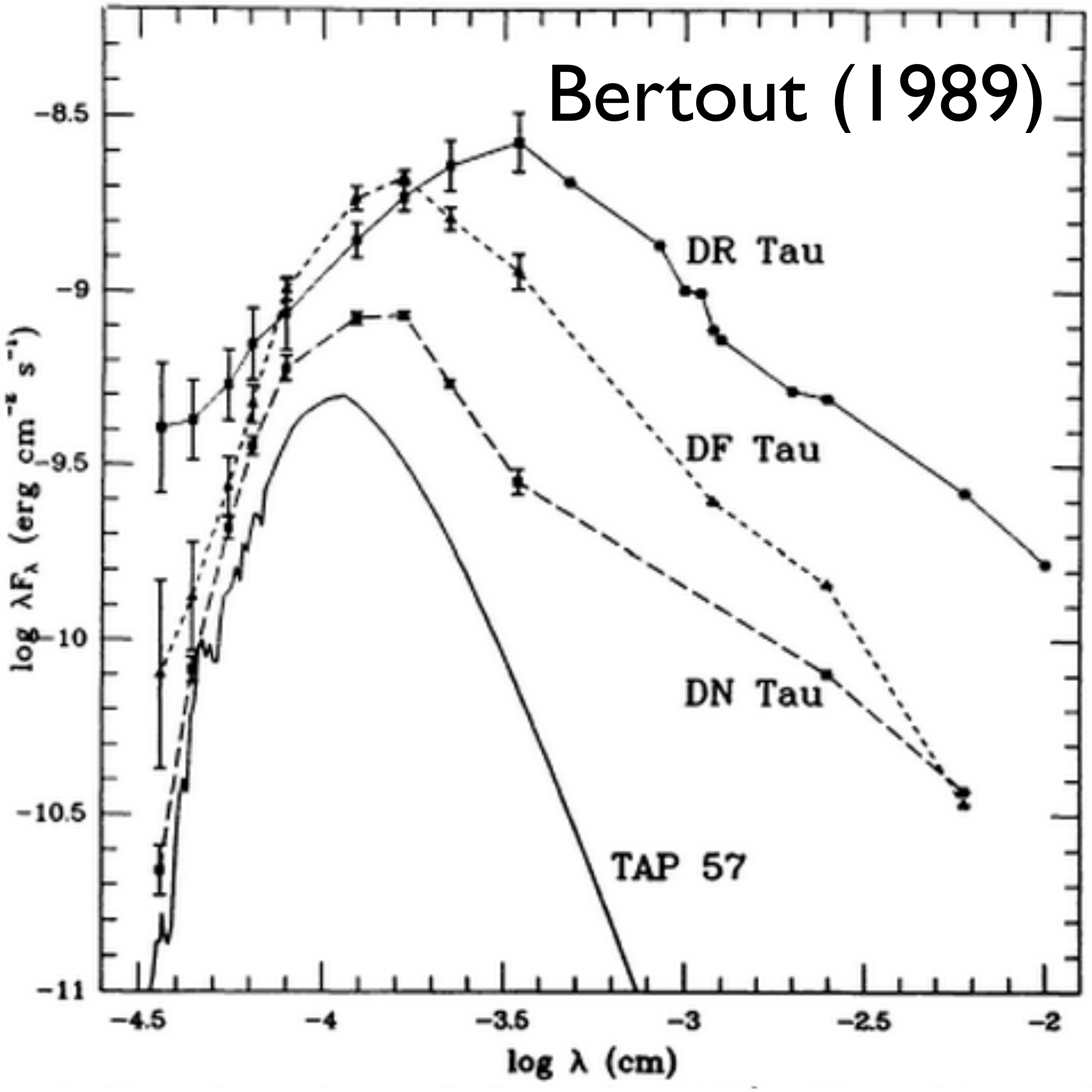
Disk accretion rates for T Tauri stars

Gullbring, Hartmann, Briceño, & Calvet

1998, ApJ 492:323−341

Disks around T Tauris

- Strong emission around some low-mass PMS stars is due to accreting circumstellar disks

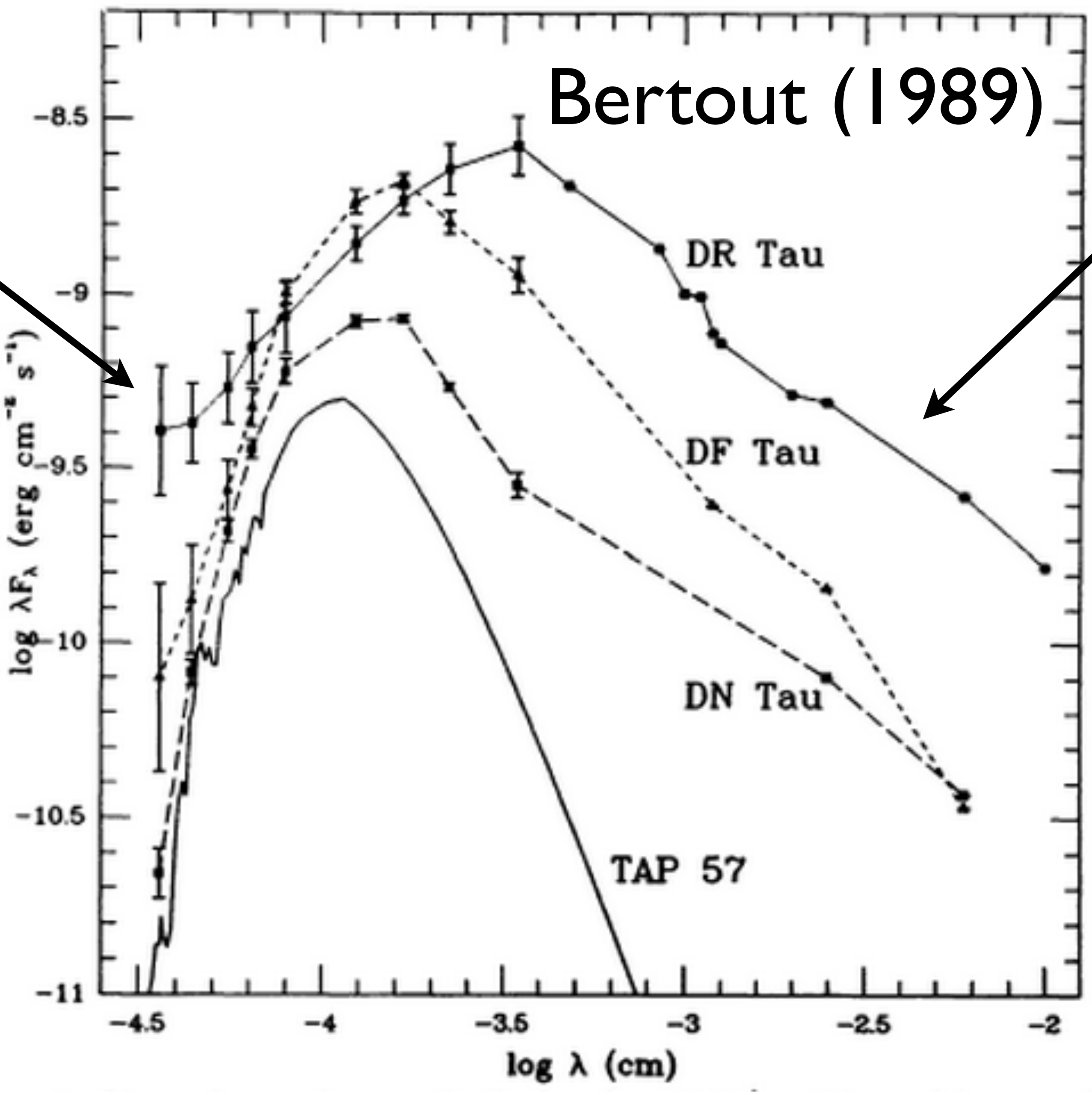

Bertout (1989)

- Excess luminosity depends on the accretion rate
- Excess due to accretion is difficult to estimate
- Irradiation from the central star is an important heat source

Accretion rate?

UV continuum excess

produced by disk material landing on the stellar surface



Bertout (1989)

IR continuum excess

produced by viscous dissipation in the disk

+

re-processed starlight

Accretion rate from the UV

- We need to distinguish between the stellar photosphere and the accretion-produced emission
- We need to correct for the extinction (color of the underlying star + color of the hot excess)
- Assumptions about the geometry of the accretion
- Result: very different accretion rates in the literature (difference of 1 order of mag for the same star!)

New approach

- Obtain flux-calibrated spectra in the 3200 − 5400 Å range
- Determine depth of stellar photospheric features
- Determine veiling
- Estimate relative proportion of stellar emission and hot continuum as a function of wavelength
- Result: U band magnitude and accretion luminosity is closely related
- Broad-band photometry + stellar spectral type → accretion rate

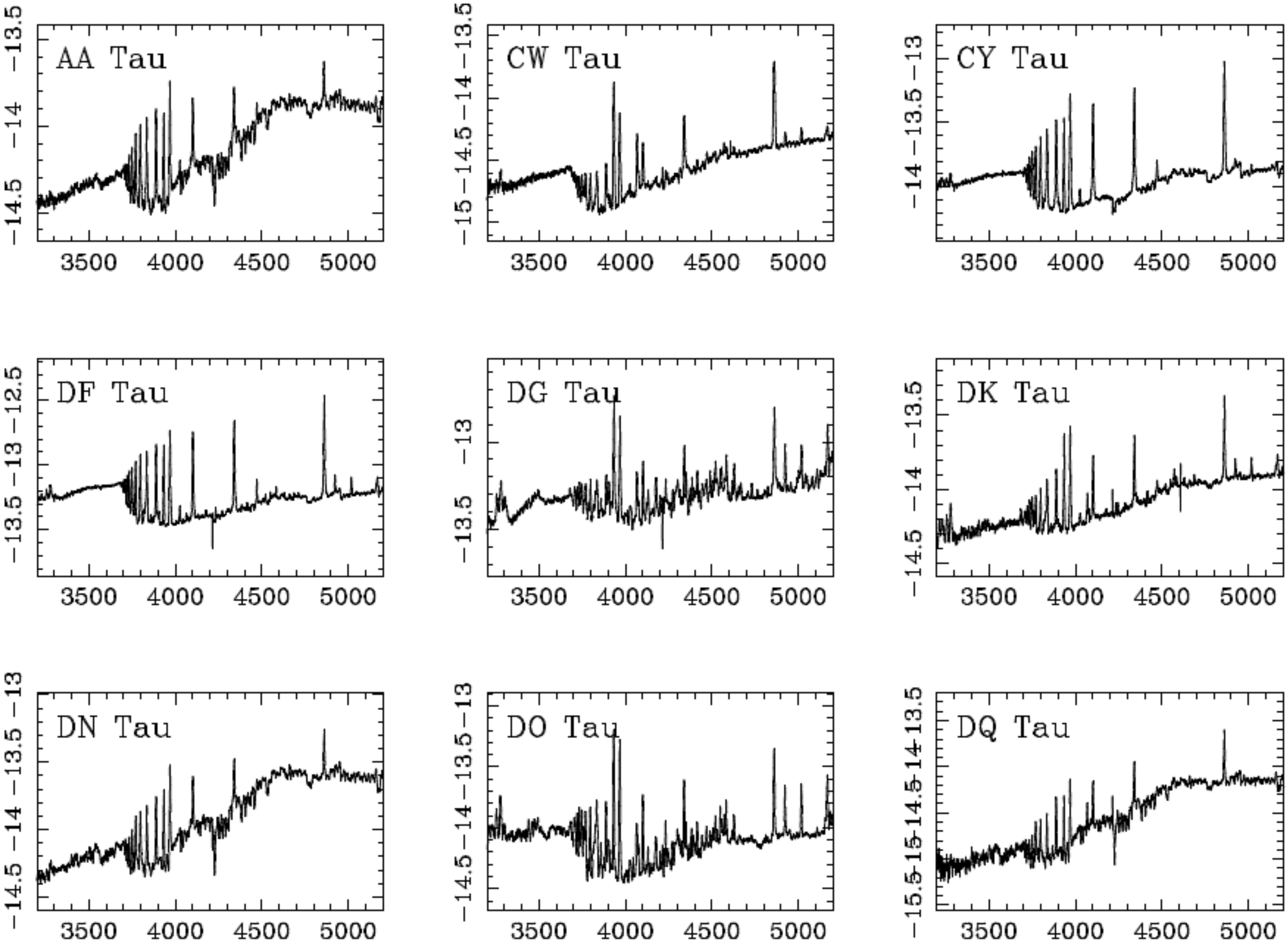
Observations

- Medium-resolution spectrophotometry of PMS stars in Taurus Auriga
- Multiple Mirror Telescope (MMT): six 1.8 m-diameter telescopes operated as one single telescope with an effective diameter of 4.5 m
- Sample: 3 WTTS, 26 CTTS, spectrophotometric standards (MS stars)
- HeNeAr lamp for wavelength calibration

