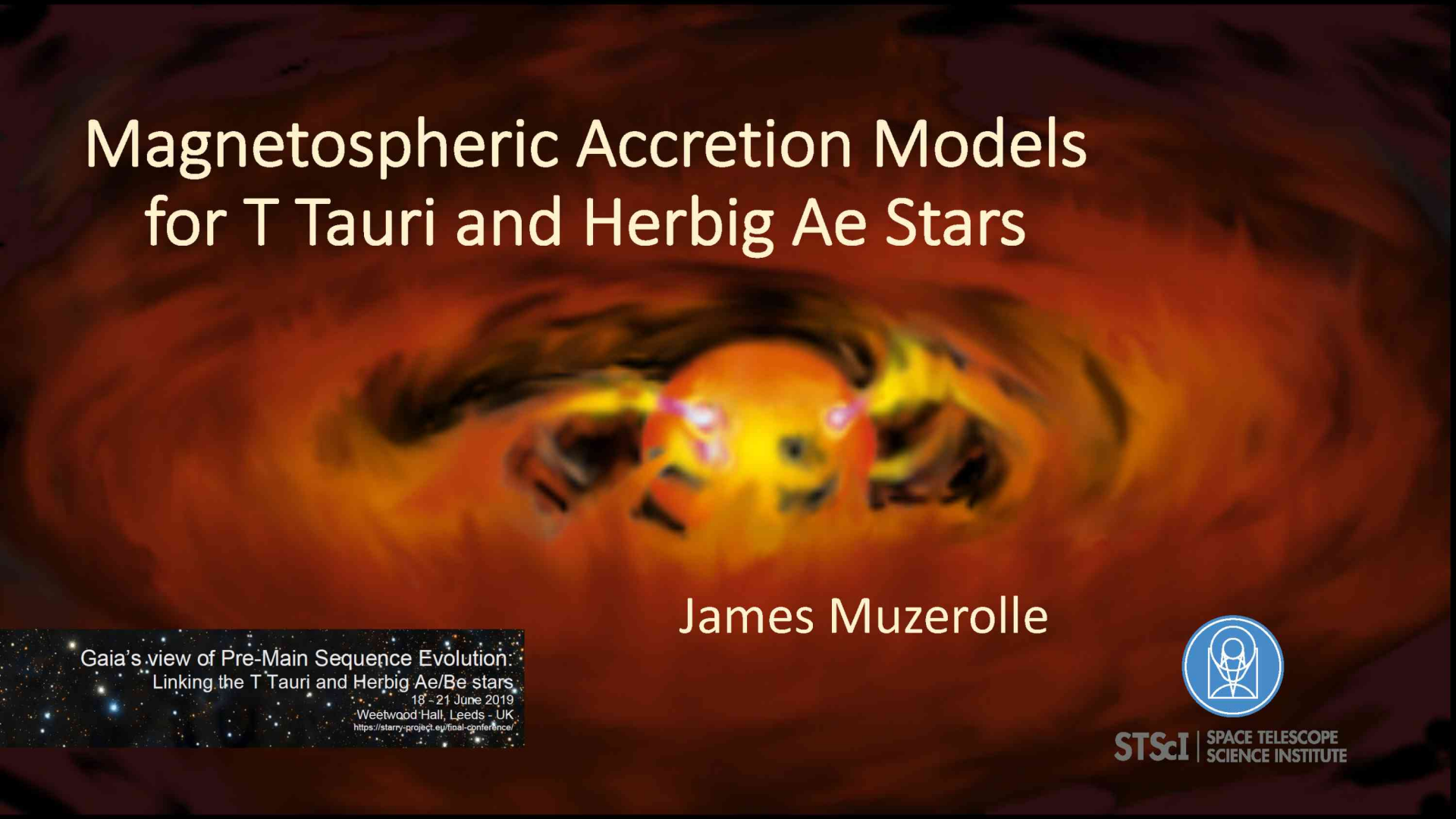
Magnetospheric Accretion Models for T Tauri and Herbig Ae Stars



James Muzerolle

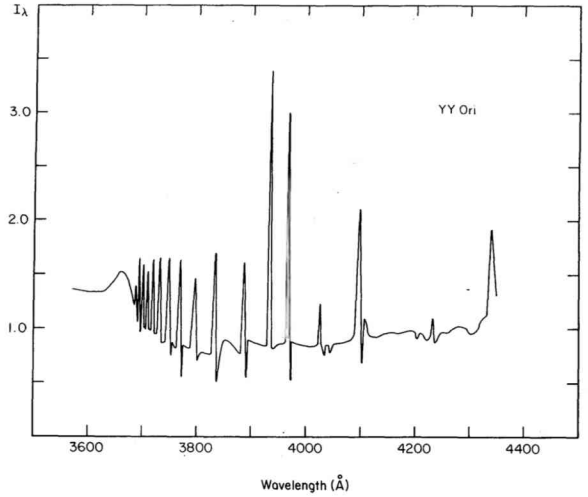
Gaia's view of Pre-Main Sequence Evolution:
Linking the T Tauri and Herbig Ae/Be stars
18 - 21 June 2019
Weetwood Hall, Leeds - UK
https://starry-project.eu/final-conference/

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

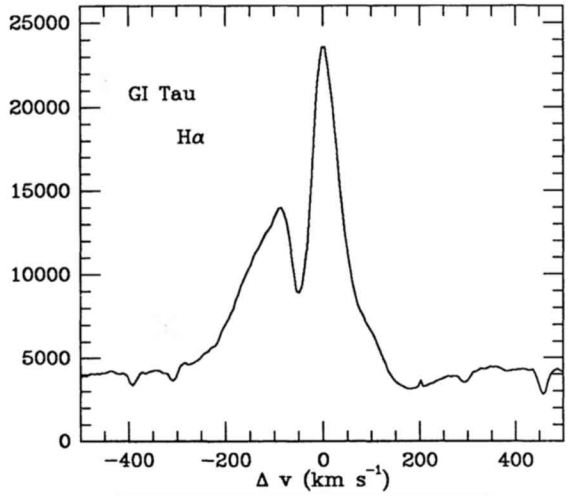
motivation

emission tracers of gas motion show both infall & outflow

- YY Orionis stars: prominent UV excess, permitted emission lines with variable redshifted absorption components (RAC)
- CTTSs: many Hα profiles exhibit bluehifted absorption (BAC), and occasional RAC

