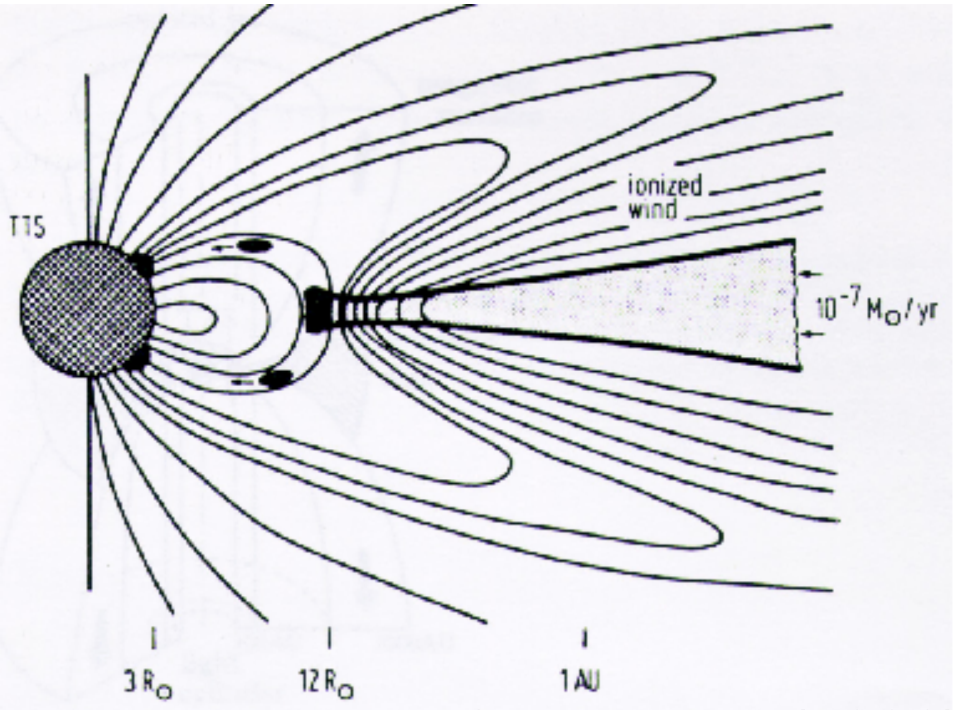
Accretion rates and accretion tracers of Herbig AeBe stars

Mendigutía et al. 2011
A&A 535, A99

Magnetospheric accretion



Camenzind (1990)

- For T Tauri stars: accepted paradigm
- Inner disk is truncated
- Matter is accelerated through magnetic field lines
- Hot accretion shocks on the stellar surface
- Explains continuum excess, line veiling
- Modeling yields accretion rate estimates that correlate with spectroscopic features → spectral lines can be used as accretion rate tracers

Magnetospheric accretion

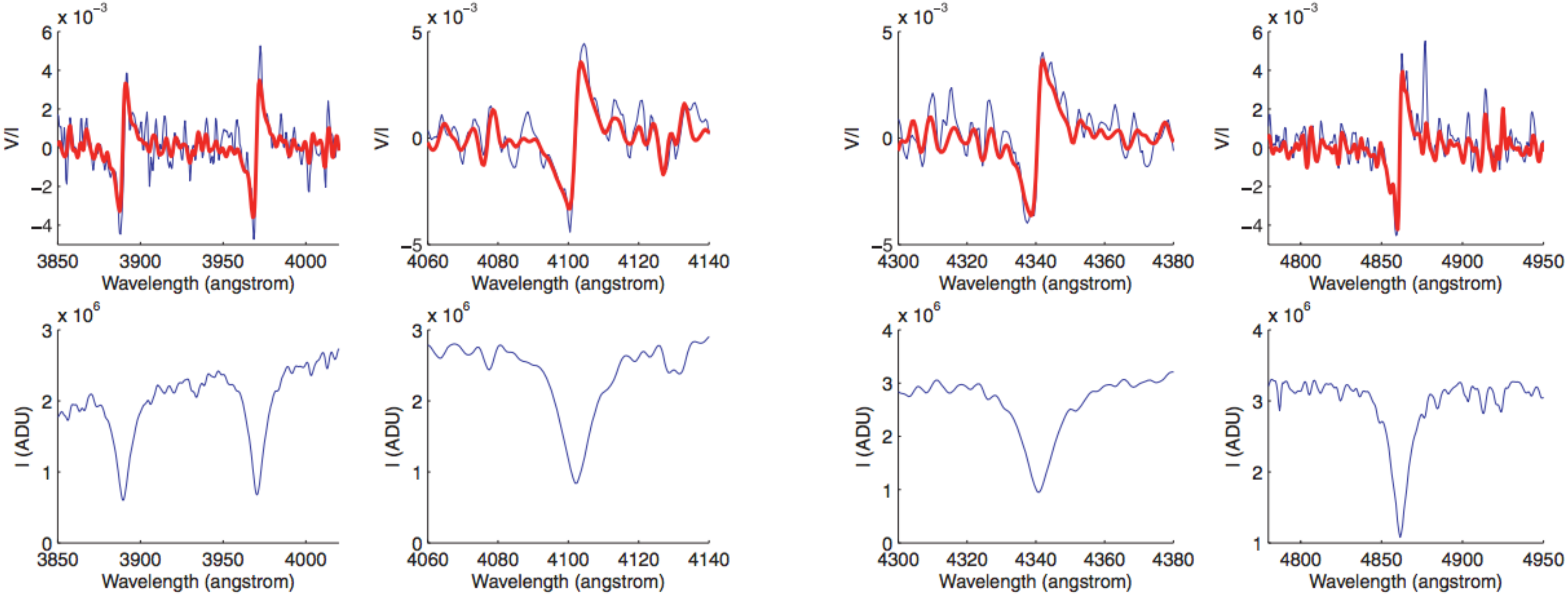
- What about Herbig Ae/Be stars?
- Herbig Ae/Be stars are the massive (1 – 10 M_{Sun}) counterparts of T Tauri stars
- How do they accrete? What's the difference?
- MS stars earlier than about A6 (2 M_{Sun}) have no convective zone → no dynamo → no magnetic field
- In young stars: convective zone may appear at earlier spectral types OR slowly decaying fossil field → may have weak magnetic fields
- MA may be expected in the intermediate mass regime

Magnetic field measurements

- **Magnetic field** is detected in some Herbig Ae stars (Wade et al. 2007, Hubrig et al. 2009): typically < 0.5 kG (cf. several kG for T Tauris)
- **Method**: measure the circular polarization of line emission due to the line-of sight component of the star's magnetic field
- **Measured quantity**: line intensity-weighted average over the stellar disk of the line-of-sight component, called "longitudinal field" or "effective field"

$$\frac{V}{I} = -g_{\mathrm{eff}}\, C_z\, \lambda^2\, \frac{1}{I}\, \frac{\mathrm{d}I}{\mathrm{d}\lambda}\, \langle B_z \rangle$$

Magnetic field measurements

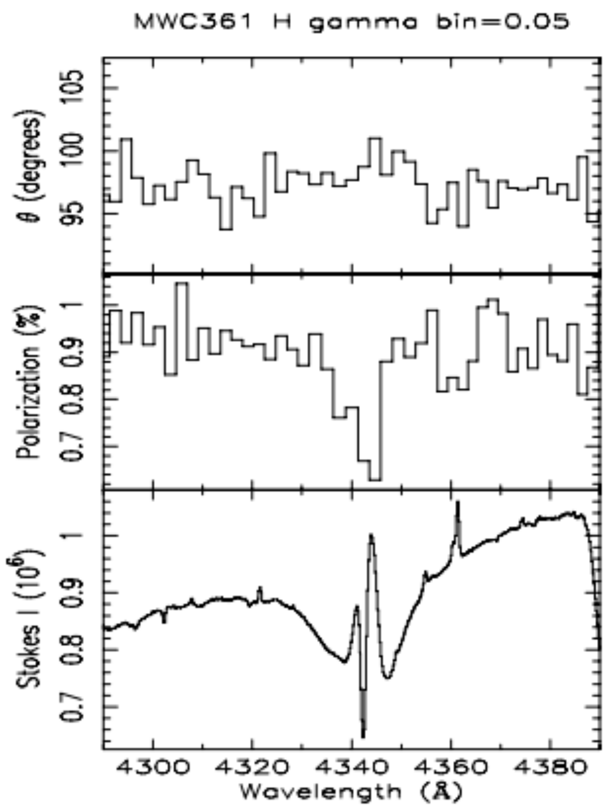


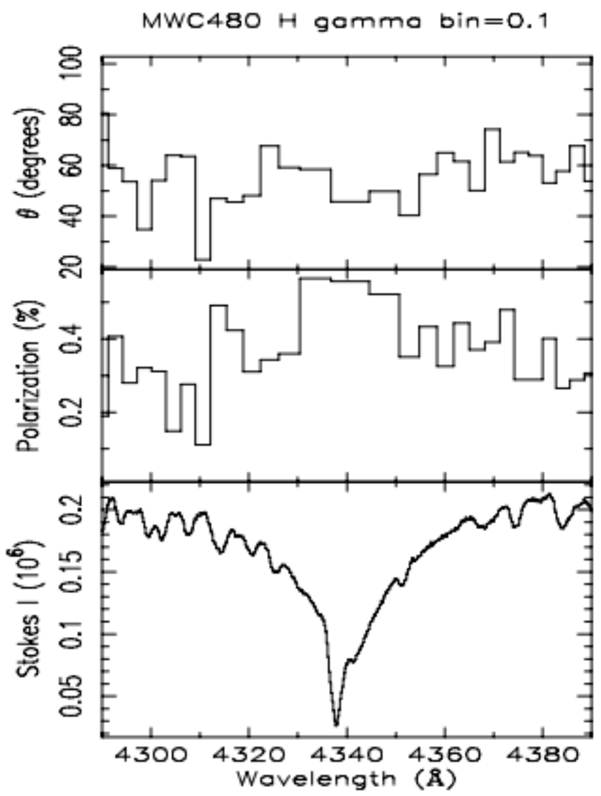
H8 CaH CaK+Hε Hδ Hγ Hβ

Wade et al. (2007)

Hints for MA in HAe's

- Spectropolarimetry of the Halpha line points to MA (Vink et al. 2002, 2003, Mottram et al. 2007):
  - HBe stars: Halpha is depolarized compared to the continuum
  - HAe and T Tauri stars: Halpha is polarized compared to the continuum

