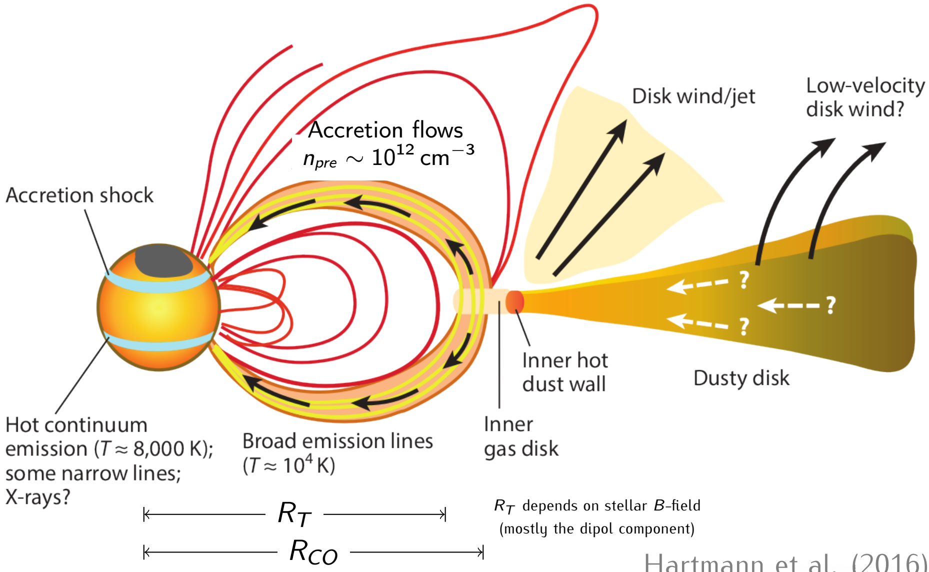
Accretion in T Tauri and Herbig Ae/Be Stars

P. Christian Schneider
Hamburger Sternwarte

Gaia's view of Pre-Main Sequence Evolution
Leeds, June 19th, 2019

Sketch for accretion w/ **strong magnetic** field



R_T depends on stellar B-field
(mostly the dipol component)

Hartmann et al. (2016)

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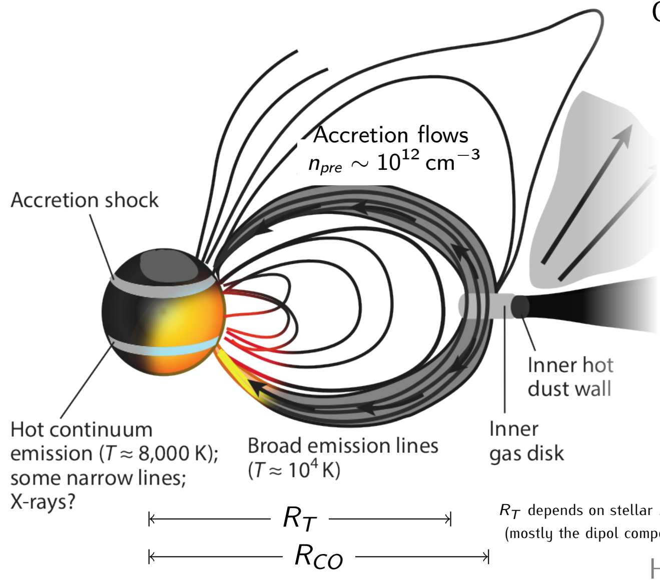

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Outline:

- Accretion shock

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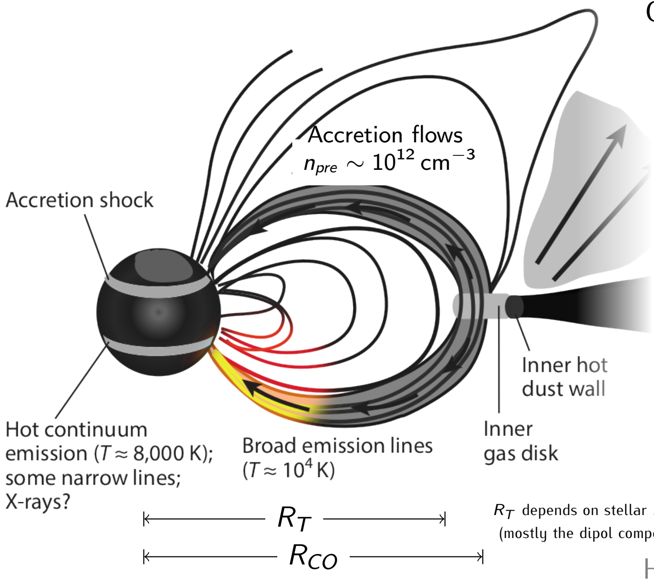