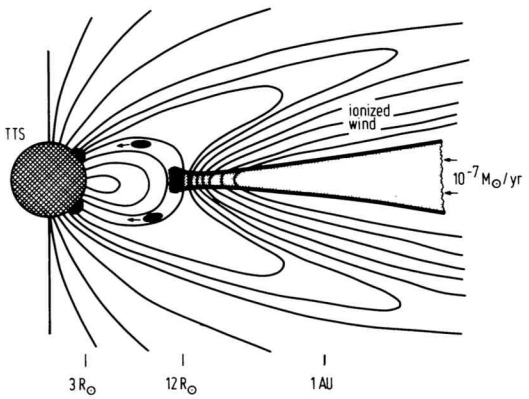


Walker 1972



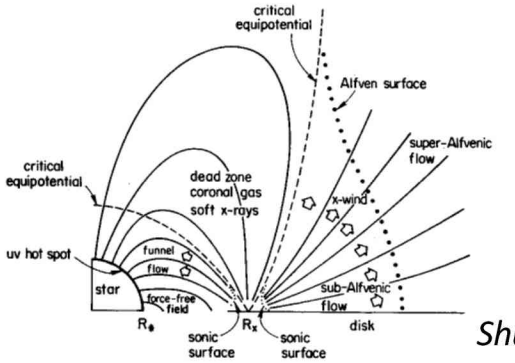
Calvet & Hartmann 1992

magnetospheric accretion theory



Camenzind 1990

- Ghosh & Lamb (1979): magnetic neutron stars
- Konigl (1991): applied to TTSs
- Camenzind (1990): connection to outflows
- Shu+ (1994): X-wind model



Shu + 1994

emission line RT models

Hartmann, Hewett, & Calvet (1994):

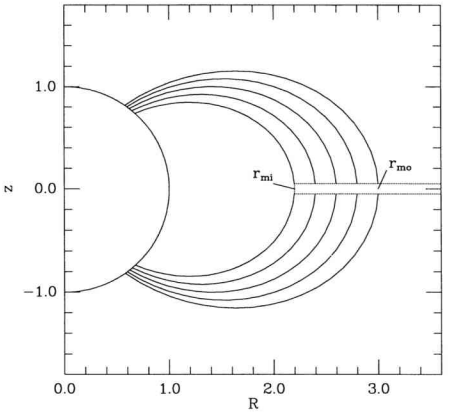
- calculated Balmer profiles with Sobolev approx.
- dipole field geometry defined by inner, outer boundaries at disk plane
- velocity field given by ballistic infall, constrained along field lines

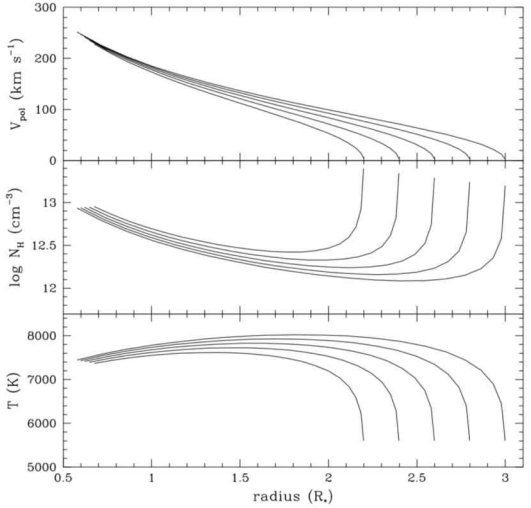
$$v_p = \left[\frac{2GM}{R_*}\left(\frac{R_*}{r} - \frac{R_*}{r_m}\right)\right]^{1/2}$$

- density field assuming steady flow along field lines

$$\rho \propto \dot{M}\, R_*^{-3/2} M_*^{-1/2}$$

- assumed temperature distribution given by volumetric heating rate, schematic radiative cooling law

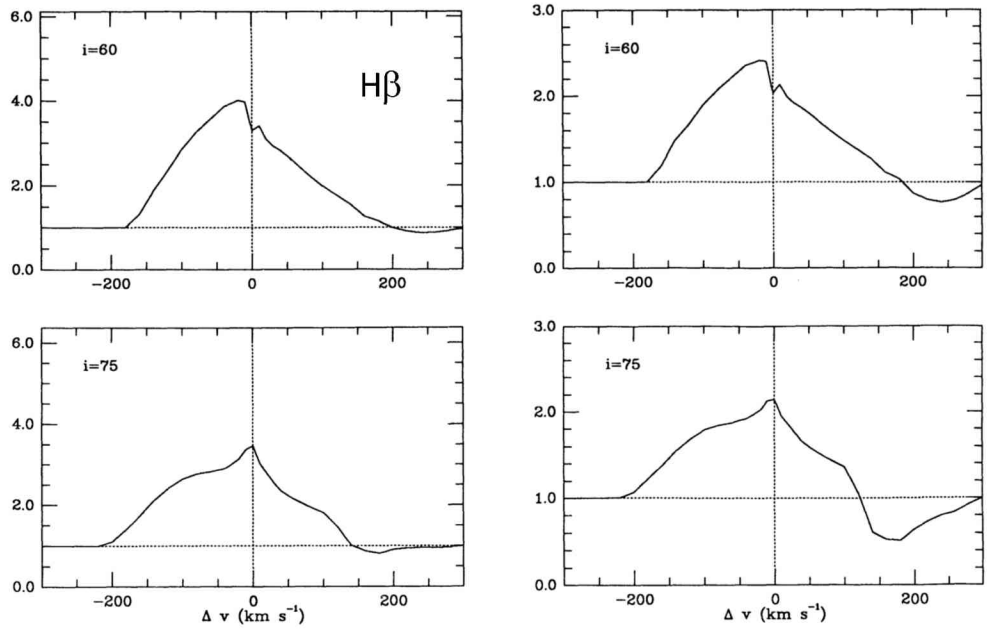




emission line RT models

Hartmann, Hewett, & Calvet (1994):

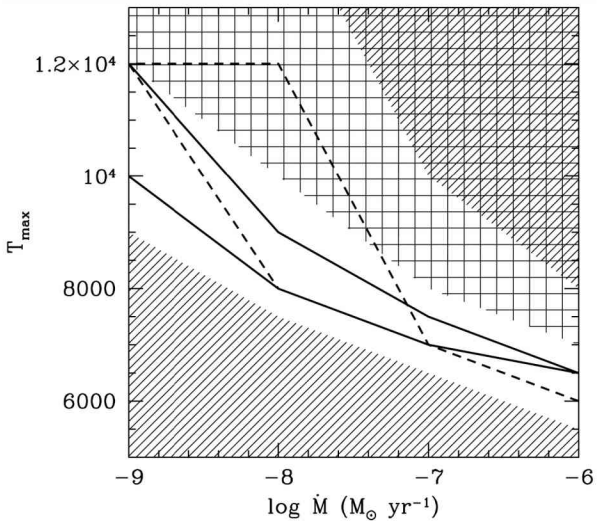
- Balmer profiles match some observed characteristics – line asymmetry, RAC