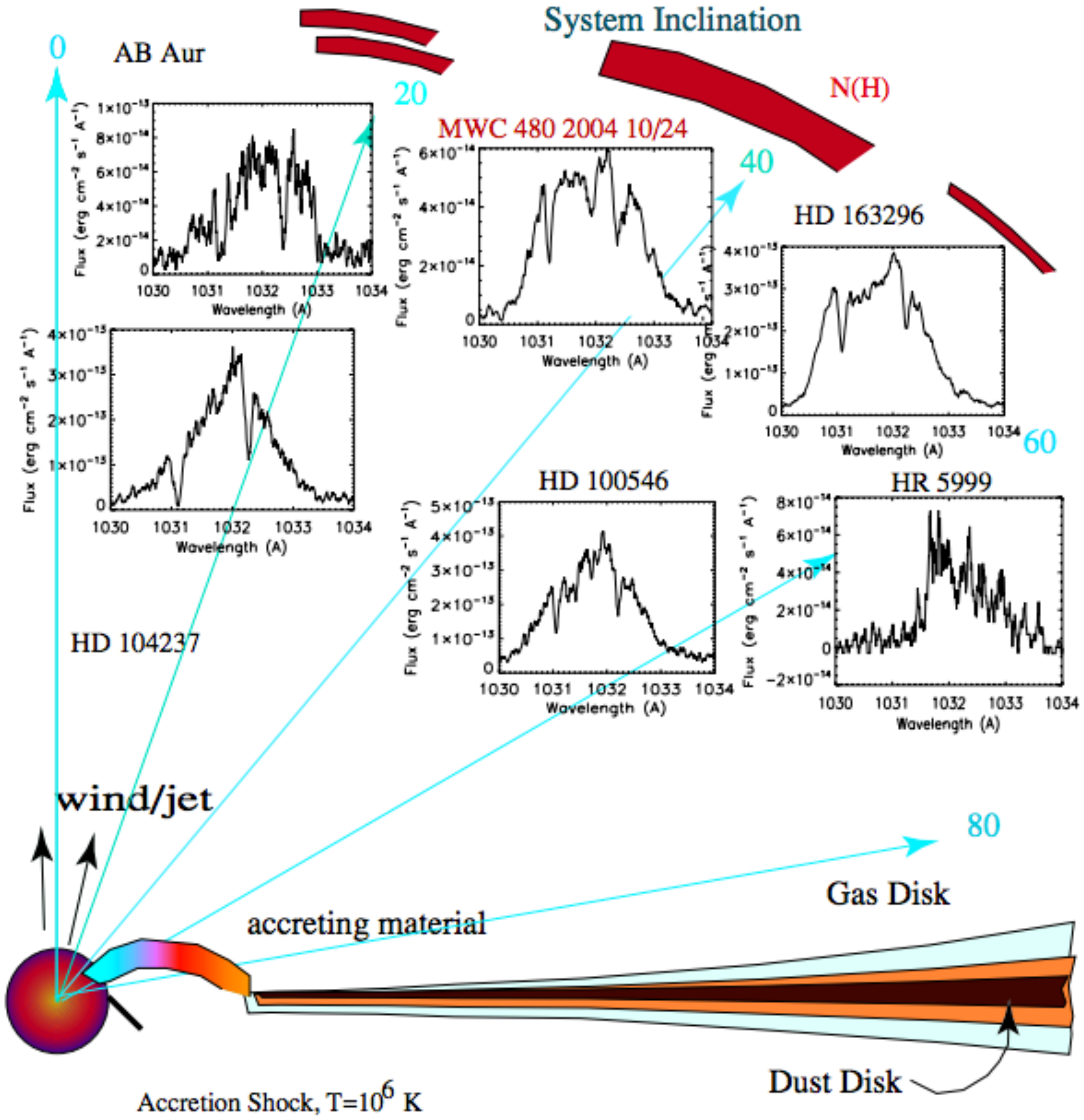




Mottram et al. (2007)

Hints for MA in HAe's

- Accretion goes through high latitude funnels (Grady et al. 2010, Brittain et al. 2009)
- High-velocity redshifted absorption point to infalling material at close to free-fall velocities (Natta et al. 2000, Mora et al. 2002, 2004)



Grady et al. (2010)

Intermediate mass T Tau's

- IMTTS: intermediate mass T Tauri star
- ETTS: early-type T Tauri star
- GTTS: G-type T Tauri star
- 1 −5 M_{Sun} mass range (same as Herbig Ae stars, but these are early K to late F)
- First modeling of MA for IMTTS: Calvet et al. 2004
- Result: there is a correlation between accretion rate and Brγ luminosity
- Problem with doing the same study for HAe stars: stellar photosphere and accretion shock both have the same temperature (~ 8000 K) → it's difficult to separate them, measure excess emission, and measure its luminosity

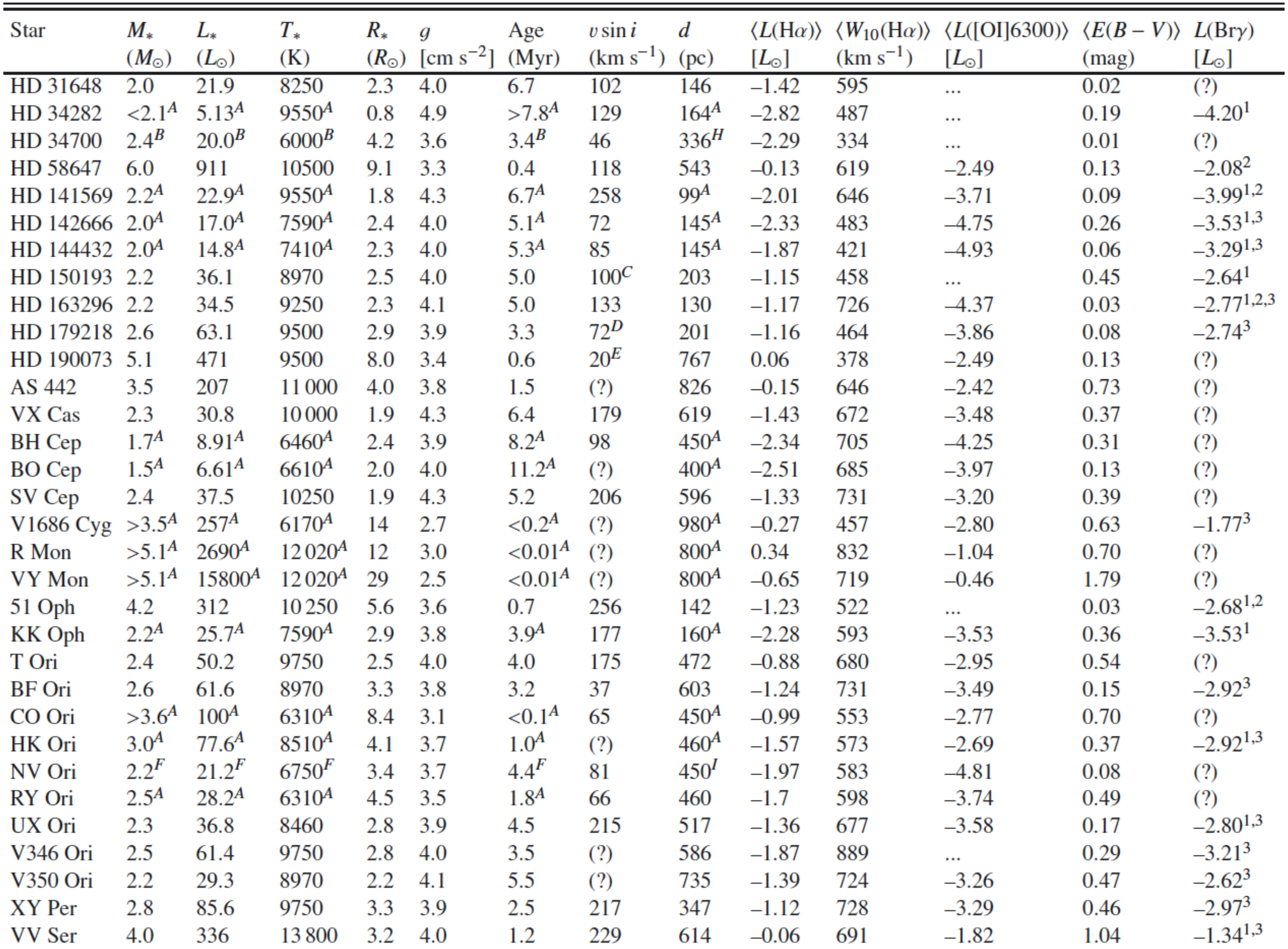
Aim of this paper

- Apply shock modeling within the context of MA
- Reproduce the strength of the Balmer excess for a sample of HAeBe stars
- Compare the accretion rates derived above with the strength of the Hα and [OI]6300 emission lines and the Brγ luminosity
- Estimate accretion rate variability from multi-epoch data

Sample and observations

- 38 stars: 28 HAeBe stars, 10 IMTTs (F−G type)
- All of them have IR excess (dusty disks)
- All of them show Hα emission (active accretion)
- Multi-epoch Hα and [OI]6300 spectra (mid-resolution, R~5000), multi-epoch UBV photometry, spectra and photometry taken on the same nights
- All of them show Hα emission (active accretion)
- Subtract the stellar photosphere, deredden
- Measured quantities: mean Hα luminosity, mean Hα 10% width, mean [OI]6300 luminosity
- Non-simultaneous Brγ luminosities are taken from the literature