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Outline:

- Accretion shock

- Pre-shock

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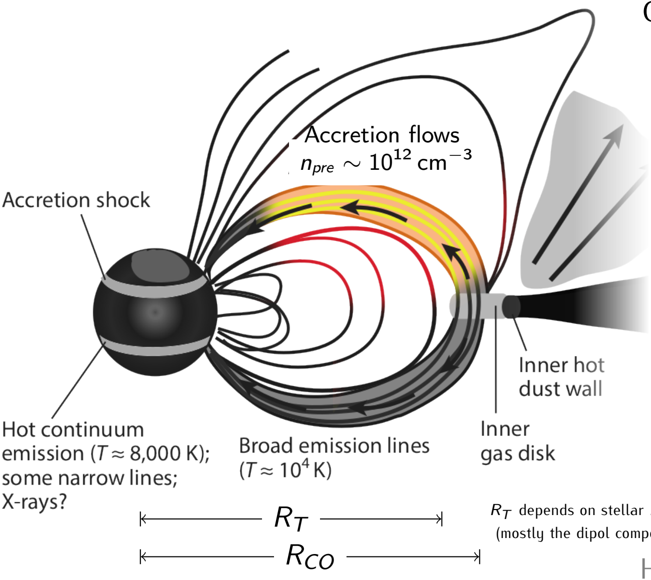

R_T depends on stellar B-field (mostly the dipol component)

Outline:

- Accretion shock

- Pre-shock

- Funnel

Hartmann et al. (2016)

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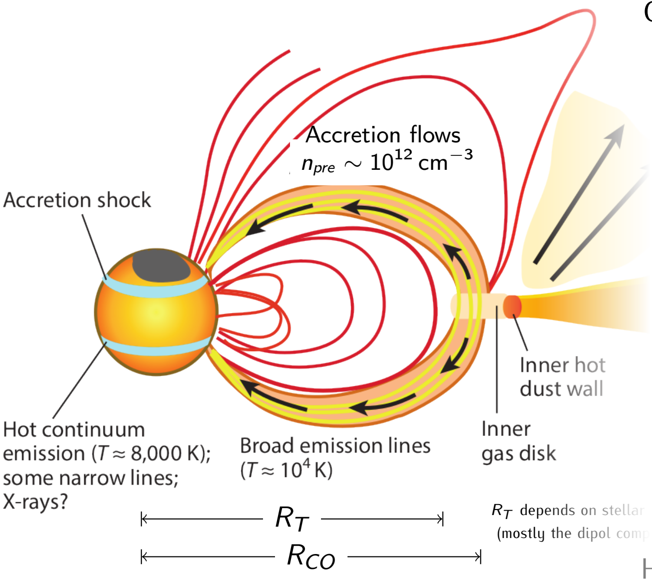


Outline:

- Accretion shock

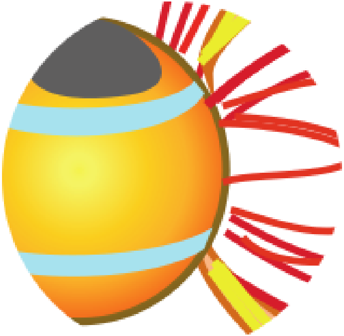
- Pre-shock

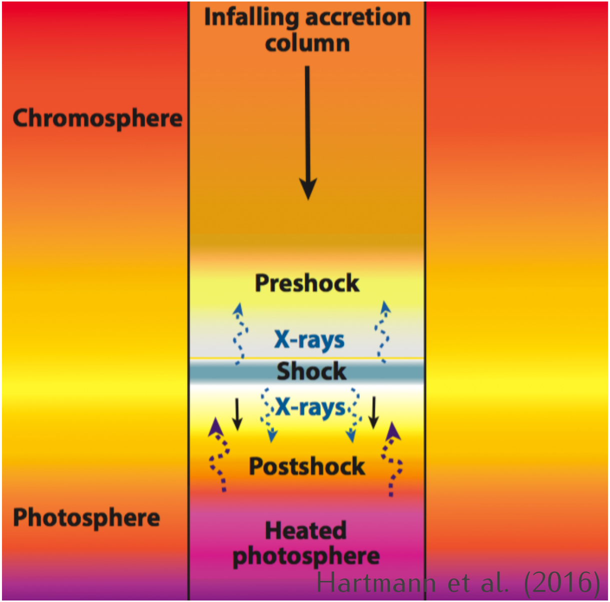
- Funnel

- Accretion Rates

Hartmann et al. (2016)