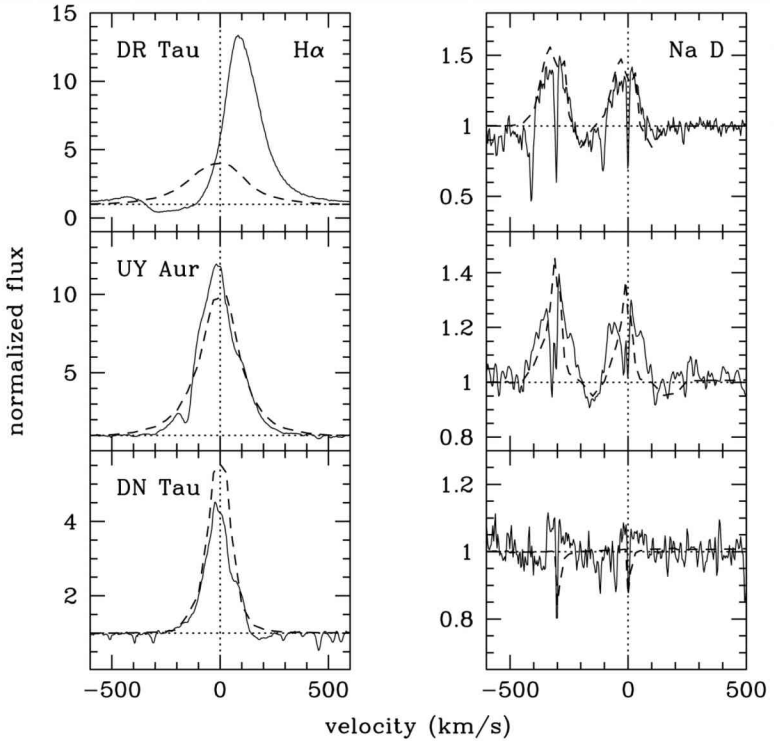


emission line RT models

Muzerolle et al. 1998, 2001:

- multi-level atom for hydrogen and sodium lines
- line broadening mechanisms
- constraints on gas temperature
- matched observed profiles, line fluxes

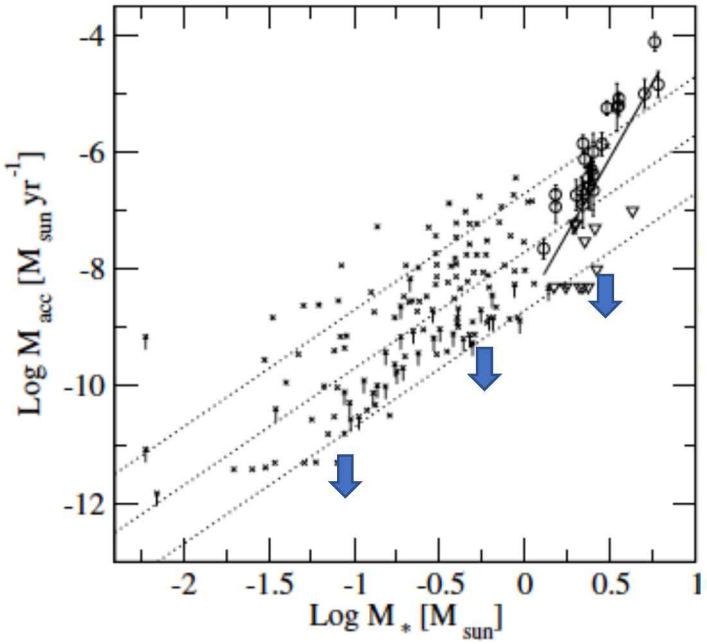




accretion rate limits

- absence of a particular indicator does *not* necessarily mean $\dot{M} = 0$!
- Hα profiles provide the most sensitive probe of low $\dot{M}$ in most cases *(cf. He I λ10830 RAC)*
- $\rho \propto \dot{M} R_*^{-\frac{3}{2}} M_*^{-\frac{1}{2}}$

  ➢ **lower limit depends inversely on stellar mass & age**



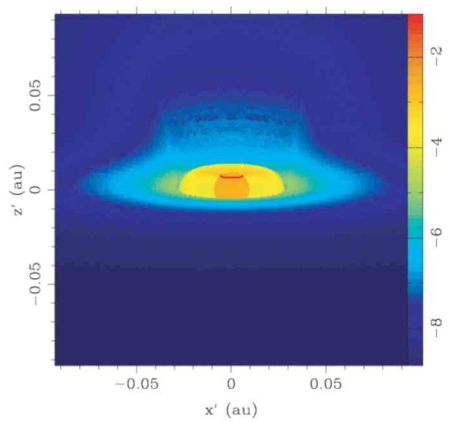
observational constraints for best results

- system inclination
  - non-zero ϕ complicates
- M*, R*
  - improvements from Gaia distances!
- corotation radius -- upper limit on R_{mo}
- magnetic field geometry (esp. for non-axisymmetric models)
- multiple emission line diagnostics
  - some constraint on T_{gas}

limitations of line models

- unknown gas heating mechanism(s) – adopted temperature distribution is ad-hoc
- Sobolev approx. iffy at low-vel part of flow near disk, invalidated if turbulence is significant
- real magnetospheric geometry typically more complicated – tilt wrt rotation axis, multipolar components
- need wind component for BAC, some emission (?)
- difficulty reproducing symmetric profiles, high-velocity blue wings (esp. Paschen, Brackett lines)

adding a wind component

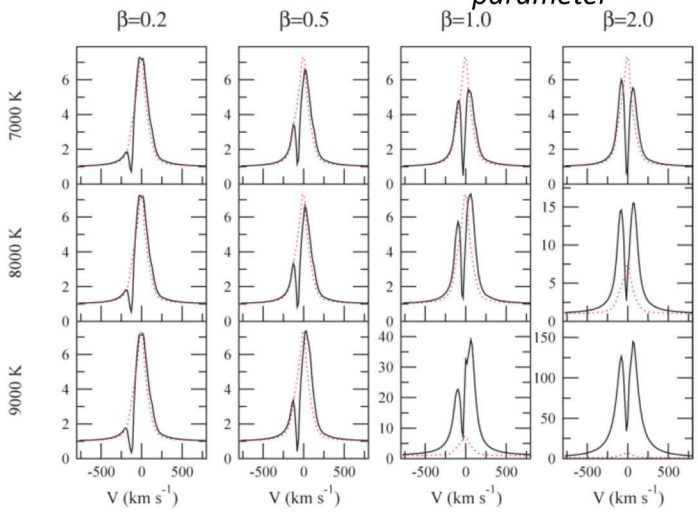


variants of Blandford & Payne model

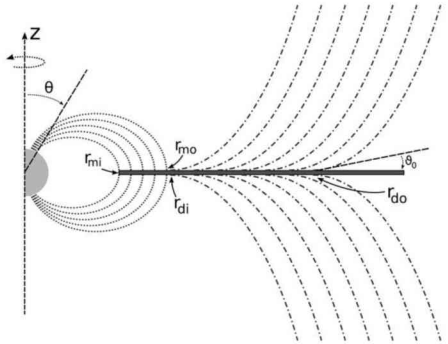
- reproduces Hα BAC
- minimal wind emission for most plausible (?) parameters
  - ➢ multiple degeneracies w/ T, mass loss rate, size, etc