Sample and observations



Star	M_* ($M_\odot$)	L_* ($L_\odot$)	T_* (K)	R_* ($R_\odot$)	g [cm s^{-2}]	Age (Myr)	$v \sin i$ (km s^{-1})	d (pc)	$\langle L(\mathrm{H}\alpha)\rangle$ [$L_\odot$]	$\langle W_{10}(\mathrm{H}\alpha)\rangle$ (km s^{-1})	$\langle L([\mathrm{OI}]6300)\rangle$ [$L_\odot$]	$\langle E(B-V)\rangle$ (mag)	$L(\mathrm{Br}\gamma)$ [$L_\odot$]
HD 31648	2.0	21.9	8250	2.3	4.0	6.7	102	146	–1.42	595	...	0.02	(?)
HD 34282	<2.1[A]	5.13[A]	9550[A]	0.8	4.9	>7.8[A]	129	164[A]	–2.82	487	...	0.19	–4.20[1]
HD 34700	2.4[B]	20.0[B]	6000[B]	4.2	3.6	3.4[B]	46	336[H]	–2.29	334	...	0.01	(?)
HD 58647	6.0	911	10500	9.1	3.3	0.4	118	543	–0.13	619	–2.49	0.13	–2.08[2]
HD 141569	2.2[A]	22.9[A]	9550[A]	1.8	4.3	6.7[A]	258	99[A]	–2.01	646	–3.71	0.09	–3.99[1,2]
HD 142666	2.0[A]	17.0[A]	7590[A]	2.4	4.0	5.1[A]	72	145[A]	–2.33	483	–4.75	0.26	–3.53[1,3]
HD 144432	2.0[A]	14.8[A]	7410[A]	2.3	4.0	5.3[A]	85	145[A]	–1.87	421	–4.93	0.06	–3.29[1,3]
HD 150193	2.2	36.1	8970	2.5	4.0	5.0	100[C]	203	–1.15	458	...	0.45	–2.64[1]
HD 163296	2.2	34.5	9250	2.3	4.1	5.0	133	130	–1.17	726	–4.37	0.03	–2.77[1,2,3]
HD 179218	2.6	63.1	9500	2.9	3.9	3.3	72[D]	201	–1.16	464	–3.86	0.08	–2.74[3]
HD 190073	5.1	471	9500	8.0	3.4	0.6	20[E]	767	0.06	378	–2.49	0.13	(?)
AS 442	3.5	207	11 000	4.0	3.8	1.5	(?)	826	–0.15	646	–2.42	0.73	(?)
VX Cas	2.3	30.8	10 000	1.9	4.3	6.4	179	619	–1.43	672	–3.48	0.37	(?)
BH Cep	1.7[A]	8.91[A]	6460[A]	2.4	3.9	8.2[A]	98	450[A]	–2.34	705	–4.25	0.31	(?)
BO Cep	1.5[A]	6.61[A]	6610[A]	2.0	4.0	11.2[A]	(?)	400[A]	–2.51	685	–3.97	0.13	(?)
SV Cep	2.4	37.5	10250	1.9	4.3	5.2	206	596	–1.33	731	–3.20	0.39	(?)
V1686 Cyg	>3.5[A]	257[A]	6170[A]	14	2.7	<0.2[A]	(?)	980[A]	–0.27	457	–2.80	0.63	–1.77[3]
R Mon	>5.1[A]	2690[A]	12 020[A]	12	3.0	<0.01[A]	(?)	800[A]	0.34	832	–1.04	0.70	(?)
VY Mon	>5.1[A]	15800[A]	12 020[A]	29	2.5	<0.01[A]	(?)	800[A]	–0.65	719	–0.46	1.79	(?)
51 Oph	4.2	312	10 250	5.6	3.6	0.7	256	142	–1.23	522	...	0.03	–2.68[1,2]
KK Oph	2.2[A]	25.7[A]	7590[A]	2.9	3.8	3.9[A]	177	160[A]	–2.28	593	–3.53	0.36	–3.53[1]
T Ori	2.4	50.2	9750	2.5	4.0	4.0	175	472	–0.88	680	–2.95	0.54	(?)
BF Ori	2.6	61.6	8970	3.3	3.8	3.2	37	603	–1.24	731	–3.49	0.15	–2.92[3]
CO Ori	>3.6[A]	100[A]	6310[A]	8.4	3.1	<0.1[A]	65	450[A]	–0.99	553	–2.77	0.70	(?)
HK Ori	3.0[A]	77.6[A]	8510[A]	4.1	3.7	1.0[A]	(?)	460[A]	–1.57	573	–2.69	0.37	–2.92[1,3]
NV Ori	2.2[F]	21.2[F]	6750[F]	3.4	3.7	4.4[F]	81	450[I]	–1.97	583	–4.81	0.08	(?)
RY Ori	2.5[A]	28.2[A]	6310[A]	4.5	3.5	1.8[A]	66	460	–1.7	598	–3.74	0.49	(?)
UX Ori	2.3	36.8	8460	2.8	3.9	4.5	215	517	–1.36	677	–3.58	0.17	–2.80[1,3]
V346 Ori	2.5	61.4	9750	2.8	4.0	3.5	(?)	586	–1.87	889	...	0.29	–3.21[3]
V350 Ori	2.2	29.3	8970	2.2	4.1	5.5	(?)	735	–1.39	724	–3.26	0.47	–2.62[3]
XY Per	2.8	85.6	9750	3.3	3.9	2.5	217	347	–1.12	728	–3.29	0.46	–2.97[3]
VV Ser	4.0	336	13 800	3.2	4.0	1.2	229	614	–0.06	691	–1.82	1.04	–1.34[1,3]

Description of the model

- Accreting HAeBe stars show excess continuum compared to MS stars with similar spectral type in the Balmer discontinuity region.
- We model this Balmer excess to provide estimate of the accretion rate
- Total flux per wavelength unit: $F_\lambda = f F_\lambda^{\rm col} + (1 - f) F_\lambda^{\rm phot}$

f: filling factor (portion of the stellar surface covered by accretion columns)

$F^{\rm phot}$: undisturbed stellar photosphere (Kurucz model with appropriate T_* and log g)

$F^{\rm col}$: flux from the column (BB with $T_{\rm col}$: $F_{\rm col} = \sigma T_{\rm col}^4$)

Description of the model

- Total luminosity of the column:

$$L^{\mathrm{col}} = F^{\mathrm{col}} A = \left(\mathcal{F} + F^{\mathrm{phot}}\right) \times A = \xi L_{\mathrm{acc}} + F^{\mathrm{phot}} A$$

  F: inward flux of energy carried by the accretion column

  $F^{\mathrm{phot}} \times A$: outward stellar radiation below the accretion shock

  $A = f 4\pi R_*^2$

  $L_{\mathrm{acc}} = G M_* \dot{M}_{\mathrm{acc}} / R_*$

  $\xi = 1 - R_*/R_{\mathrm{i}}$

  R_{i} is the disk truncation radius

- Once F and R_{i} are fixed, T_{col} and f can be calculated for a given set of stellar and accretion parameters

Description of the model

- How to fix R_i?
- It should be less than the corotation radius: $R_{\rm cor} = \left(\frac{GM_*R_*^2}{v_*^2}\right)^{1/3}$

  v_* is the stellar rotational velocity (from $v \sin i$)
- Once $T_{\rm col}$ and f are determined, the total flux as a function of wavelength can be calculated

