Hot Inner Winds from T Tauri Stars

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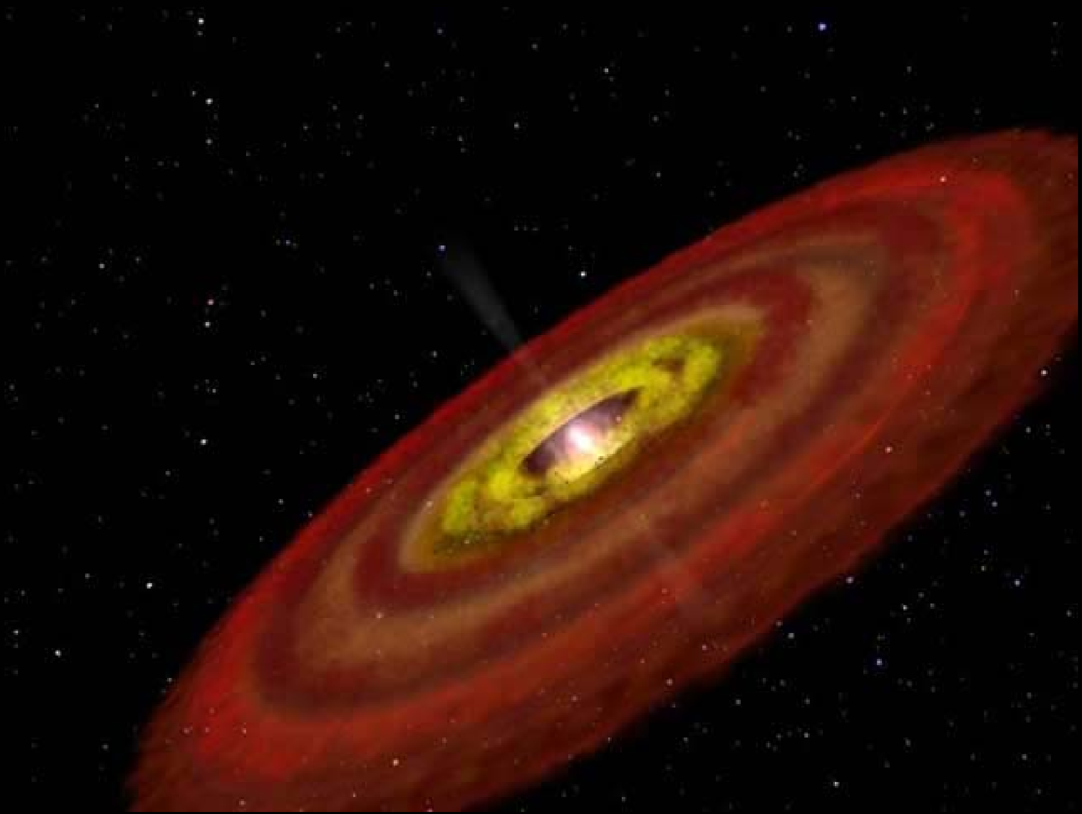
Rice University

Protostellar Jets in Context, 7 July 2008



Cool Winds from T Tauri Stars

Known for many years

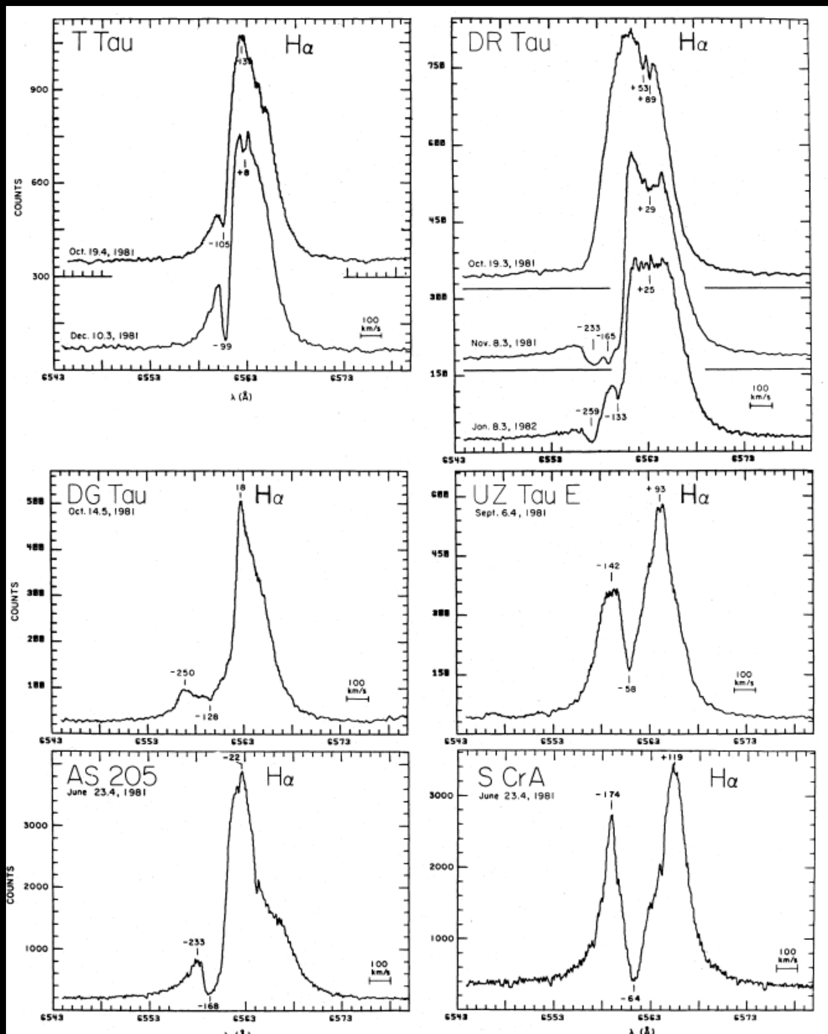
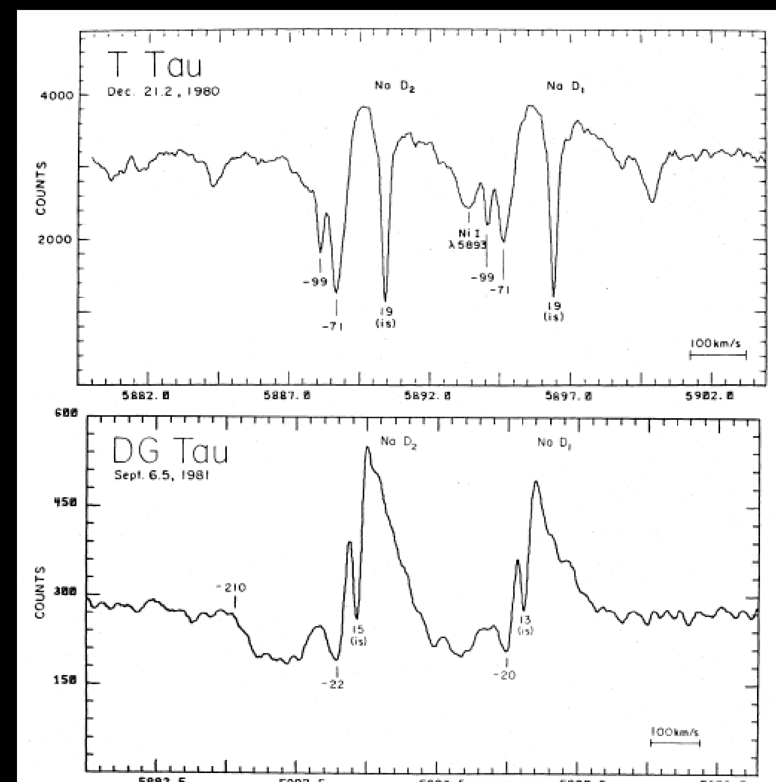


FIG. 3.—Hα line profiles

758

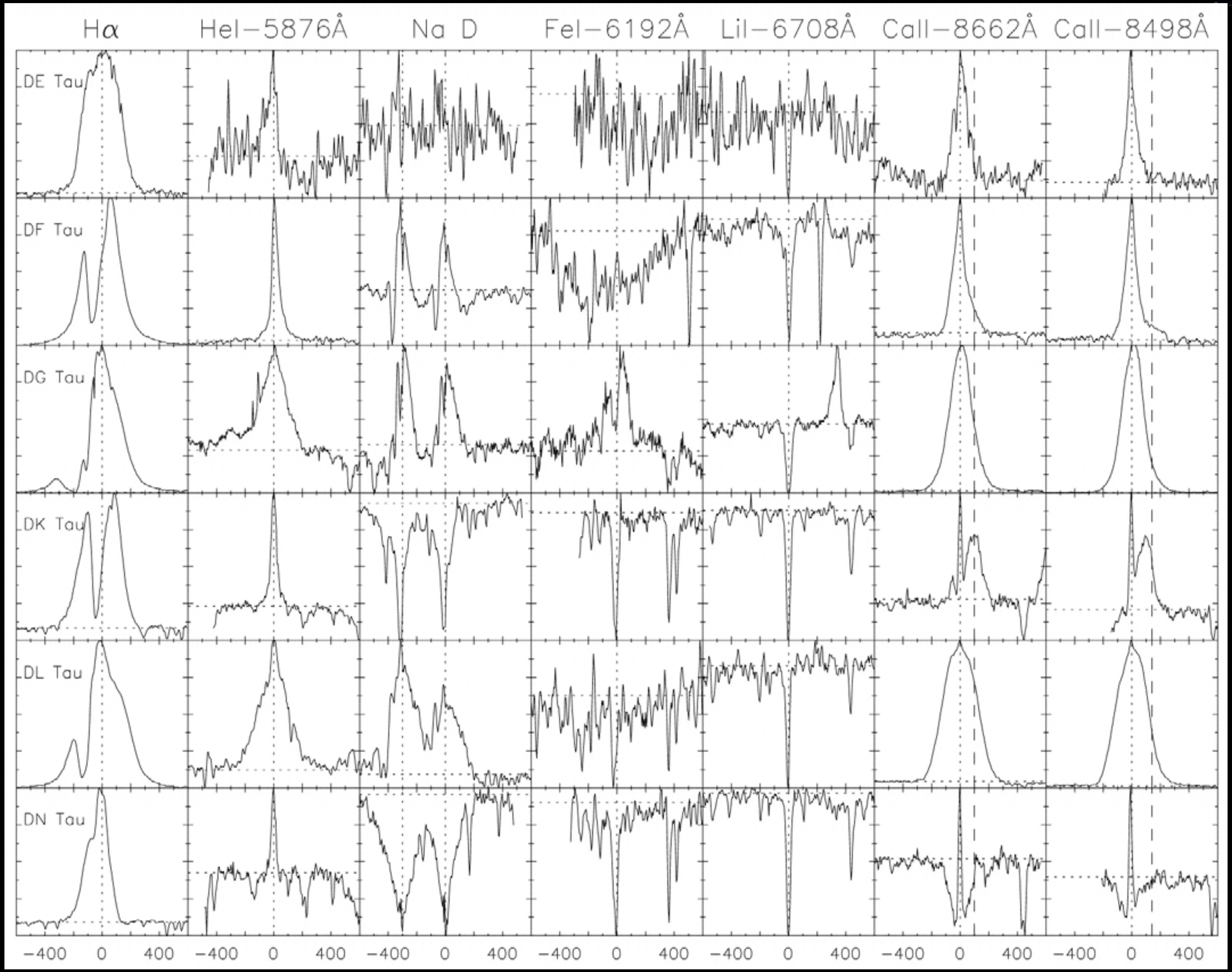
Mundt 1984, ApJ, 280, 749



Cool Winds from T Tauri Stars

Known for many years

Alencar & Basri 2000, AJ, 119, 1881



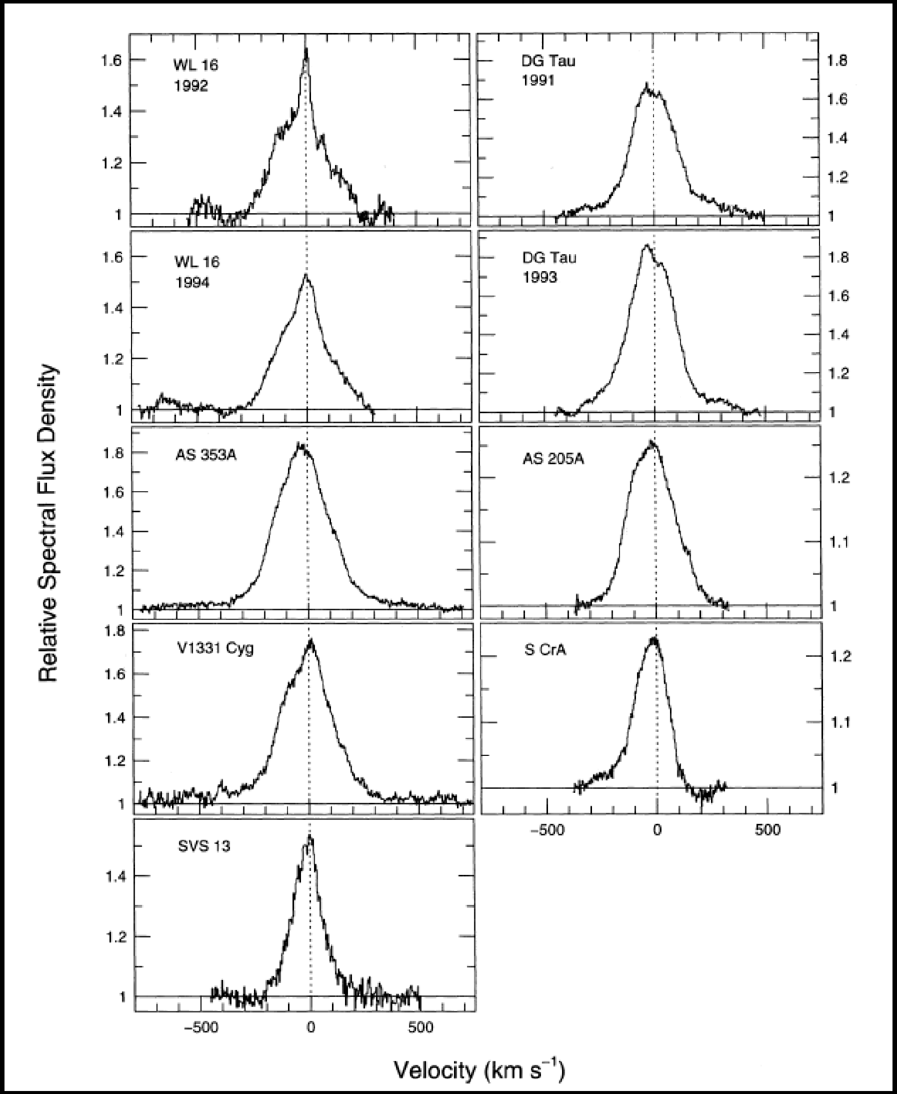
Cool Winds from T Tauri Stars

Mass Loss Rate and Temperature Estimates (not exhaustive)

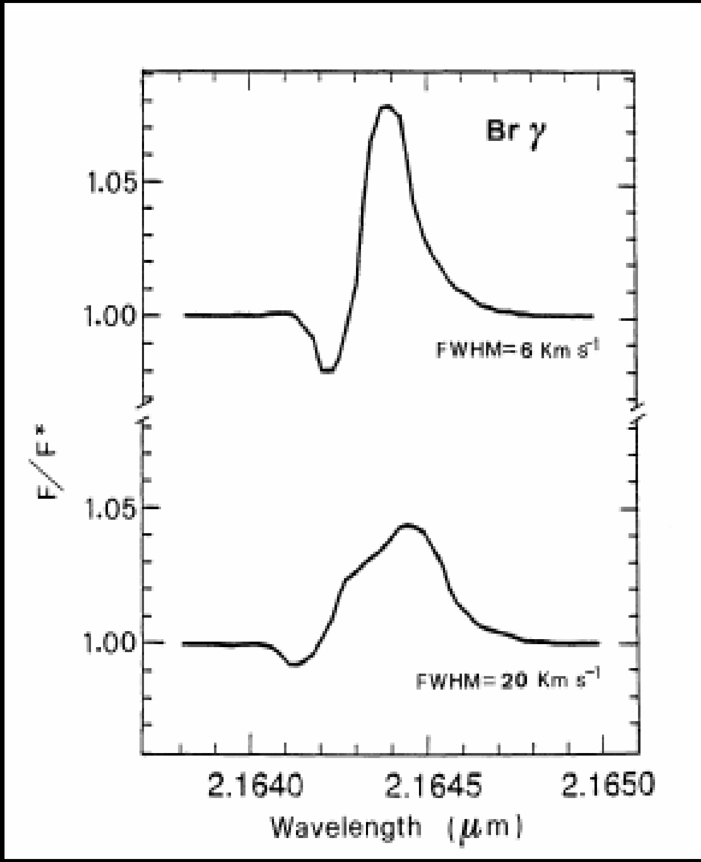
- Kuhi 1964, ApJ, 140, 1409: Spherical wind: ~10^{-8} Msol/yr, ~4500 K
- DeCampli 1981, ApJ, 244, 124: up to 10^{-7} Msol/yr; *cool* winds (not coronal)
- Mundt 1984: Na D lines show the winds are *cool* and accelerated close to the star
- Hartmann et al. 1990, ApJ, 349, 168: Spherical winds: *few* × 10^{-8} Msol/yr; ~ 8,000 K
- Natta & Giovanardi 1990, ApJ, 356, 646: Spherical modeling of Na D profiles: 10^{-8} - 10^{-7} Msol/yr; 6000 - 6500 K
- Calvet et al. 1992, ApJ, 386, 229: *Close* disk wind: *few* × 10^{-8} Msol/yr; ~ 8,000 K
- Johns & Basri 1995, ApJ, 449, 341: Spherical wind: 5 × 10^{-9} Msol/yr; ~8,000 K