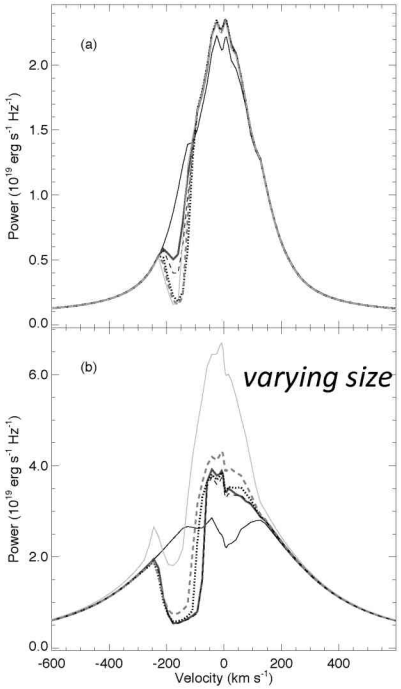
Kurosawa+ 2006

varying acceleration parameter



Lima+ 2010

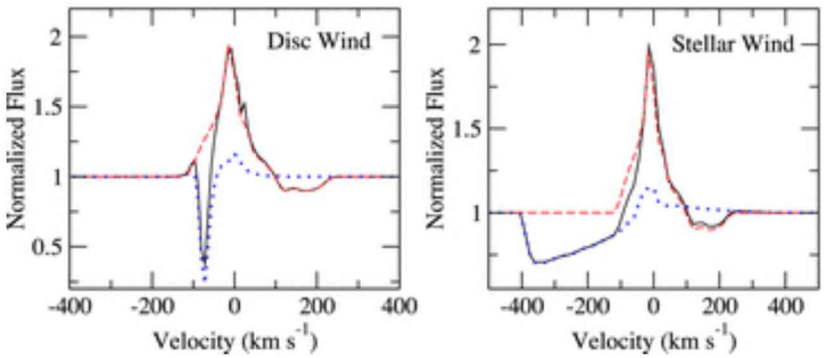


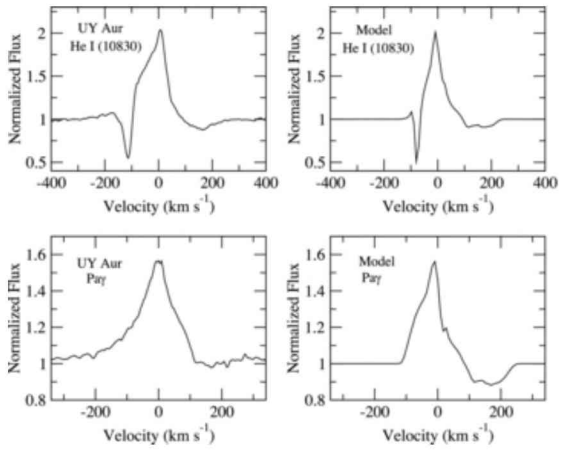


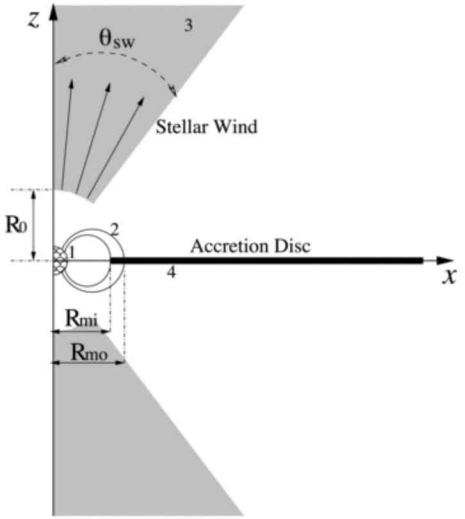
more wind

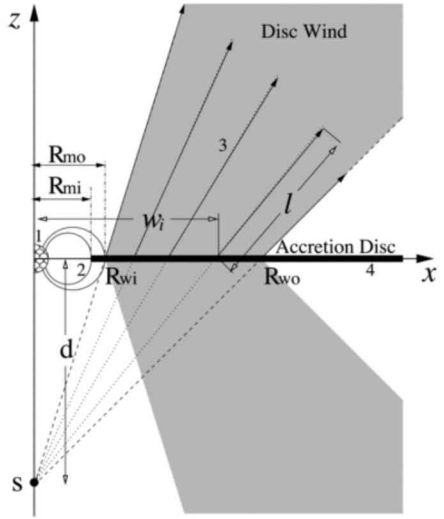
combining disk and stellar wind: Kurosawa+ 2011

- first treatment of X-ray photoionization -> He I λ10830 line
- combined modeling of Hα, He I may help constrain wind temperature