$M_* = 2.5\ M_{\rm Sun}$

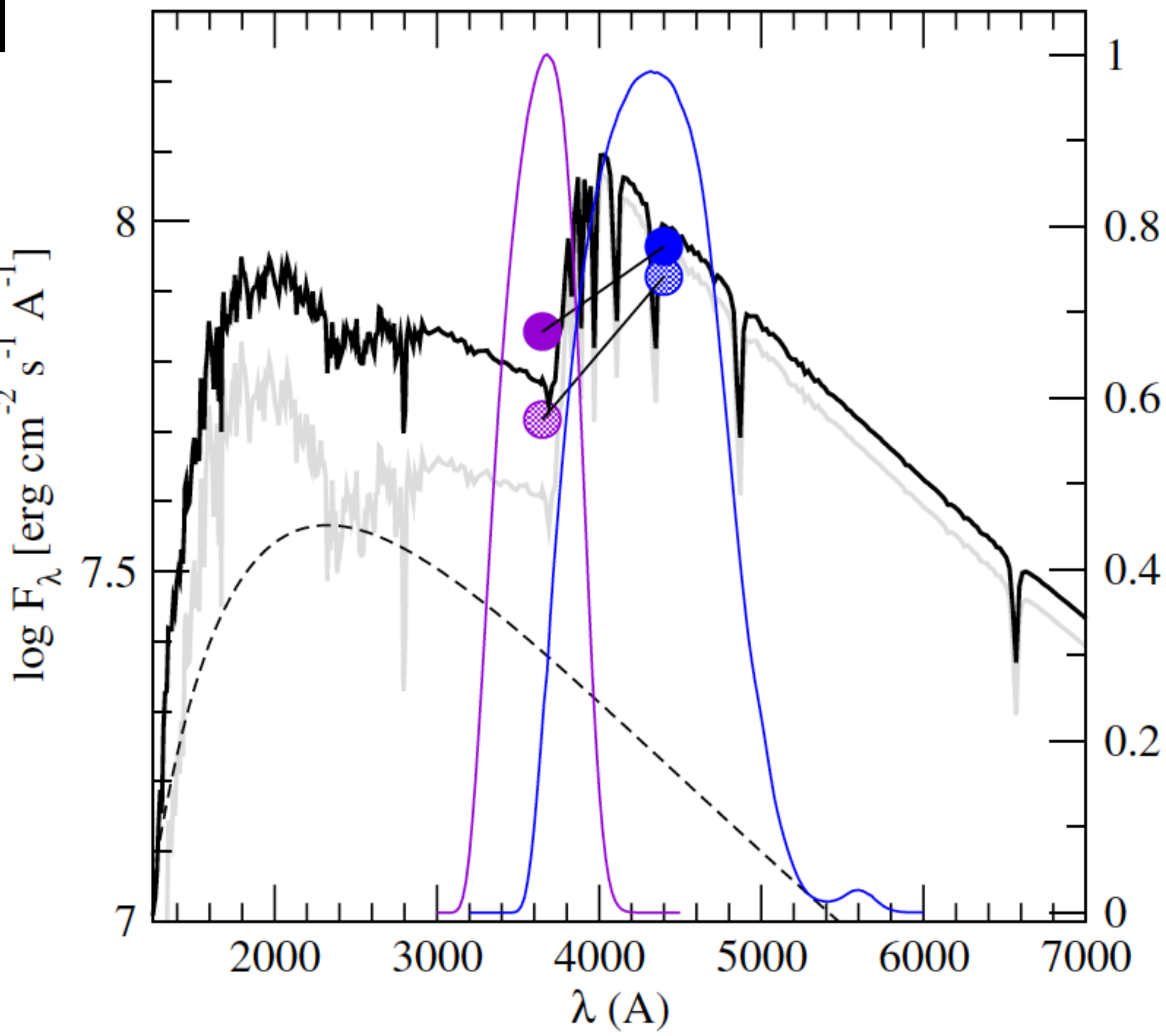
$R_* = 2.6\ R_{\rm Sun}$

$T_* = 9000$ K

$F = 10^{12}$ erg/cm^2/s

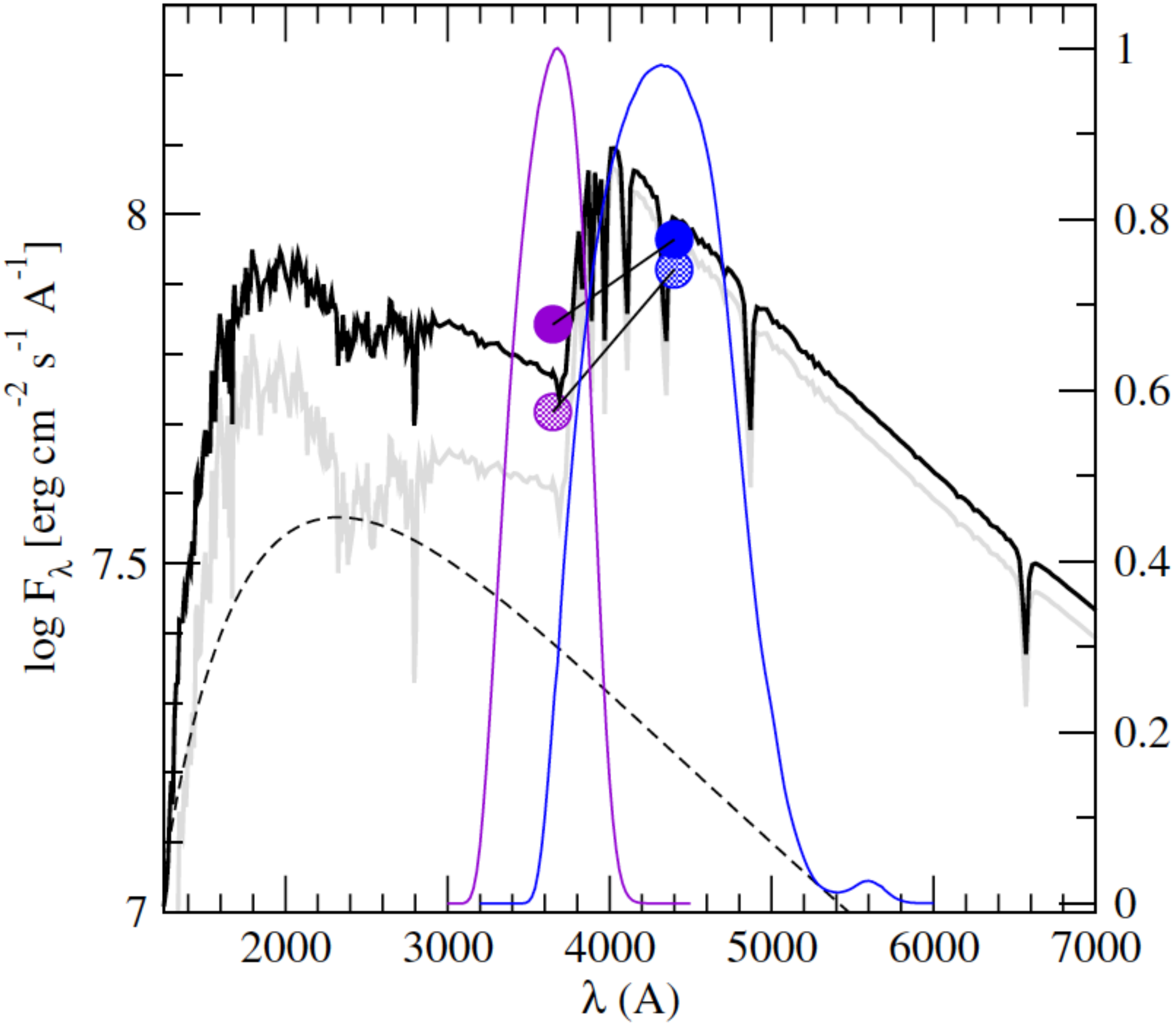
$T_{\rm col}$=12 470 K

$R_i = 2.5\ R_*$



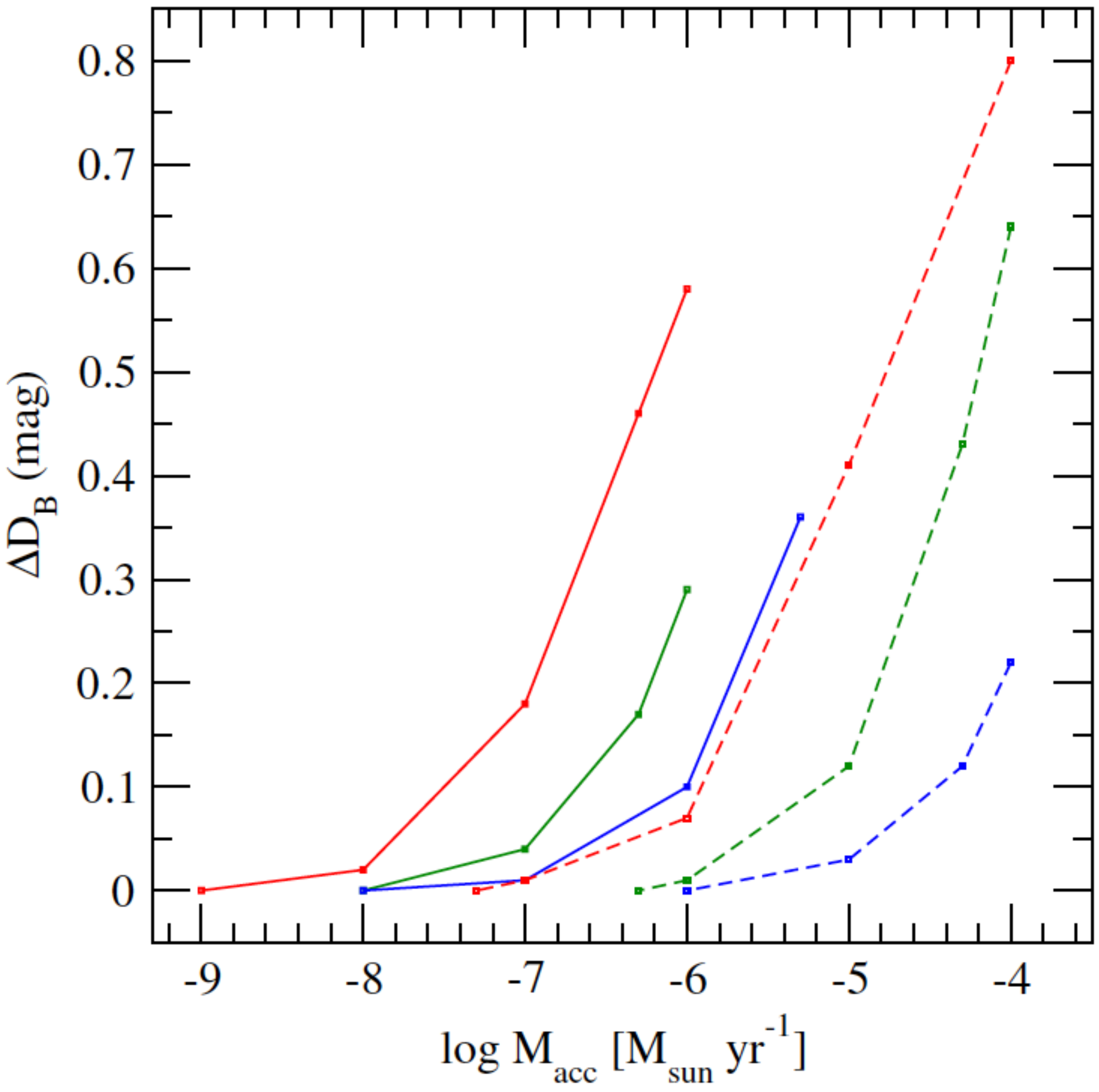
Balmer excess

- For a given set of stellar and accreting parameters, the excess in the Balmer discontinuity is defined as: $\Delta D_B = (U - B)_{\mathrm{phot}} - (U - B)_{\mathrm{total}}$
- Calculated from the synthetic spectra by taking into account the filter profiles

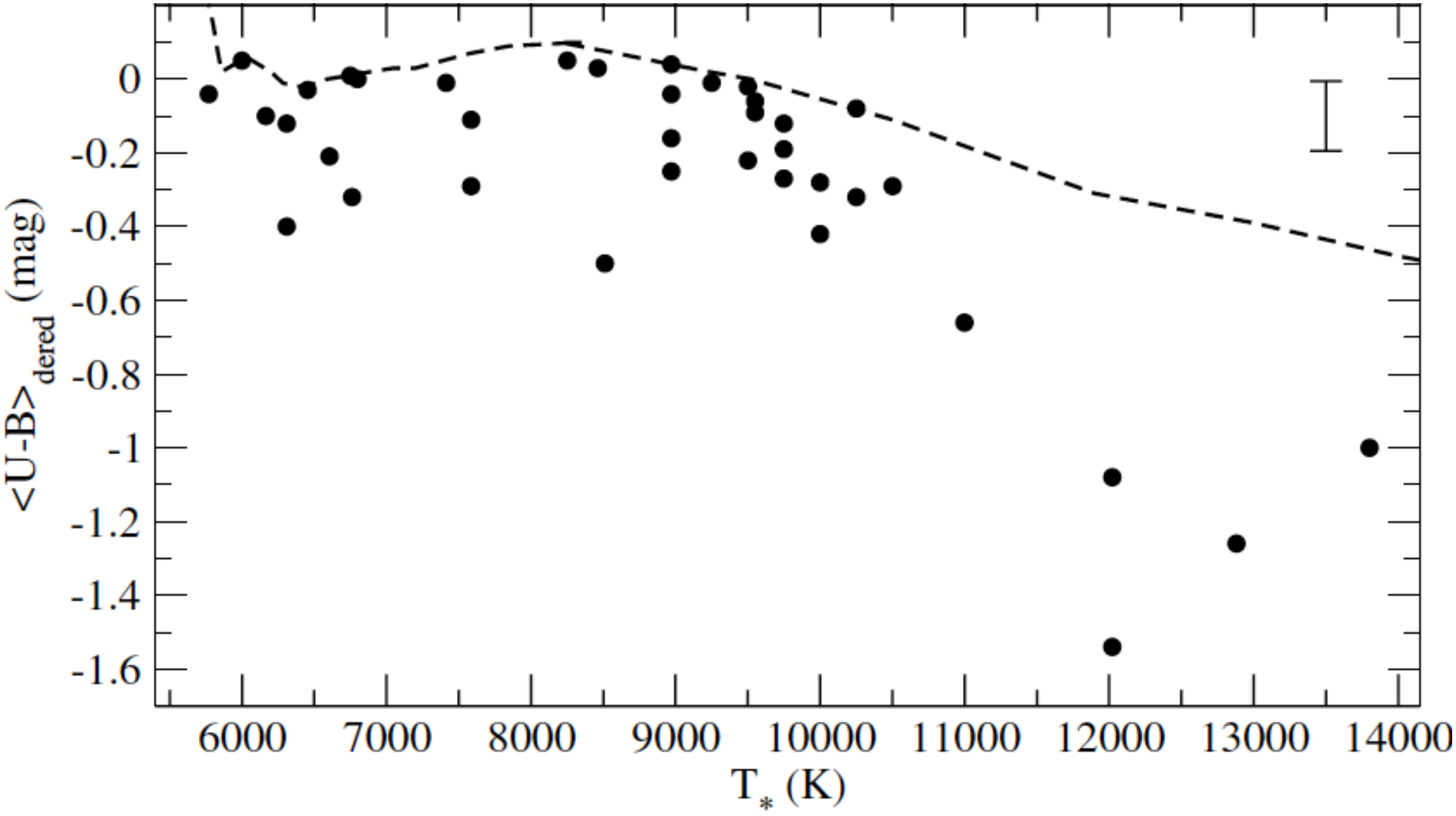


Balmer excess

- Red: T_* = 6500 K
- Green: T_* = 9000 K
- Blue: T_* = 12 500 K
- Solid lines: log g = 4.0
- Dashed lines: log g = 3.0