Accretion shock emission

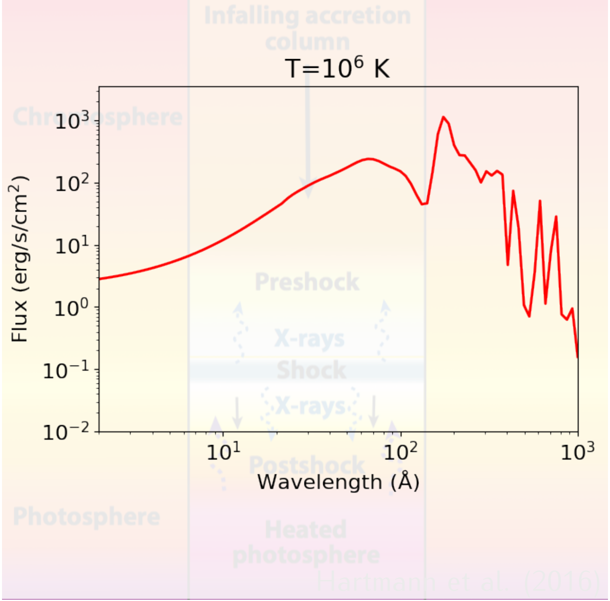




Hartmann et al. (2016)

- $10^6\,\mathrm{K}\left(\frac{M_\star}{0.5M_\odot}\right)\left(\frac{2R_\odot}{R_\star}\right)$
- Shock cools via X-ray emission
- Some X-rays heat surrounding material
- Some escape and may be observed
- Escape fraction debated Lamzin (1999), Günther et al. (2007), Sacco et al. (2008,2010), Kurosawa et al. (2011), Orlando et al. (2013), Bonito et al. (2014), Colombo et al. (2016)

Accretion Shock Characteristics



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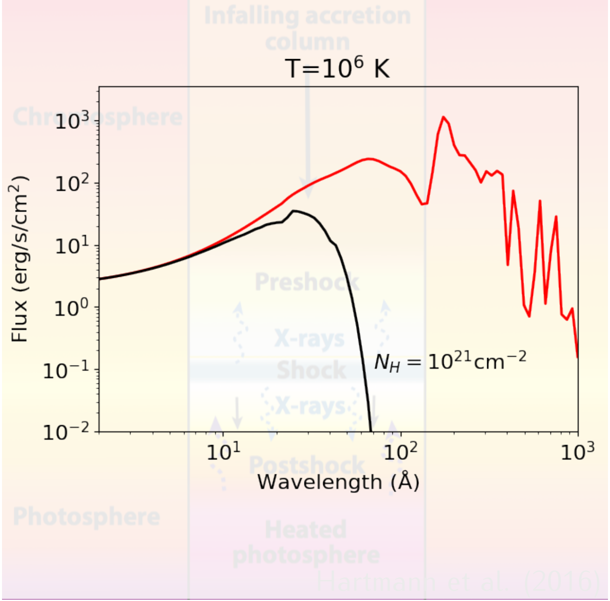

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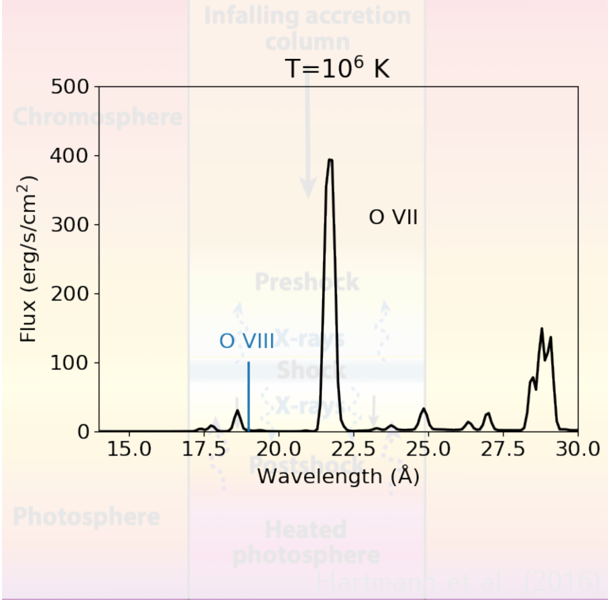