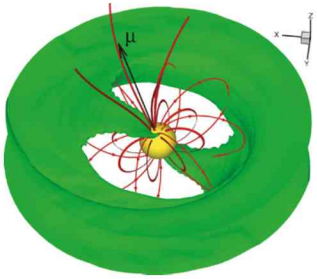


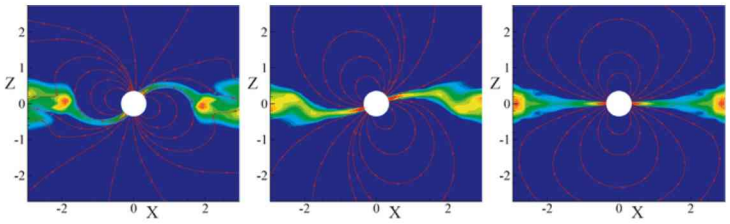






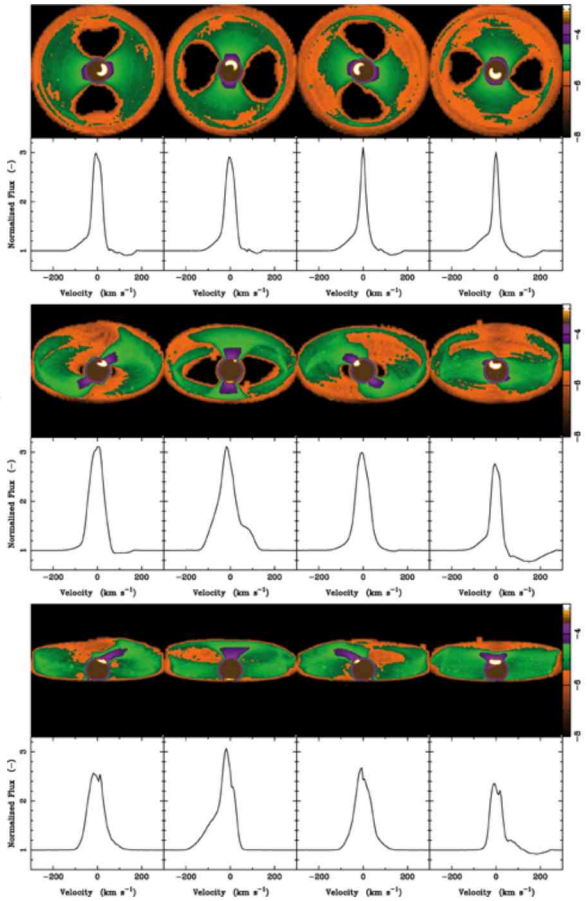
varying magnetosphere geometry





- MHD simulations with effects of tilted dipole, complex field components (Romanova+ 2014, etc)
- MC 3D RT models can treat arbitrary geometries, though still subject to other similar constraints as 2D (Sobolev approx., gas temperature, etc)
- Kurosawa+ (2008) investigated effect of changing magnetosphere tilt angle μ

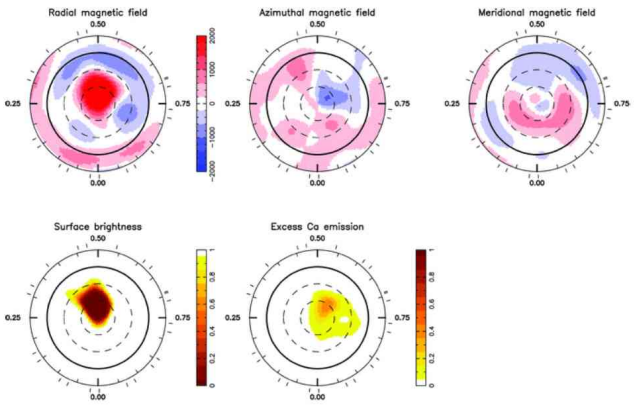
Pa β with
μ = 15
i = 10, 60, 80



test case: V2129 Oph

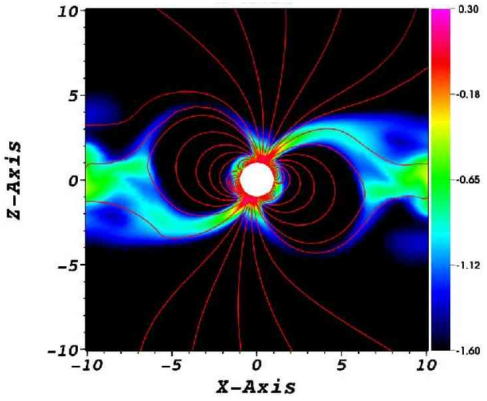
Donati+ (2011) magnetic field geometry reconstruction

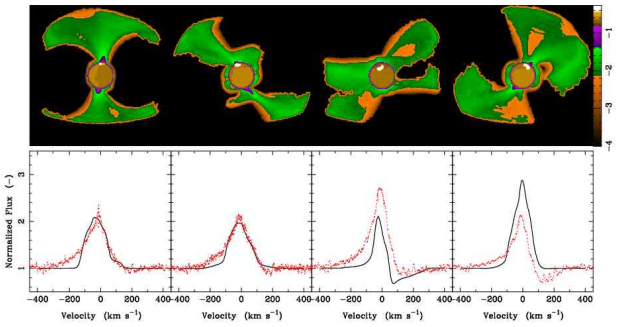
- ESPaDOnS spectropolarimetry
- LSD Stokes I & V profiles from Ca II & He I emission, photospheric abs. lines
- 2.1 kG octupole, 0.9 kG dipole, ϕ~20 deg
- $\dot{M}$ ~ 10^{-9} Msun/yr



Alencar+ (2012) emission line models using Donati reconstruction

- line profile variability primarily from rotation of the flow





accretion shock models

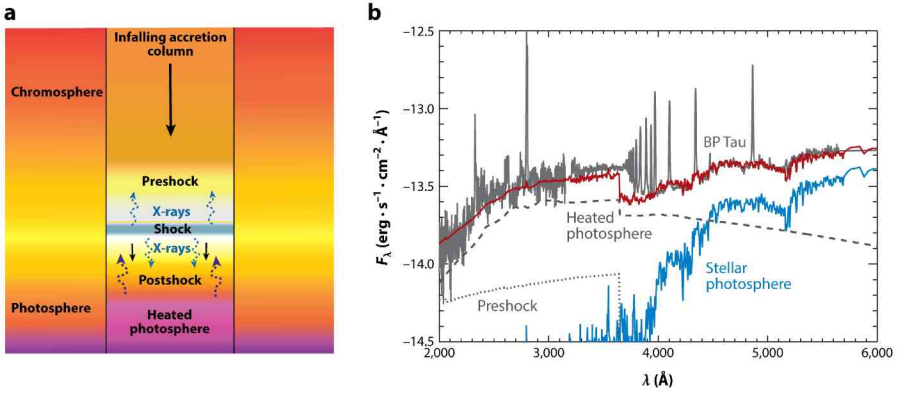
Calvet & Gullbring (1998) 1D shock model

- FUV, Balmer continuum from (opt. thin) preshock region
- Balmer and Paschen continuum from (opt. thick) heated photosphere region
- fit parameters: energy flux $\mathcal{F}$, filling factor f
- fits to T Tauri UV/optical spectra provide measures of $\dot{M}$

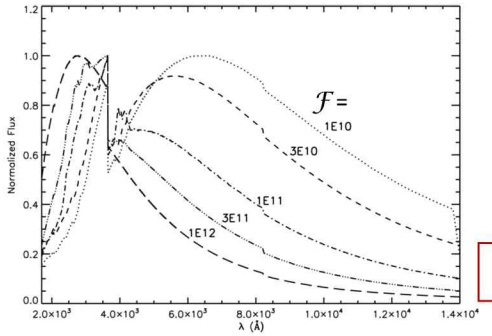
$$L = (\mathcal{F} + F_*) \cdot f \; 4\pi R_*^2$$

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

- typical values: f ~ 0.1 – 1%, log $\mathcal{F}$ ~ 10.5 – 11.5
- does not explain observed veiling in the red/NIR
  - multiple flows with different $\mathcal{F}$? (Ingleby+ 2013)