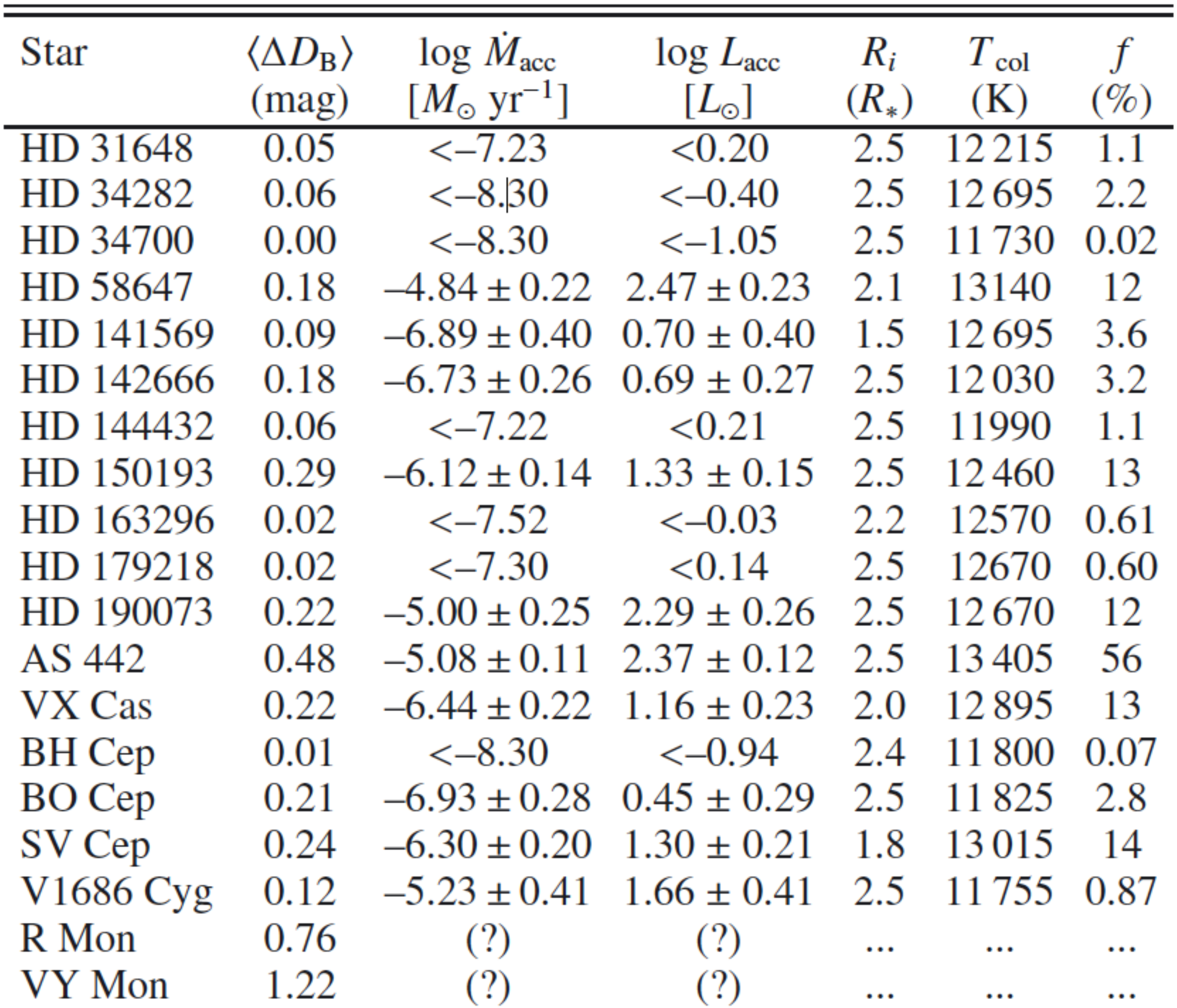
Observed mean U−B colors



$\langle U{-}B\rangle_{\rm dered}$ is the dereddened mean color from the observations in Oudmaijer et al. (2001)

$\langle U{-}B\rangle_0$ is the intrinsic color from Kenyon & Hartmann (1995)

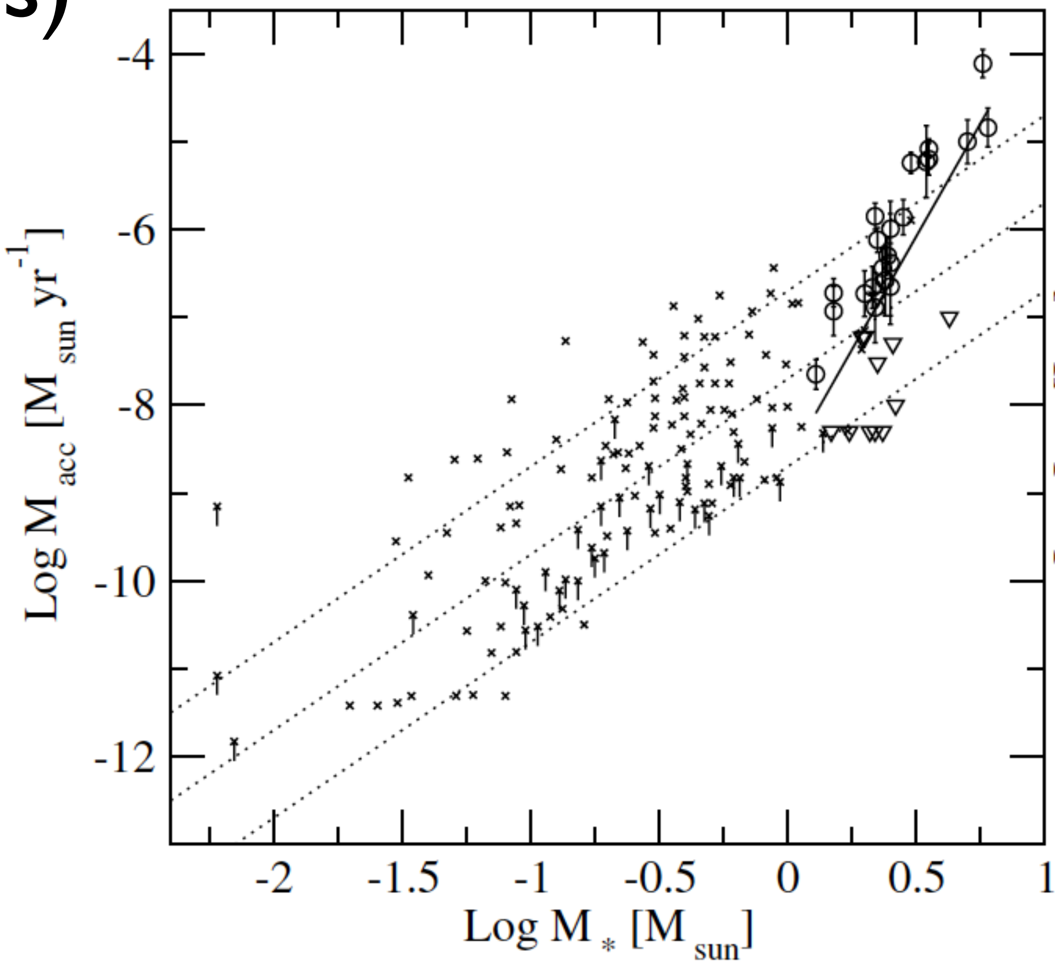
Results

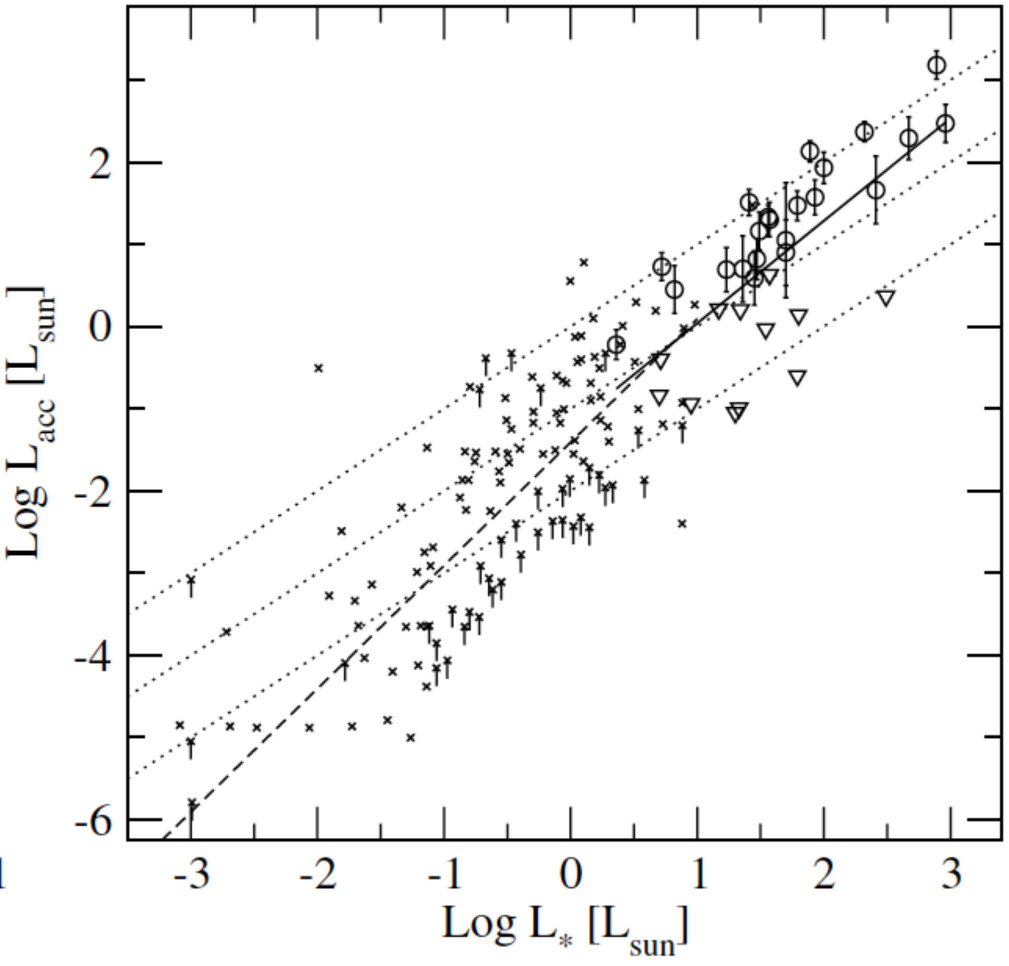


Star	$\langle \Delta D_{\mathrm{B}} \rangle$ (mag)	$\log \dot{M}_{\mathrm{acc}}$ $[M_\odot\ \mathrm{yr}^{-1}]$	$\log L_{\mathrm{acc}}$ $[L_\odot]$	R_i (R_*)	T_{col} (K)	f (%)
HD 31648	0.05	<–7.23	<0.20	2.5	12 215	1.1
HD 34282	0.06	<–8.30	<–0.40	2.5	12 695	2.2
HD 34700	0.00	<–8.30	<–1.05	2.5	11 730	0.02
HD 58647	0.18	–4.84 ± 0.22	2.47 ± 0.23	2.1	13140	12
HD 141569	0.09	–6.89 ± 0.40	0.70 ± 0.40	1.5	12 695	3.6
HD 142666	0.18	–6.73 ± 0.26	0.69 ± 0.27	2.5	12 030	3.2
HD 144432	0.06	<–7.22	<0.21	2.5	11990	1.1
HD 150193	0.29	–6.12 ± 0.14	1.33 ± 0.15	2.5	12 460	13
HD 163296	0.02	<–7.52	<–0.03	2.2	12570	0.61
HD 179218	0.02	<–7.30	<0.14	2.5	12670	0.60
HD 190073	0.22	–5.00 ± 0.25	2.29 ± 0.26	2.5	12 670	12
AS 442	0.48	–5.08 ± 0.11	2.37 ± 0.12	2.5	13 405	56
VX Cas	0.22	–6.44 ± 0.22	1.16 ± 0.23	2.0	12 895	13
BH Cep	0.01	<–8.30	<–0.94	2.4	11 800	0.07
BO Cep	0.21	–6.93 ± 0.28	0.45 ± 0.29	2.5	11 825	2.8
SV Cep	0.24	–6.30 ± 0.20	1.30 ± 0.21	1.8	13 015	14
V1686 Cyg	0.12	–5.23 ± 0.41	1.66 ± 0.41	2.5	11 755	0.87
R Mon	0.76	(?)	(?)	...	...	...
VY Mon	1.22	(?)	(?)	...	...	...