The Winds Get Colder

Najita et al. 1996, ApJ, 456, 292



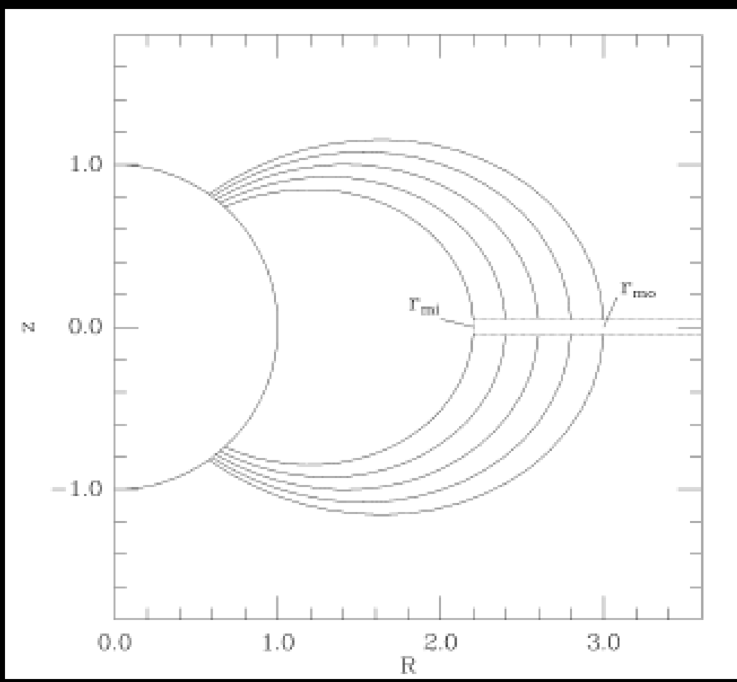
Natta & Giovanardi 1990, ApJ, 356, 646

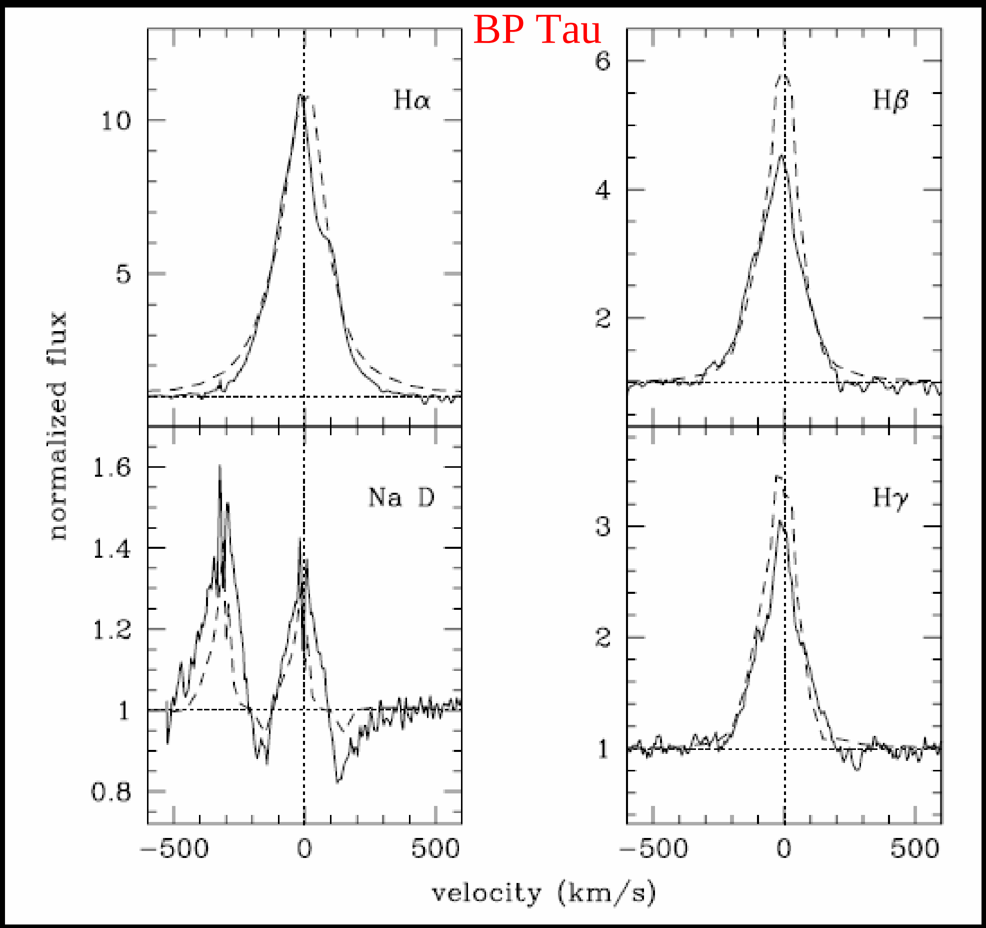


The Winds Cease to Blow

Hartmann et al. 1994, ApJ, 426, 669

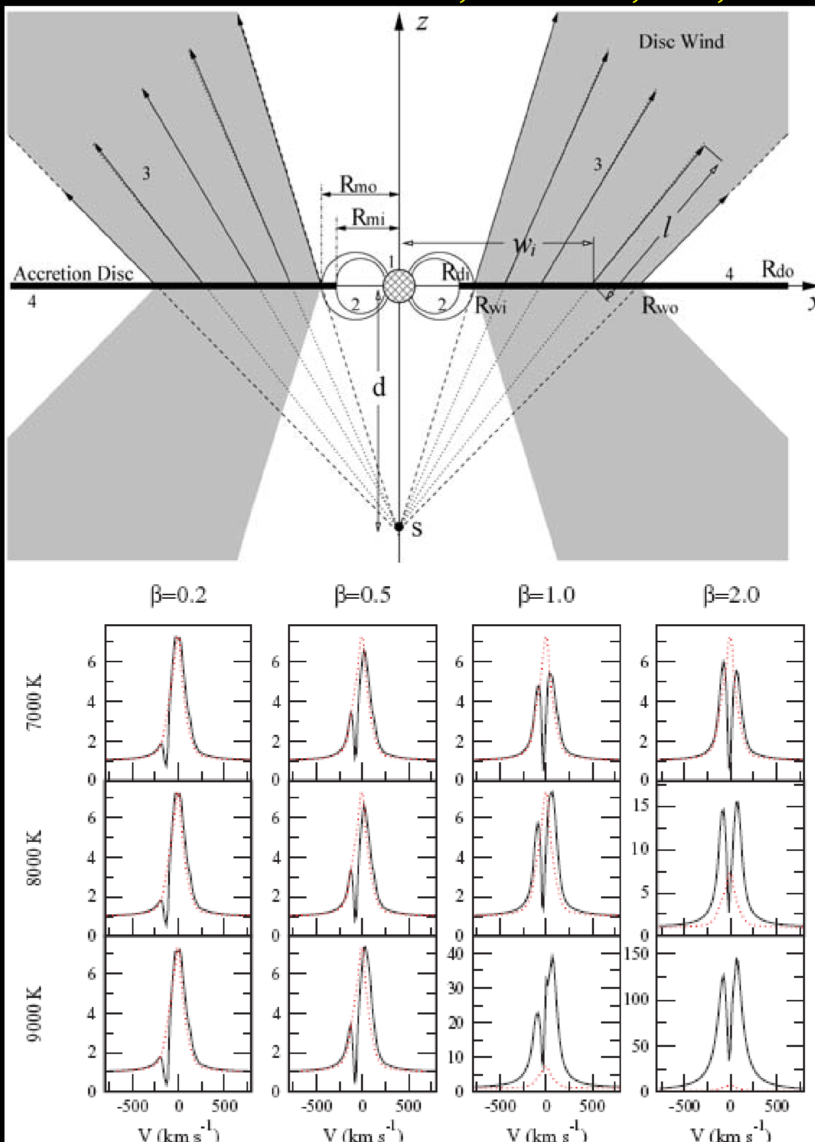
Muzerolle et al. 2001, ApJ, 550, 944



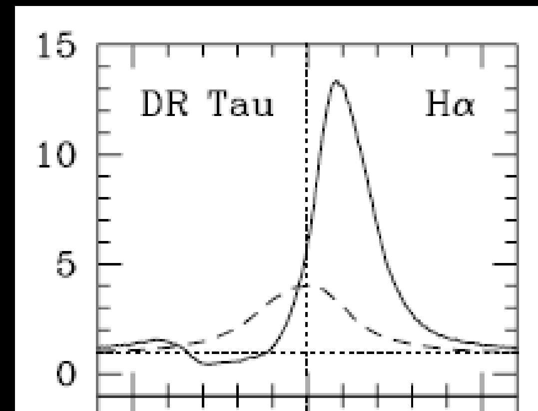


And They Blow Once More

Kurosawa et al. 2006, MNRAS, 370, 580



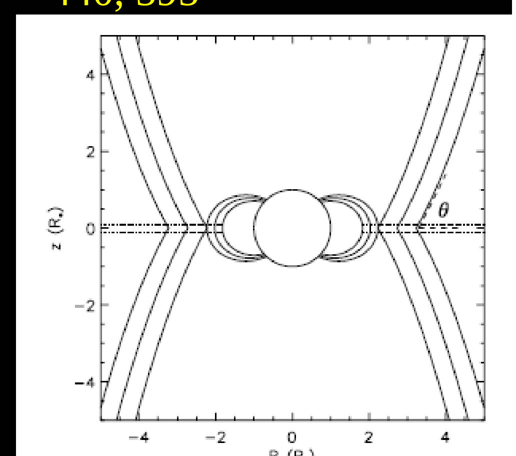
Muzerolle et al. 2001

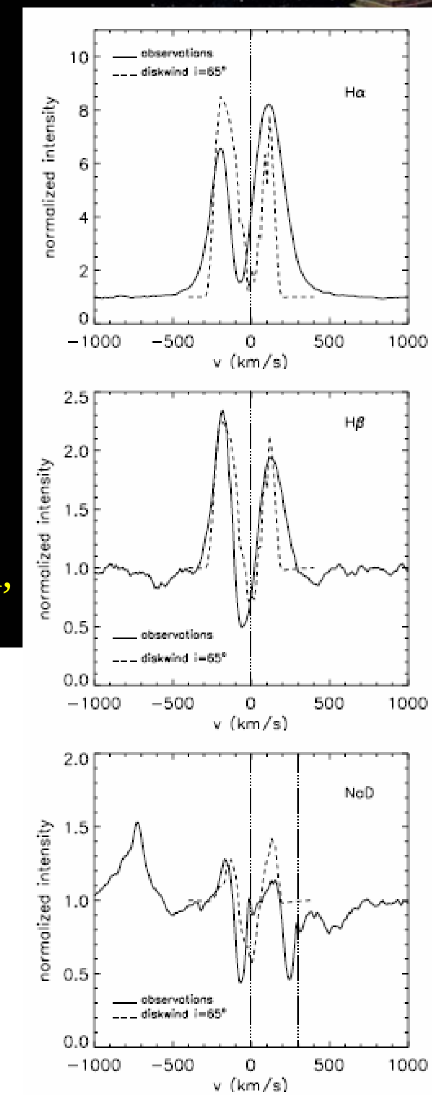


$M_W / M_{acc} \sim 0.1$

$T < 10{,}000$ K

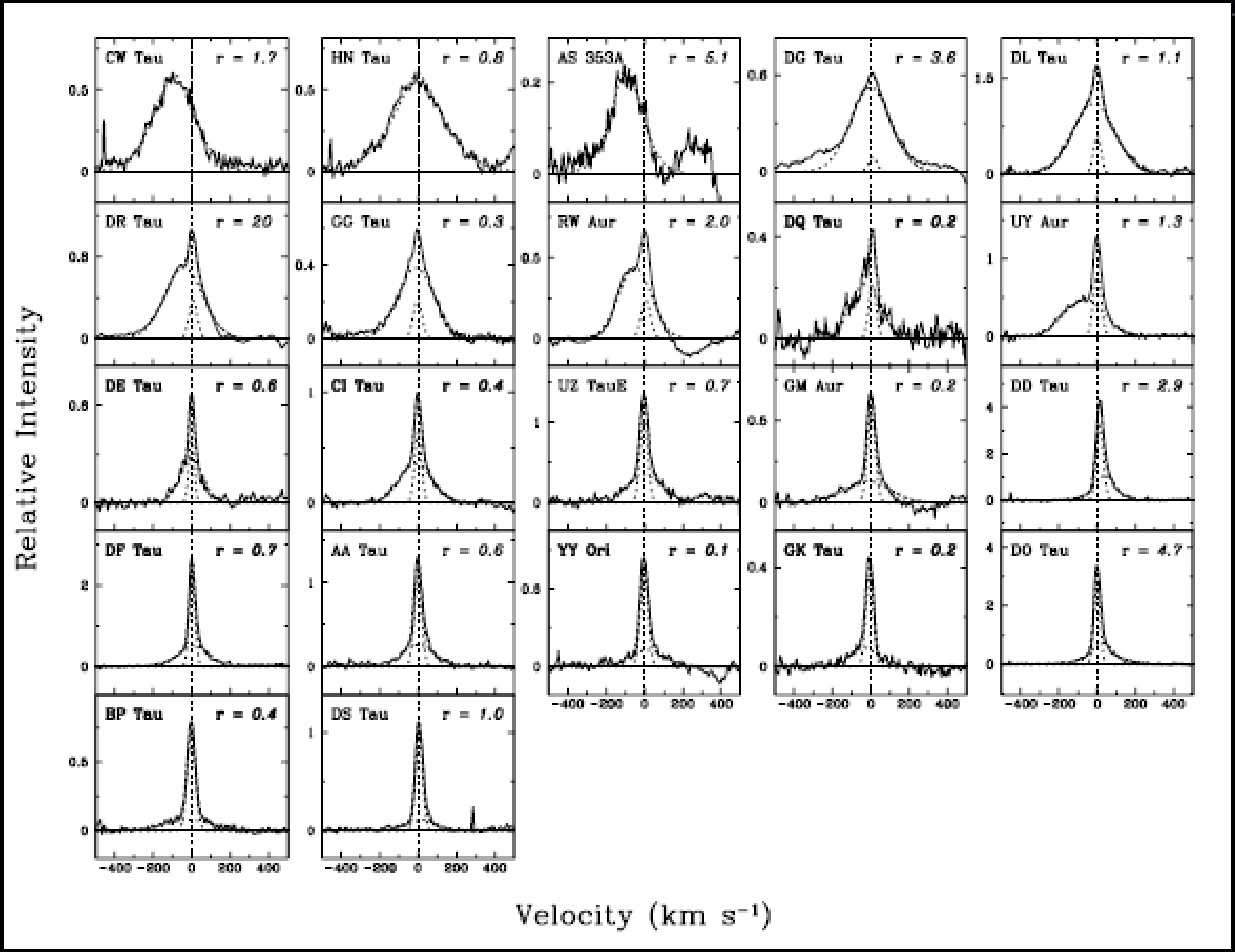
Alencar et al. 2005, A&A, 440, 595





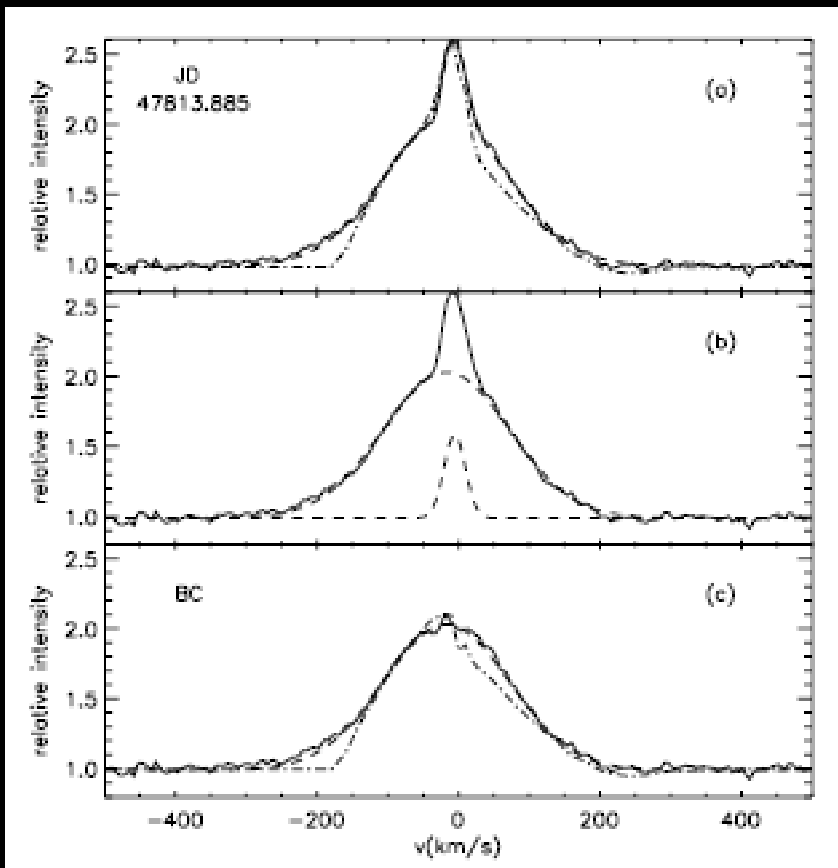
The Winds Start to Get Hotter

Observations of He I 5876; Beristain et al. 2001, ApJ, 551, 1037

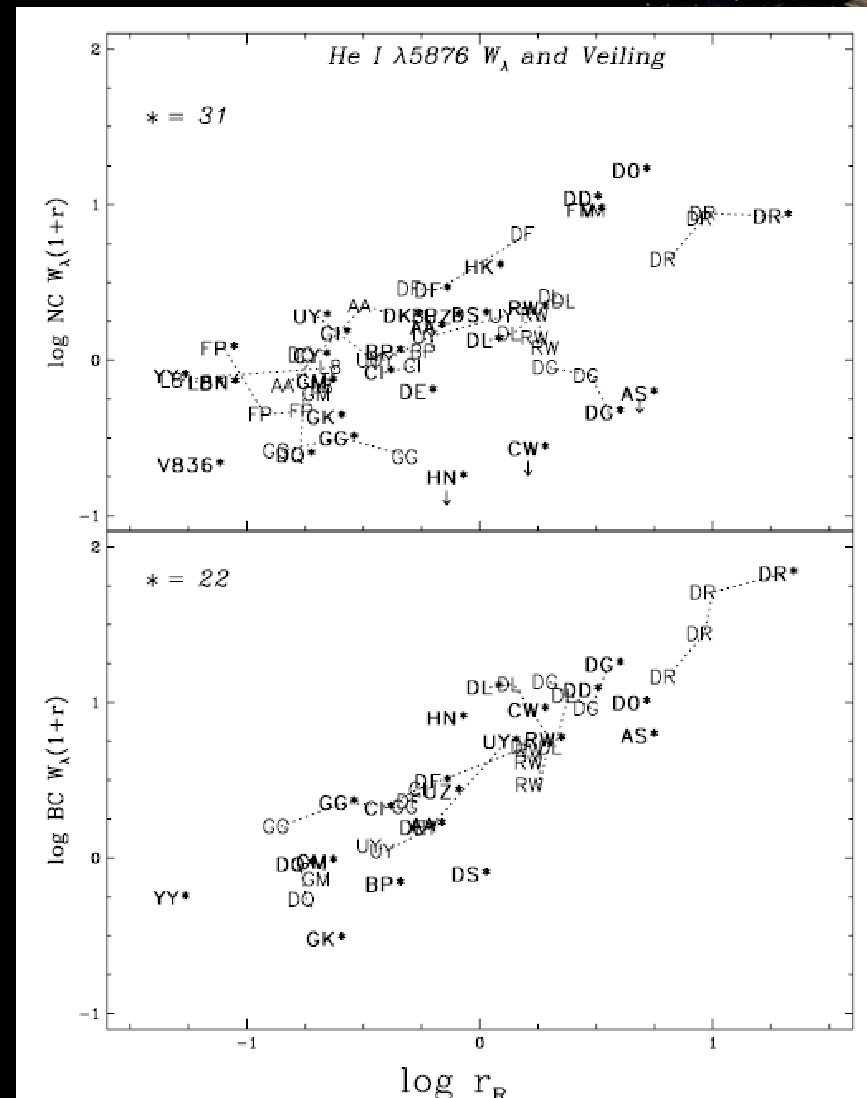