Hartmann L, et al. 2016.
Annu. Rev. Astron. Astrophys. 54:135–80

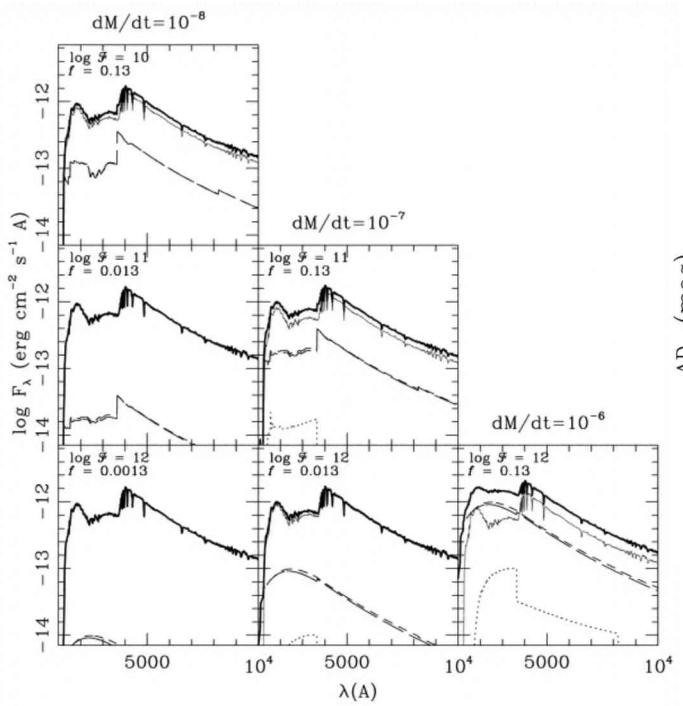


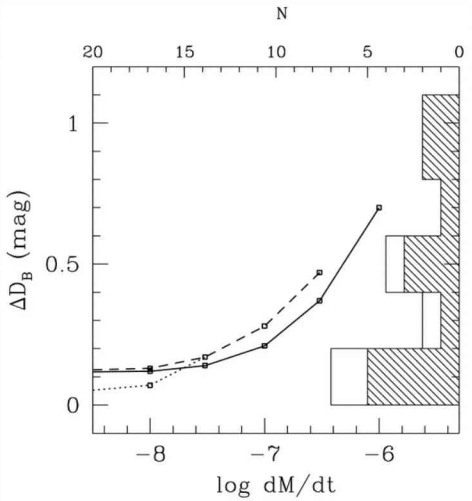
Ingleby+ 2013

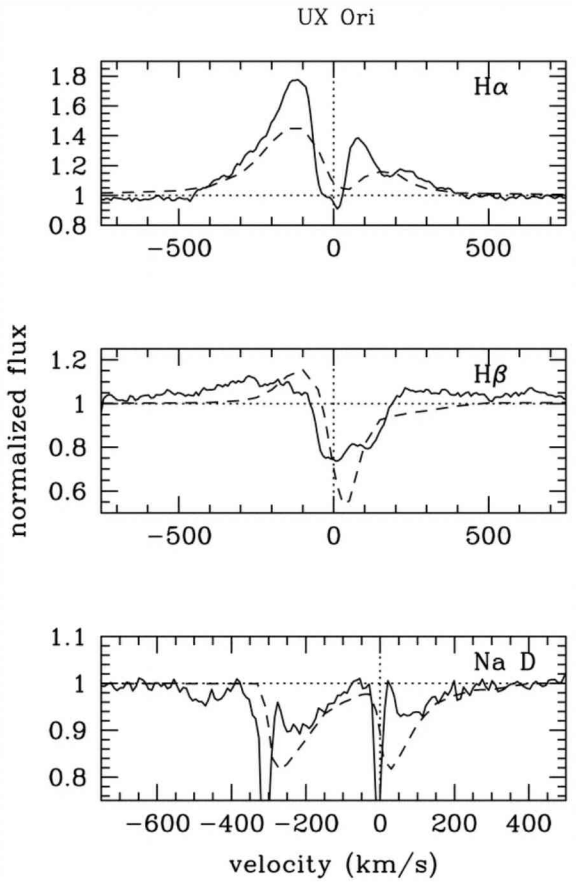
Herbig Ae/Be stars

Muzerolle+ (2004) first models

- reasonable fits to permitted lines for UX Ori
- set of shock models using A2 photosphere - ΔD_B parameter could be used as a diagnostic of $\dot{M}$



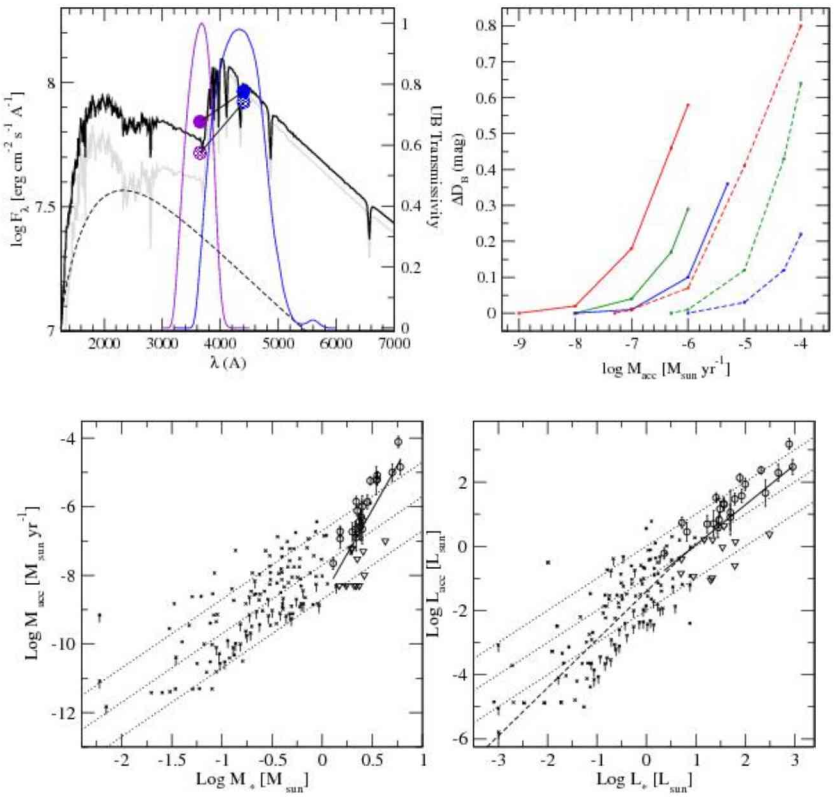


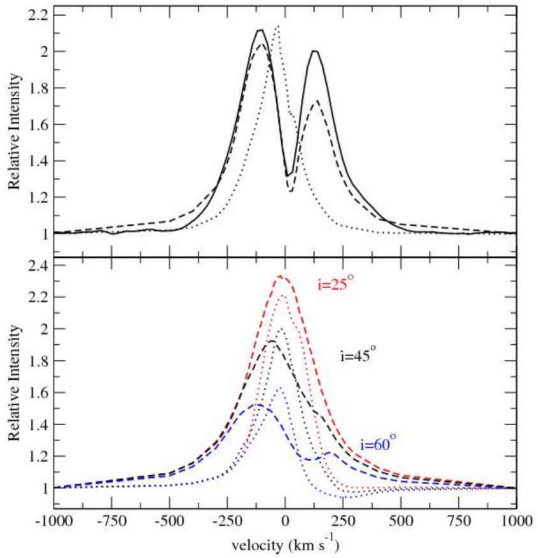


Herbig Ae/Be stars

Mendigutia+ (2011): more line models, demographics from shock models *(also Donehew & Brittain 2011)*

models for different T_*, log *g* ->
ΔD_B calibration depends on these!