Correlations

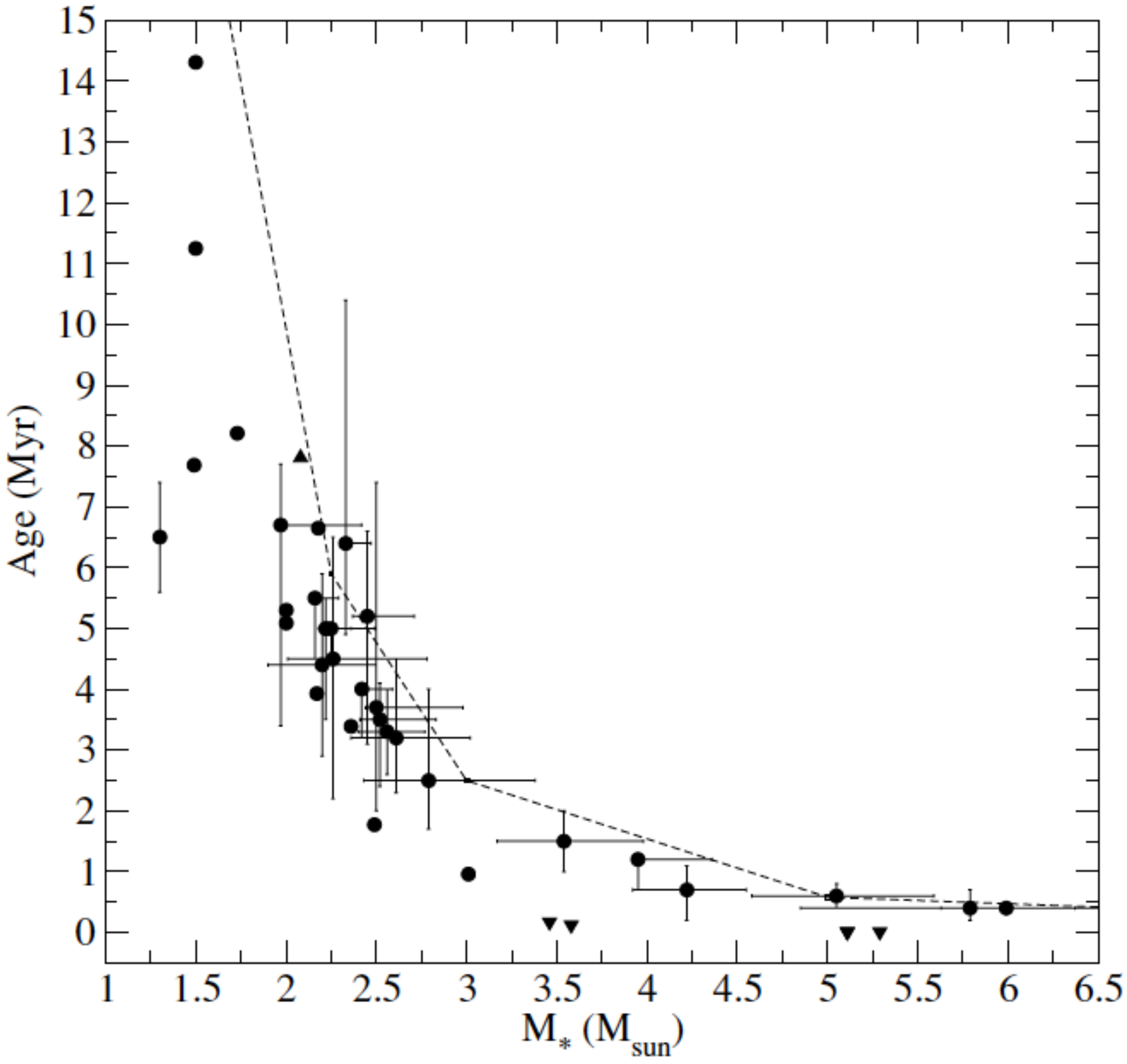
- Missing parameters: for some stars, the Balmer excess is so high that we would need accretion rates on the order of $10^{-2} - 10^{-1}$ M_{Sun}/yr with $F \gg 10^{12}$ erg/cm^2/s and $f = 1$
- Median accretion rate: 2 x 10^{-7} M_{Sun}/yr
- $\dot{M}_{acc} \sim M_*^5$, $L_{acc} \sim L_*^{1.2}$ ($\dot{M}_{acc} \sim M_*^2$, $L_{acc} \sim L_*^{1.5}$ for lower mass stars)





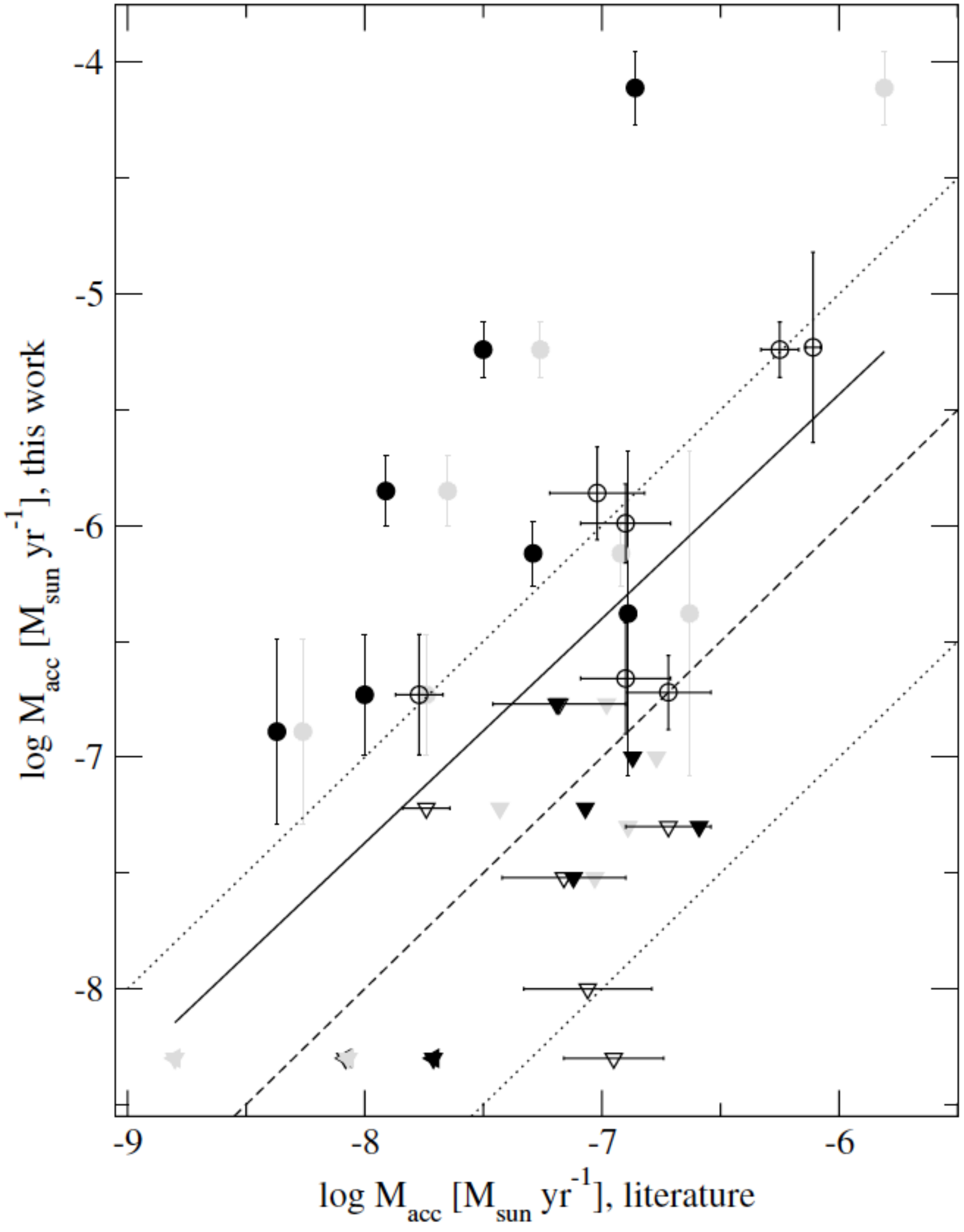
$\dot{M}_{acc}$ vs. M_*

- $\dot{M}_{acc} \sim M_*^5$
- Steep slope is related to faster evolution of higher mass stars:
- Less massive stars tend to be older → accrete less
- More massive stars tend to be younger → accrete more

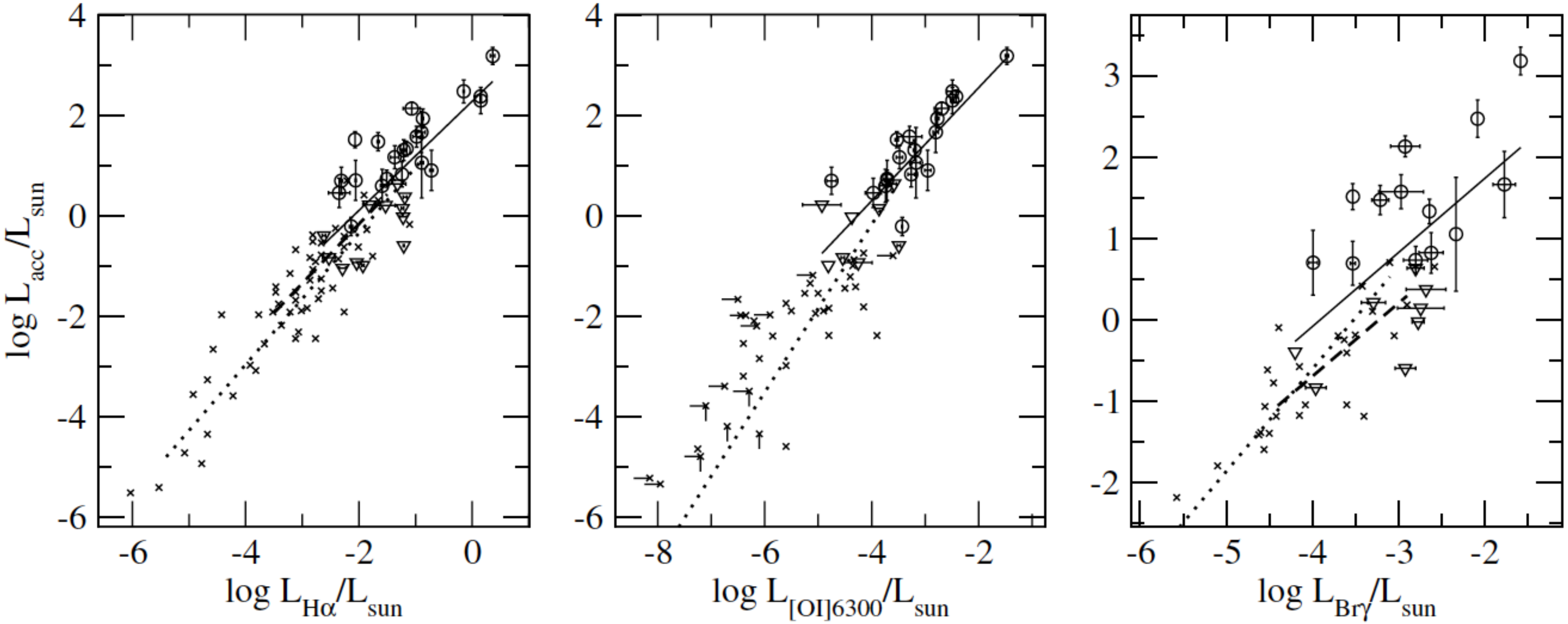


Comparison to prev. results

- Empirical calibration between accretion luminosity and Br γ luminosity for IMTTs (Calvet et al. 2004)
- Garcia Lopez et al. (2006) used this for Herbig stars to derive accretion rates
- Good linear correlation between Garcia Lopez and this work