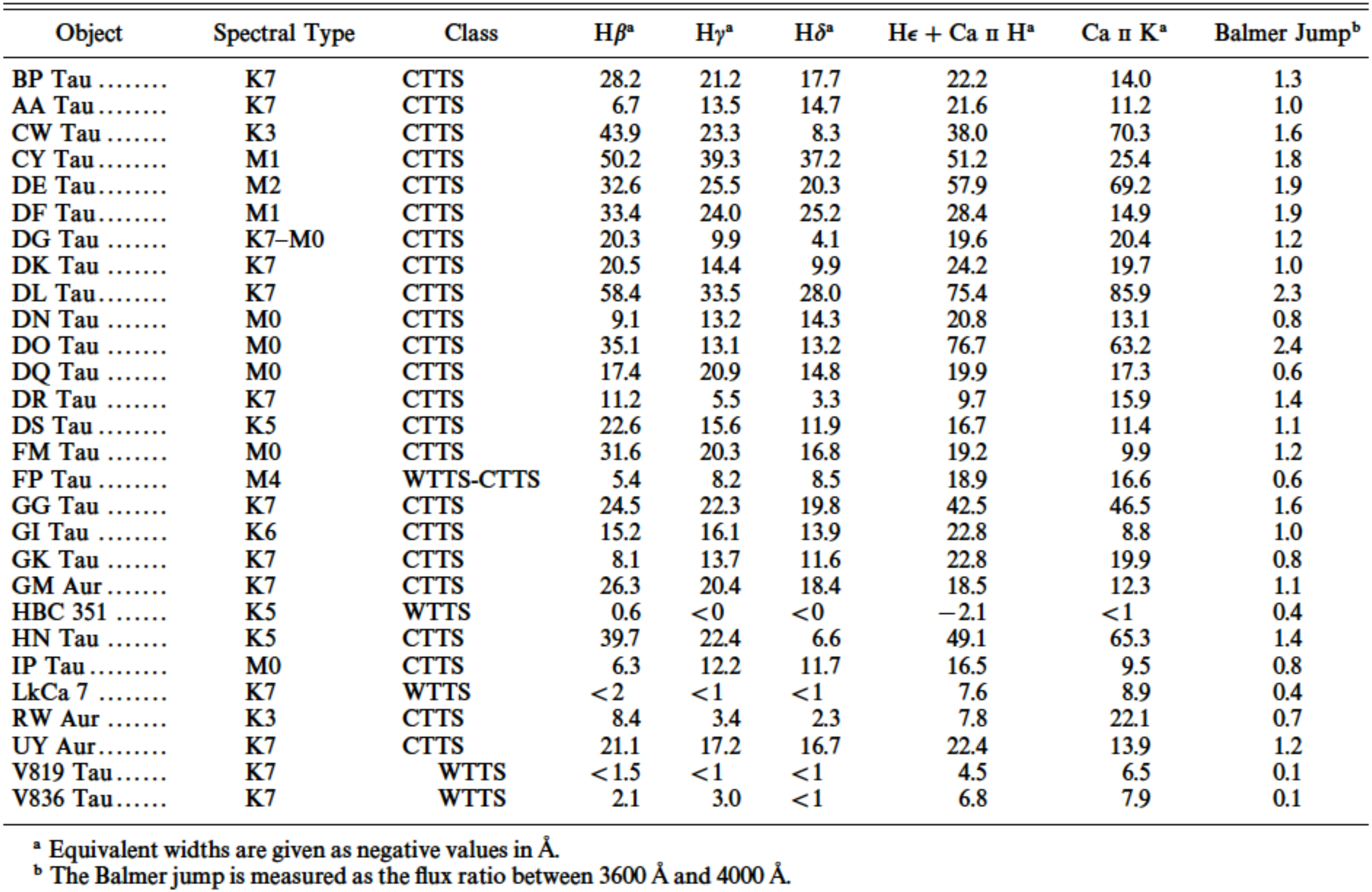
Data reduction

- Data reduction in iraf
- Determine atmospheric extinction law by measuring flux standards at different airmasses
- Uncertainties in the total flux: wavelength-dependent errors, variable transparency, slit loss
- Final flux precision: 5% (12-15% at the edges of the spectra)
- Result: flux-calibrated spectra for the targets; Balmer-jump, H and Ca lines

Results: spectra



Results: EWs etc...



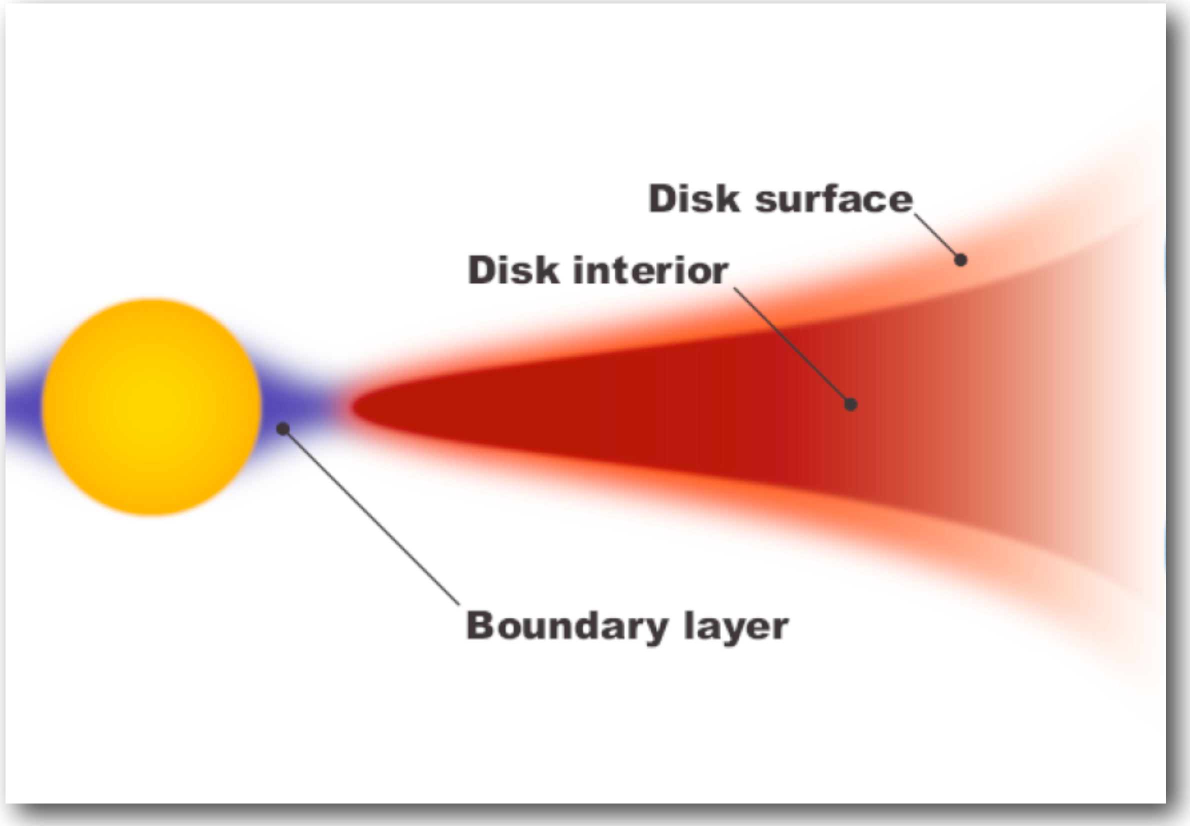
Object	Spectral Type	Class	Hβ[a]	Hγ[a]	Hδ[a]	Hϵ + Ca II H[a]	Ca II K[a]	Balmer Jump[b]
BP Tau	K7	CTTS	28.2	21.2	17.7	22.2	14.0	1.3
AA Tau	K7	CTTS	6.7	13.5	14.7	21.6	11.2	1.0
CW Tau	K3	CTTS	43.9	23.3	8.3	38.0	70.3	1.6
CY Tau	M1	CTTS	50.2	39.3	37.2	51.2	25.4	1.8
DE Tau	M2	CTTS	32.6	25.5	20.3	57.9	69.2	1.9
DF Tau	M1	CTTS	33.4	24.0	25.2	28.4	14.9	1.9
DG Tau	K7–M0	CTTS	20.3	9.9	4.1	19.6	20.4	1.2
DK Tau	K7	CTTS	20.5	14.4	9.9	24.2	19.7	1.0
DL Tau	K7	CTTS	58.4	33.5	28.0	75.4	85.9	2.3
DN Tau	M0	CTTS	9.1	13.2	14.3	20.8	13.1	0.8
DO Tau	M0	CTTS	35.1	13.1	13.2	76.7	63.2	2.4
DQ Tau	M0	CTTS	17.4	20.9	14.8	19.9	17.3	0.6
DR Tau	K7	CTTS	11.2	5.5	3.3	9.7	15.9	1.4
DS Tau	K5	CTTS	22.6	15.6	11.9	16.7	11.4	1.1
FM Tau	M0	CTTS	31.6	20.3	16.8	19.2	9.9	1.2
FP Tau	M4	WTTS-CTTS	5.4	8.2	8.5	18.9	16.6	0.6
GG Tau	K7	CTTS	24.5	22.3	19.8	42.5	46.5	1.6
GI Tau	K6	CTTS	15.2	16.1	13.9	22.8	8.8	1.0
GK Tau	K7	CTTS	8.1	13.7	11.6	22.8	19.9	0.8
GM Aur	K7	CTTS	26.3	20.4	18.4	18.5	12.3	1.1
HBC 351	K5	WTTS	0.6	<0	<0	−2.1	<1	0.4
HN Tau	K5	CTTS	39.7	22.4	6.6	49.1	65.3	1.4
IP Tau	M0	CTTS	6.3	12.2	11.7	16.5	9.5	0.8
LkCa 7	K7	WTTS	<2	<1	<1	7.6	8.9	0.4
RW Aur	K3	CTTS	8.4	3.4	2.3	7.8	22.1	0.7
UY Aur	K7	CTTS	21.1	17.2	16.7	22.4	13.9	1.2
V819 Tau	K7	WTTS	<1.5	<1	<1	4.5	6.5	0.1
V836 Tau	K7	WTTS	2.1	3.0	<1	6.8	7.9	0.1

[a] Equivalent widths are given as negative values in Å.

[b] The Balmer jump is measured as the flux ratio between 3600 Å and 4000 Å.