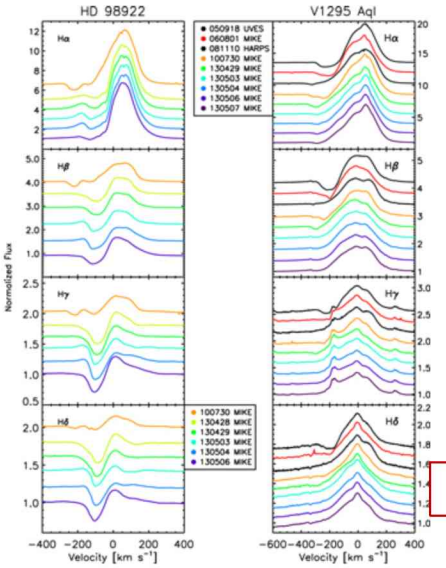




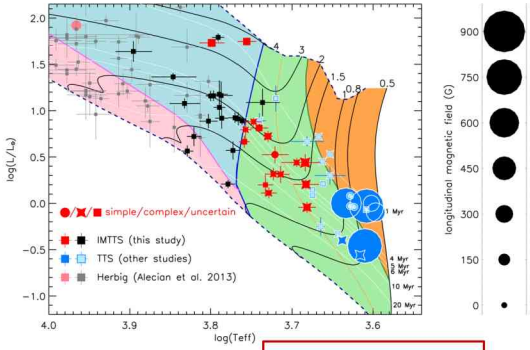
BF Ori Hα models with rotation (vsini=37 km/s)

limitations for Herbig stars

- many stars show P Cygni profiles
  - ➢ stronger (stellar?) winds
- fast rotation means small magnetosphere
  - ➢ difficult to produce sufficient emission
  - ➢ consistent with small observed infall velocities in He I (Cauley & Johns-Krull 2014)
- higher accretion rates
  - ➢ higher mass loss rates -- emission from the wind?
- M_*, R_* more uncertain (until Gaia!)
- uncertain magnetic field strengths & geometries
  - similar emission for stars w/ and w/o detected B fields (Mendigutia+)
  - no infall signatures in HBe He I (Cauley & Johns-Krull 2014)



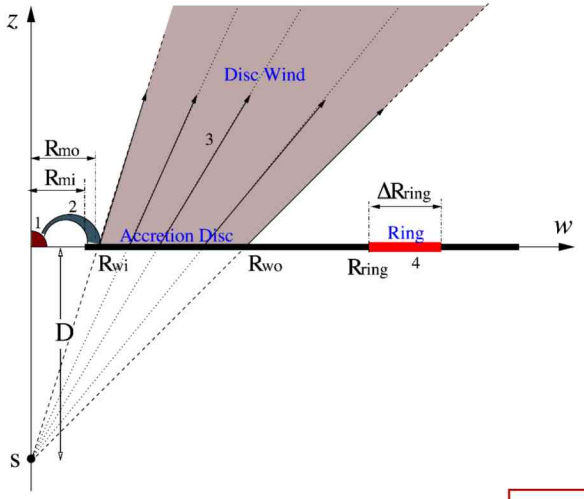
Aarnio+ 2017

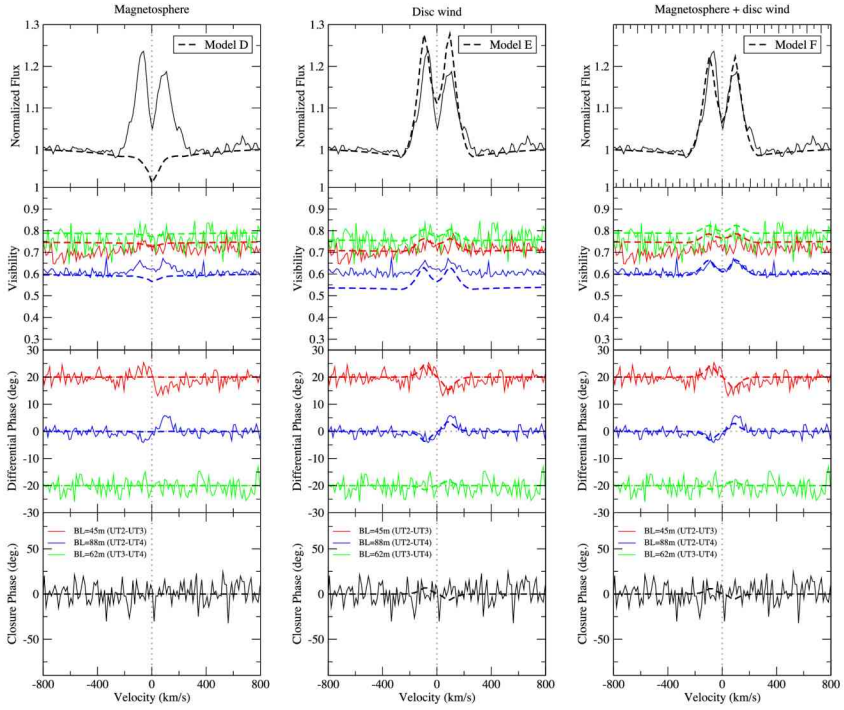


Villebrun+ 2019

Herbig stars: winds

- Herbig Be star HD 58647: emission from a disk wind?