Accretion tracers



Herbig stars

T Tauri stars

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 2.28(\pm0.25) + 1.09(\pm0.16) \times \log\left(\frac{L_{\rm H\alpha}}{L_\odot}\right)$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 4.80(\pm0.50) + 1.13(\pm0.14) \times \log\left(\frac{L_{\rm [OI]6300}}{L_\odot}\right)$$

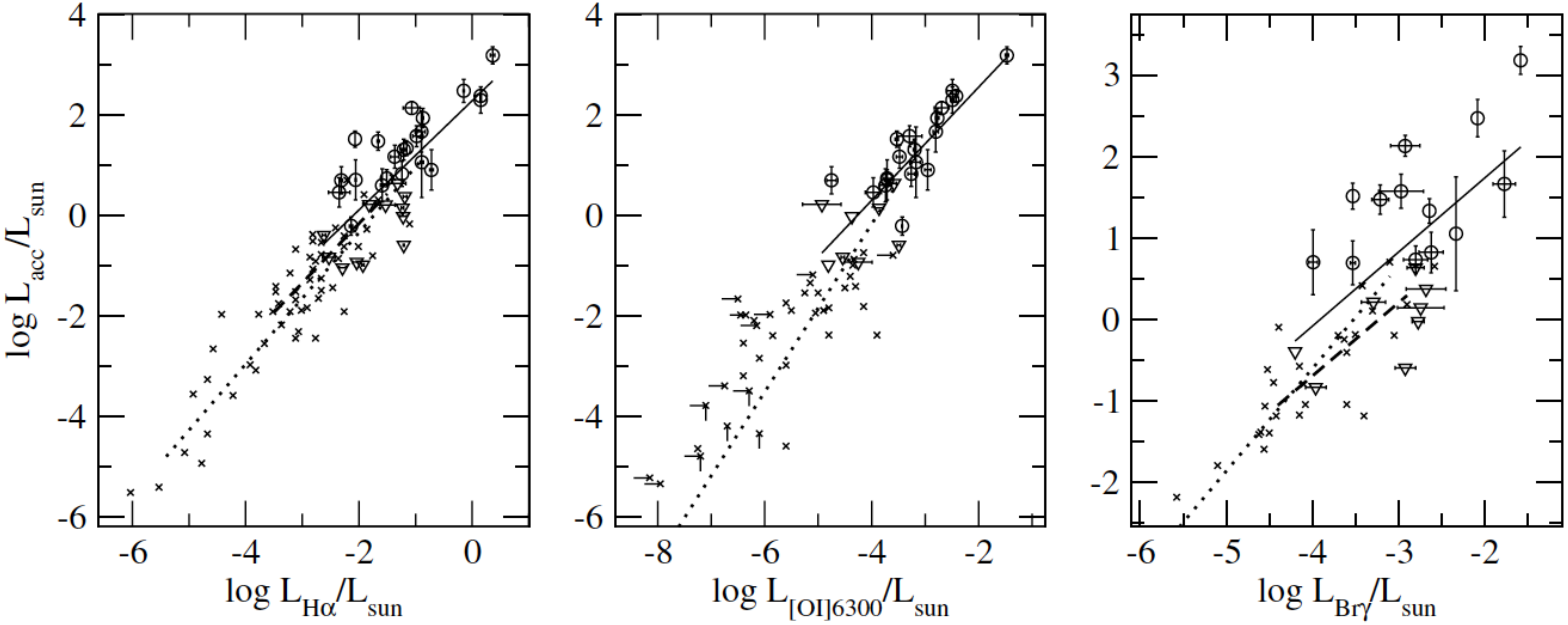
$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 3.55(\pm0.80) + 0.91(\pm0.27) \times \log\left(\frac{L_{\rm Br\gamma}}{L_\odot}\right).$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 2.27(\pm0.70) + 1.31(\pm0.16) \times \log\left(\frac{L_{\rm H\alpha}}{L_\odot}\right)$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 6.50(\pm2.18) + 1.67(\pm0.28) \times \log\left(\frac{L_{\rm [OI]6300}}{L_\odot}\right)$$

$$\log\left(\frac{L_{\rm acc}}{L_\odot}\right) = 4.43(\pm0.79) + 1.26(\pm0.19) \times \log\left(\frac{L_{\rm Br\gamma}}{L_\odot}\right).$$

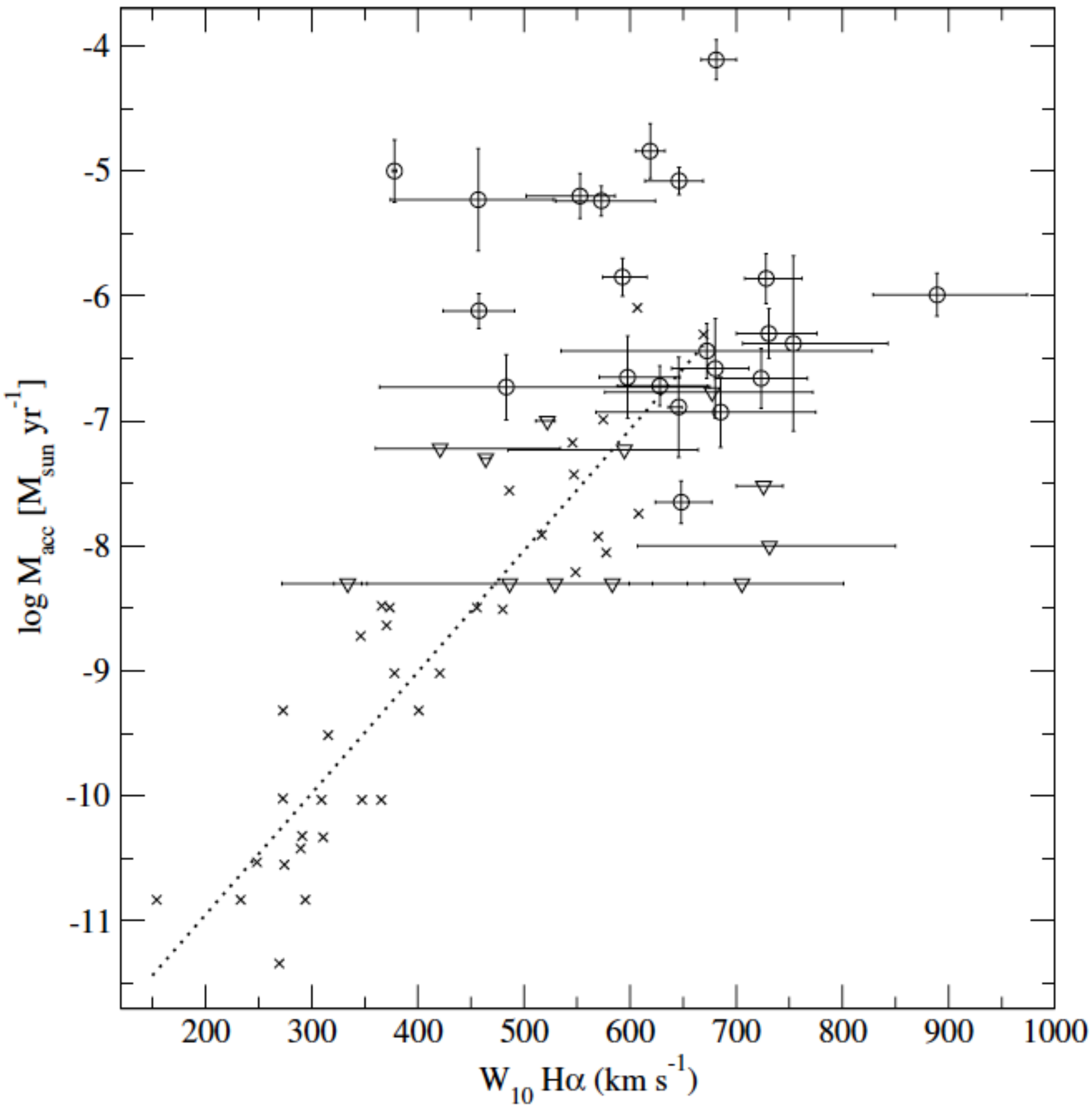
Accretion tracers



- Decrease of slope for the HAeBe regime
- Big scatter in the Brγ data (can probably be decreased if we use simultaneous data)