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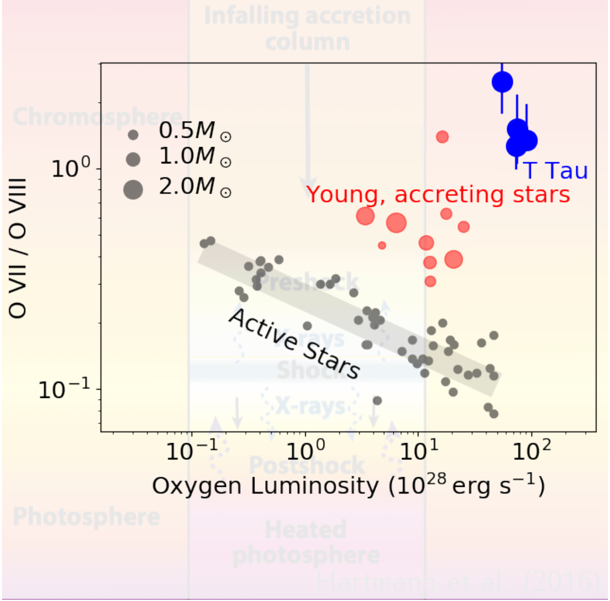

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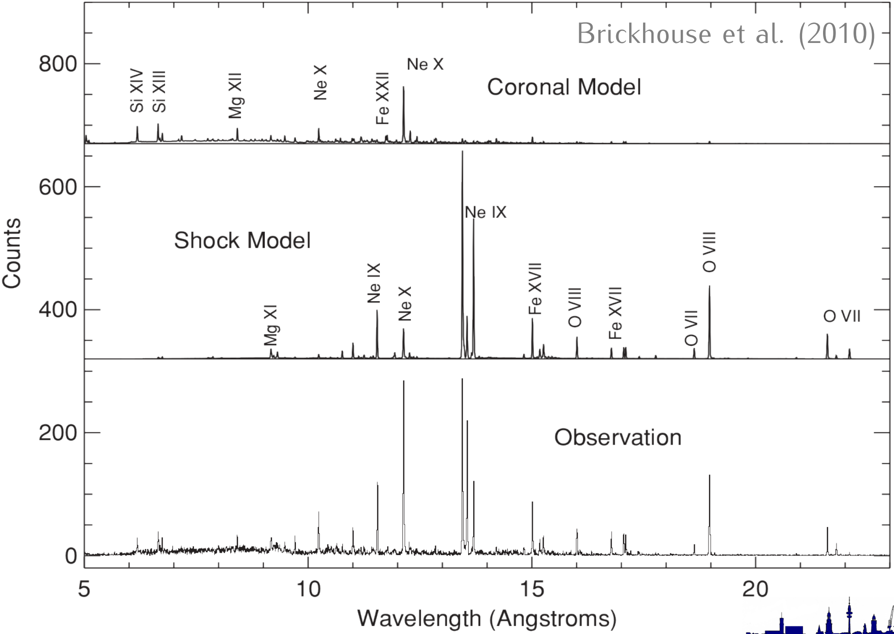
TW Hya in X-rays