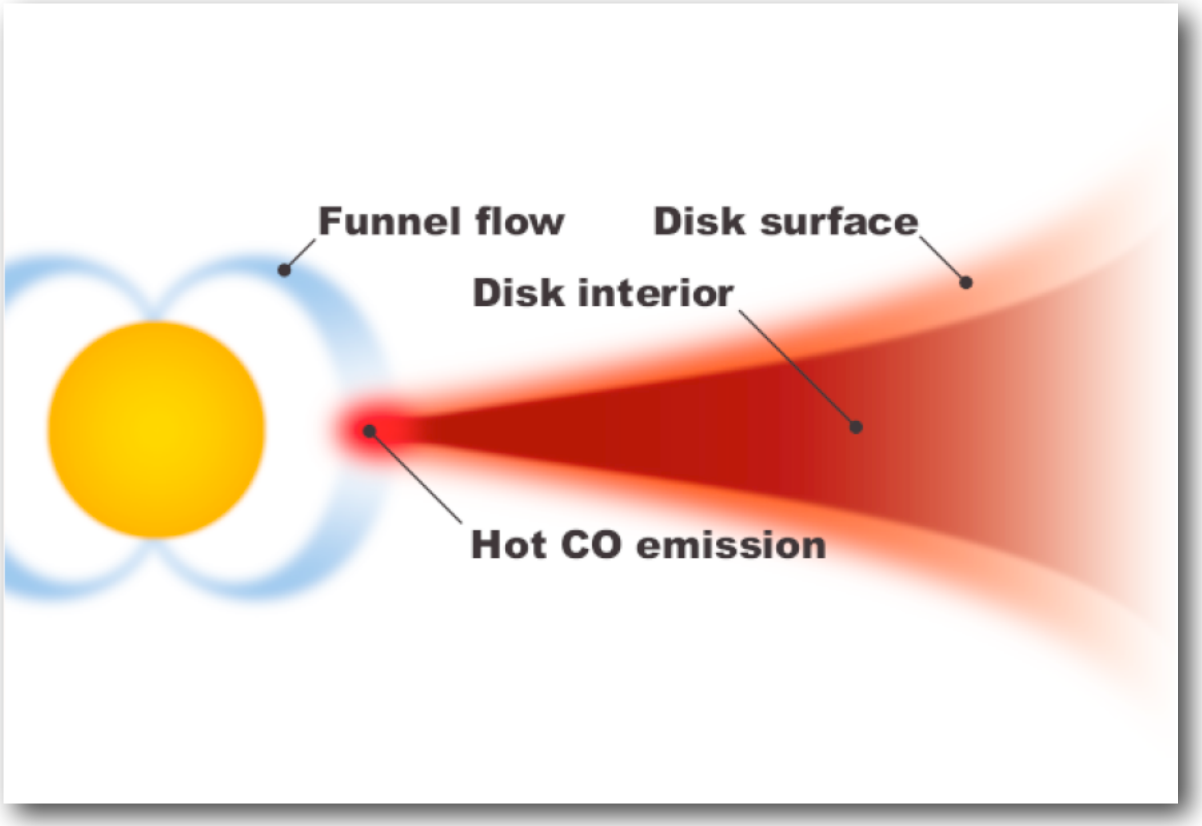
Origin of the hot continuum

boundary layer



Lynden-Bell & Pringle (1974)

magnetospheric accretion



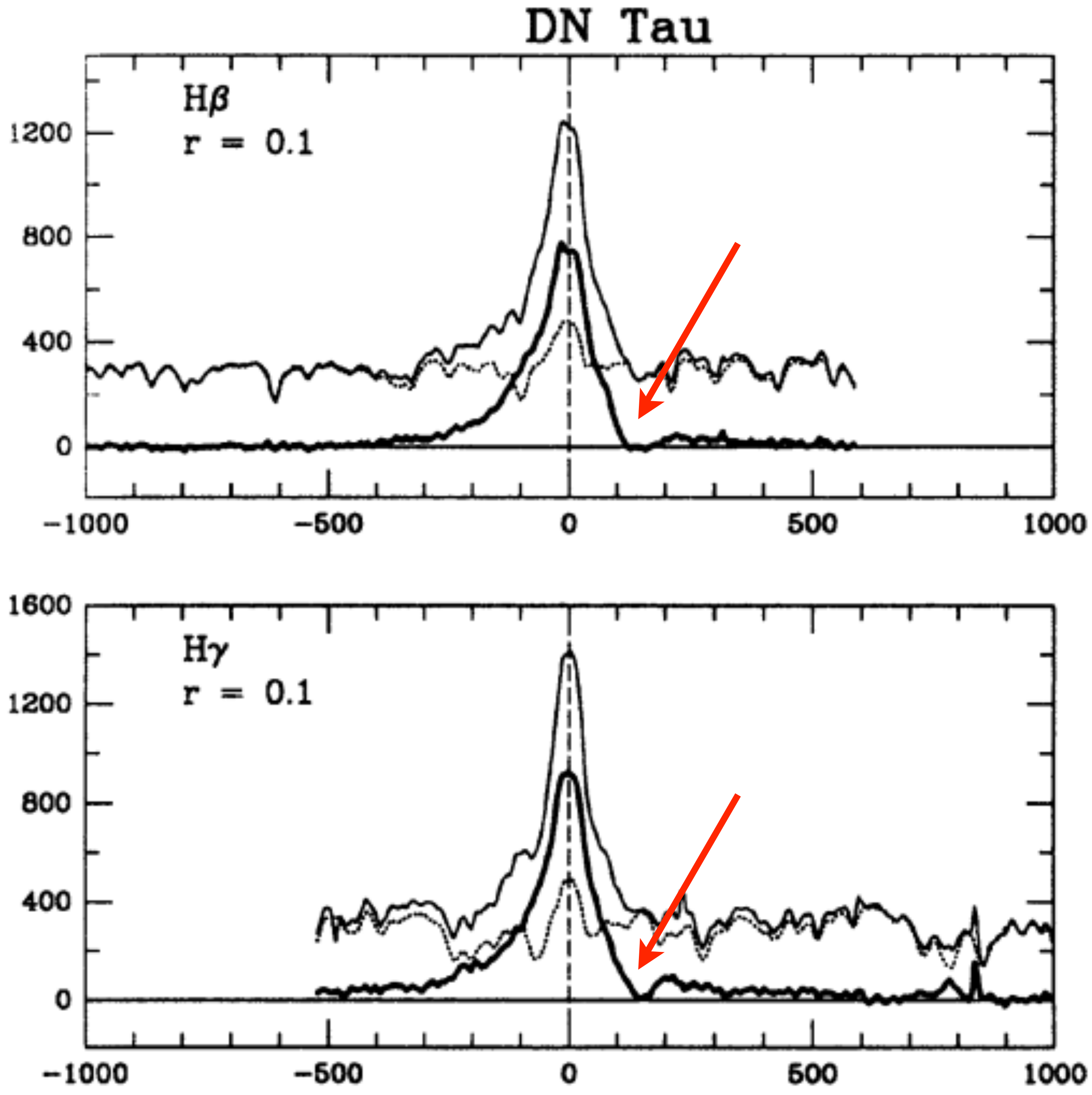
Kamenzind (1990)
Königl (1991)

Magnetospheric accretion

Pros: it explains

- hot spots rotating with the star
- absence of inner disk emission
- slower rotation of stars with inner disks (due to the disk torque communicated to the star by the magnetic field)
- emission line profiles of permitted lines (inverse P Cygni redshifted absorption features)

Redshifted absorption



Indicates mass infall at high velocities (free-falling gas along the magnetic field lines)

Edwards et al (1994)

Assumptions

- Accretion flow lands on a small area on the stellar surface
- Most of the stellar photosphere is unaffected by the accretion process
- Spectrum of CTTS = stellar photosphere + hot emission
- Spectrum of the hot emission is unknown a priori
- Both components are reddened by interstellar extinction

Veiling

- Excess emission is a continuous emission
- Excess emission fills up the photospheric absorption lines (veiling)
- The veiling at different wavelengths gives information about the spectral shape of the hot excess

$$r = \frac{F_l^o/F_c^o - F_l^*/F_c^*}{1 - F_l^o/F_c^o}$$

- *l*: line, *c*:continuum
  o: veiled object, *: stellar photosphere
- Reddening-independent parameter

Uncertainties

- We need a good stellar photosphere template (for F_l*/F_c*)
- We need to separate continuum veiling and line veiling (when non-photospheric emission lines fill up the photospheric absorption lines) → needs good spectral resolution
- Iron lines around 4500 Å are especially bothersome
- Most suitable region to measure *r*:
  4150 Å − 4440 Å and 4700 Å − 5200 Å

Observed flux

- If the stellar flux F_c^* is known, then the excess emission: $F^E = r\,F_c^*$

- If the CTTS has the same photospheric emission as the stellar template, then the stellar flux is

$$F_i^* = C_1\,F_i^t 10^{0.4 A_i{}^t}$$

where A_i is the interstellar extinction in band i, and C_l accounts for the different solid angles of the stars

- The observed flux:

$$F_i^o = (F_i^* + F_i^E)10^{-0.4 A_i{}^o} = \boxed{C_1} F_i^t\,10^{0.4(A_i{}^t - \boxed{A_i{}^o})}(1 + r_i)$$

Fitting procedure

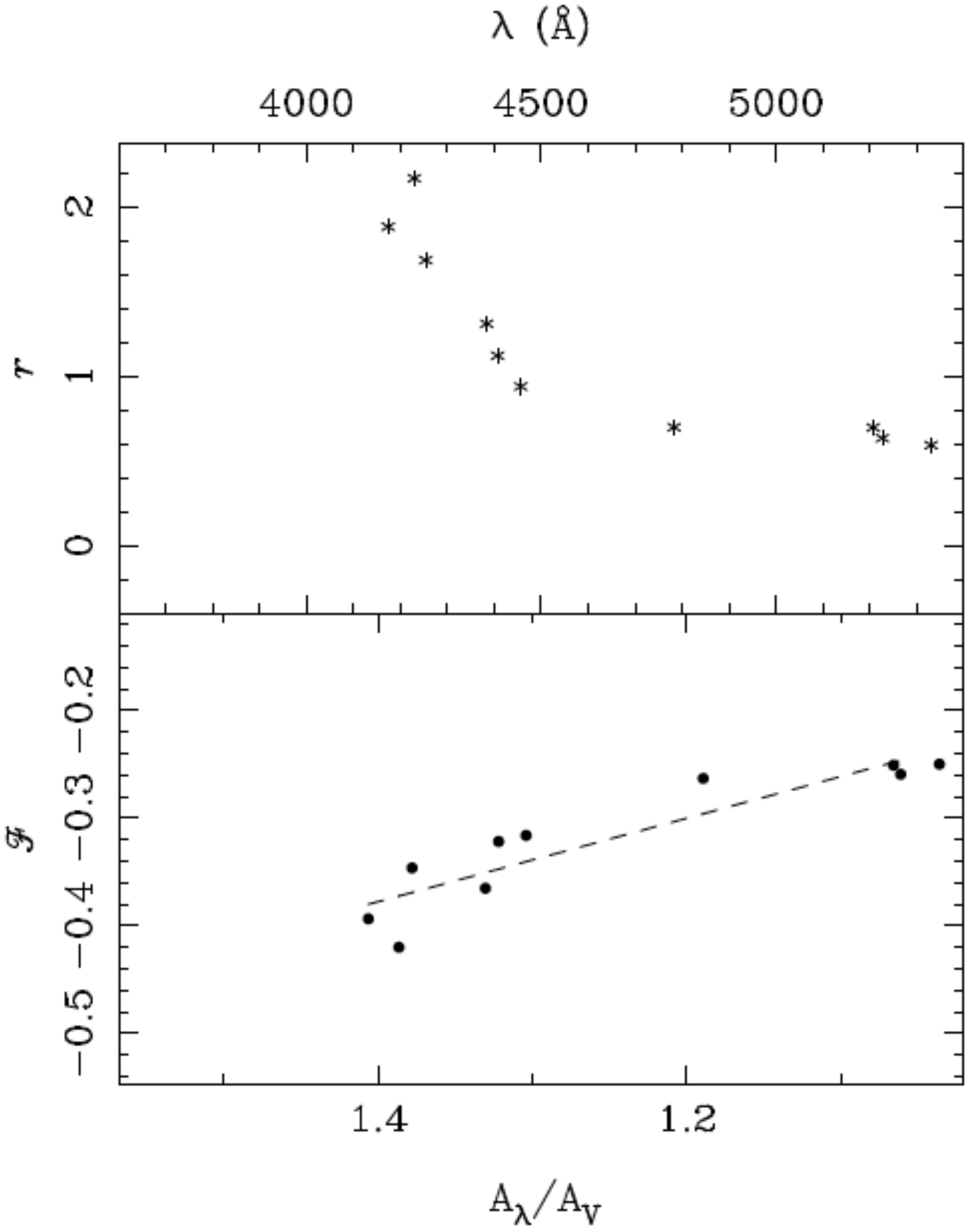
$$F_i^o = (F_i^* + F_i^E)10^{-0.4A_{i^o}} = \boxed{C_1} F_i^t 10^{0.4(A_{i^t} - \boxed{A_{i^o}})}(1 + r_i)$$