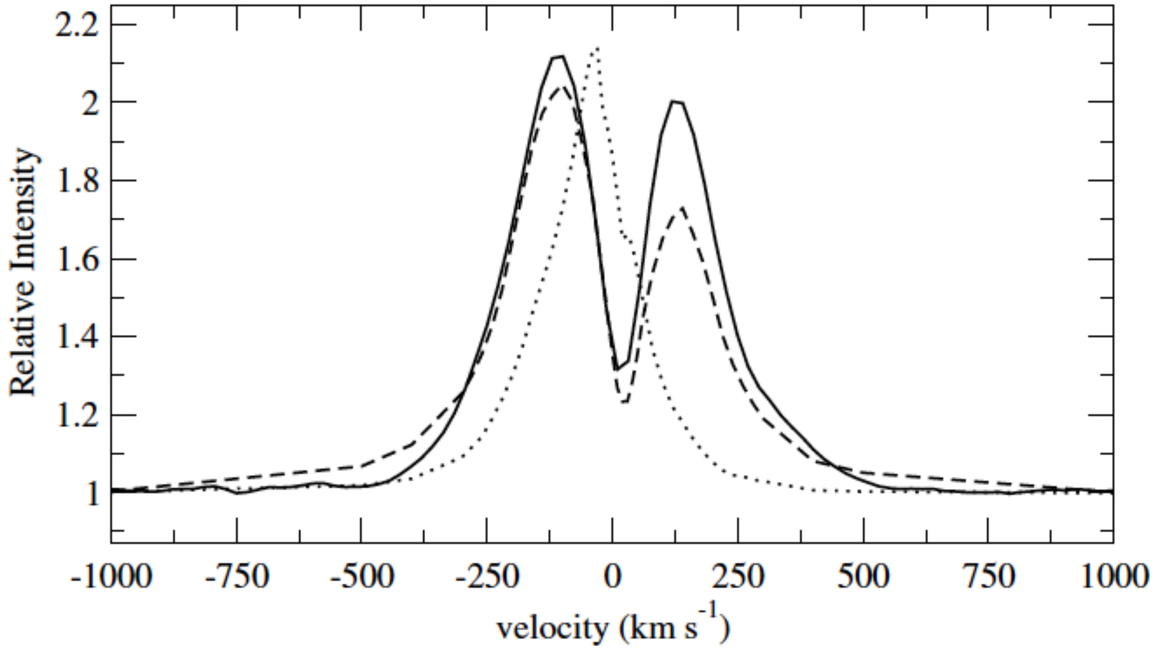
Accretion vs Hα 10% width

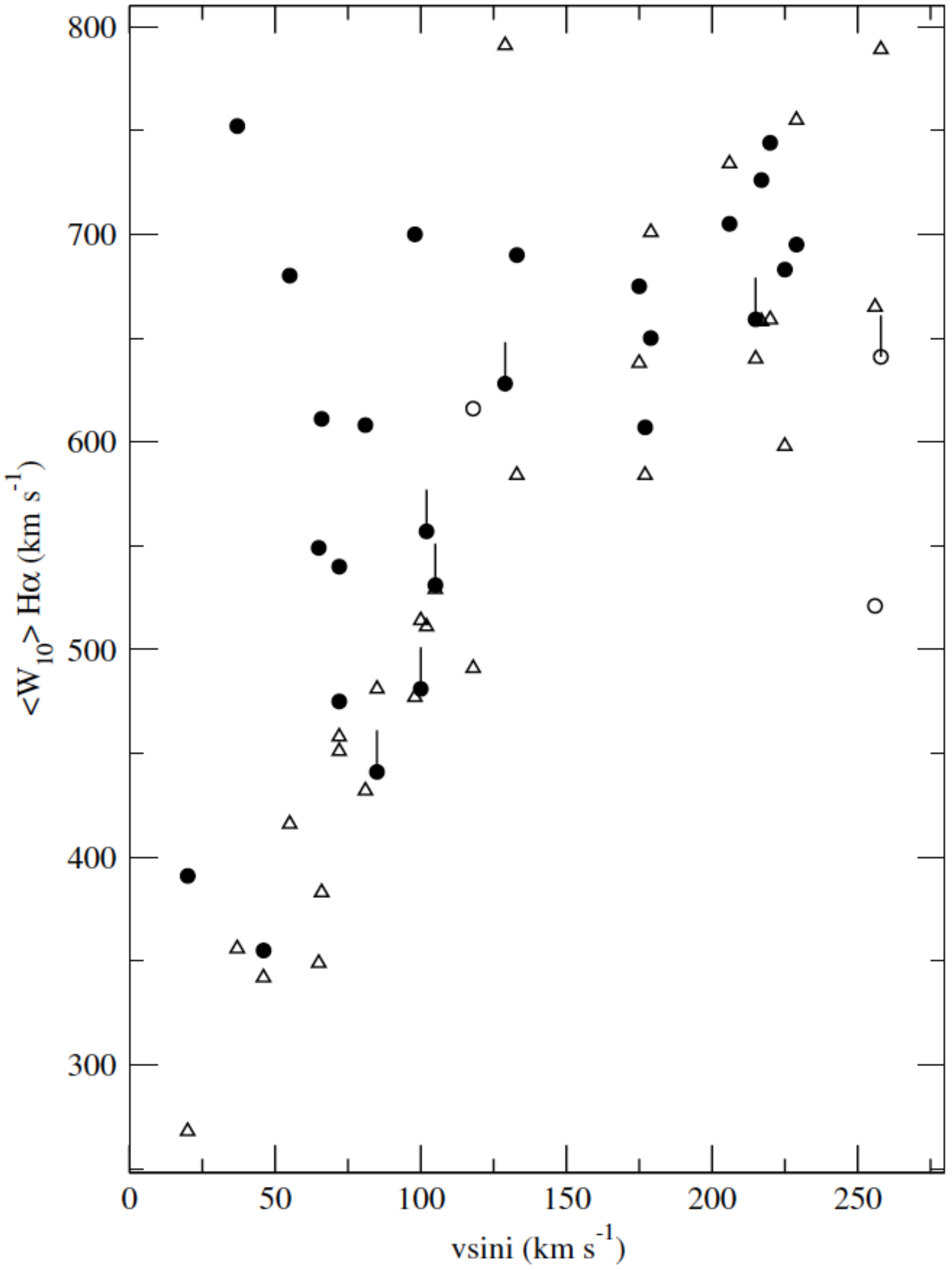
- Width of the Hα line at 10% of the peak intensity: widely used accretion tracer for low-mass stars
- Correlation breaks for HAeBe stars!
- Reason: typically high rotation rates of massive stars influence the width of the Hα line



Rotation vs Hα 10% width

- Indeed, Hα 10% width correlates with *v* sin *i*
- Influence of stellar rotation can be qualitatively modeled from MA (using the model of Muzerolle et al. 2001)



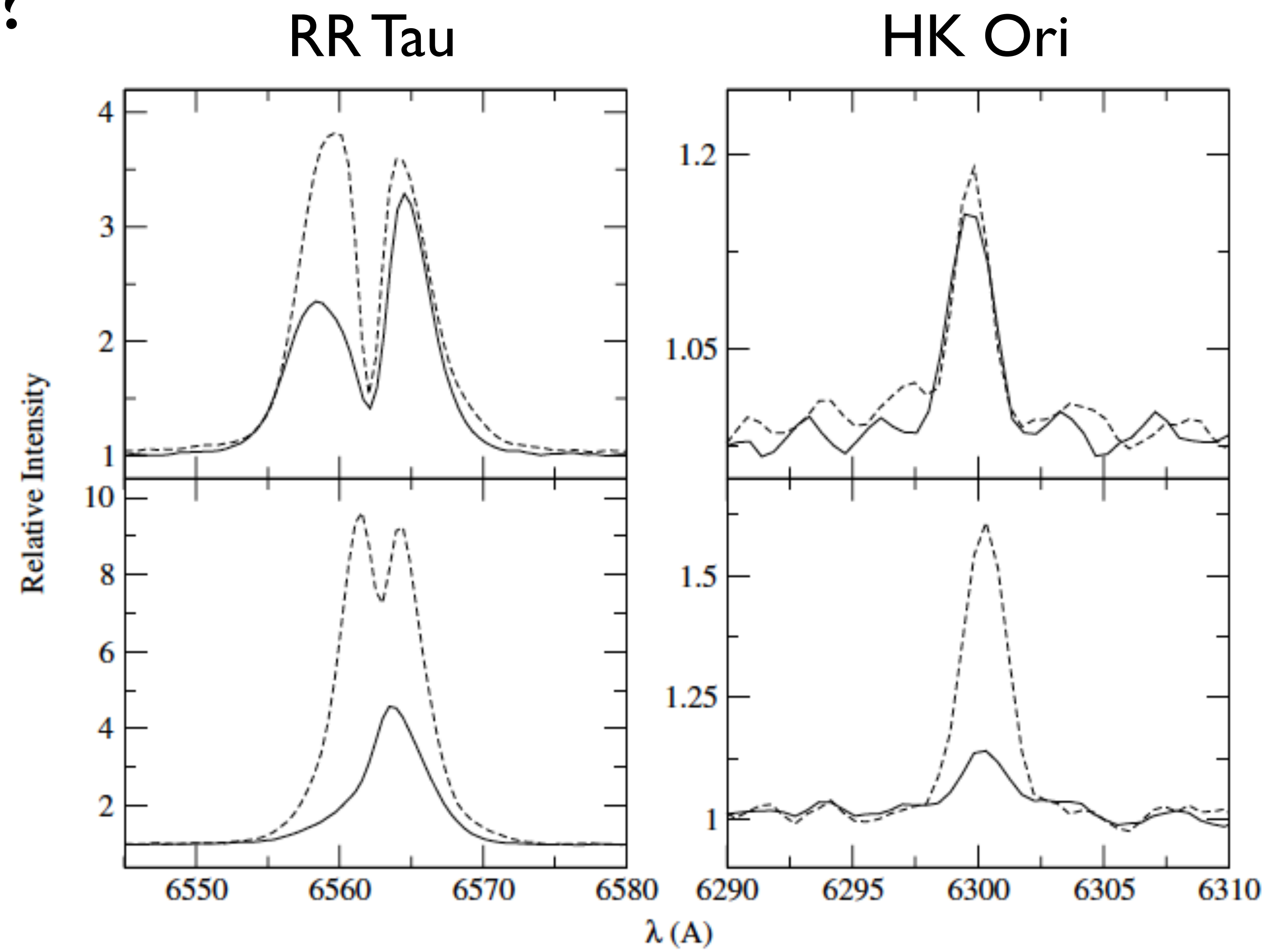


Variability of accretion

- Photometry and spectra used in this work were taken during four campaigns on different months
- Multi-epoch Balmer excesses were derived from individual $U - B$ and $B - V$ data
- Multi-epoch Hα and [OI]6300 luminosities were derived
- Most stars show constant Balmer excess (within the uncertainties); variation < 0.2 mag → factor of < 5 in $\dot{M}_{acc}$
- Two most extreme cases:
  V1686 Cyg: Balmer excess changed from 0.04 mag to 0.18 mag → implies an accretion rate change of a factor < 5
  WW Vul: Balmer excess changed from 0.14 mag to 0.04 mag → implies a accretion rate change of a factor < 4

Limitations

- Few data points (typically 3 per star, 7 at most)
- Cases where the Balmer excess changes, but the corresponding Hα and [OI]6300 luminosities do not vary accordingly, as expected
- Maybe there is a time lag?
- Need more data
- VLT/X-Shooter: multi-epoch, high resolution spectra covering simultaneously the UV to near-IR wavelength range



Origin of empirical cal.?

- How does the accretion influence line formation?
- The Hα and Brγ lines come from the accretion column
- Influence of winds is becoming more important with increasing stellar mass → explains the decrease in the slope of the Hα calibration when compared to lower mass stars
- Origin of the [OI]6300 line?
  - accretion-powered outflow
  - UV illumination of the disk surface (UV excess ↔ accretion shock)

Origin of empirical cal.?

- Lines are related to typical accretion rates, but variability decoupled from Balmer excess → origin and strength of lines are influenced by diff. processes apart from accretion!
- Important caveat: maybe L_{acc} correlate with L_{line} only because both L_{acc} and L_{line} correlate with L_*!

Summary

- We applied shock modeling within the context of MA to 38 HAeBe stars, reproduced the strength of the Balmer excess, and determined mass accretion rates (typical value: 2×10^{-7} M_{Sun}/yr)
- Steep dependence on stellar mass (most massive HAeBes are the youngest, and strongest accretors)
- We obtained empirical expressions to relate accretion and the Hα, [OI]6300, and Brγ luminosities. Trends are similar to lower-mass stars, but slopes are shallower
- Hα line width at 10% of the peak intensity cannot be used to estimate accretion rate due to rotational broadening

Summary

- Accretion rate changes from the Balmer excess are typically < 0.5 dex, and is usually uncorrelated with the variability of the Hα and [OI]6300 lines
- Origin of empirical calibration between accretion and line luminosities may be driven by a common dependence on stellar luminosity???
- Shock models fail to reproduce the Balmer excess of the four hottest stars in our sample → magnetically driven accretion in HAe stars, but some other kind of accretion in HBe stars
- This is not a test of MA! MA seems OK, but the observations could be explained by some different scenario

Papers to present on Nov 19

- Gullbring et al. 2000: The structure and emission of the accretion shock in T Tauri stars. II The ultraviolet-continuum emission (ApJ 544, 927−932)
- Mendigutía et al. 2012: Accretion-related properties of Herbig Ae/Be stars. Comparison with T Tauris (A&A 543, A59)
- Muzerolle et al. 1998: A Br gamma probe of disk accretion in T Tauri stars and embedded young stellar objects (AJ 116, 2965−2974)
- Natta et al. 2004: Accretion in brown dwarfs: An infrared view (A&A 424, 603−612)