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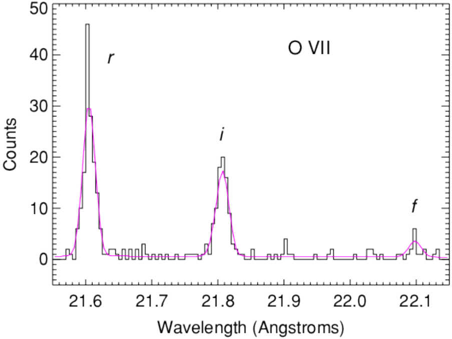
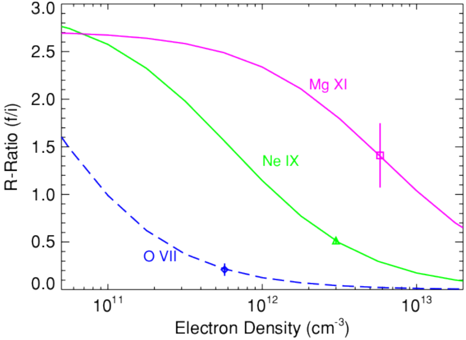
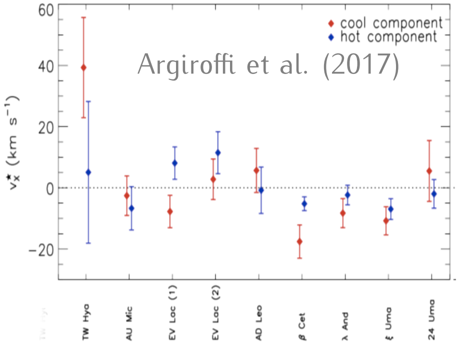


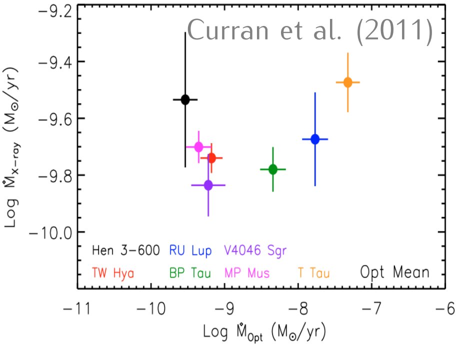


Brickhouse et al. (2010)

- Derived densities increase with
  - increasing formation temperature
  - decreasing wavelength
  - increasing absorbing column
- Incompatible with 1d shock models
- Some line fluxes compatible with $\dot{M}_{acc} \sim 10^{-10}\, M_\odot\, \mathrm{yr}^{-1}$

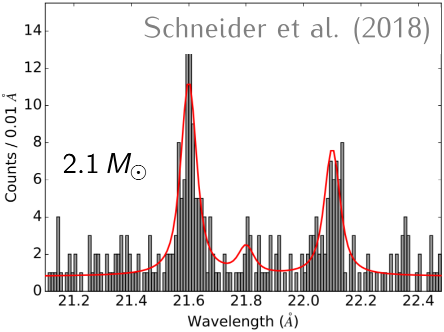
Accretion driven X-ray emission

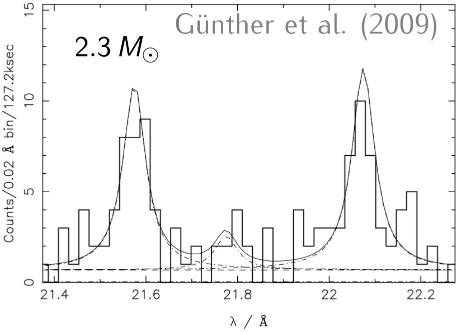




- Excess emission from cool plasma wrt active stars
- Slight redshift in accretion related lines ($\rightarrow$ equatorial region)
- X-ray derived accretion rates: $\log \dot{M}_{acc} = -10 \cdots -9$
  Perhaps correlated, but far from 1:1

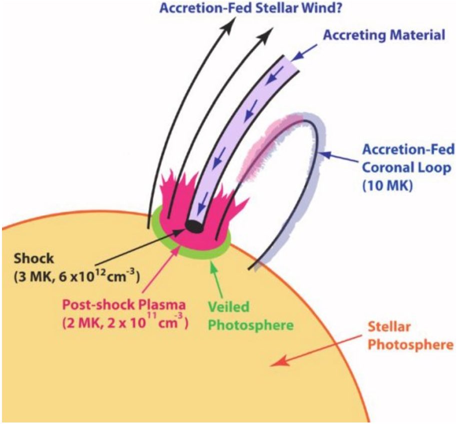
T Tau and HD 163296 in X-rays



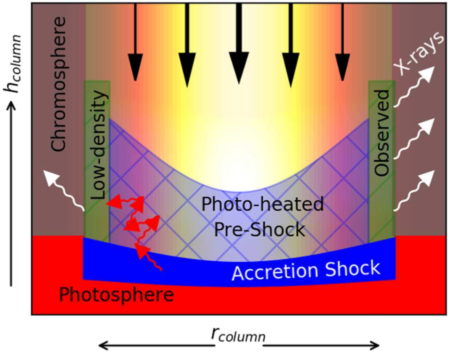


- Densities $\log n_e \lesssim 10 \ldots 11\,\mathrm{cm}^{-3}$
- $\dot{M}_{acc} \lesssim 10^9\, M_\odot\,\mathrm{yr}^{-1}$
- Attributing the O VII emitting plasma to an accretion shock requires $f \gtrsim 1.0$