The Winds Start to Get Hotter

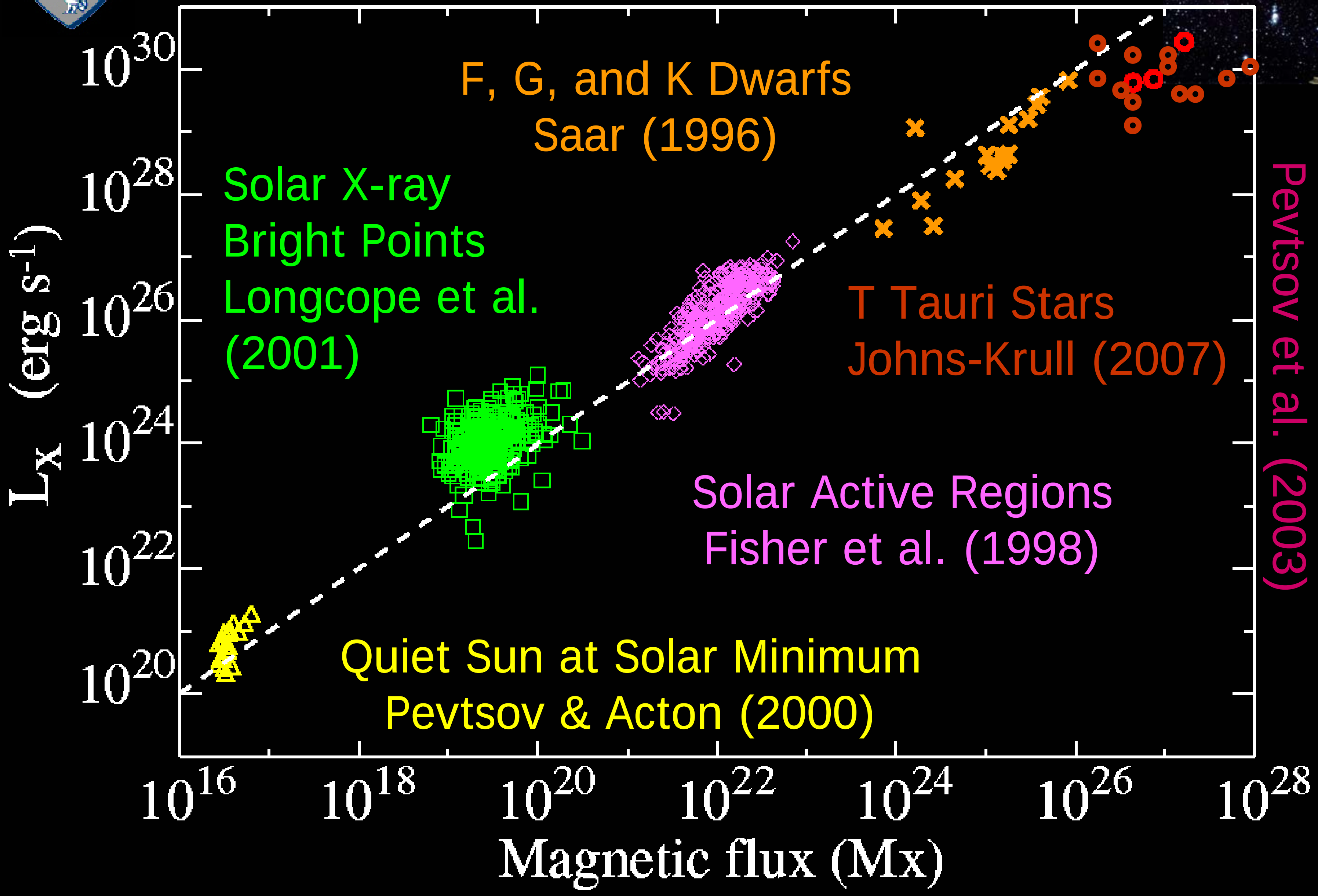
Observations of He I 5876; Beristain et al. 2001, ApJ, 551, 1037



Alencar et al. 2001, ApJ, 122, 3335

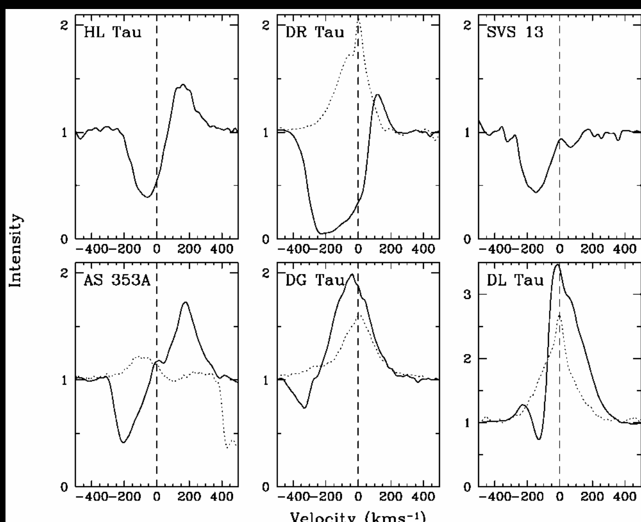


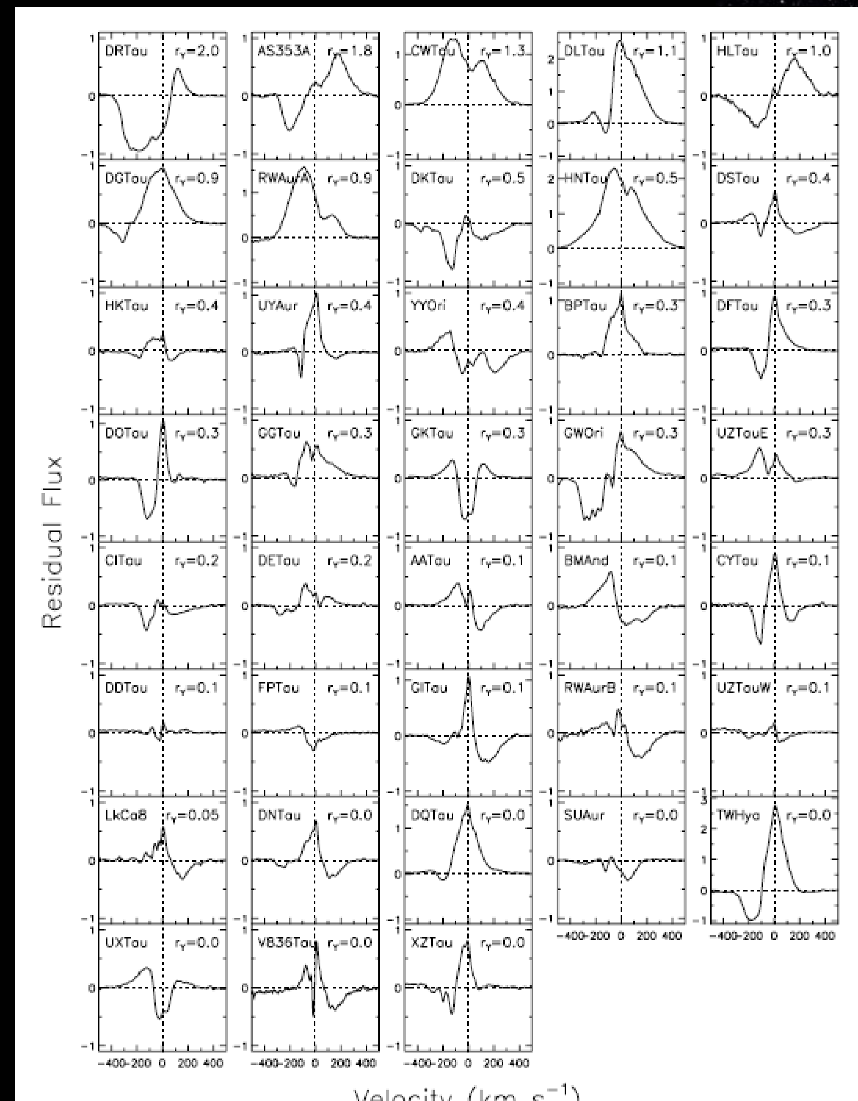
X-ray Emission Limits T_e Sensitivity



The Winds Start to Get Hotter

Edwards et al. 2003, ApJ, 599, L41
Edwards et al. 2006, ApJ, 646, 319
Observations of He I 10830



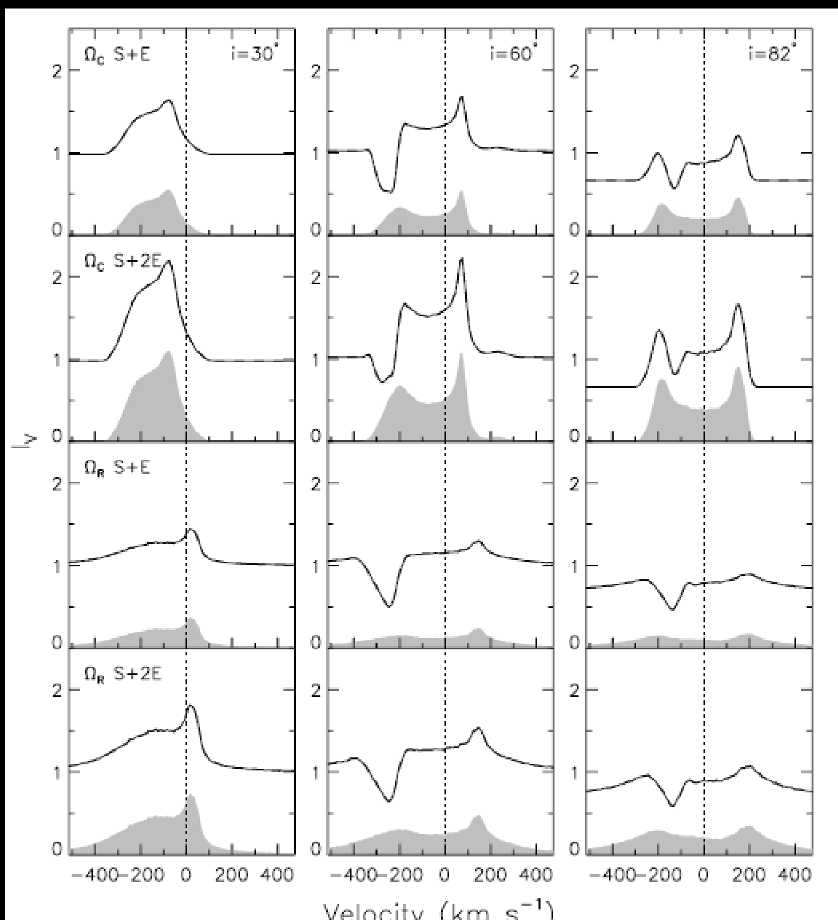


71% Show Blue-shifted absorption below the stellar continuum

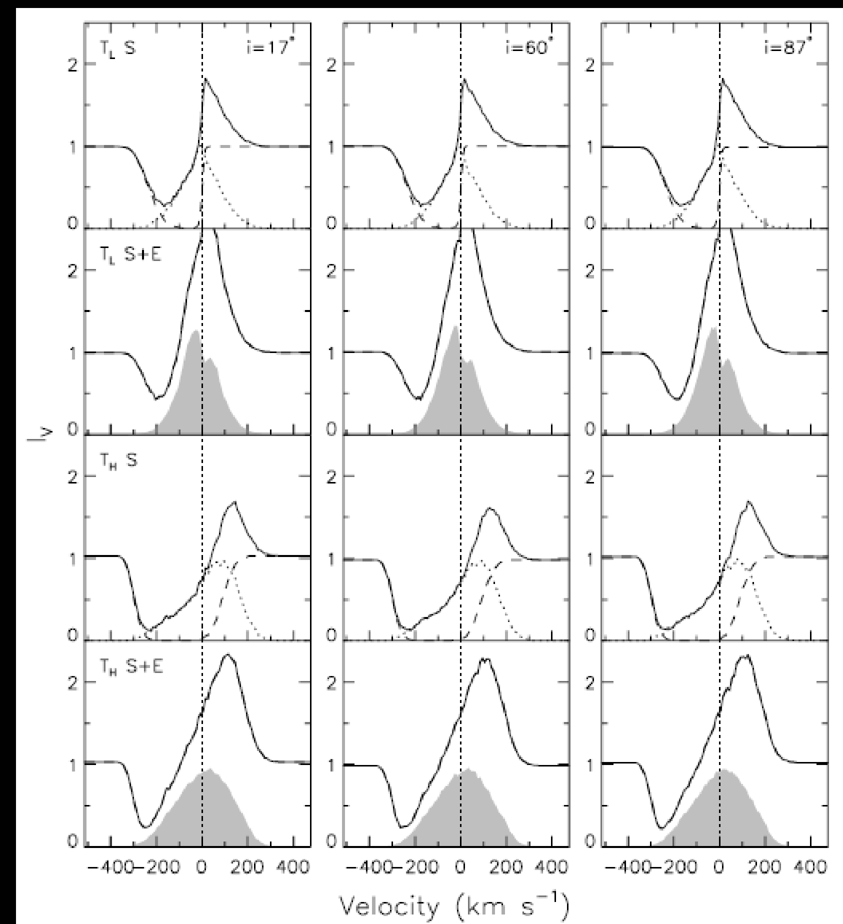
The Winds Start to Get Hotter

Kwan et al. 2007, ApJ, 657, 897
Models of He I 10830

Disk Winds: 30%

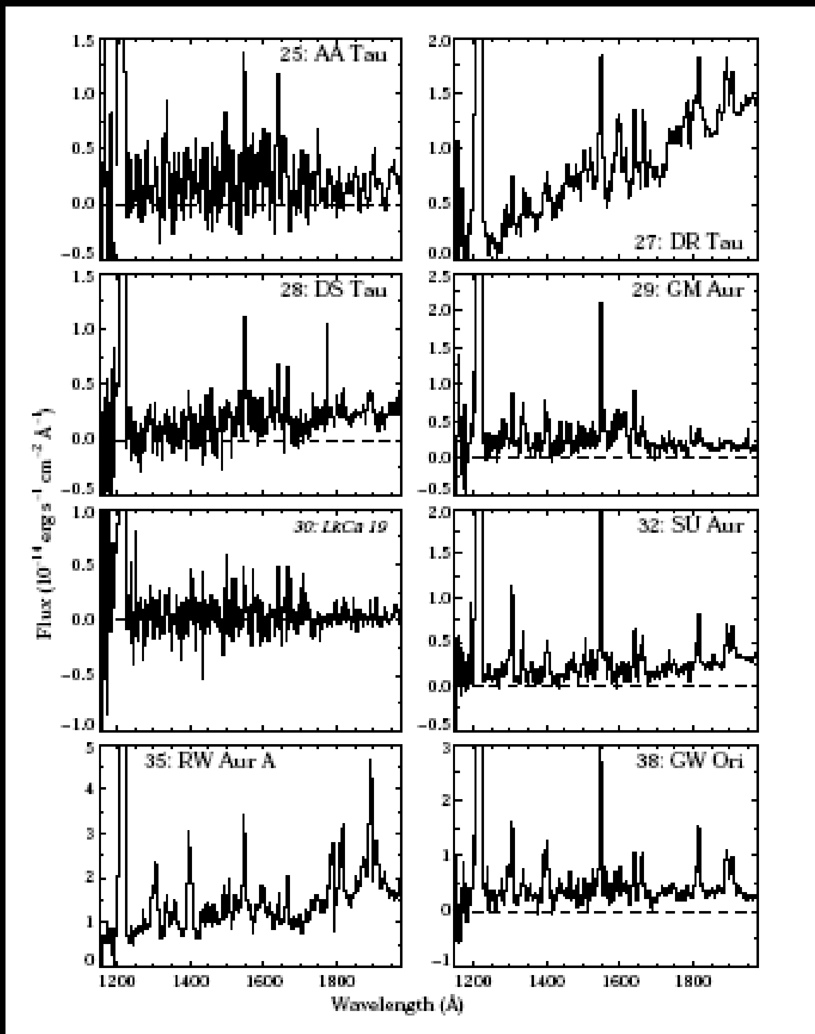


Stellar Winds: 40 - 60%

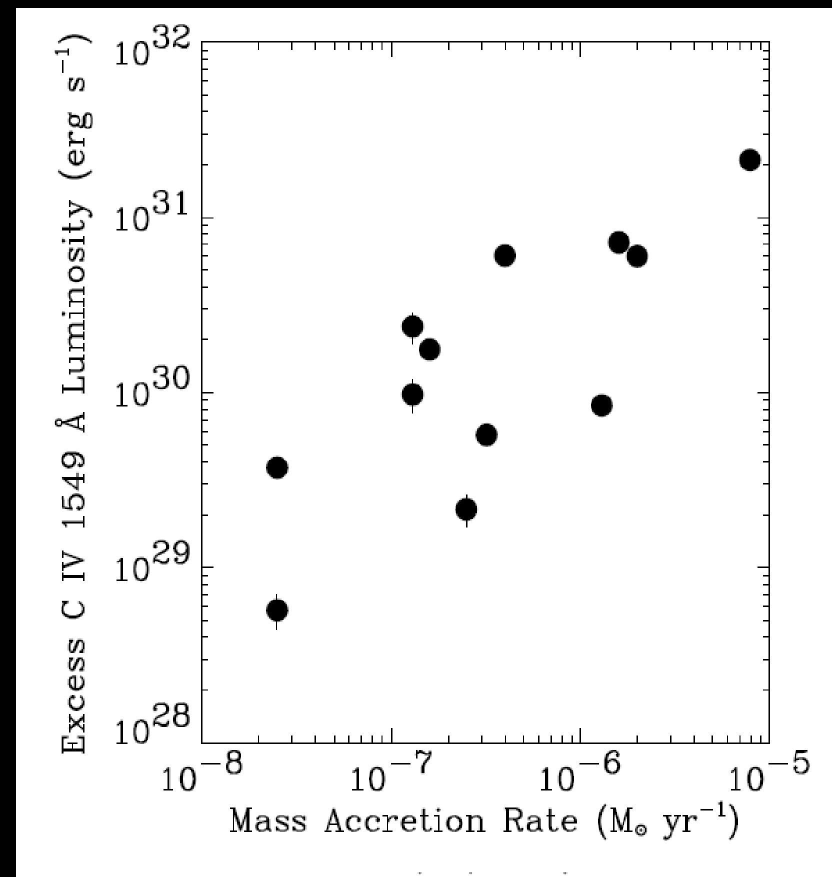


Up to *few* × 10^5 K?