- If we measure N lines, we have N equations for 2 unknowns
- Typically, 5 – 15 photospheric lines are suitable for veiling measurements
- In practice, we use this equation:

$$2.5 \log \left[\frac{F_i^t}{F_i^o} (1 + r_i) \right] = w_i(A_V^o - A_V^t)2.5 \log C_1$$

where $w_i = A_i / A_V$

Fitting procedure



$$2.5 \log\left[\frac{F_i^t}{F_i^o}(1+r_i)\right] =$$

$$w_i(A_V^o - A_V^t)2.5 \log C_1$$

Fit a line

Slope gives $A_V{}^o - A_V{}^t$

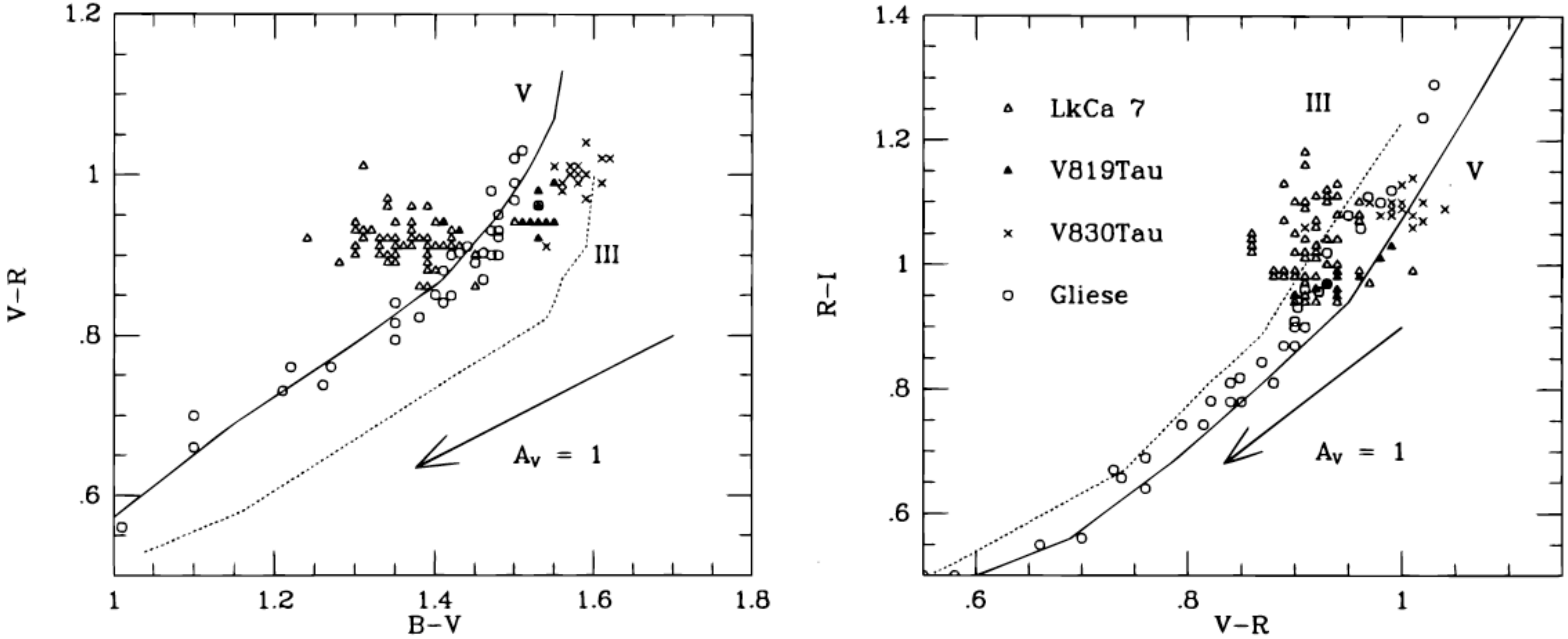
Zero point gives C_1

Colors of WTTSs and A_V

- The outlined procedure to estimate extinction relies on the assumption that the intrinsic CTTS spectrum is accurately represented by the template spectrum
- Best templates are WTTSs (non-accreting T Tauri)
- Sometimes we use nearby MS stars if no T Tau with the desired spectral type (or $T_{\rm eff}$) is available
- We should precisely know A_V^t !!! (critical with WTTS templates)

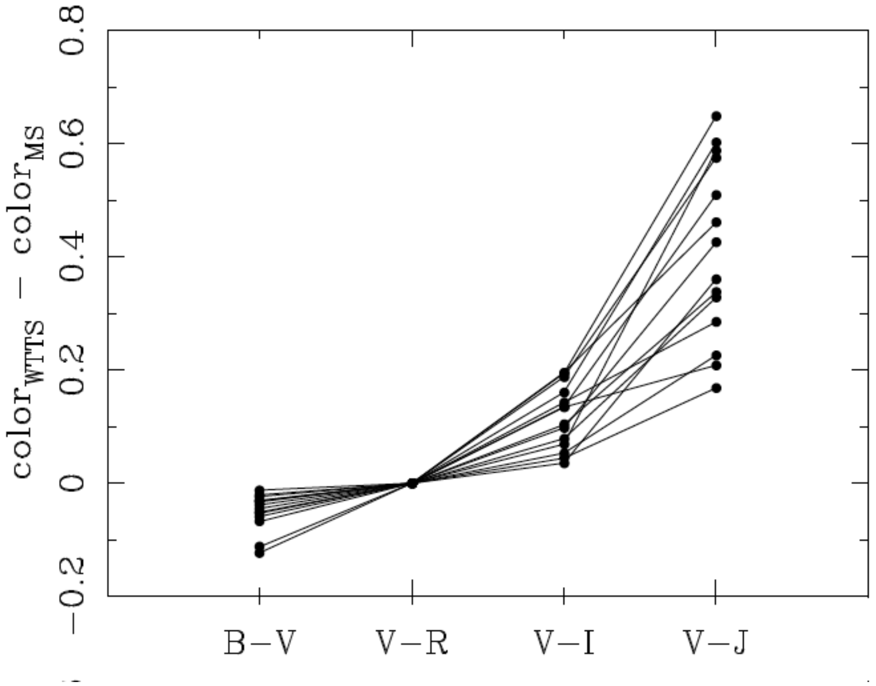
Example for a bad case

- LkCa7 (WTTS)
  $A_V = -0.03$ mag from $B-V$
  $A_V = 0.45$ from $V-R$
  $A_V = 0.9$ mag from $V-I$



Color anomalies

- Common trend among WTTS: A_V tends to increase as we use redder colors
- Sources of this color anomaly:
  - Errors in the color calibration? Unlikely. Same procedure works for dwarfs stars.
  - Gravity effects? (WTTS have different colors than MS stars due to lower log g?) Unlikely. Same procedure works for giants. Moreover, WTTSs are closer to dwarfs than to giants.