Accretion Shock Summary



Brickhouse et al. (2010)

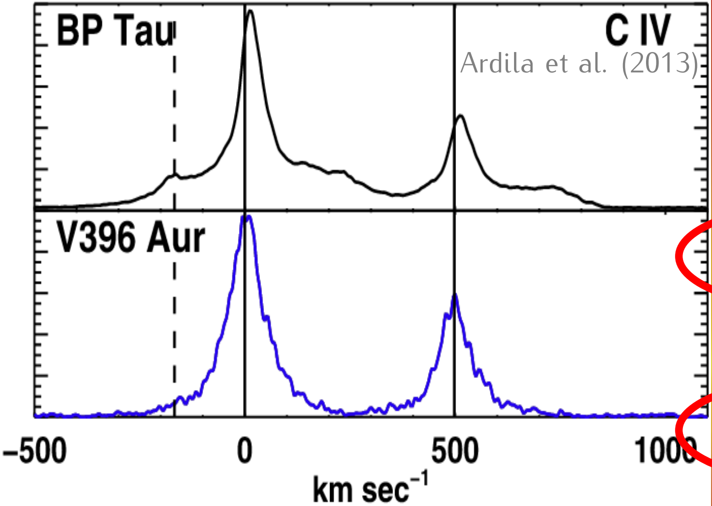


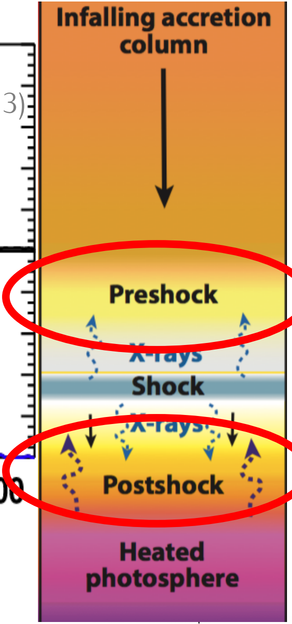
Schneider et al. (2018)

- Plasma not **directly** related to accretion shock needed
- Hot plasma “surrounding” the primary accretion stream
- Perhaps stellar winds in IMTTs and HAeBEs?

Pre-shock material?