Valenti et al. 2000, ApJS, 129, 399



Johns-Krull et al. 2000, ApJ, 539, 815



The Origin of the Hot Lines

Ardila 2007, IAUS, 243, 103

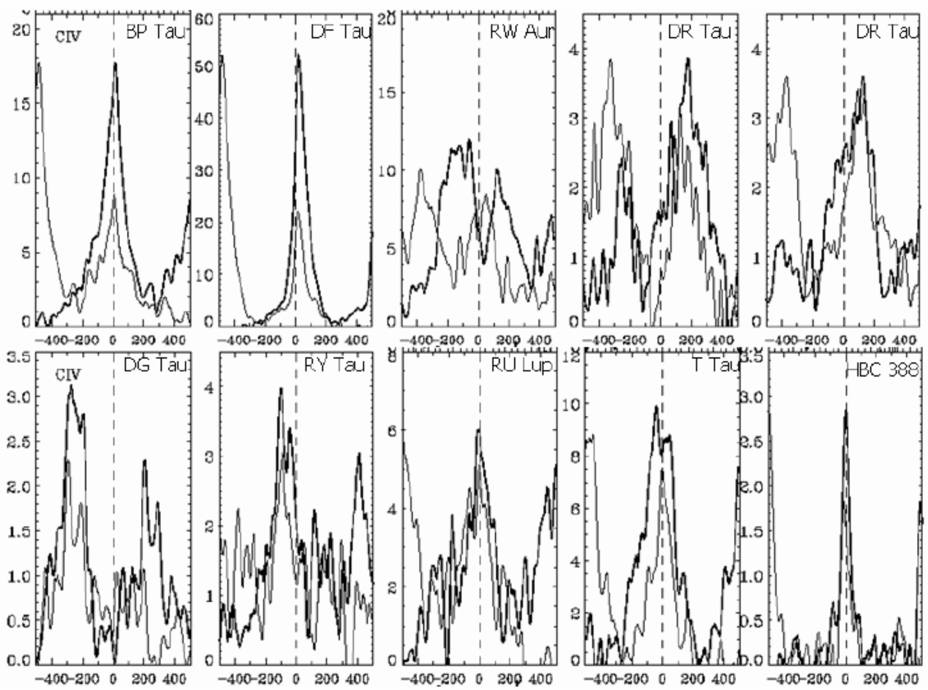


Figure 6. Examples of C IV lines in a variety of CTTs and one WTTs. The units are the same as in Figure 5. Both C IV lines are plotted in each panel, with the optically thicker member o the doublet indicated by the thicker line. The WTTs is HBC 388 (lower right) and it serves as a benchmark for the emission from a naked atmosphere. Two epochs are shown for DR Tau 1993, 4th panel from the left on top; 1995, 5th panel from the left on top. Adapted from Ardila *et al.* (2002).

Gunther & Schmitt 2008, A&A, 481, 735

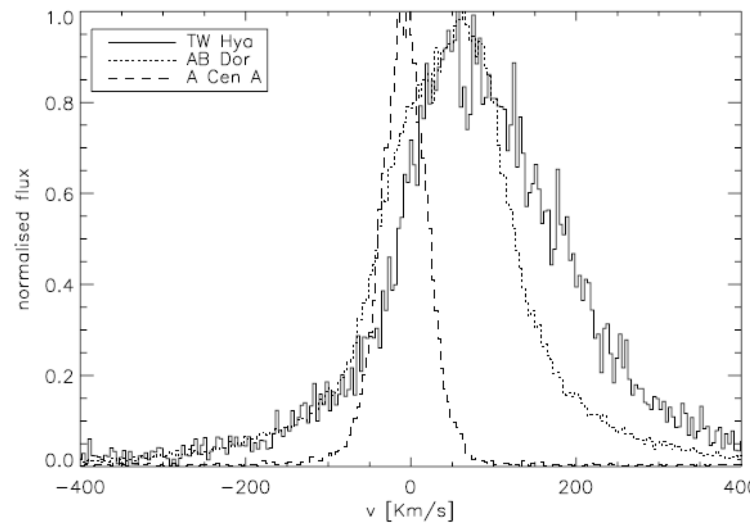
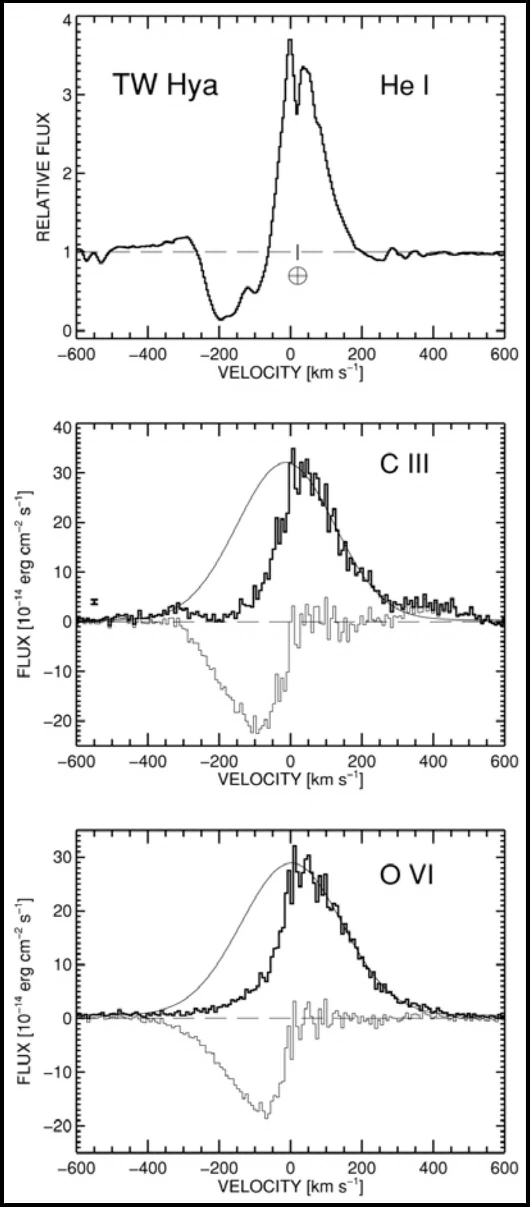


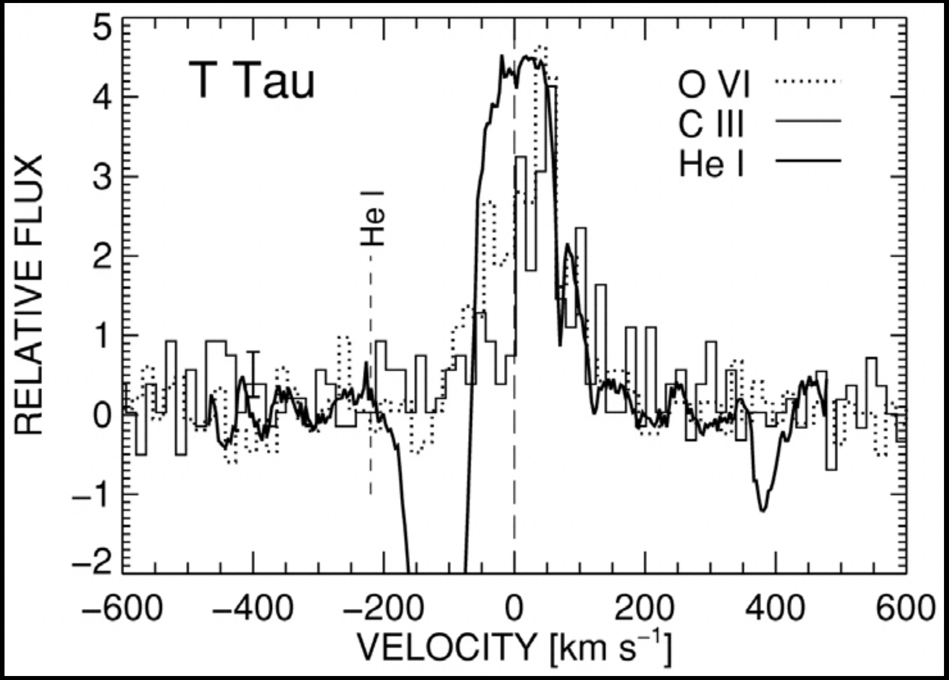
Fig. 6. Comparison of the O VI 1031.91 Å line for three stars.

The Case for Winds



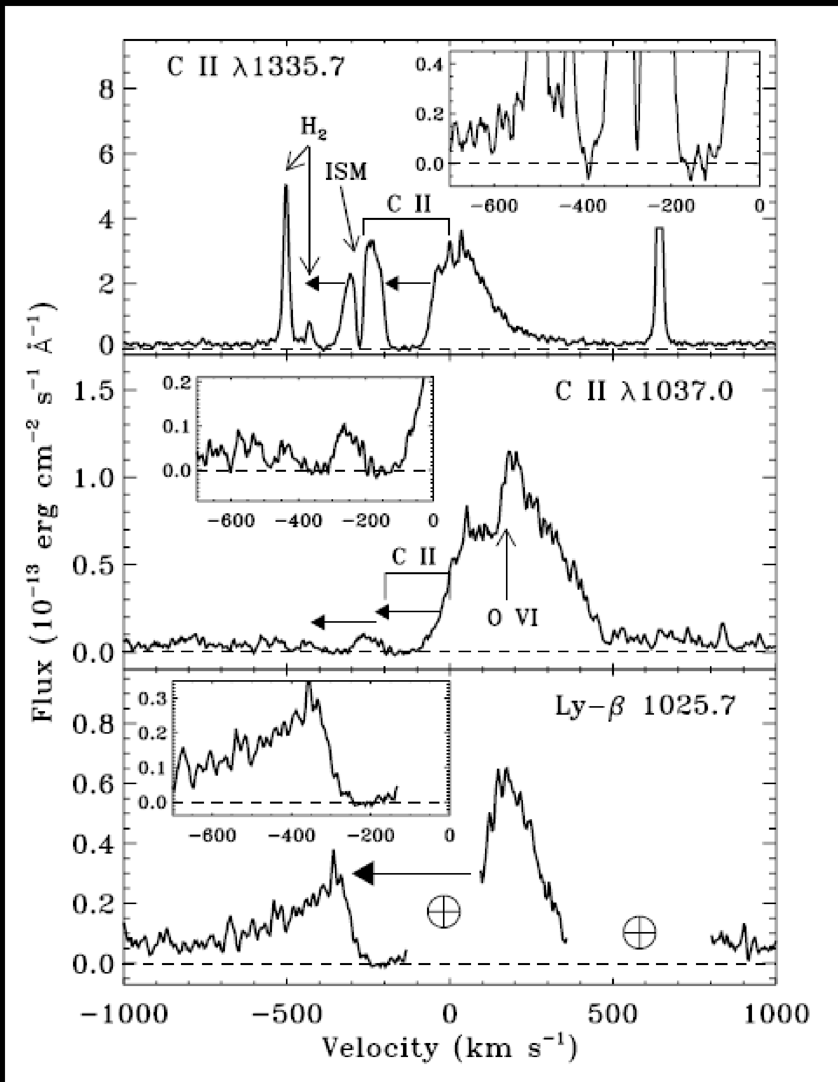
Dupree et al. 2005, ApJ, 625, L131

He I 10830 & FUSE Obs. of CIII & O VI



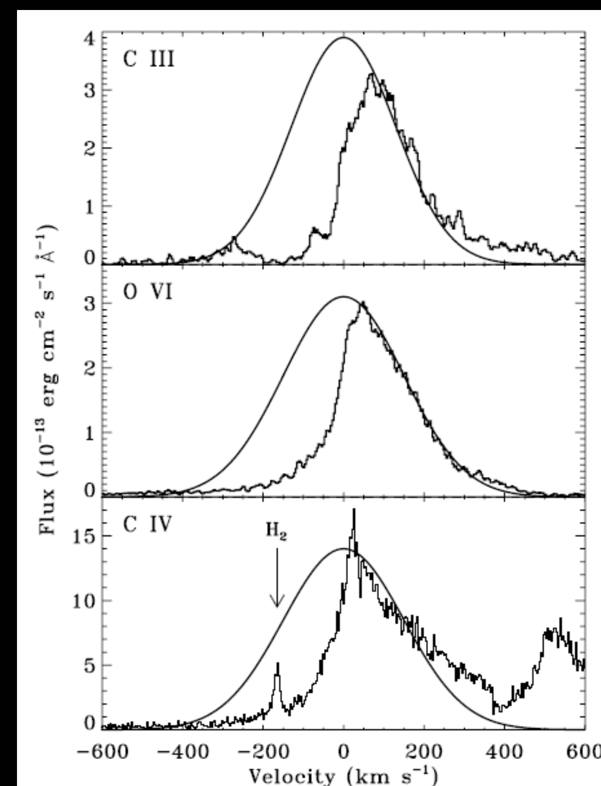
Does It Hold Up for TW Hya?

Johns-Krull & Herczeg 2007, ApJ, 655, 345



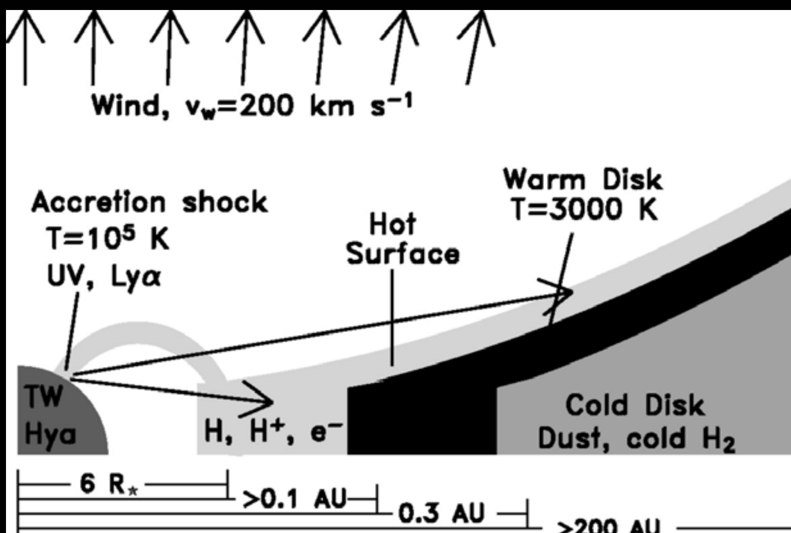
No:

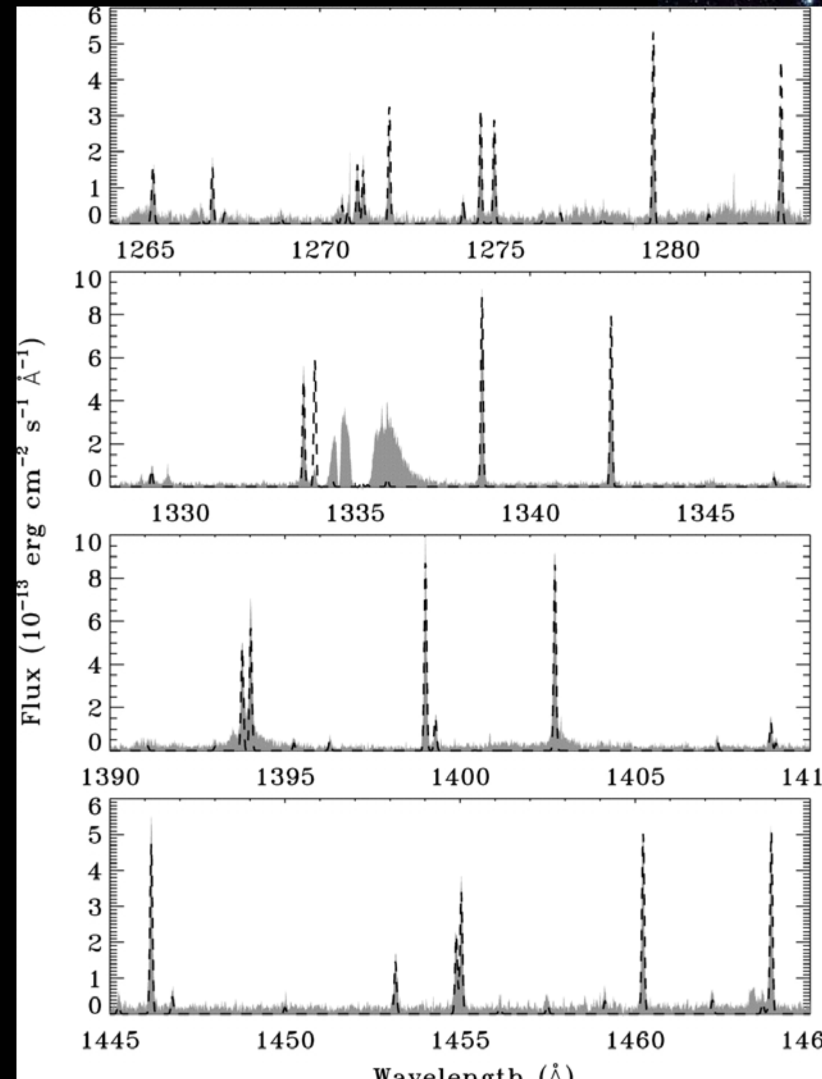
1. No absorption below continuum
2. No H_2 absorption by C IV
3. No multiplet absorption