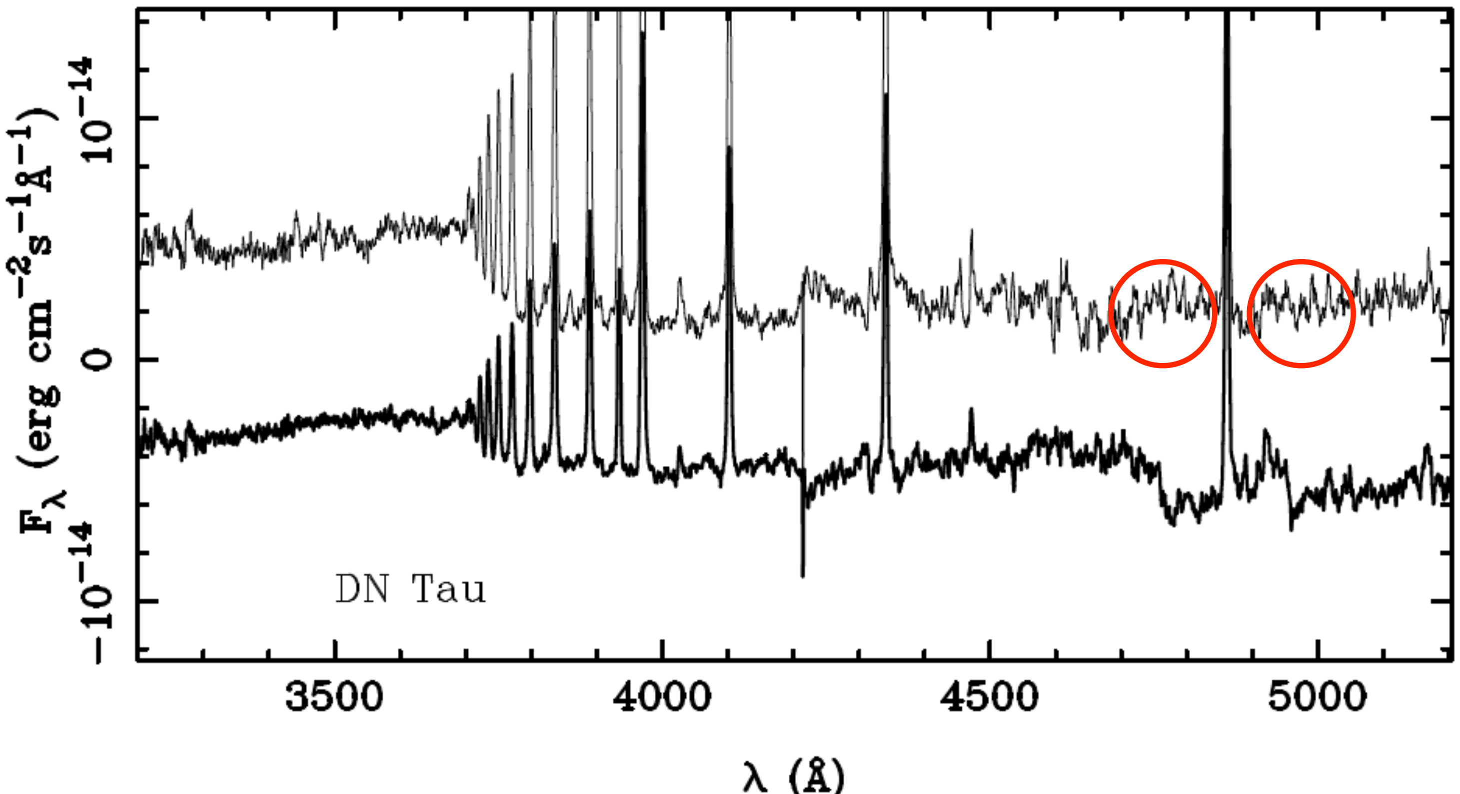


Color anomalies

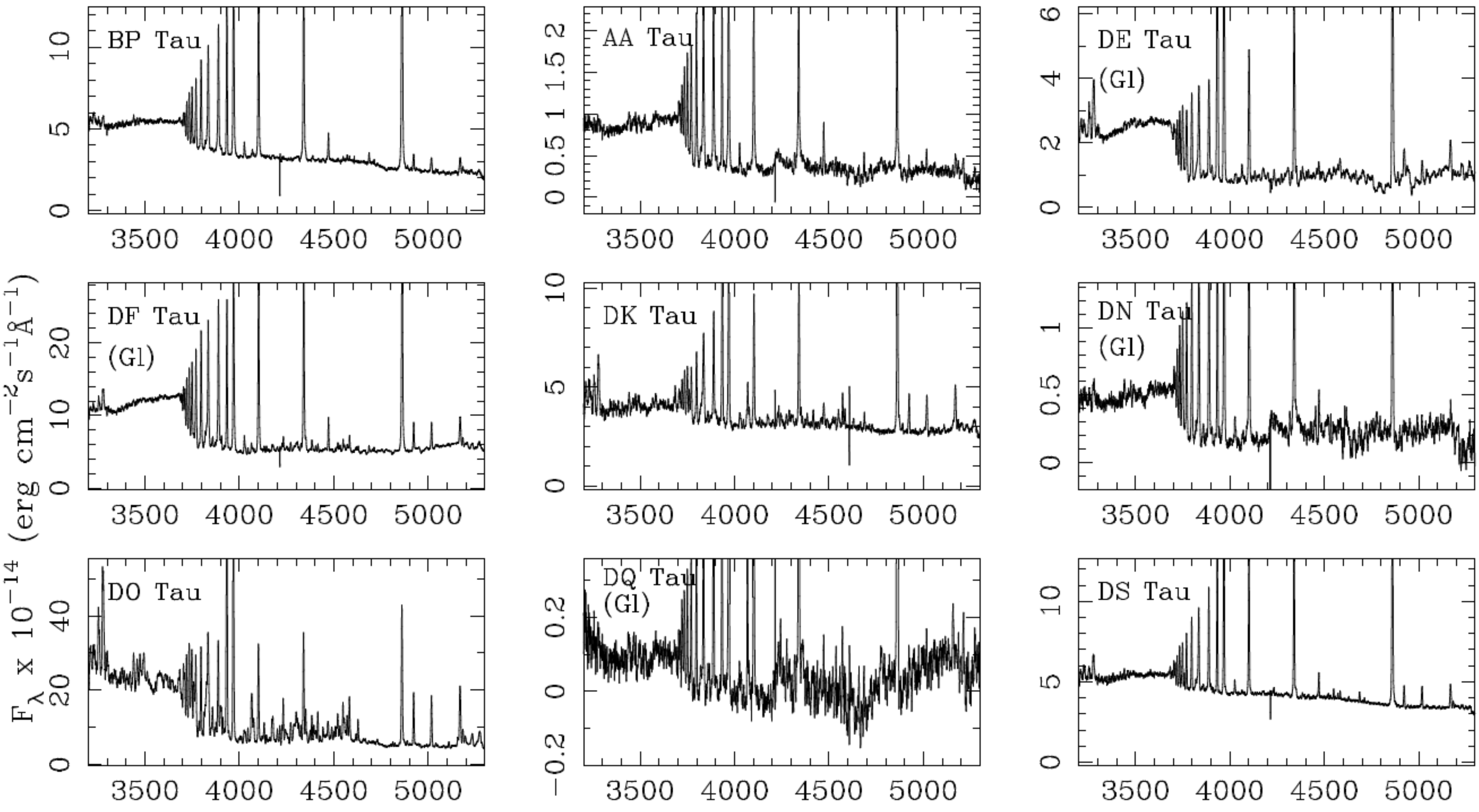
- Sources of this color anomaly:
  - Errors in spectral typing? Unlikely. Anomalies are present for all spectral types.
  - Anomalous extinction? (Larger R_V). Unlikely to produce an effect as large as what is observed.
  - Binary companions? (Fainter, cooler component). Unlikely to explain all stars.
  - Spots? Qualitatively, it may work. Quantitatively? $50 - 70\%$ of the stellar surface must be covered by spots. However, light curves show that spots must be smaller.

Choice of template stars

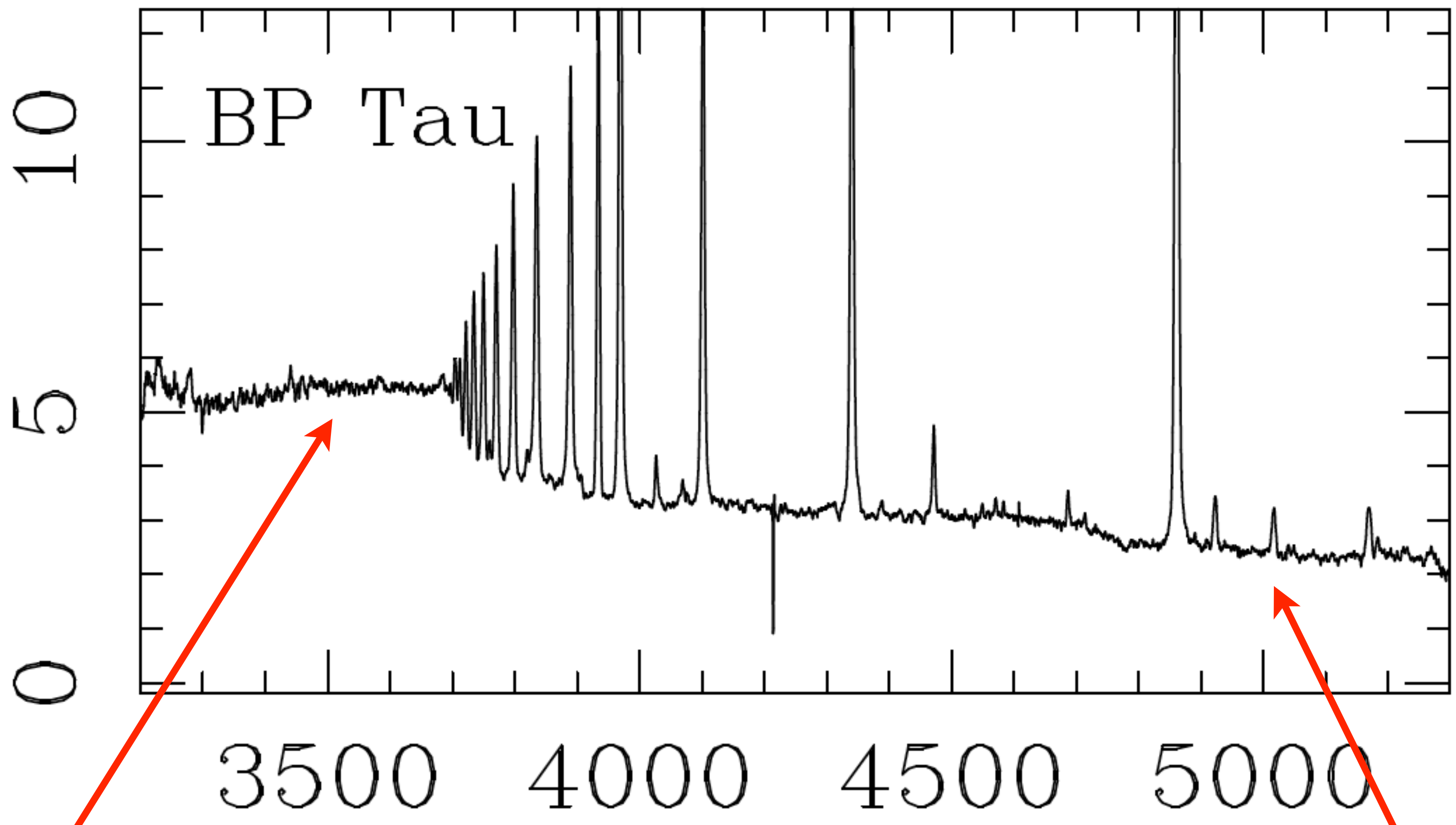
- Conclusion: we don't know the reason for the color anomaly: let's stick to the *V*−*R* color, which seems OK.
- We'll assume a normal extinction law.
- Template stars: V819 Tau (K7), Gl 913 (M0), Gl 038 (M2), Gl 051 (M7)
- The excess spectrum of DN Tau using two different templates:



Resulting excess spectra



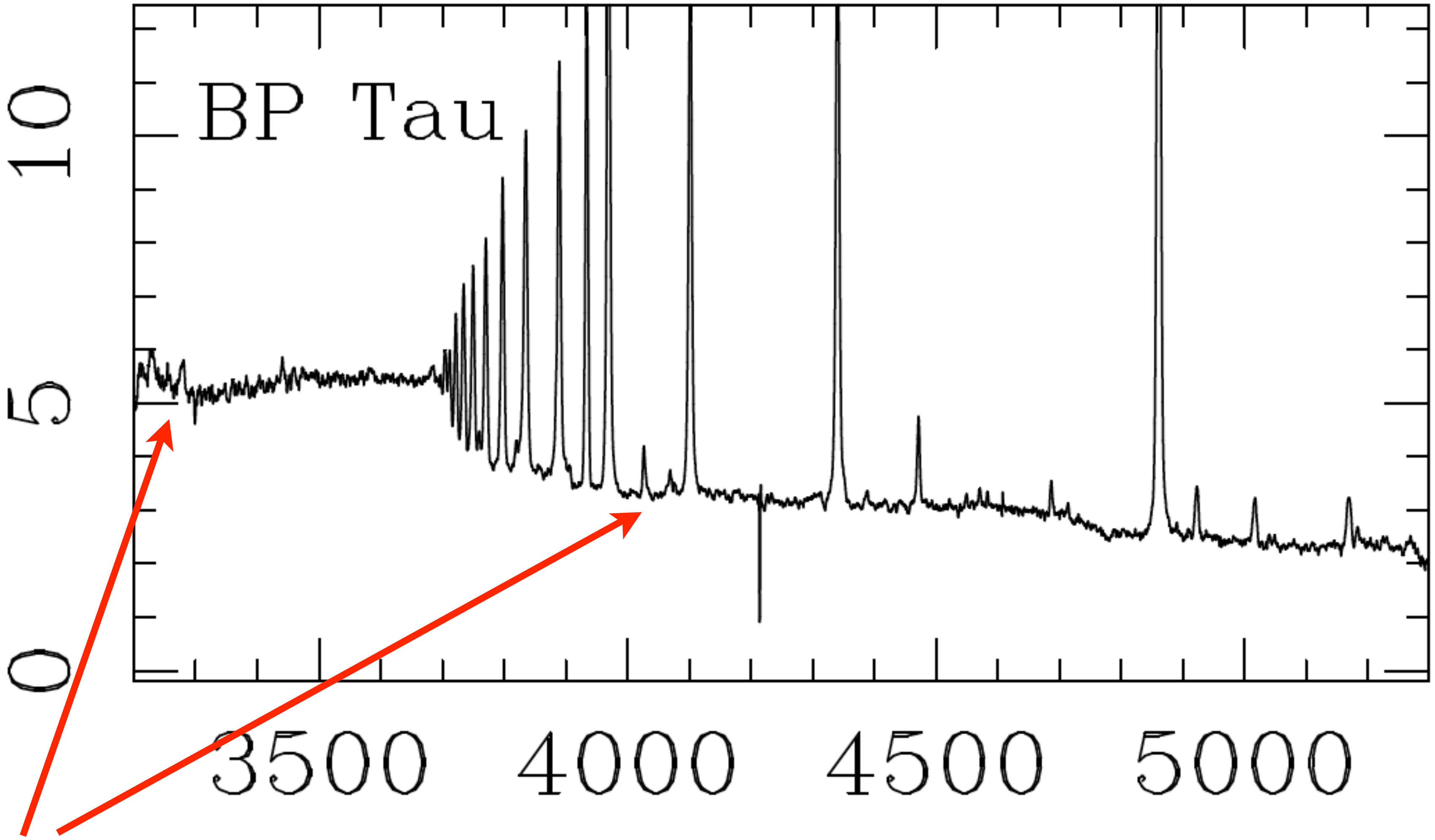
Resulting excess spectra



increasing Balmer-continuum

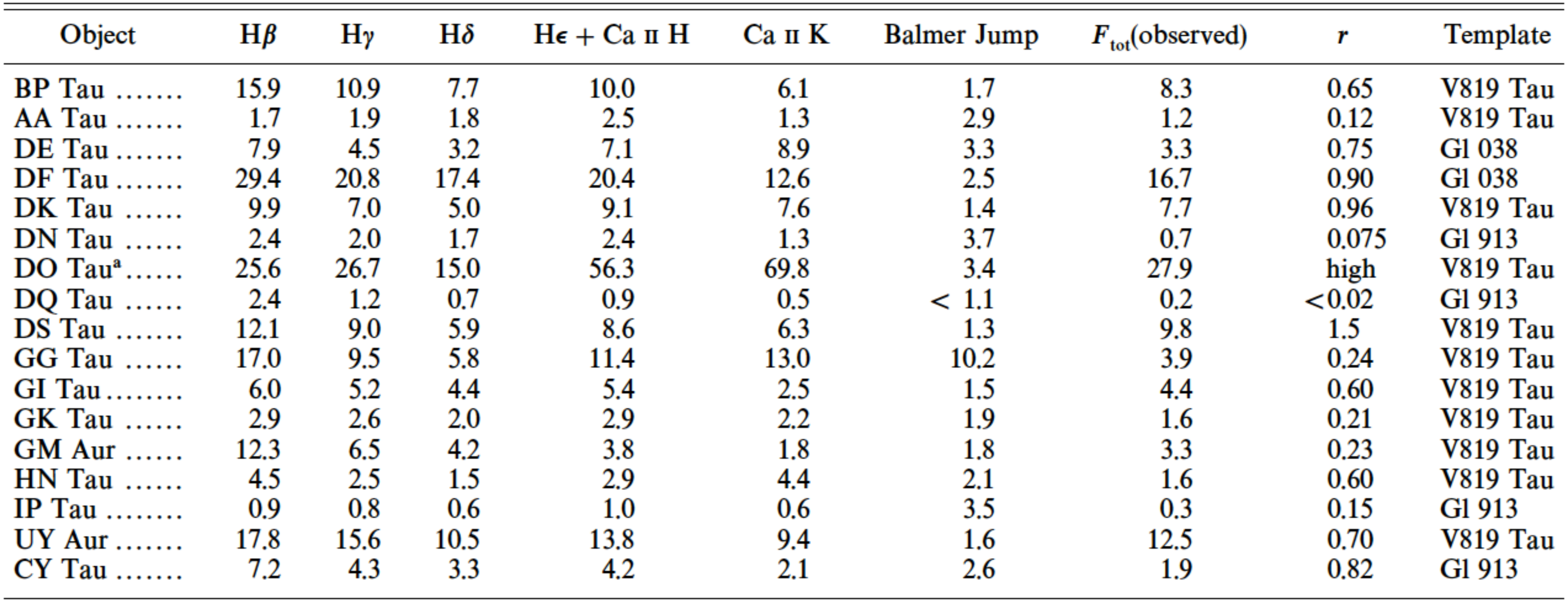
decreasing Paschen-continuum

Resulting excess spectra



many lines: HI, FeI, FeII, CaII

Resulting excess spectra

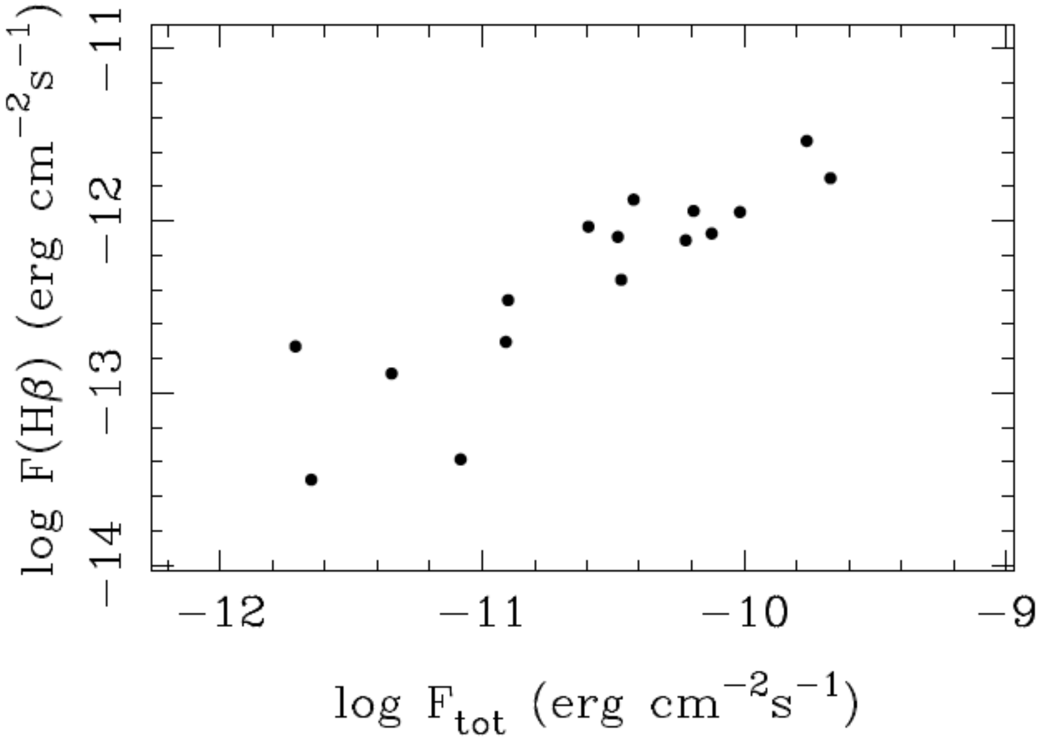


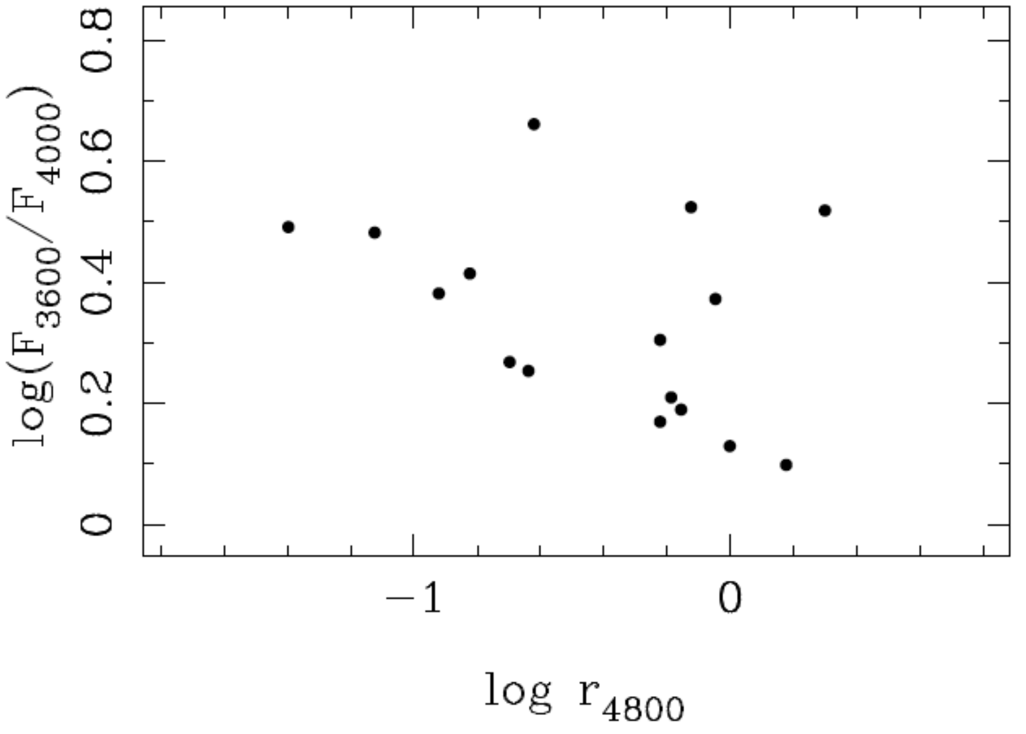
Object	Hβ	Hγ	Hδ	Hϵ + Ca II H	Ca II K	Balmer Jump	F_{tot}(observed)	r	Template
BP Tau	15.9	10.9	7.7	10.0	6.1	1.7	8.3	0.65	V819 Tau
AA Tau	1.7	1.9	1.8	2.5	1.3	2.9	1.2	0.12	V819 Tau
DE Tau	7.9	4.5	3.2	7.1	8.9	3.3	3.3	0.75	Gl 038
DF Tau	29.4	20.8	17.4	20.4	12.6	2.5	16.7	0.90	Gl 038
DK Tau	9.9	7.0	5.0	9.1	7.6	1.4	7.7	0.96	V819 Tau
DN Tau	2.4	2.0	1.7	2.4	1.3	3.7	0.7	0.075	Gl 913
DO Tau[a]	25.6	26.7	15.0	56.3	69.8	3.4	27.9	high	V819 Tau
DQ Tau	2.4	1.2	0.7	0.9	0.5	$<$ 1.1	0.2	$<$0.02	Gl 913
DS Tau	12.1	9.0	5.9	8.6	6.3	1.3	9.8	1.5	V819 Tau
GG Tau	17.0	9.5	5.8	11.4	13.0	10.2	3.9	0.24	V819 Tau
GI Tau	6.0	5.2	4.4	5.4	2.5	1.5	4.4	0.60	V819 Tau
GK Tau	2.9	2.6	2.0	2.9	2.2	1.9	1.6	0.21	V819 Tau
GM Aur	12.3	6.5	4.2	3.8	1.8	1.8	3.3	0.23	V819 Tau
HN Tau	4.5	2.5	1.5	2.9	4.4	2.1	1.6	0.60	V819 Tau
IP Tau	0.9	0.8	0.6	1.0	0.6	3.5	0.3	0.15	Gl 913
UY Aur	17.8	15.6	10.5	13.8	9.4	1.6	12.5	0.70	V819 Tau
CY Tau	7.2	4.3	3.3	4.2	2.1	2.6	1.9	0.82	Gl 913

- Excess continuum arises from the accretion shock on the stellar surface
- Excess lines arise from the infalling gas above the accretion shock in the magnetosphere (hotter!)

Correlations

- Correlations: Call K ⟺ Balmer jump, total flux ⟺ Hβ, no correlation with Fe lines
- Balmer jump decrease with increasing veiling ⟹ either the emission region becomes more optically thick with increasing accretion rate, or the Paschen and Balmer continua come from different regions