Ionized Lines: C IV

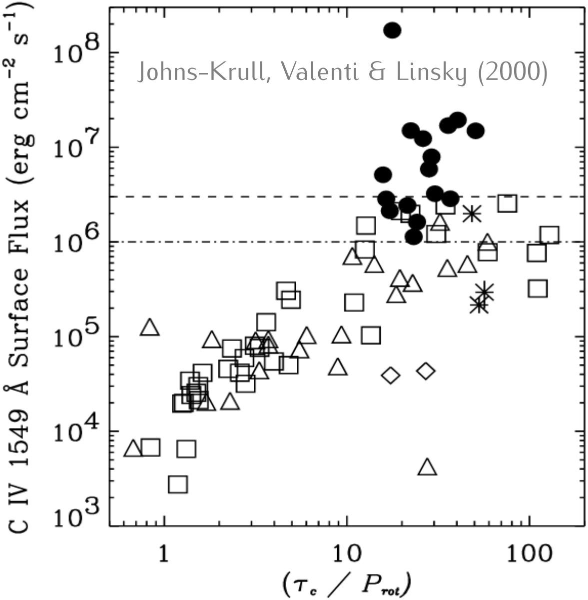




Typical profile

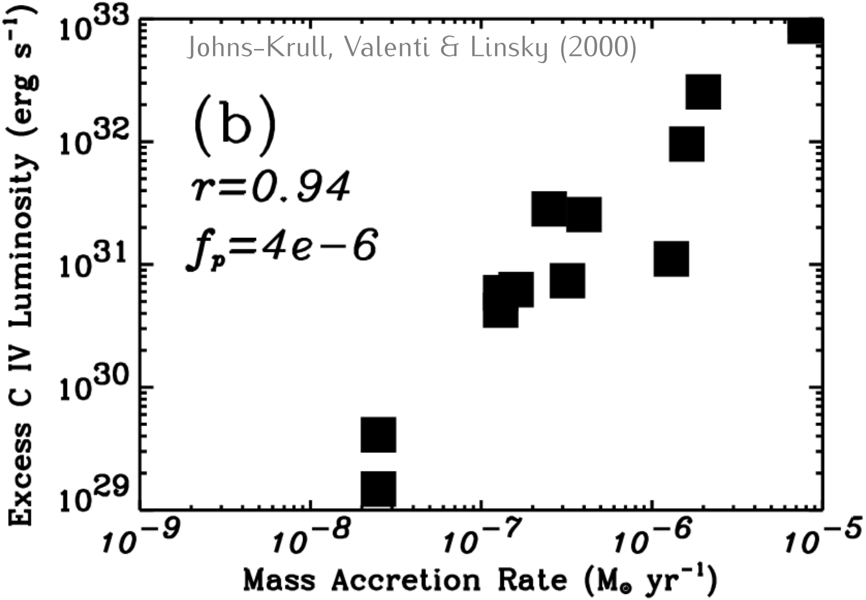
- Broad wings
- Slightly redshifted
- Close to 2:1

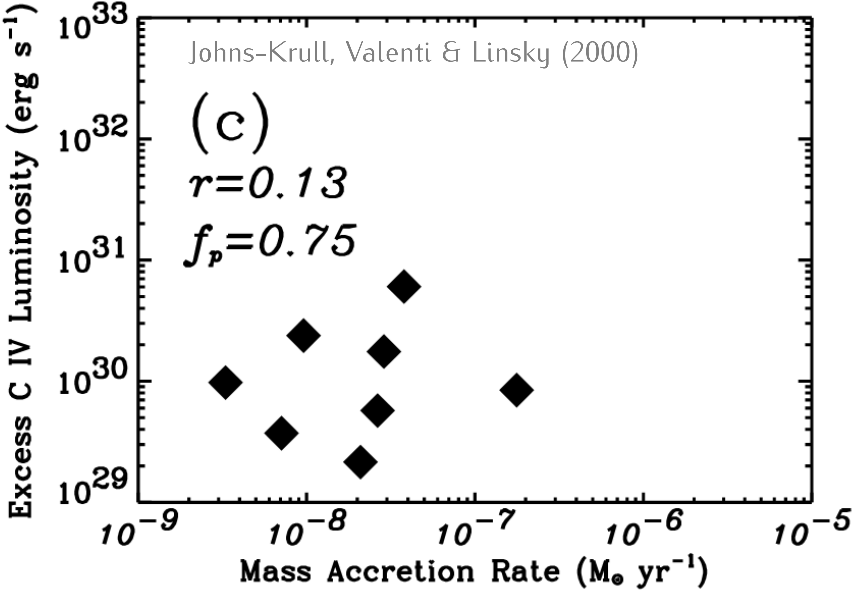
C IV demographics



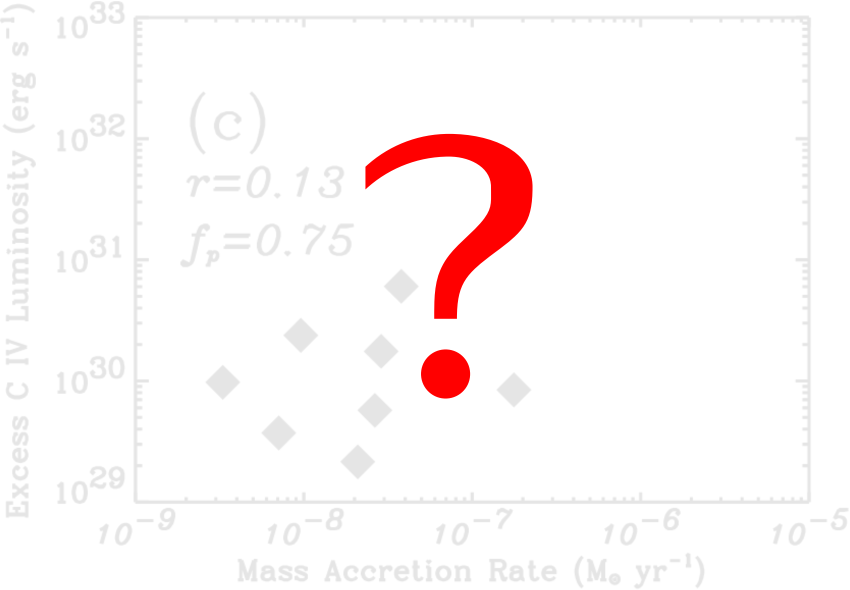
- C IV is one of the strongest (&cleanest) lines in the FUV
- Peak formation temperature: 10^5 K (not necessarily thermal T)
- Excess emission wrt active stars
- Accretion shock models predict $L_{CIV} \lesssim 10^{-3} L_{acc}$