Molecular Hydrogen from TW Hya

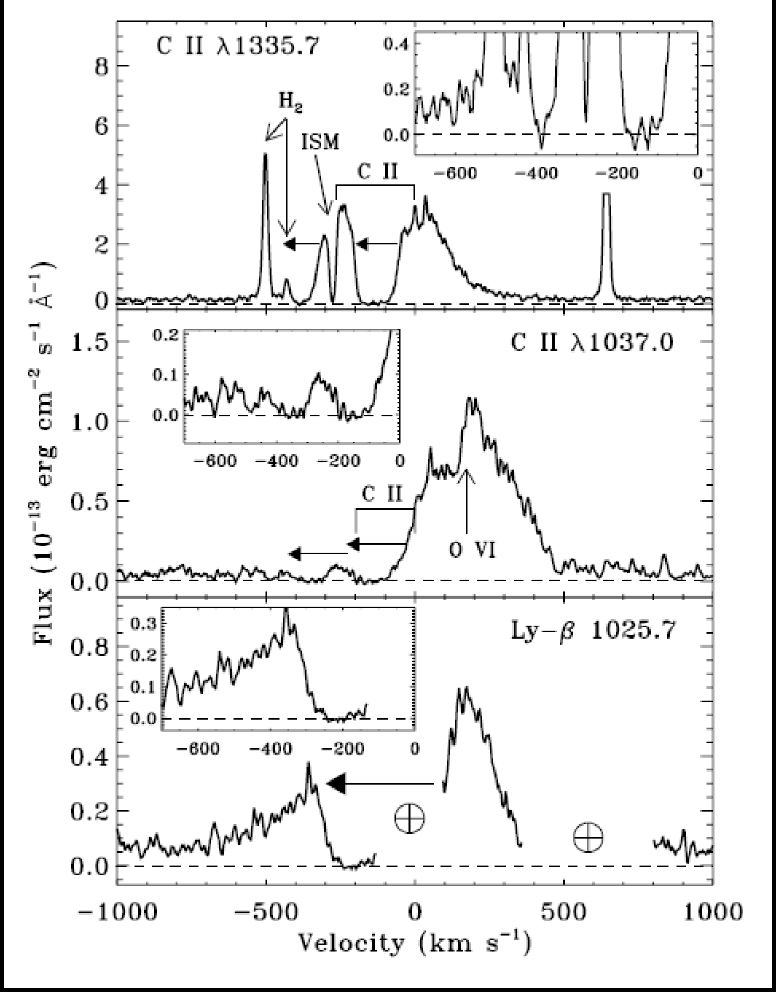
Herczeg et al. 2004, ApJ, 607, 369

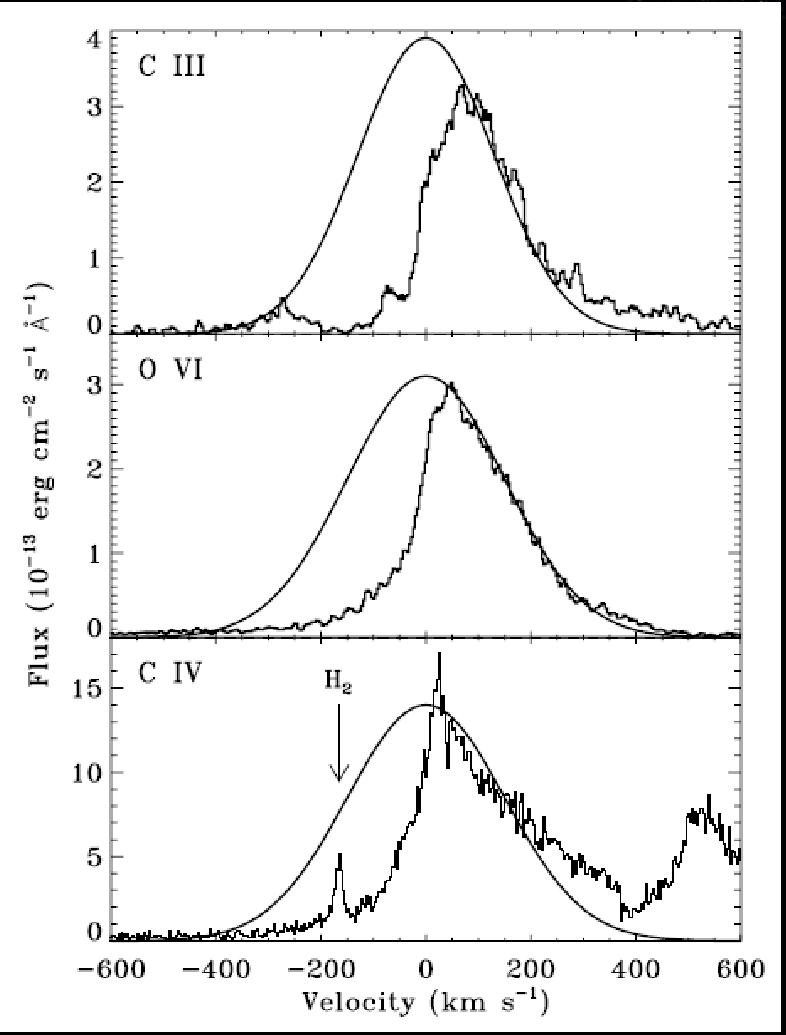




Molecular Hydrogen Absorbed by Wind

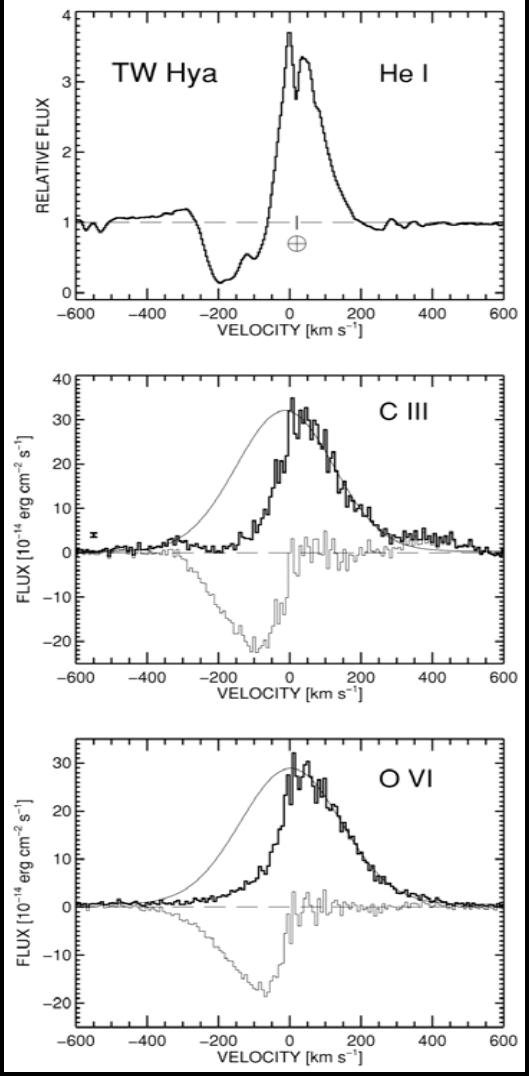
Johns-Krull & Herczeg 2007, ApJ, 655, 345

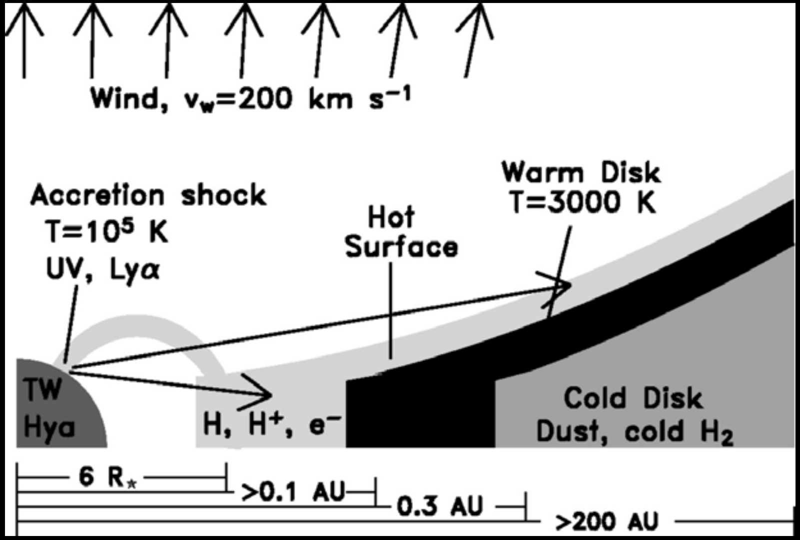




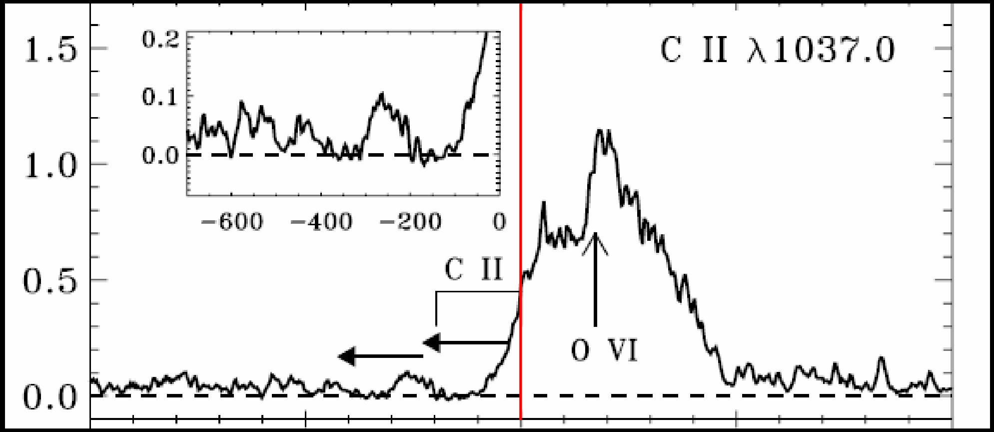
Can the Wind Cool With Distance?