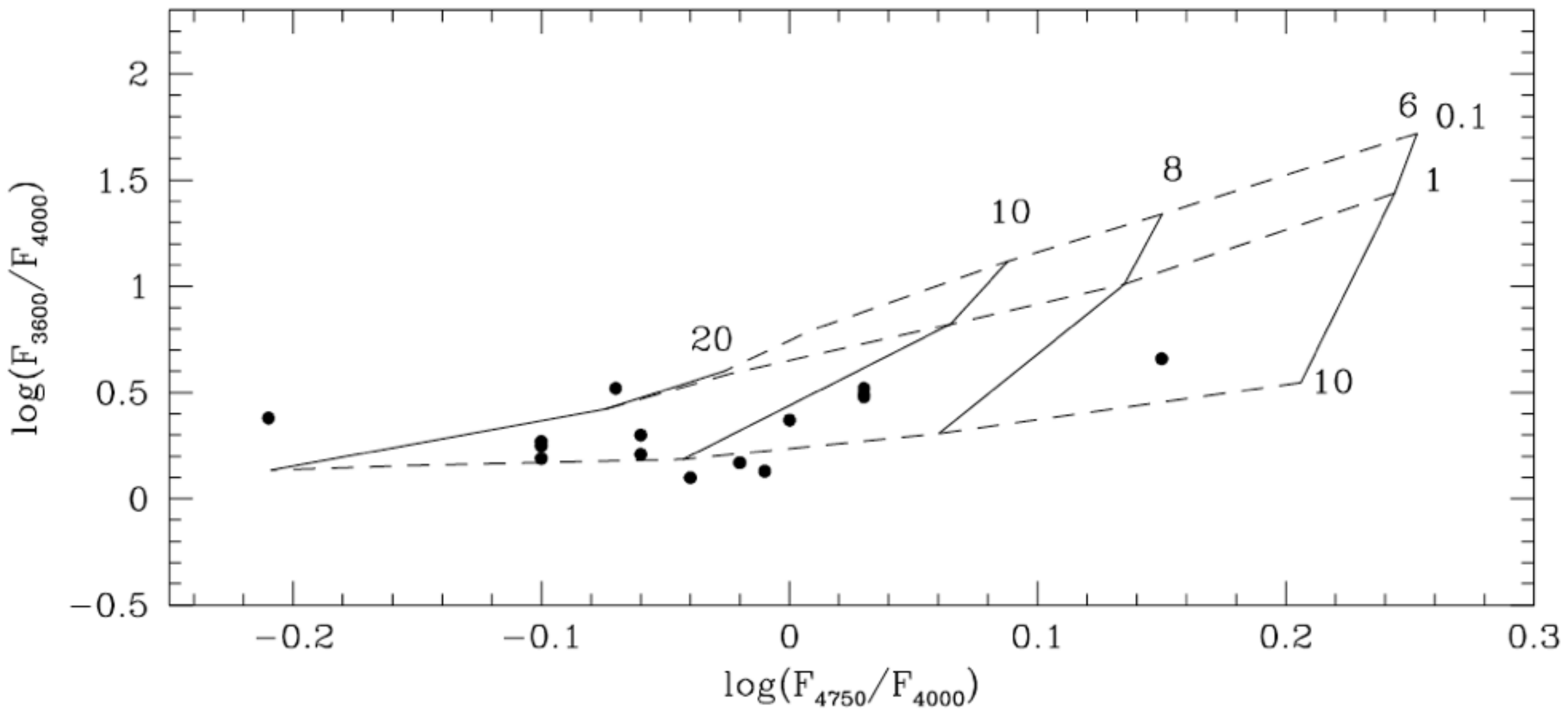


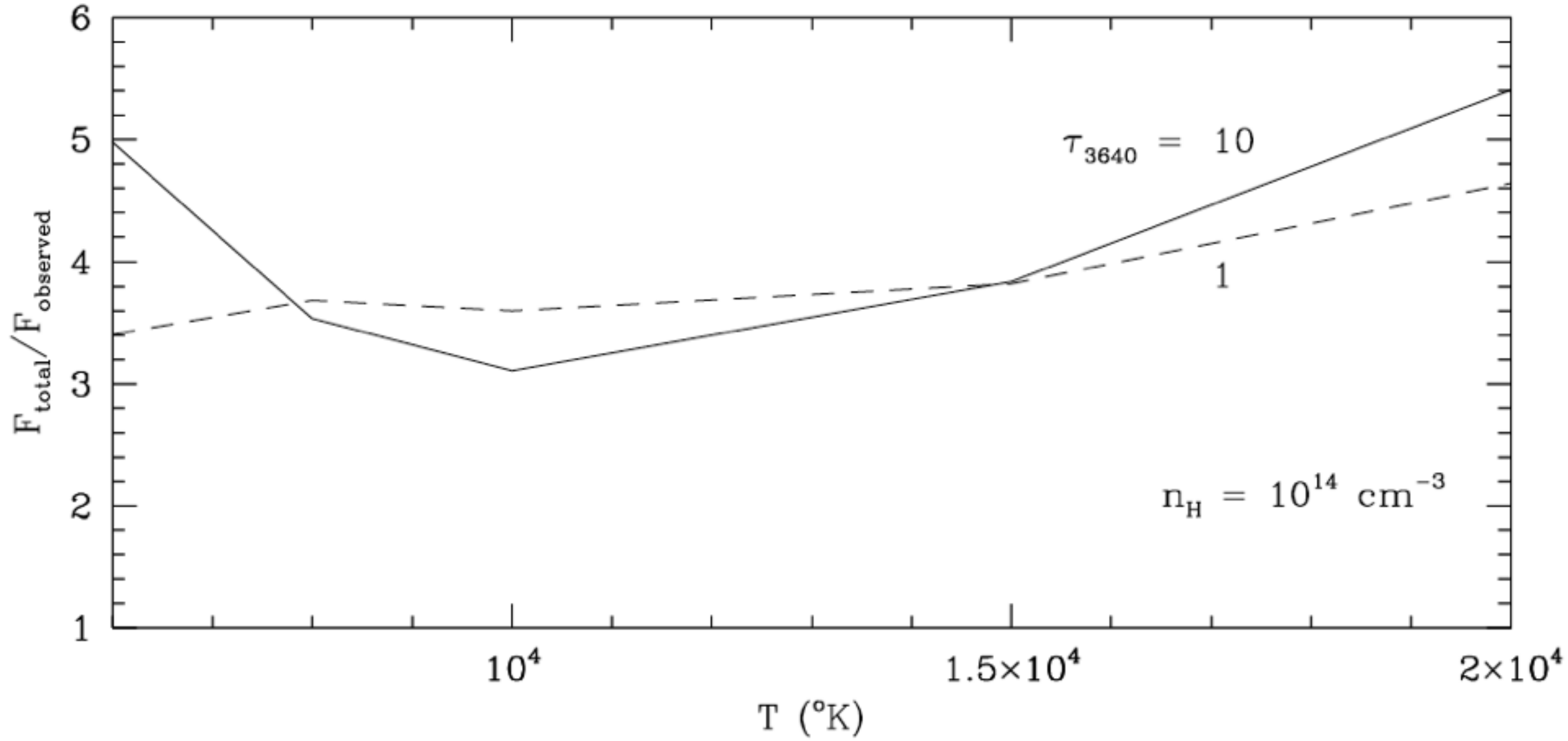


Accretion luminosity

- We only measured the excess emission between 3200 − 5400 Å range. What is the total bolometric luminosity of the excess? "Bolometric correction"
- Slab model: excess comes from a layer of material that has constant density and temperature
- Slab has 3 parameters: density, temperature and thickness (optical depth)
- Sources of opacity: H and H^-
- LTE is assumed

Slab model results





- Temperatures are typically 10 000 – 20 000 K
- The bolometric flux is 3 – 4 x what is in the observed wavelength range

Mass accretion rates

- In the magnetospheric accretion model, the accretion rate from the accretion luminosity is:

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

where M_* is the stellar mass

R_* is the stellar radius

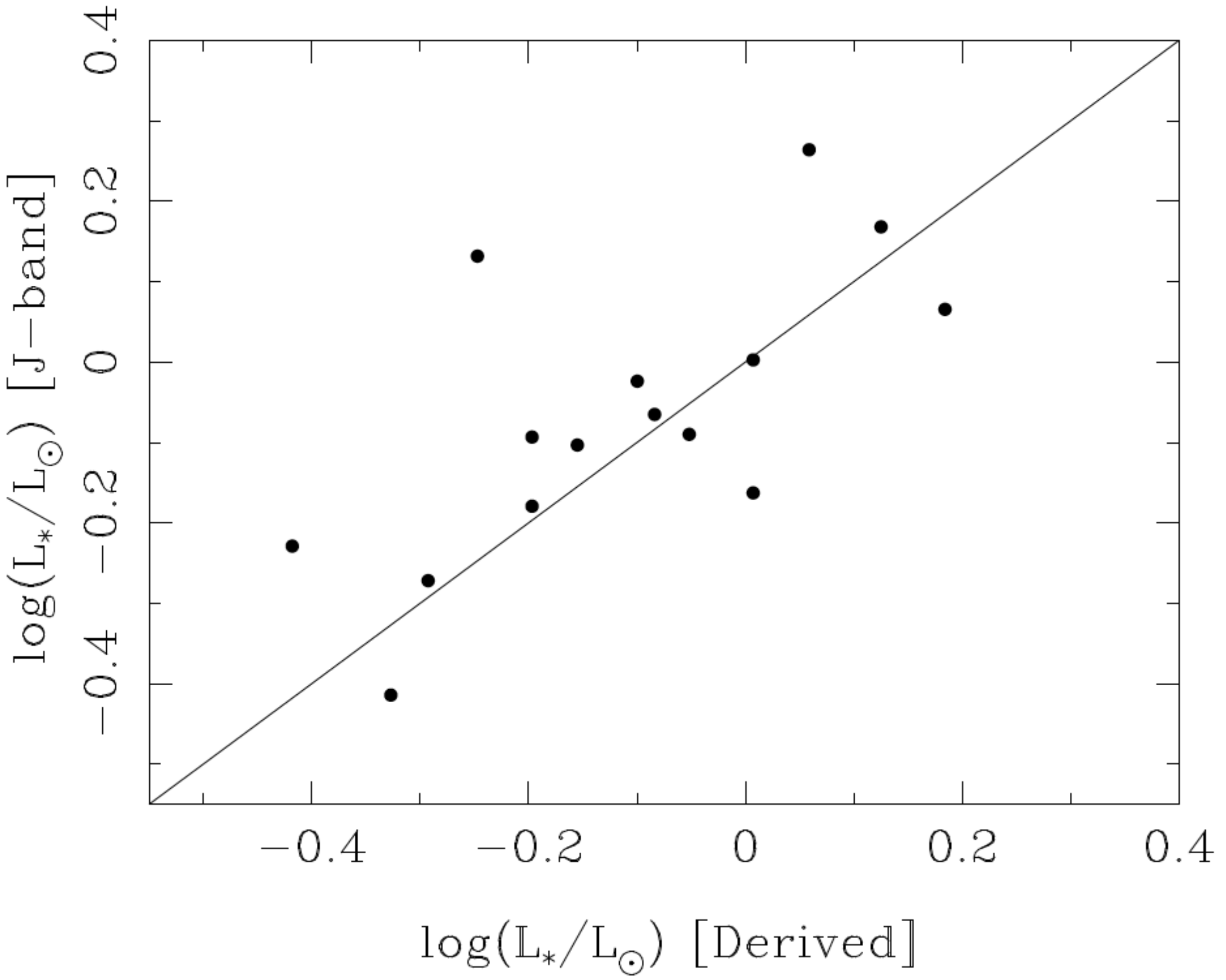
R_{in} is the disk's inner radius

- R_{in} is uncertain, depends on how the disk is coupled to the stellar magnetic field
- Typically: $R_{\mathrm{in}} = 5 - 6\ R_*$ (we'll take 5 R_*)
- Observed luminosity also depends on the inclination of the star (factor of 2 difference!) We'll ignore this.

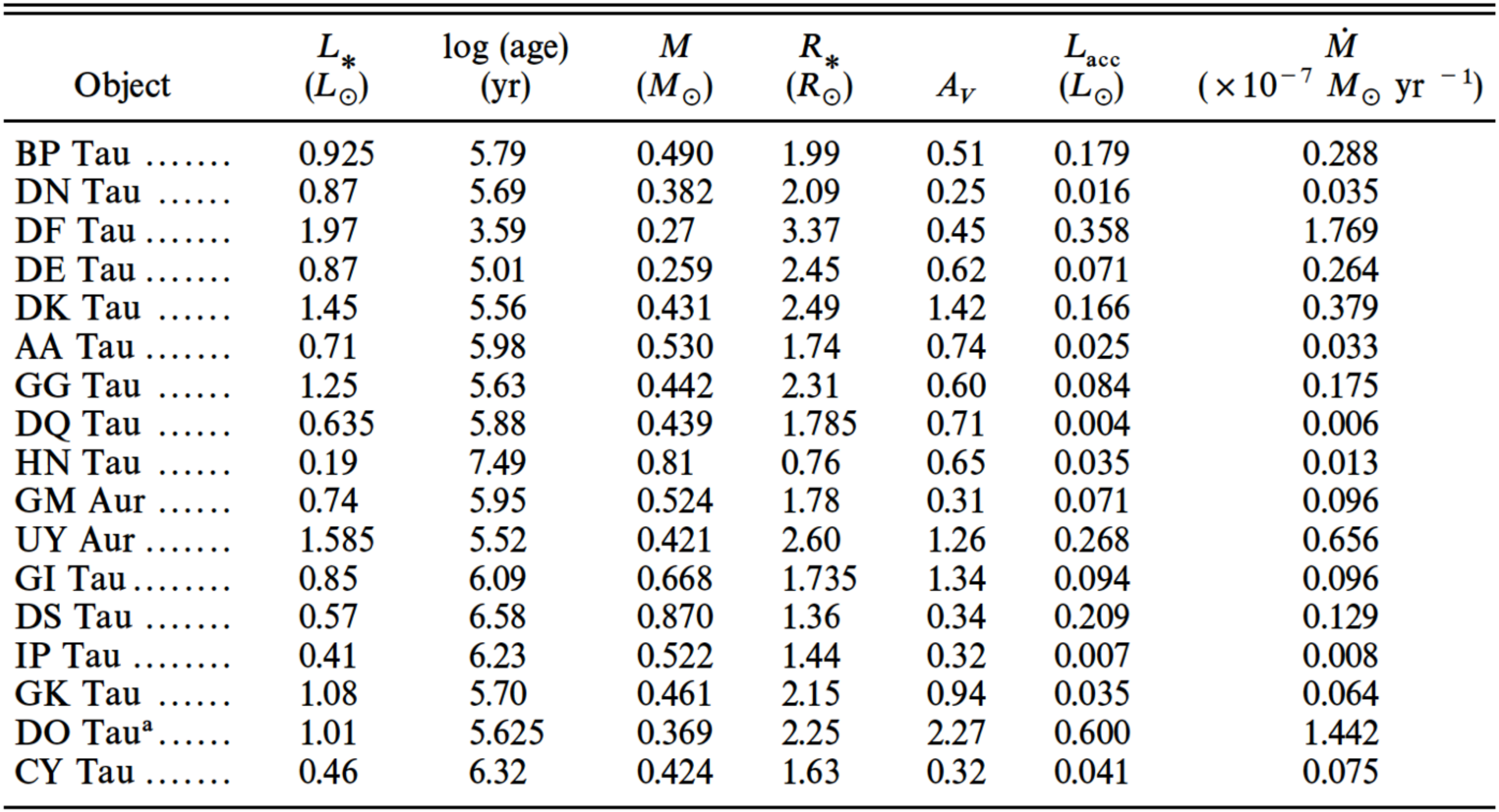
Mass accretion rates

- We need the mass and radius of the star. We estimate these from the stellar luminosity (without the excess!) and effective temperature.
- Stellar luminosity:
    - From fitted C_1 values
    - From A_V and observed *J* mag (and apply bolometric correction); we'll use the latter

