drive outflows from young stars
  - Roughly constant 10-to-1 ratio of mass accretion rate to mass loss rate
  - One is never present without the other
  - MHD models show this in action

Accretion / Outflow Connection

Conical Wind: Romanova et al.



Summary

- Magnetospheric accretion: The stellar magnetic field truncates the disk, and matter falls to the star along stellar field lines
  - T Tauri stars
  - Compact objects

- Magnetospheric accretion regulates the stellar rotation rate

- Evidence for magnetospheric accretion in TTS
  - Stellar magnetic fields are strong enough to truncate the disk
  - Blue continuum emission indicates optically thin shock emission
  - Line emission + absorption indicate freefalling gas terminating in a hot shock

- Numerical MHD models enable the study of realistic flow geometries

- Accretion must provide the energy for outflows from young stellar objects