All temperature components seem to probe the acceleration region

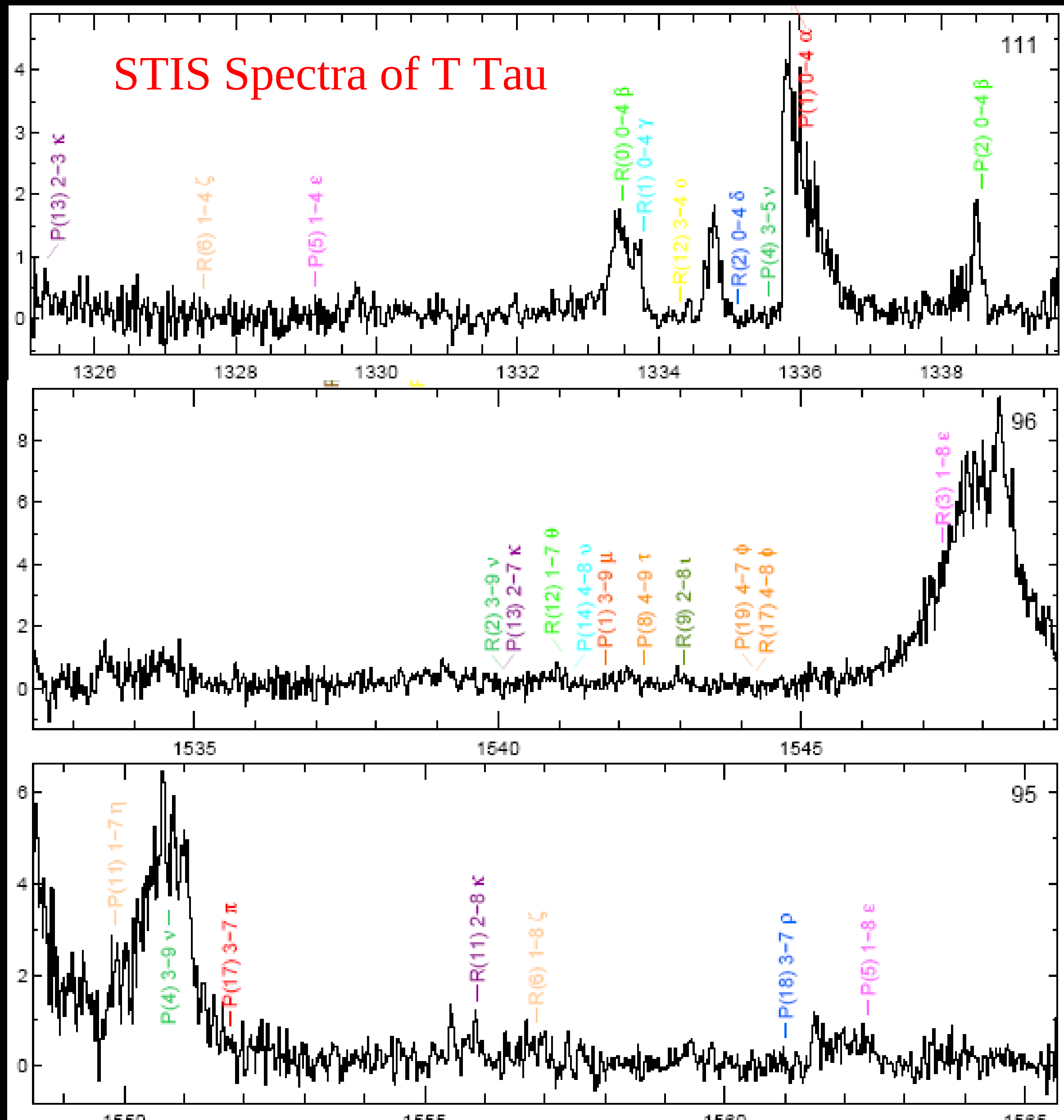




T_W = ? 10^5 K 10^4 K

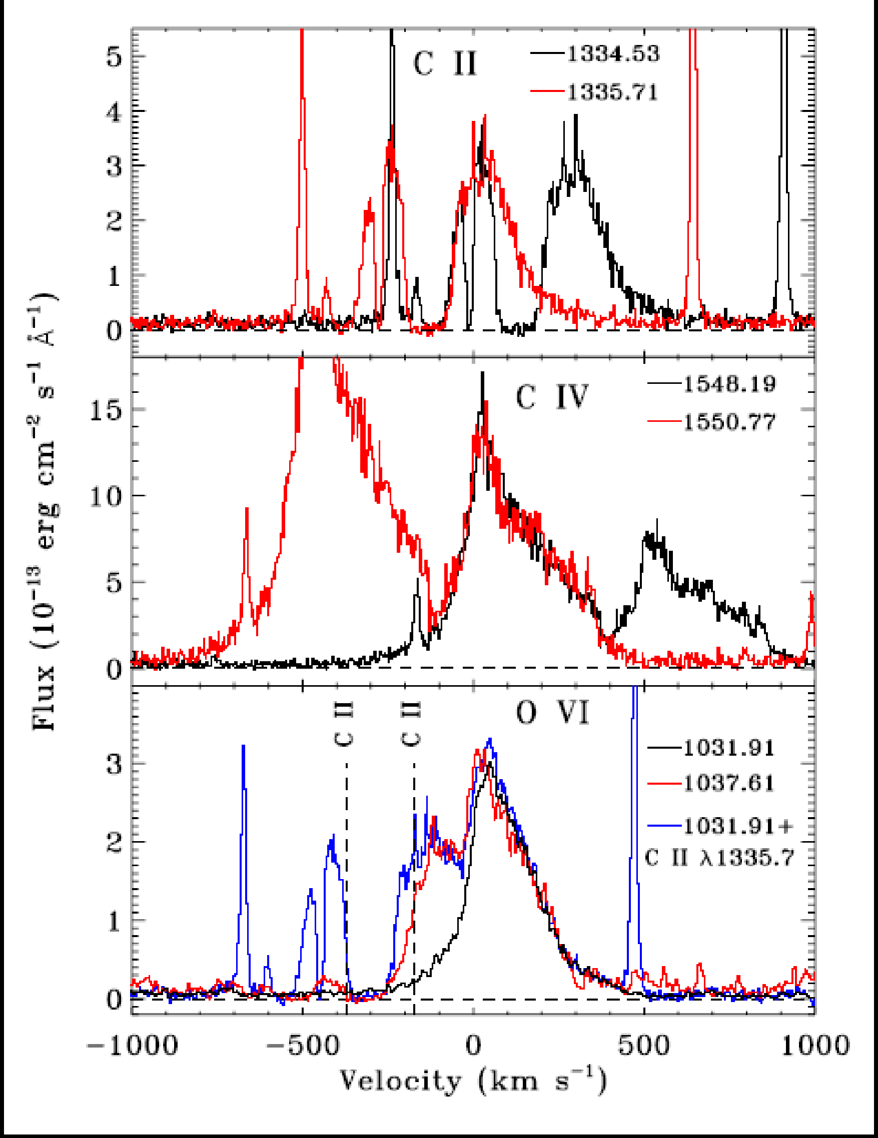


C II Wind in T Tau

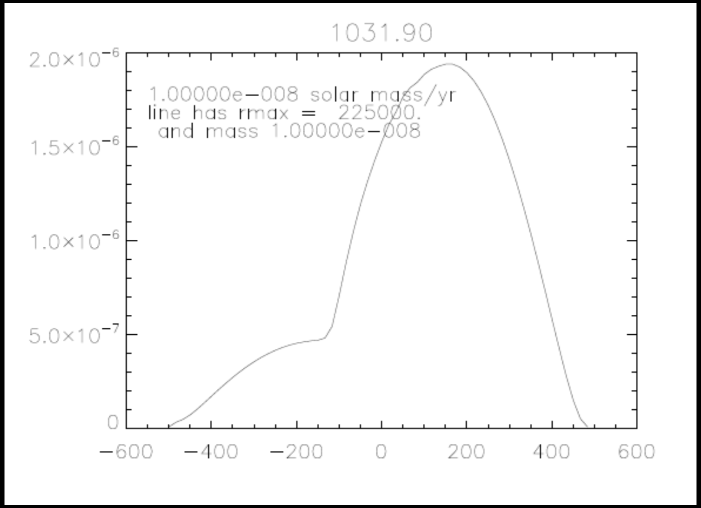


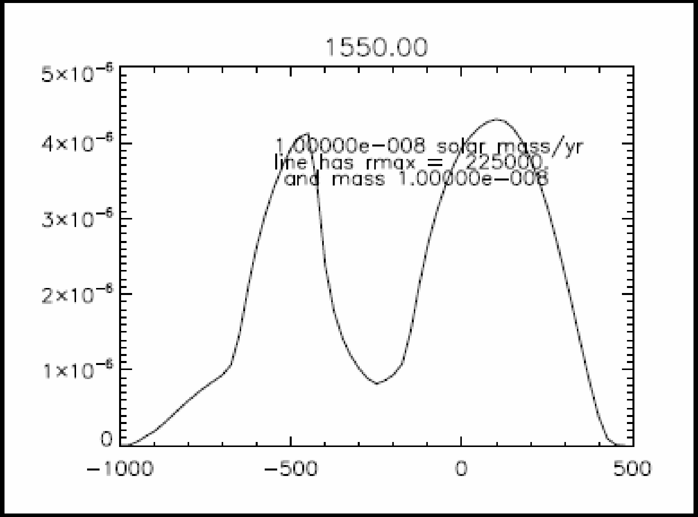
Multiplet Absorption

Johns-Krull & Herczeg 2007



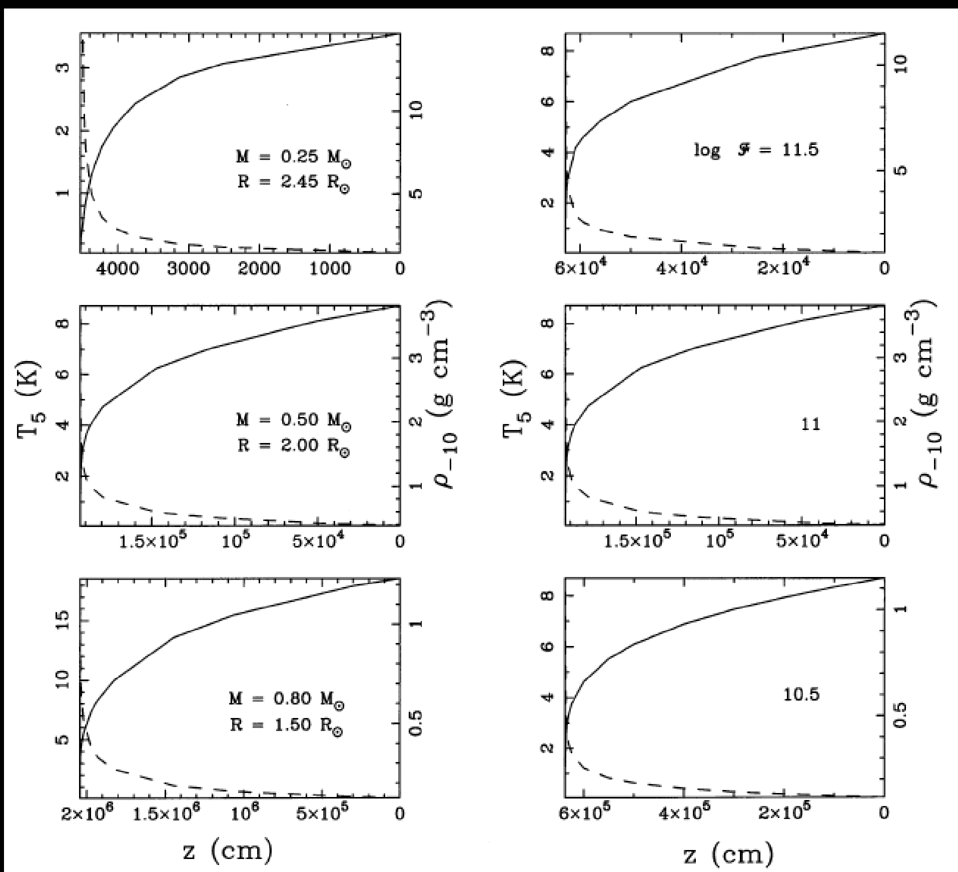
Johns-Krull et al. 2008, in prep



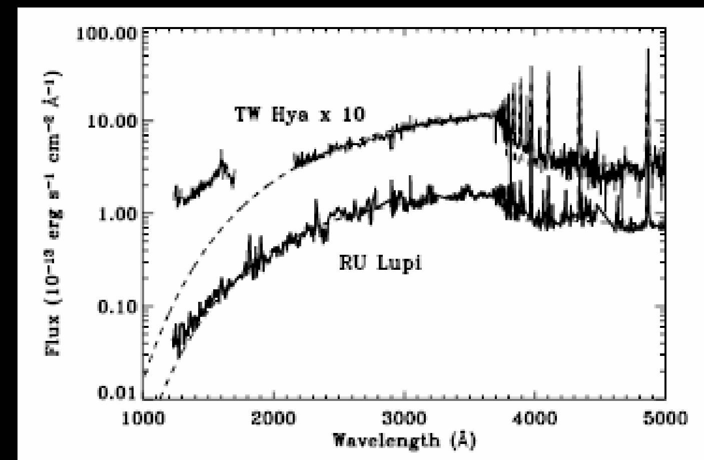


The Origin of the Hot Lines

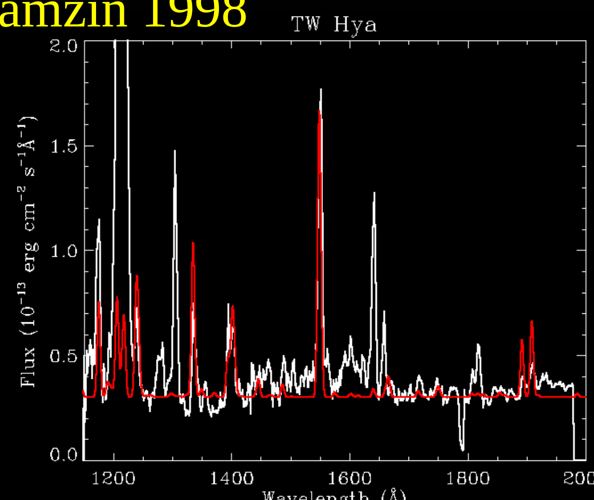
Accretion Shocks are a Natural Energy Source
e.g. Calvet & Gullbring 1998, ApJ, 509, 802



Herczeg et al. 2004, AJ, 129, 2777

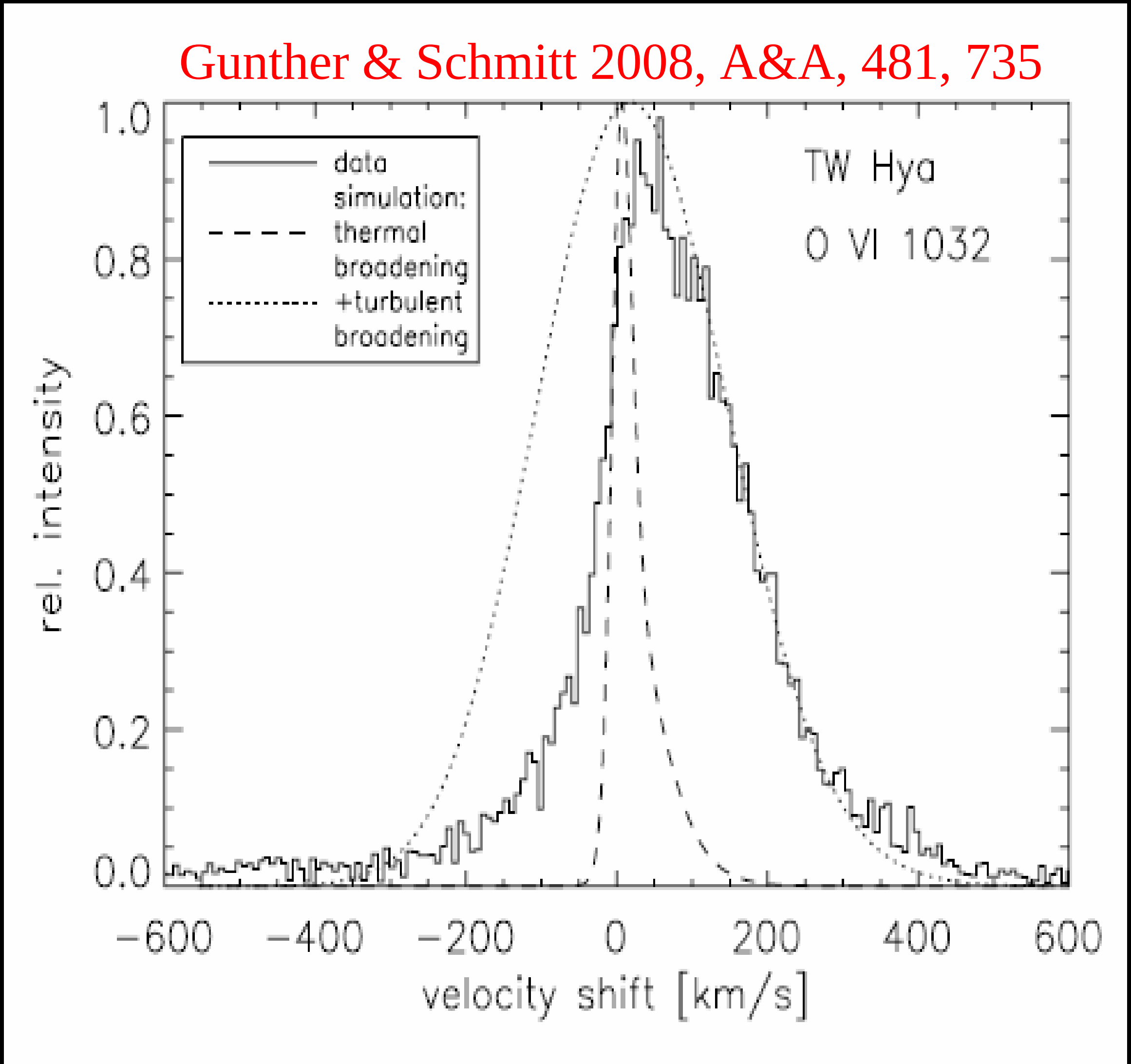


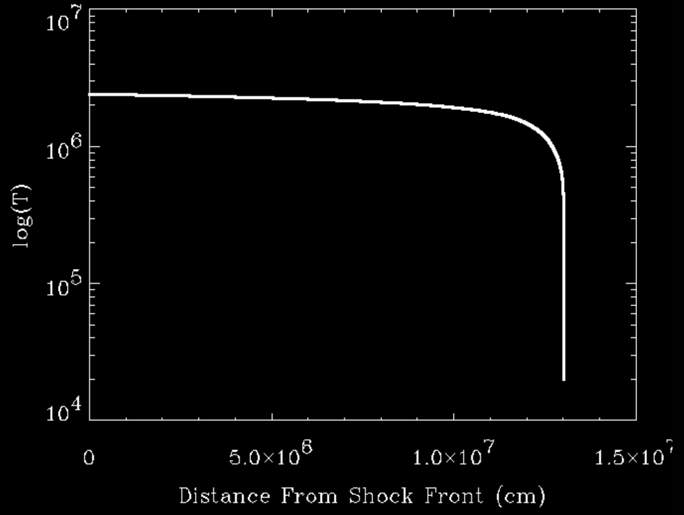
Following Ardila 2004, PhD Thesis; see also Lamzin 1998

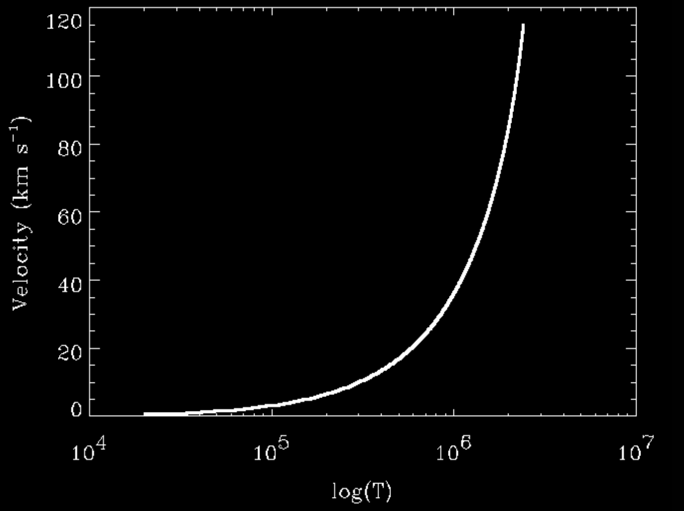


Accretion Shocks and Profile Shapes

Following Ardila 2004, PhD Thesis; see also Lamzin 1998



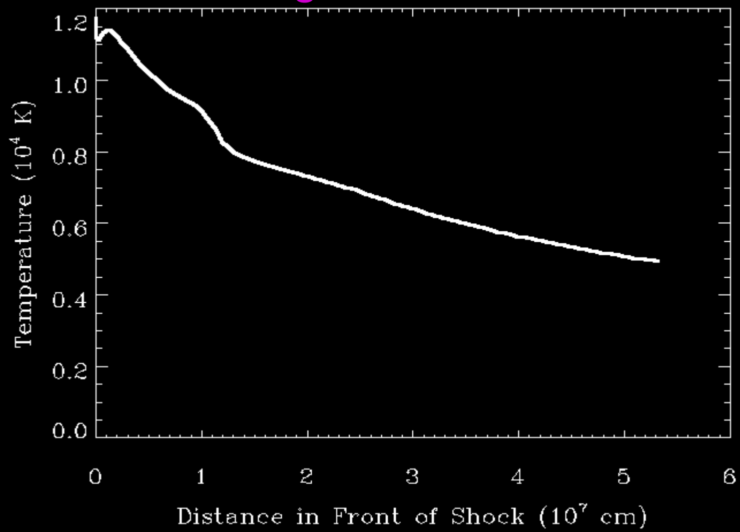




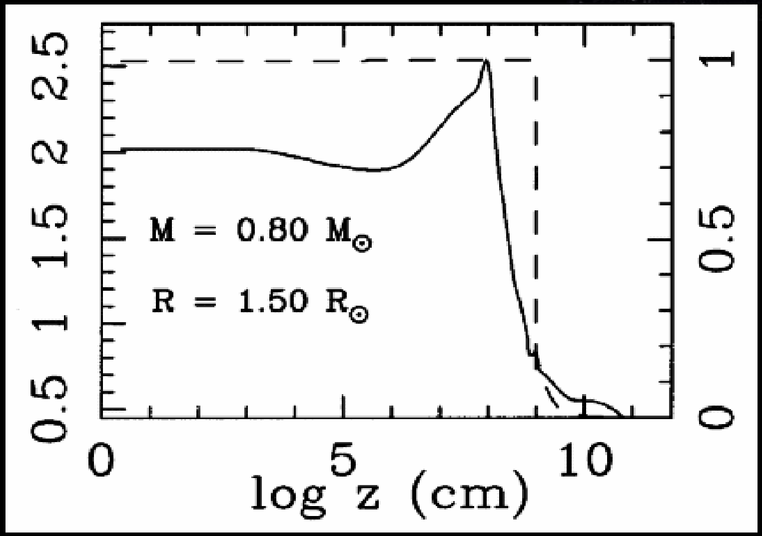
What About the Pre-Shock?