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



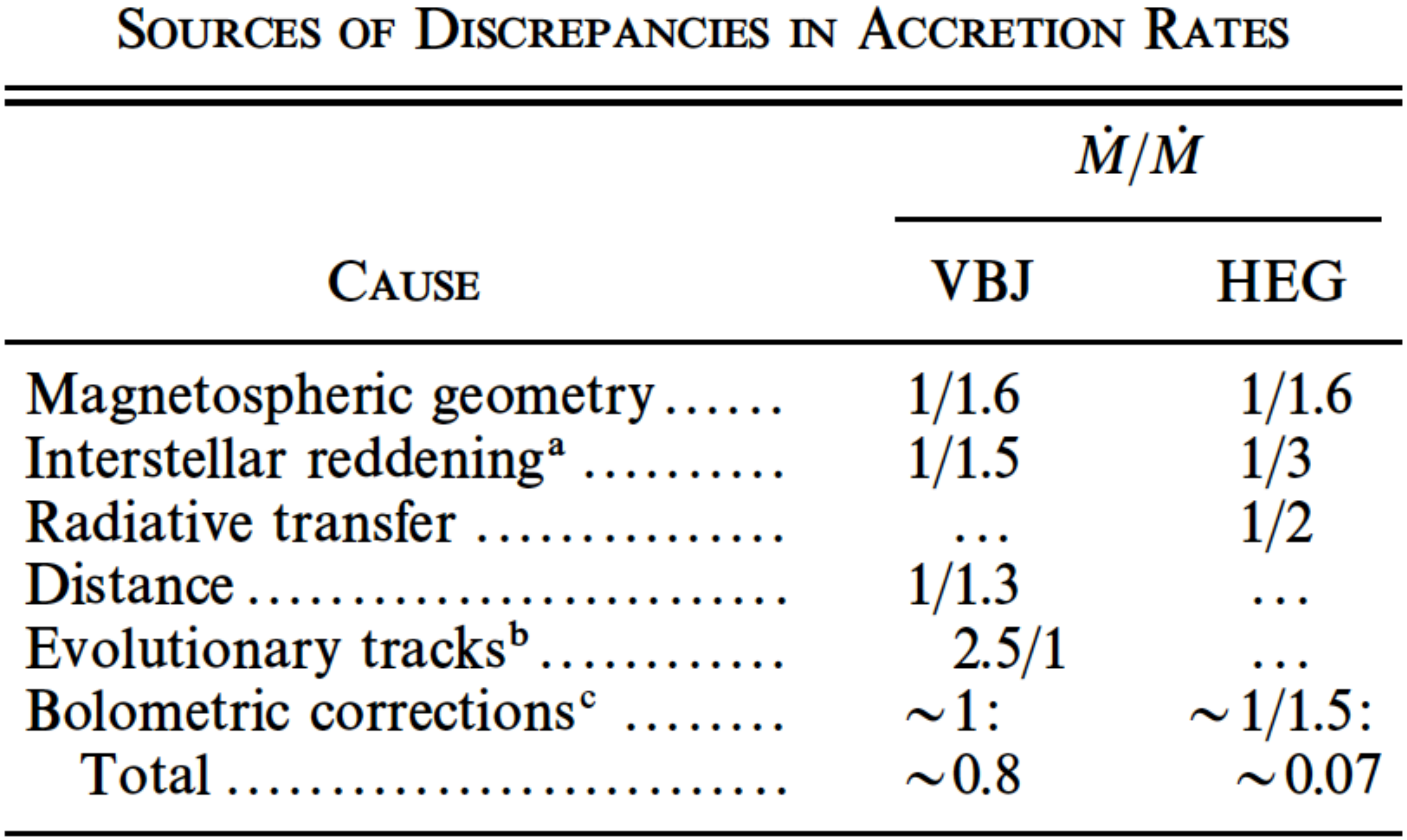
Accretion rate results



Object	L_* ($L_\odot$)	log (age) (yr)	M ($M_\odot$)	R_* ($R_\odot$)	A_V	L_{acc} ($L_\odot$)	$\dot{M}$ ($\times 10^{-7}$ $M_\odot$ yr $^{-1}$)
BP Tau	0.925	5.79	0.490	1.99	0.51	0.179	0.288
DN Tau	0.87	5.69	0.382	2.09	0.25	0.016	0.035
DF Tau	1.97	3.59	0.27	3.37	0.45	0.358	1.769
DE Tau	0.87	5.01	0.259	2.45	0.62	0.071	0.264
DK Tau	1.45	5.56	0.431	2.49	1.42	0.166	0.379
AA Tau	0.71	5.98	0.530	1.74	0.74	0.025	0.033
GG Tau	1.25	5.63	0.442	2.31	0.60	0.084	0.175
DQ Tau	0.635	5.88	0.439	1.785	0.71	0.004	0.006
HN Tau	0.19	7.49	0.81	0.76	0.65	0.035	0.013
GM Aur	0.74	5.95	0.524	1.78	0.31	0.071	0.096
UY Aur	1.585	5.52	0.421	2.60	1.26	0.268	0.656
GI Tau	0.85	6.09	0.668	1.735	1.34	0.094	0.096
DS Tau	0.57	6.58	0.870	1.36	0.34	0.209	0.129
IP Tau	0.41	6.23	0.522	1.44	0.32	0.007	0.008
GK Tau	1.08	5.70	0.461	2.15	0.94	0.035	0.064
DO Tau[a]......	1.01	5.625	0.369	2.25	2.27	0.600	1.442
CY Tau	0.46	6.32	0.424	1.63	0.32	0.041	0.075

- Accretion rates span 2 orders of magnitude
- Typically few times 10^{-8} – 10^{-9} M_{Sun}/yr

Comparison with other work



SOURCES OF DISCREPANCIES IN ACCRETION RATES

CAUSE	$\dot{M}/\dot{M}$ VBJ	$\dot{M}/\dot{M}$ HEG
Magnetospheric geometry……	1/1.6	1/1.6
Interstellar reddening[a] ……….	1/1.5	1/3
Radiative transfer ……………	…	1/2
Distance ………………………	1/1.3	…
Evolutionary tracks[b]…………	2.5/1	…
Bolometric corrections[c] …….	~1:	~1/1.5:
Total ………………………	~0.8	~0.07

L_{acc} versus *U* mag

- Aim: to estimate the accretion rate of a T Tauri from broad-band photometry
- Excess emission dominates the observed flux at < 4500 Å (stellar flux drops)
- Relation between *U*-band (λ_{eff} = 3650 Å) brightness and excess luminosity is expected.
- Such a relation would provide a way to estimate L_{acc} for large samples quickly

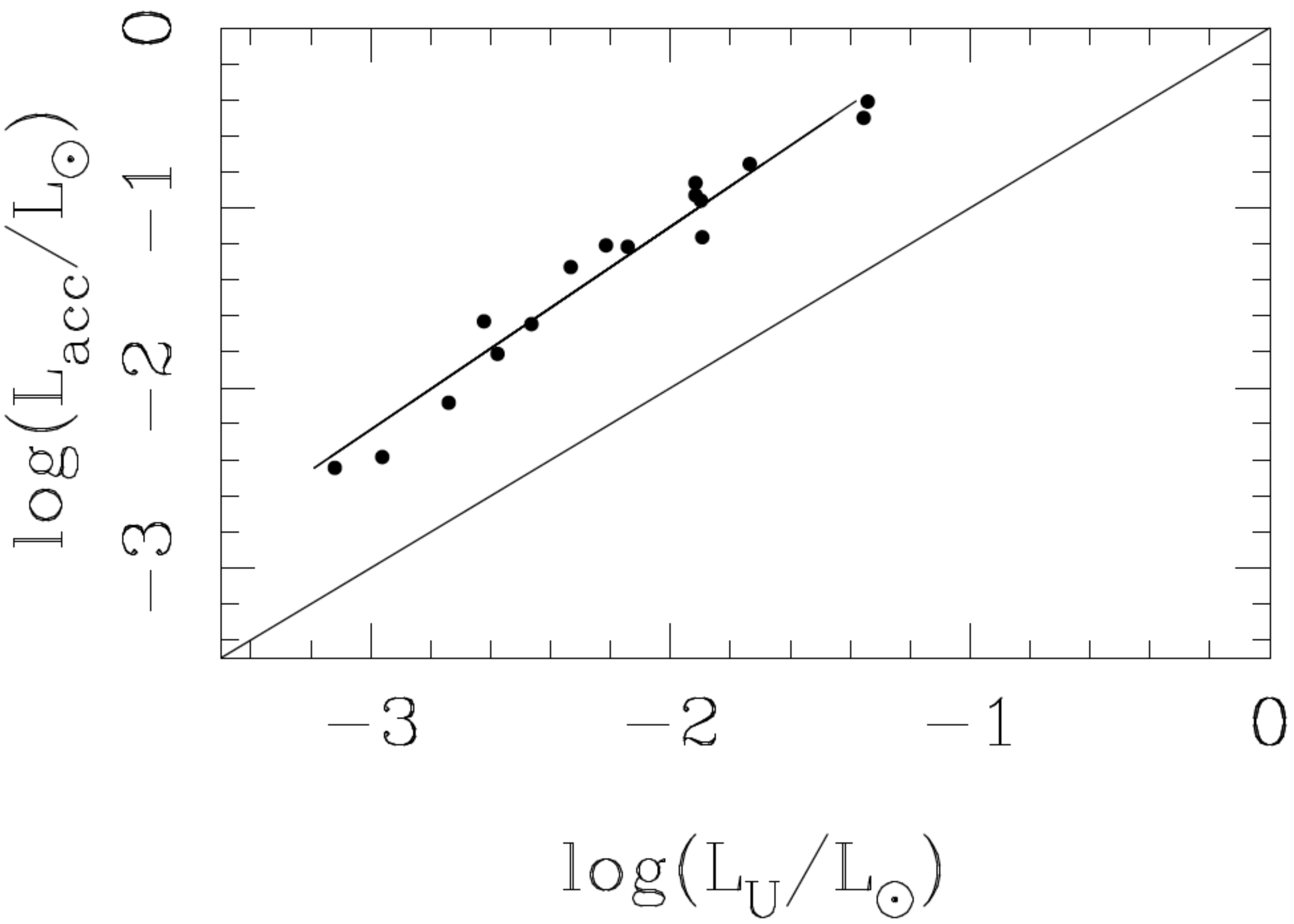
L_{acc} versus *U* mag

- L_U: dereddened *U*-band luminosity after the subtraction of the stellar photosphere
- L_U calculated in two ways:
  - synthesize from observed spectrum by taking into account the *U*-band filter profile
  - from published *U*-band magnitudes by converting them to flux
- Advantage of the first method: L_U and L_{acc} are simultaneous (intrinsic variability up to $\Delta U = 0.5$ mag)

L_{acc} versus *U* mag

- Synthetic *U*-band photometry → deredden it using the A_V we determined earlier
- Calculate the stellar contribution:
    - from the *I*-band brightness, using bolometric correction
    - use the value we determined earlier (based on *J* mag)
    - we'll use the former, though the latter may be more reliable
    - differences between the two are small

*L*acc versus *U* mag



$$\log\,(L_{\mathrm{acc}}/L_\odot) = 1.09^{+0.04}_{-0.18}\,\log\,(L_U/L_\odot) + 0.98^{+0.02}_{-0.07}$$

A_V for T Tauri stars?

- Conclusion: if the extinction is known and the stellar spectral type is known, accretion luminosity (and accretion rate) can be derived from broadband photometry.
- How to derive reliable A_V for T Tauri stars?
- The *B*−*V* color underestimates the extinction of veiled stars

$$(m_j - m_i)_0 - (m_j - m_i)_{\mathrm{obj}} = \frac{1}{R_{ji}} A_V + \log\left(\frac{1 + r_j}{1 + r_i}\right)$$

- Amount of veiling + difference in veiling between the two color bands → *V*−*R* is better

Summary

- We presented spectrophotometric data for 29 T Tauri stars in Taurus-Auriga in the 3200 − 5400 Å range
- For 17 stars that show modest veiling, we determined the interstellar extinction and the accretion rate
- Accretion rates typically range between $10^{-7} - 10^{-9}$ M_{Sun}/yr
- We found a very tight correlation between the U-band luminosity and total accretion luminosity
- Interstellar extinction is best calculated from $V-R$ color