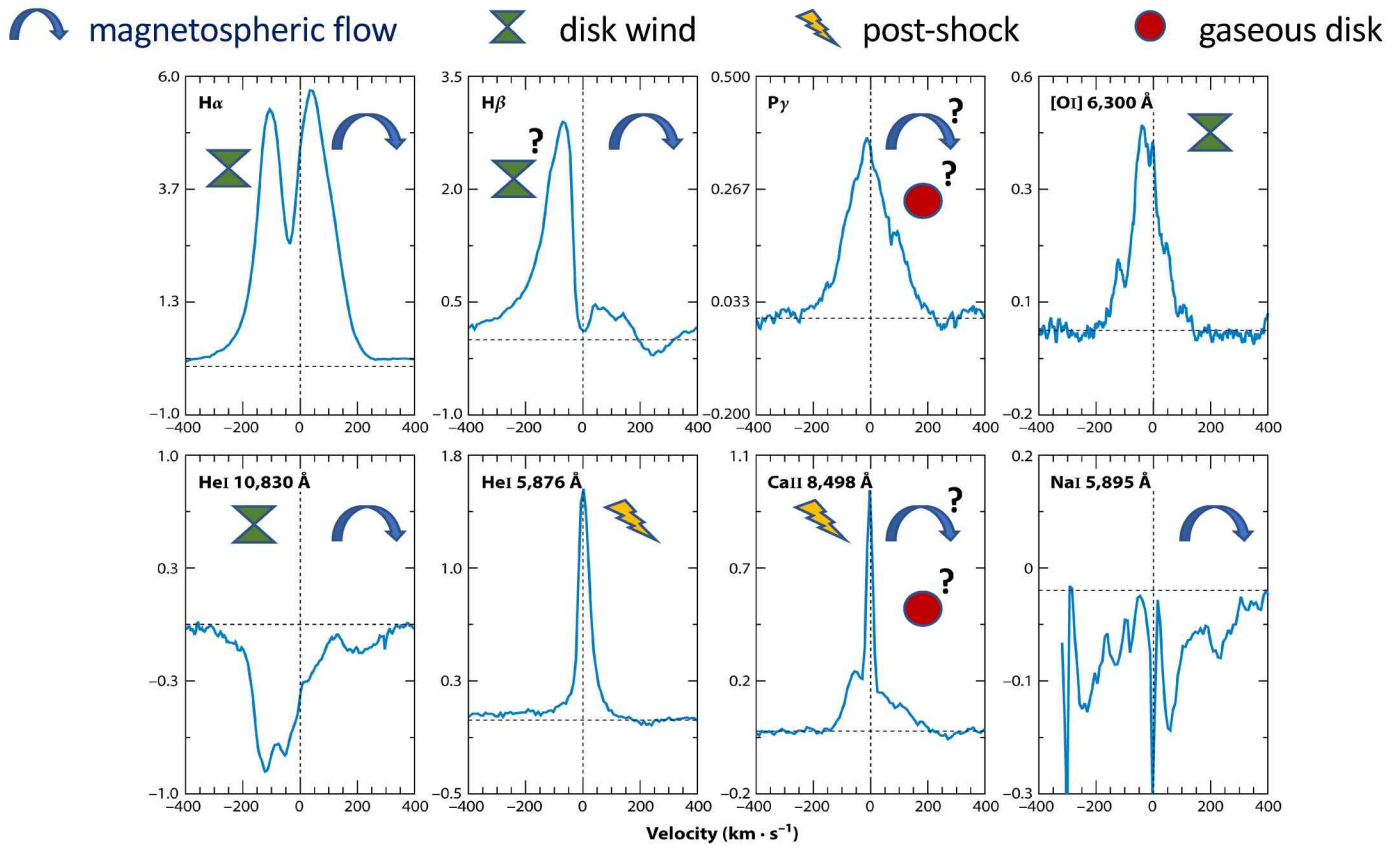




Kurosawa+ (2016)

Future

- need a more wholistic approach with different model components for different lines
  - models of line emission from accretion postshock & heated photosphere regions
    - narrow components of C IV, He I, Ca II
    - upper Balmer, Paschen, Brackett lines?
  - wind + accretion models for He I λ10830
  - models for mid-IR lines: JWST & protostellar objects
- weak accretors – better lower limits from Hα, He I models?
- planetary accretion
  - do giant planet magnetospheres mediate the flow of gas from the disk?



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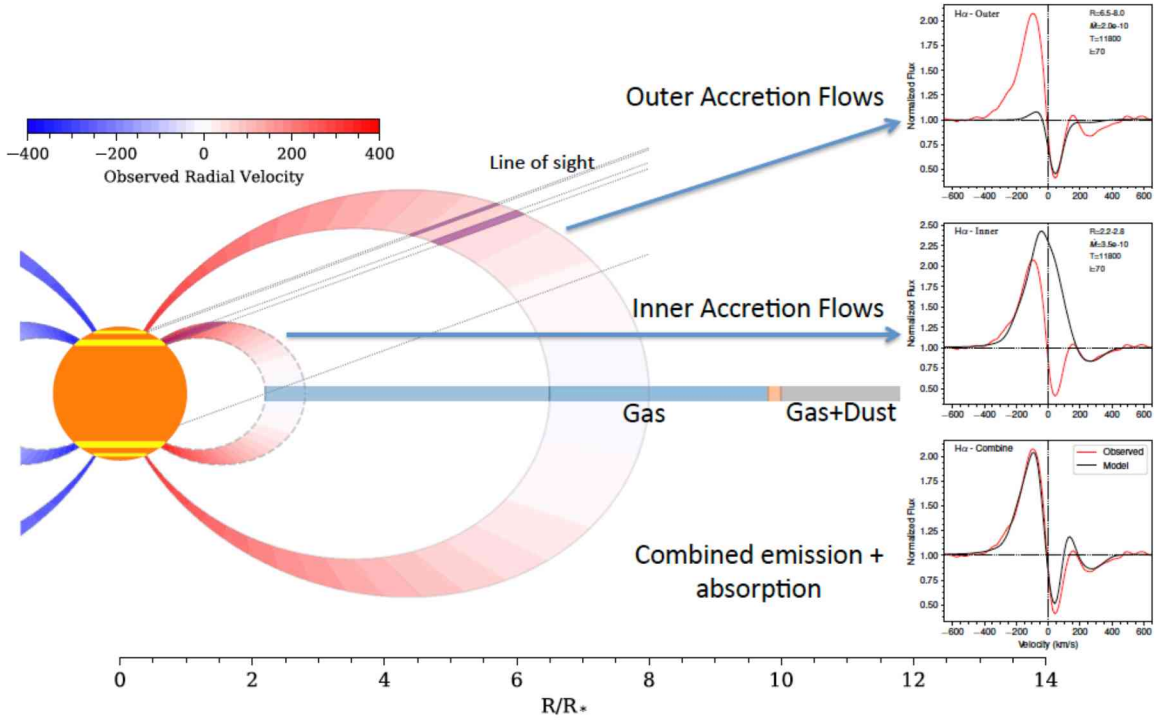
weak accretors

evidence for multiple nested flows in some systems

- see talk by Atom Thanathibodee!



Thanathibodee+ 2019

planetary accretion?

- Hα models for PDS70bc (Thanathibodee+ 2019 *in prep)*