Not much agreement currently

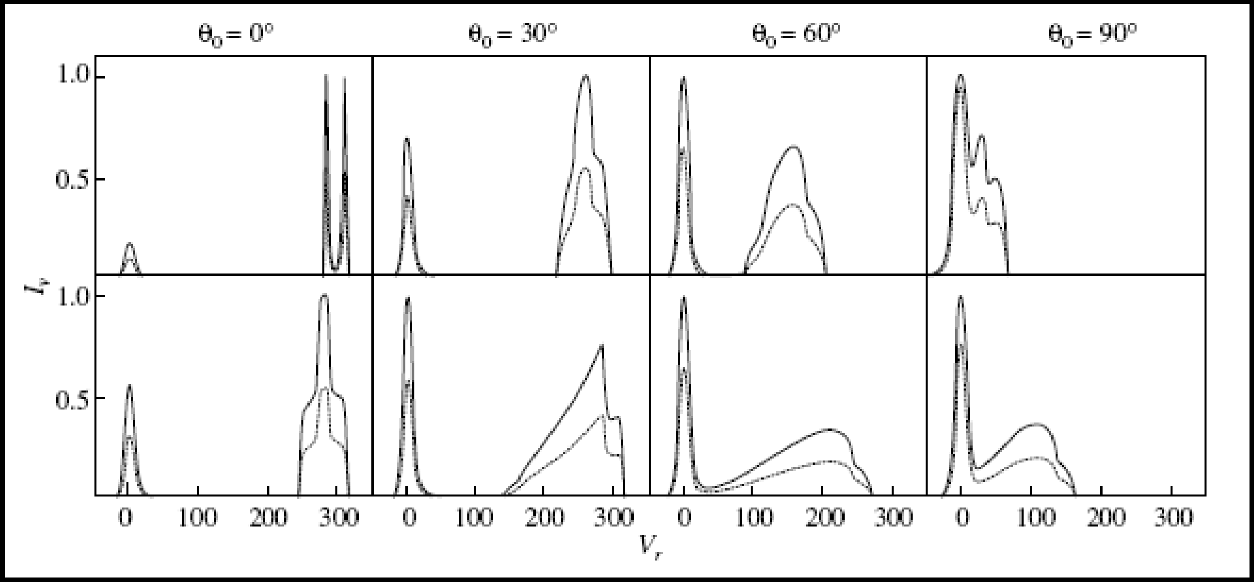
Following Ardila 2004



Calvet & Gullbring 1998

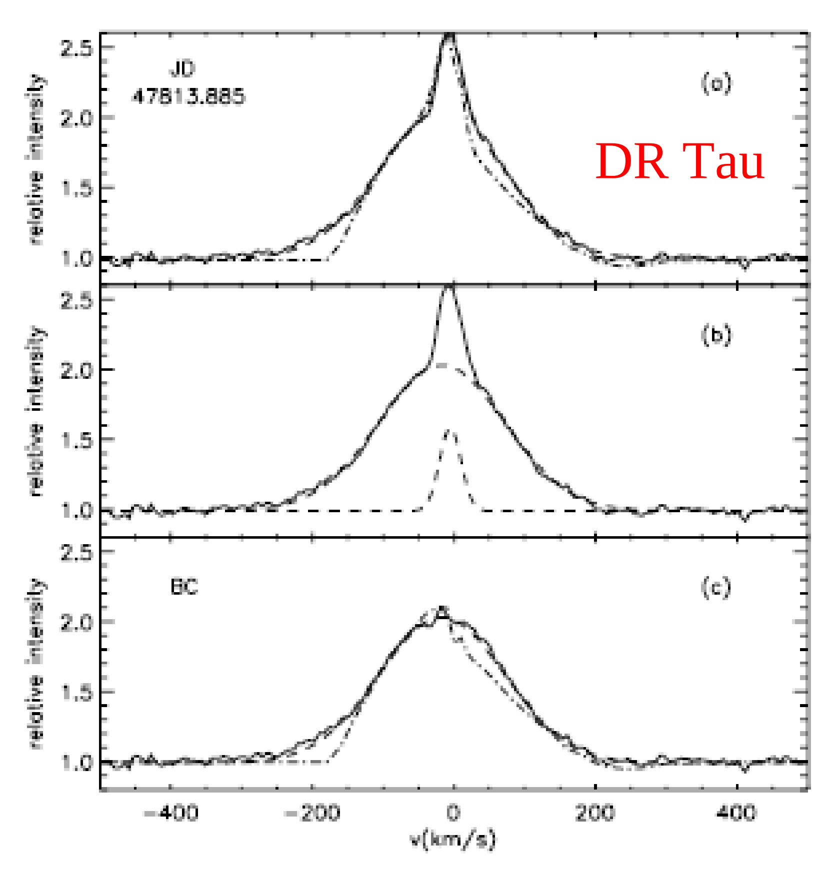


Lamzin 2003, Astron. Reports, 47, 540

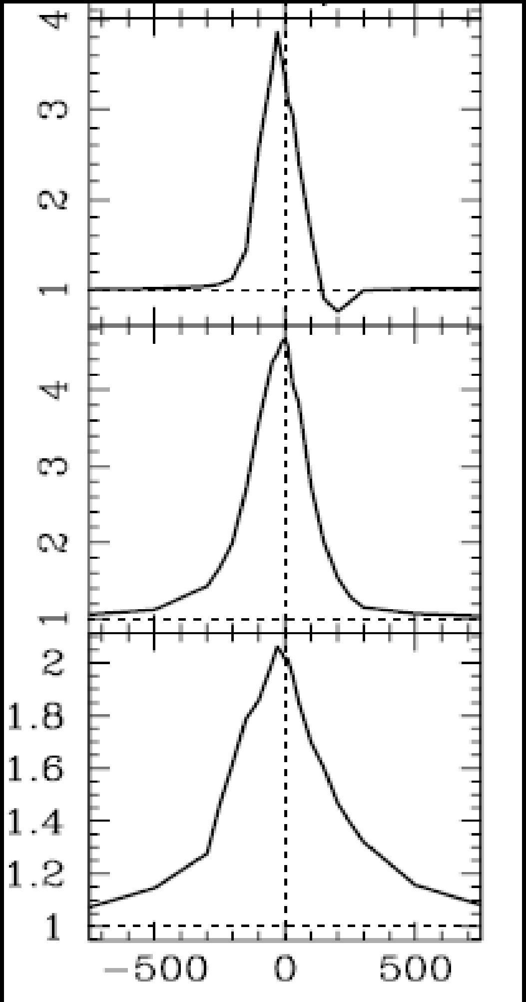


Returning to He I 5876

Alencar et al. 2001



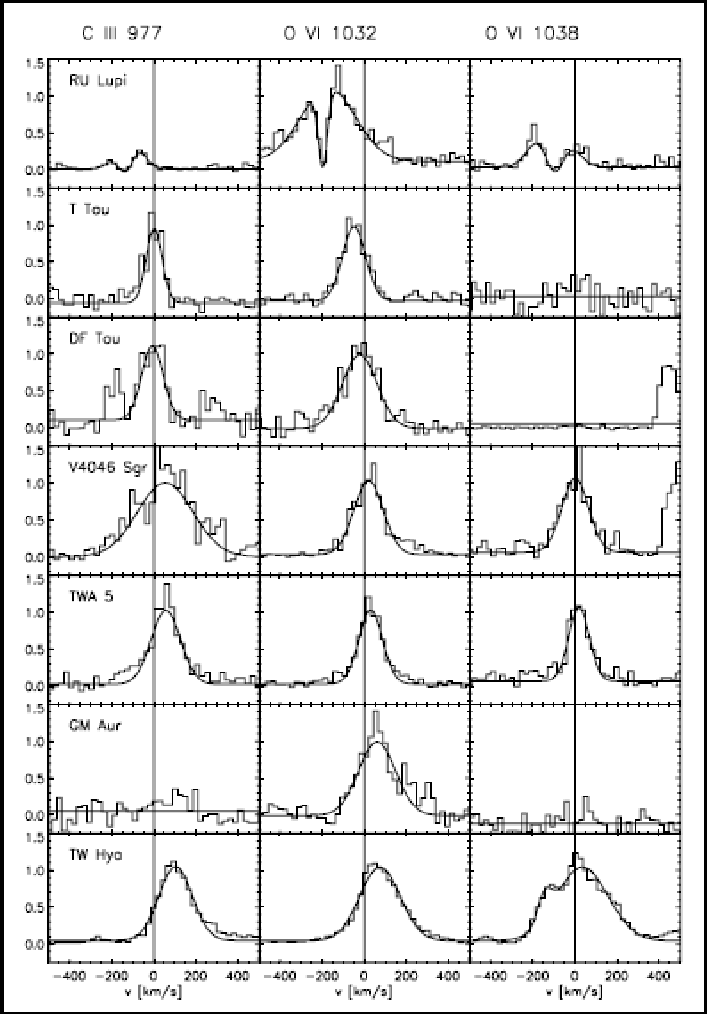
Muzerolle et al. 2001



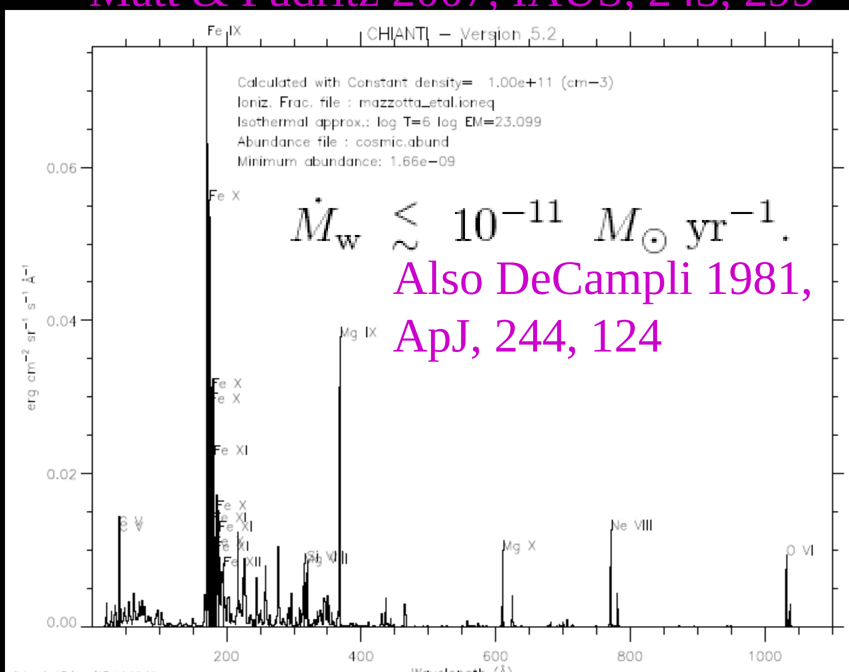
Difficulties with Winds?

- There is NO heating mechanism
- They are too bright for significant mass loss rates (see below)
- Hard to distinguish from accretion or jets (see right)

Gunther & Schmitt 2008, A&A, 481, 735



Matt & Pudritz 2007, IAUS, 243, 299

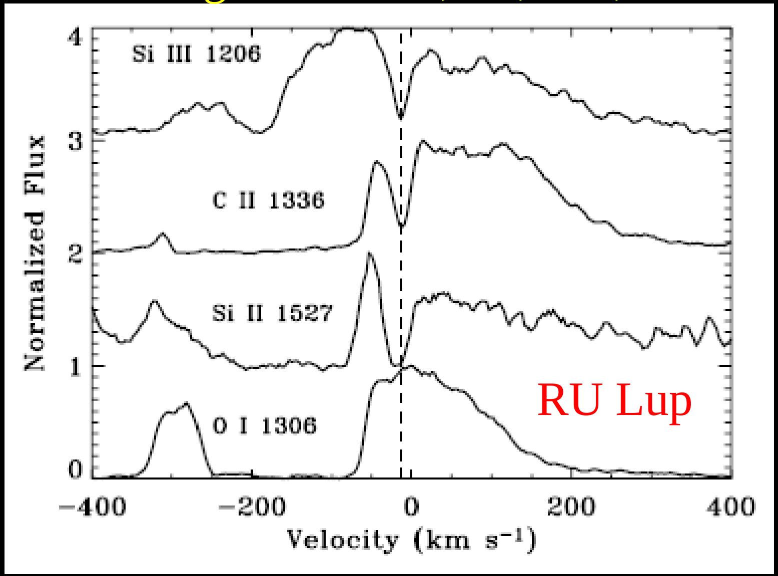


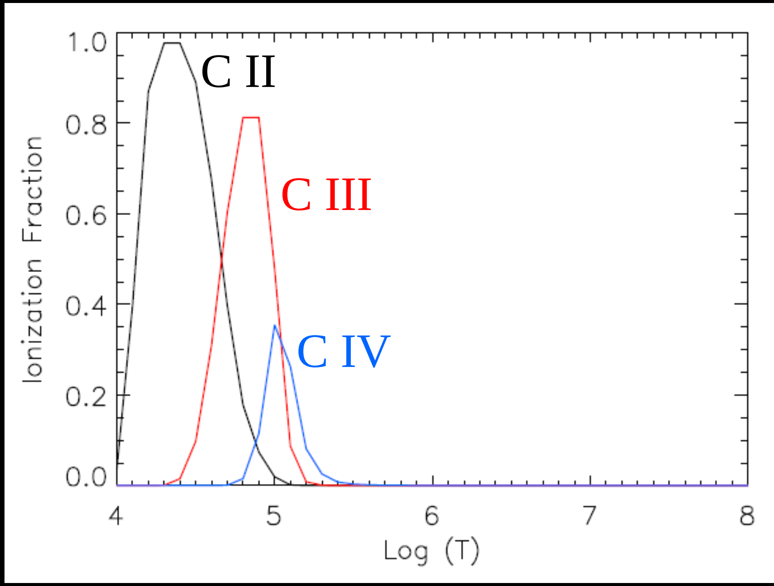
$$\dot{M}_{\rm w} \lesssim 10^{-11}\ M_\odot\ {\rm yr}^{-1}.$$

Also DeCampli 1981, ApJ, 244, 124

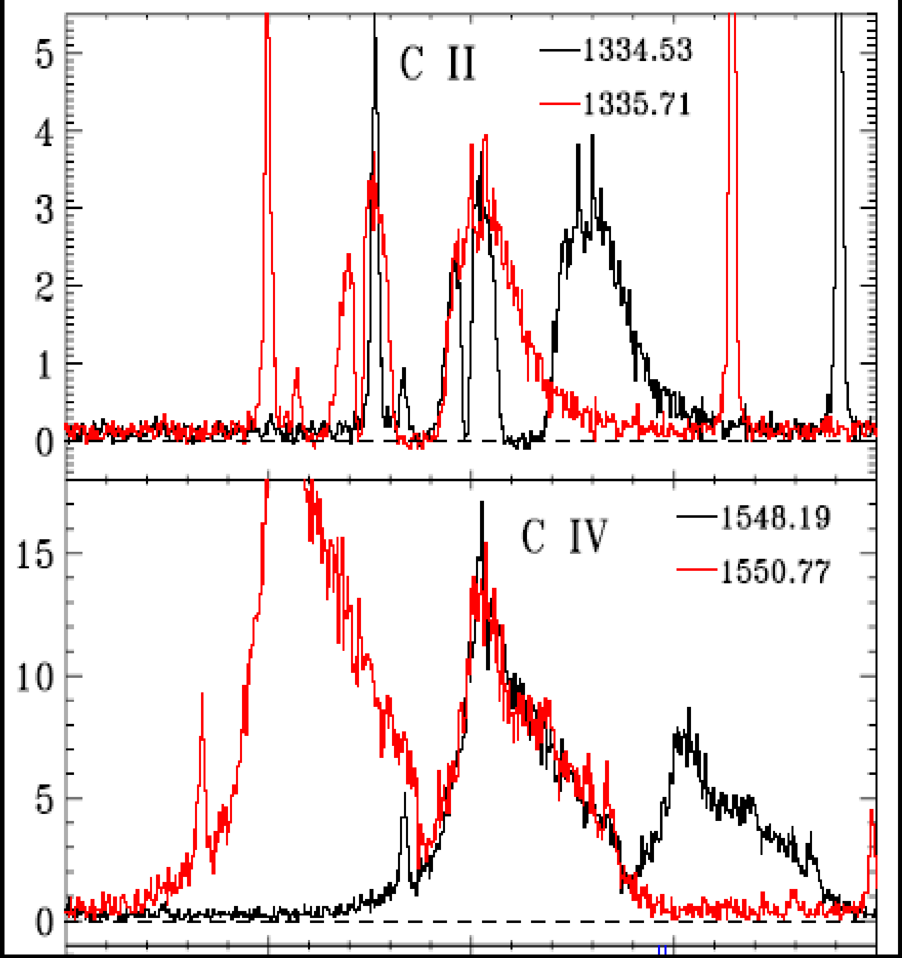
How Hot Are the Inner Winds?

Herczeg et al. 2004, AJ, 129, 2777



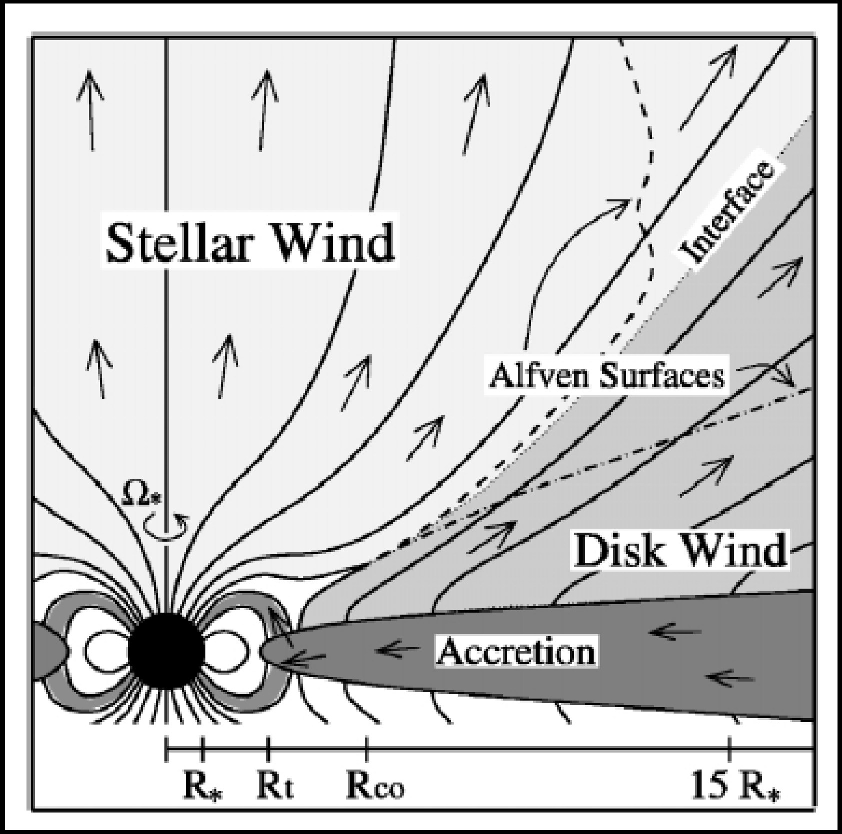


Johns-Krull & Herczeg 2007: TW Hya

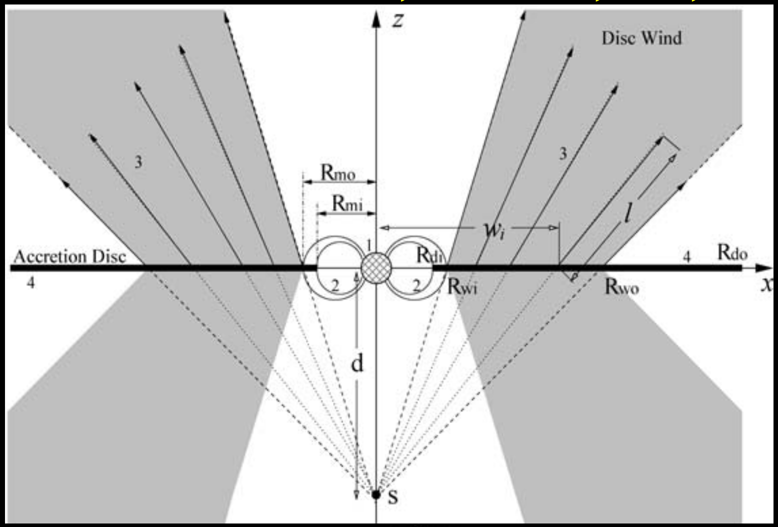


Accretion Powered Stellar Winds

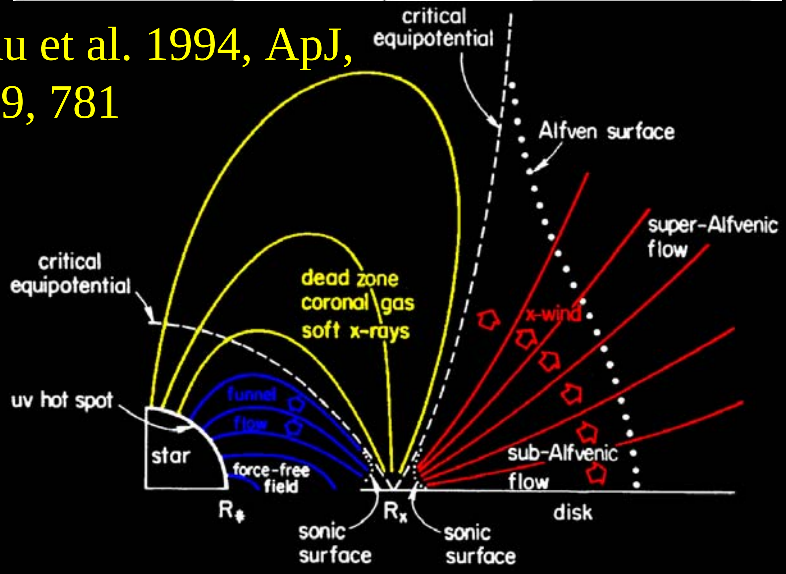
Matt & Pudritz 2005, ApJ, 632, L135



Kurosawa et al. 2006, MNRAS, 370, 580



Shu et al. 1994, ApJ, 429, 781

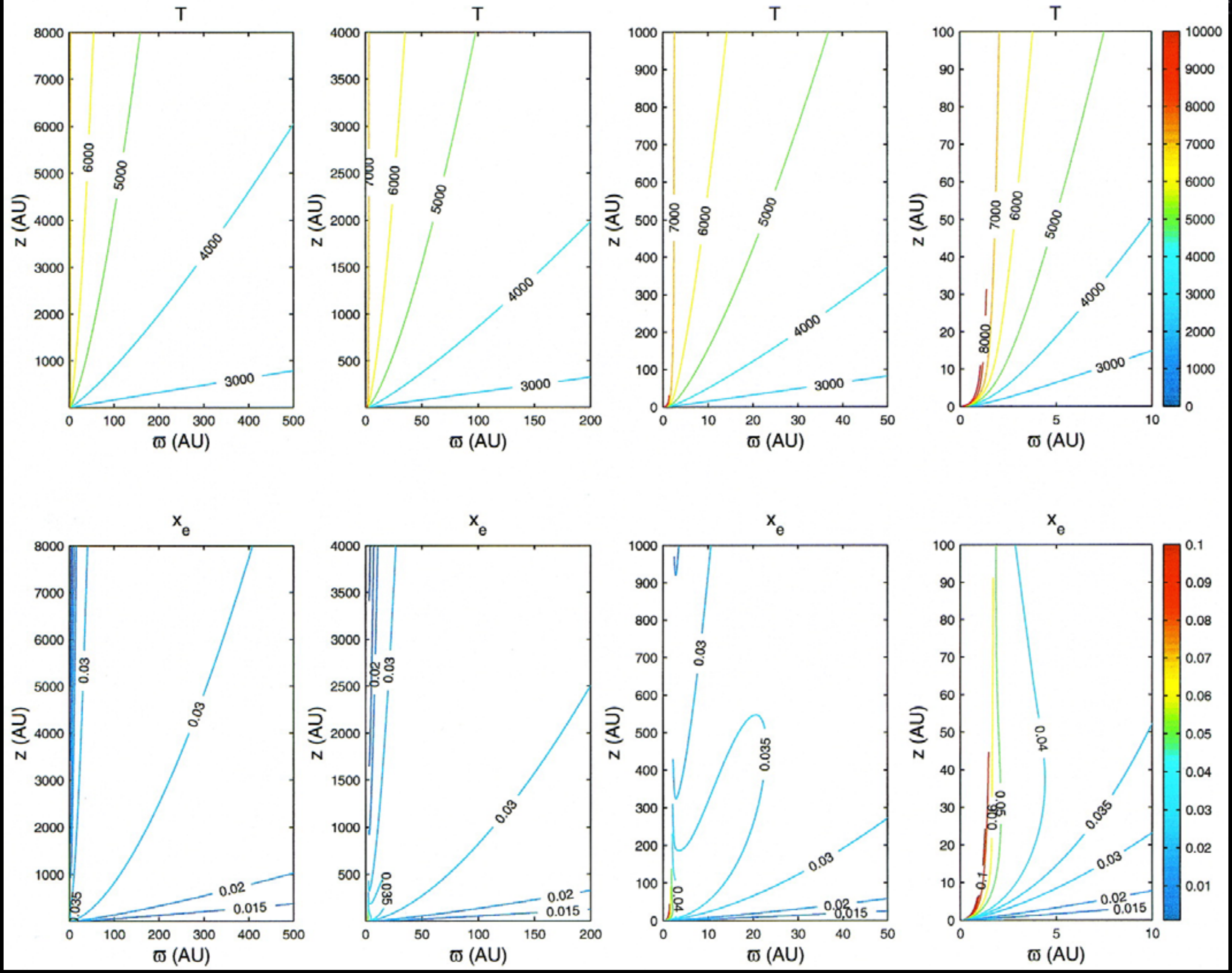


Conclusions

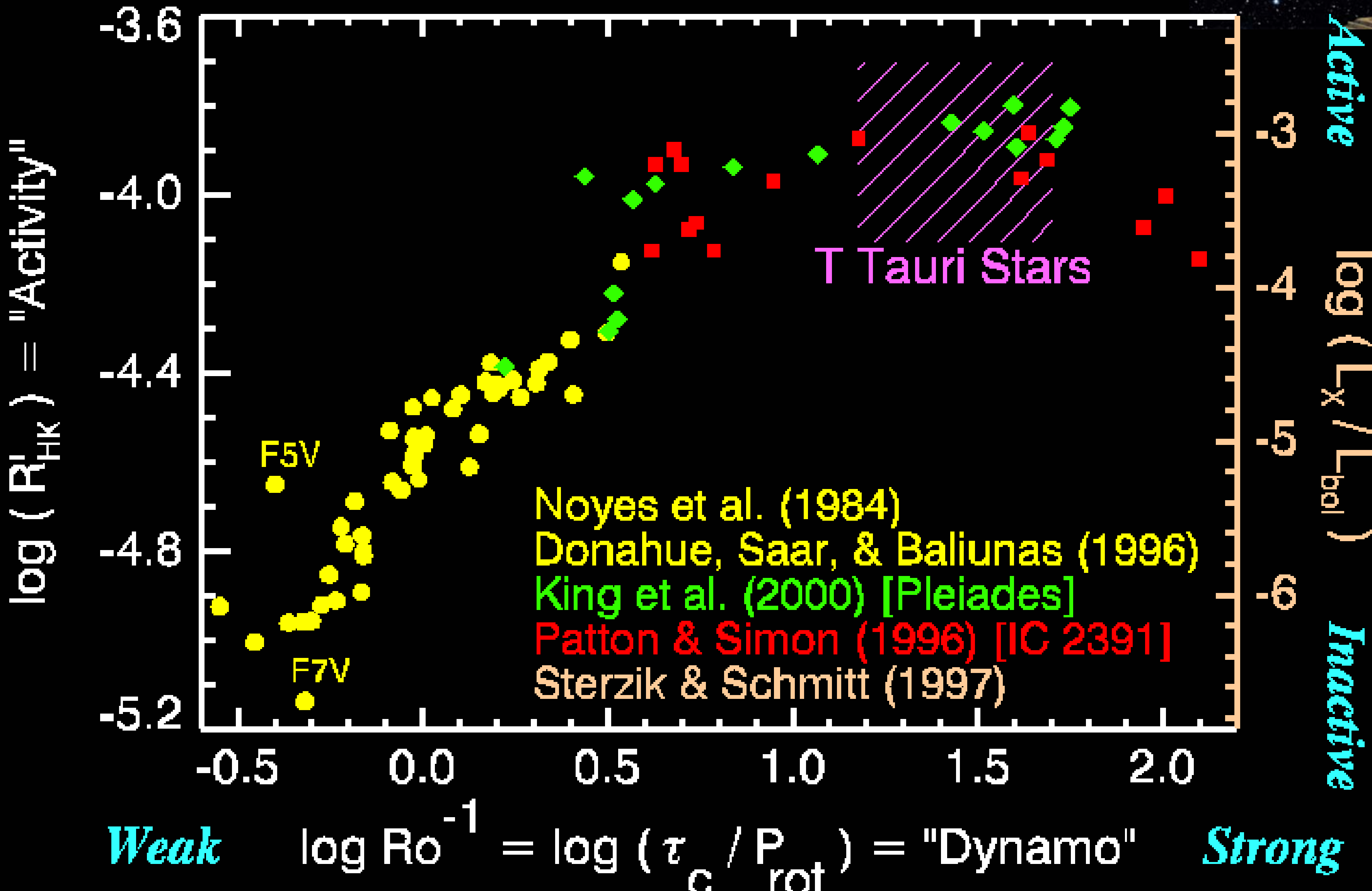
- Inner winds are clearly diagnosed in $H\alpha$, Ca II, Na I, He I (10,830), O I, N I, Si II, Si III, C II
- The interpretation is not so clear for higher temperature lines
- Due to high X-ray luminosity of TTS, temperature sensitivity of He I is reduced
- Origin of all the high temperature emission (FUV) from CTTS still uncertain, though accretion likely plays a significant role
- Dynamically significant inner wind temperature is probably less than ~ 30,000 K
- Significantly more modeling effort in needed for both winds and accretion flows to explain FUV line profiles

Heating the Winds

Shang et al. (2002):

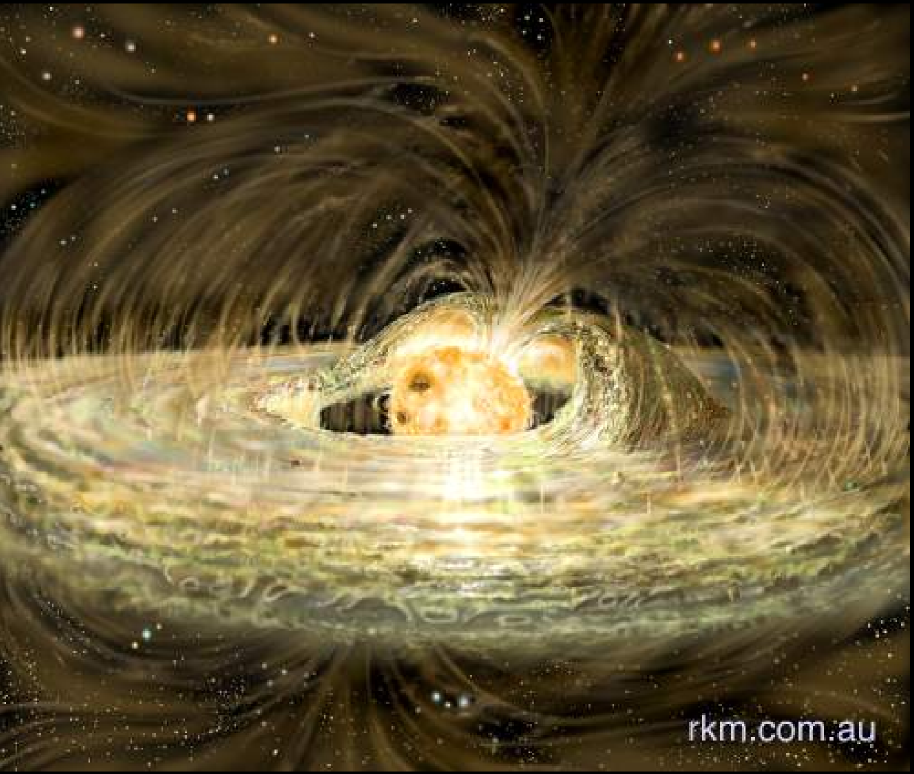


Rotation-Activity Relationship

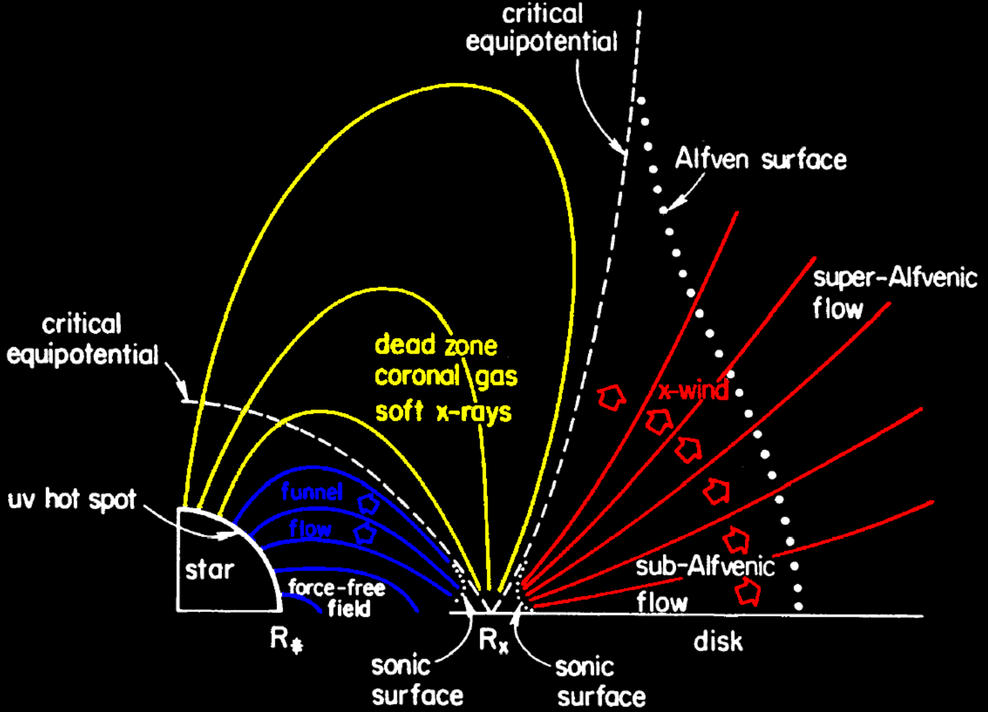


T Tauri Stars: Magnetically Controlled Accretion

- Rotation correlated with disk signatures
- Balmer line profiles
- Accretion shock models reproduce optical veiling



Shu et al. (1994)



Theory gives field at some point in the disk

Theoretical Predictions

Konigl (1991):

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

Cameron & Campbell (1993):

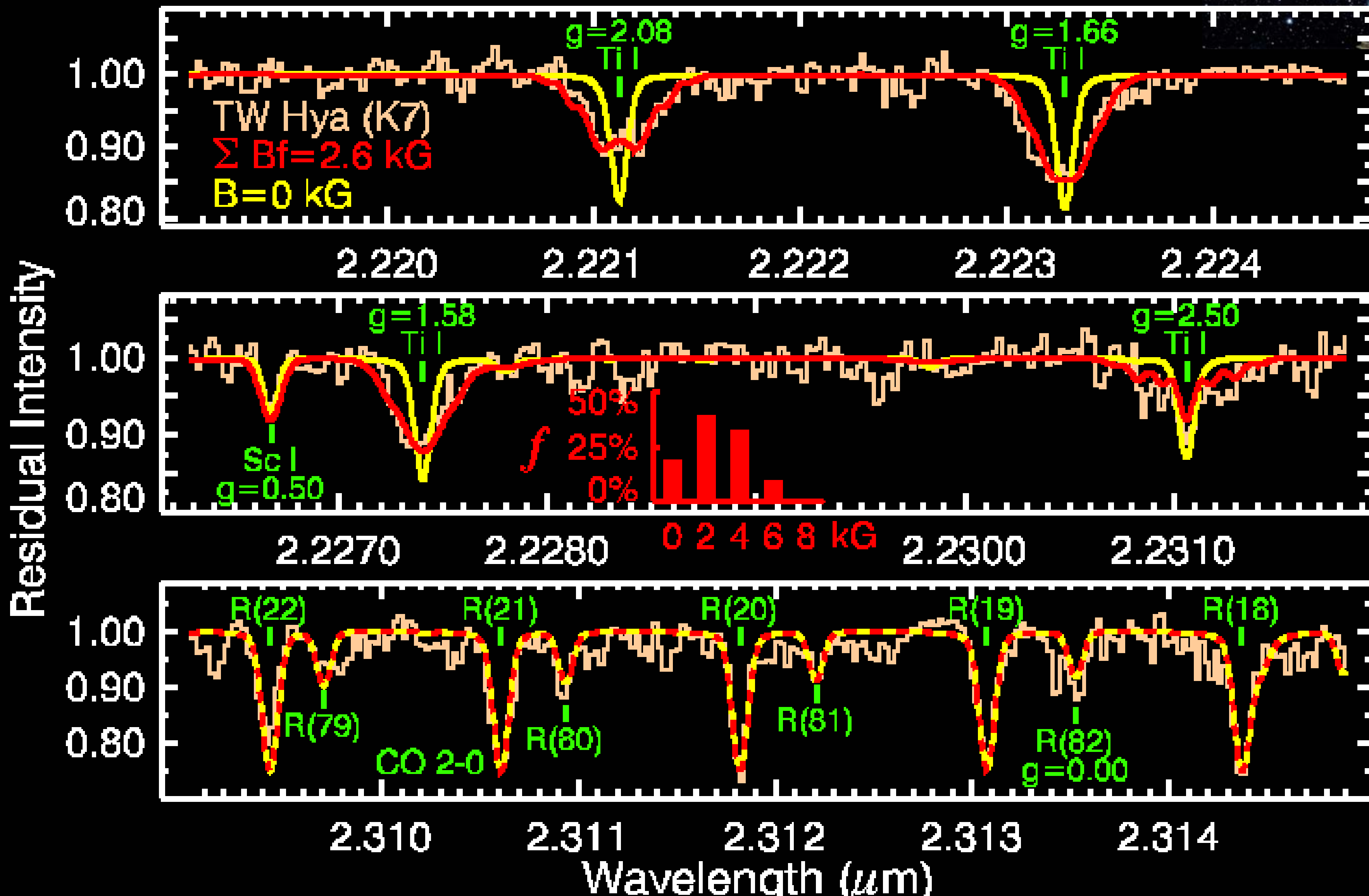
$$B_* = 1.10\, \gamma^{-1/3} \left(\frac{M_*}{1 M_\odot}\right)^{2/3} \left(\frac{\dot{M}}{10^{-7}\, M_\odot\, \mathrm{yr}^{-1}}\right)^{23/40} \left(\frac{R_*}{1 R_\odot}\right)^{-3} \left(\frac{P_*}{1 \mathrm{d}}\right)^{29/24} \mathrm{kG}$$

Shu et al. (1994):

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

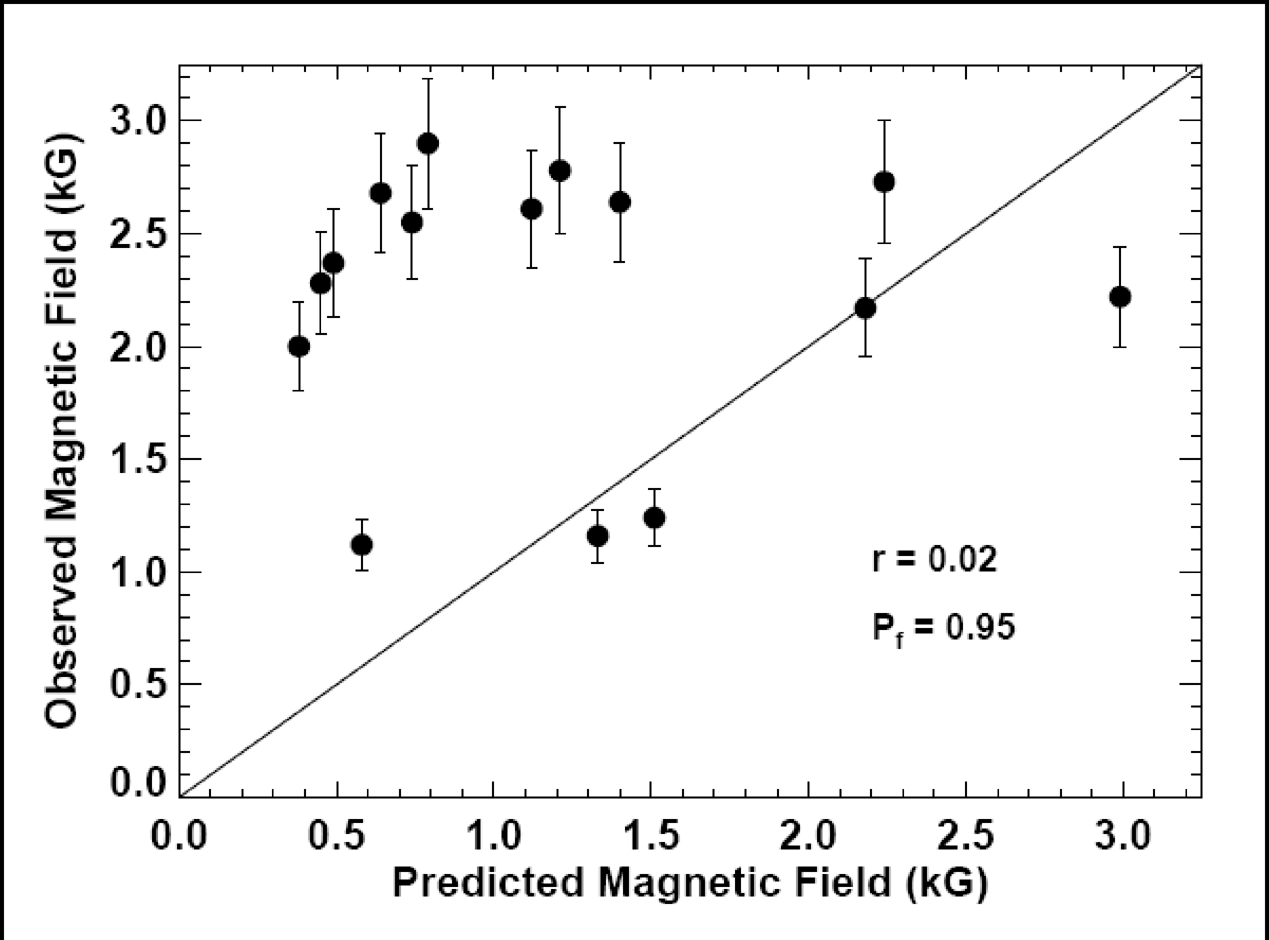
TW Hya: CTTS

Yang, Johns-Krull, & Valenti (2005)



Predicted vs. Observed Mean Fields

Johns-Krull (2007)



Caveats:

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

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