C IV vs accretion




Johns-Krull, Valenti & Linsky (2000)
(c)
r=0.13
f_p=0.75
Excess C IV Luminosity (erg s^-1)
10^29
10^30
10^31
10^32
10^33
Mass Accretion Rate (M_⊙ yr^-1)
10^-9
10^-8
10^-7
10^-6
10^-5

C IV vs accretion



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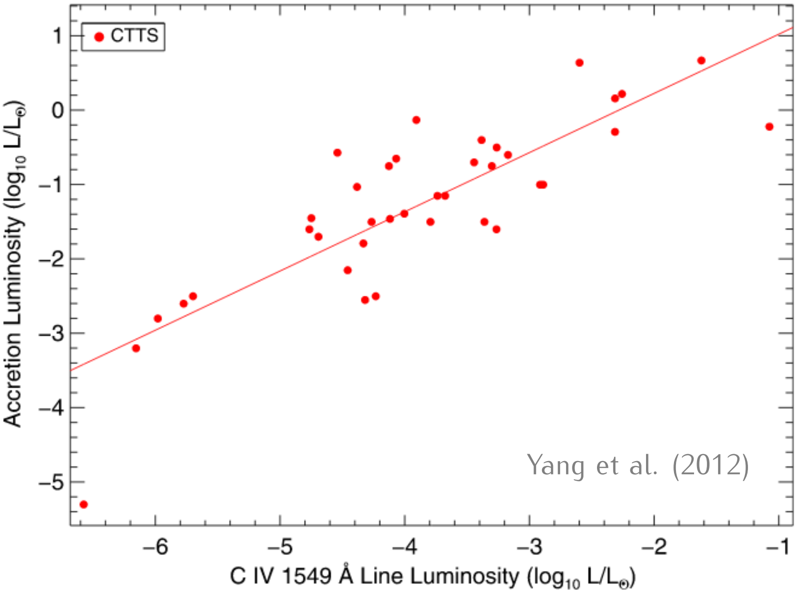
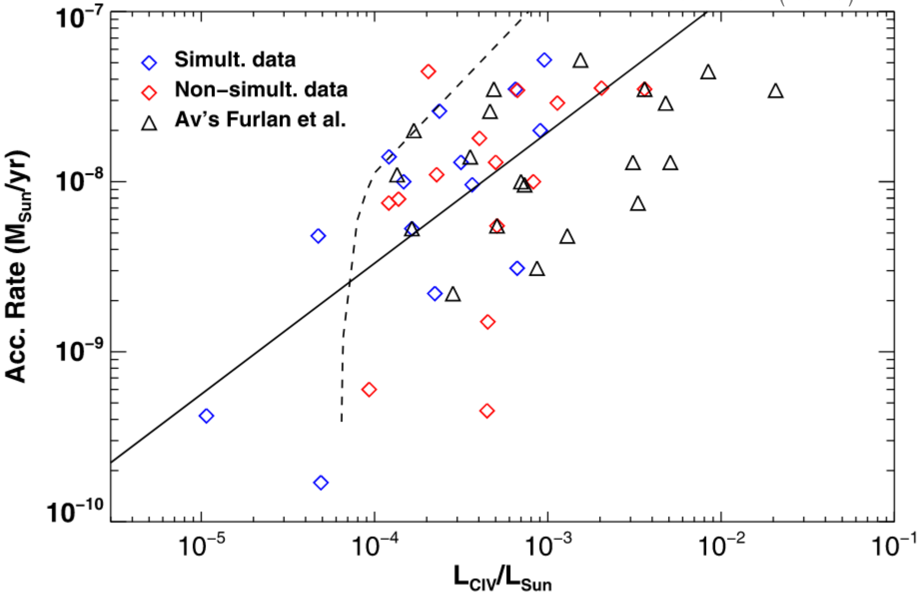


C IV vs accretion

Ardila et al. (2013)



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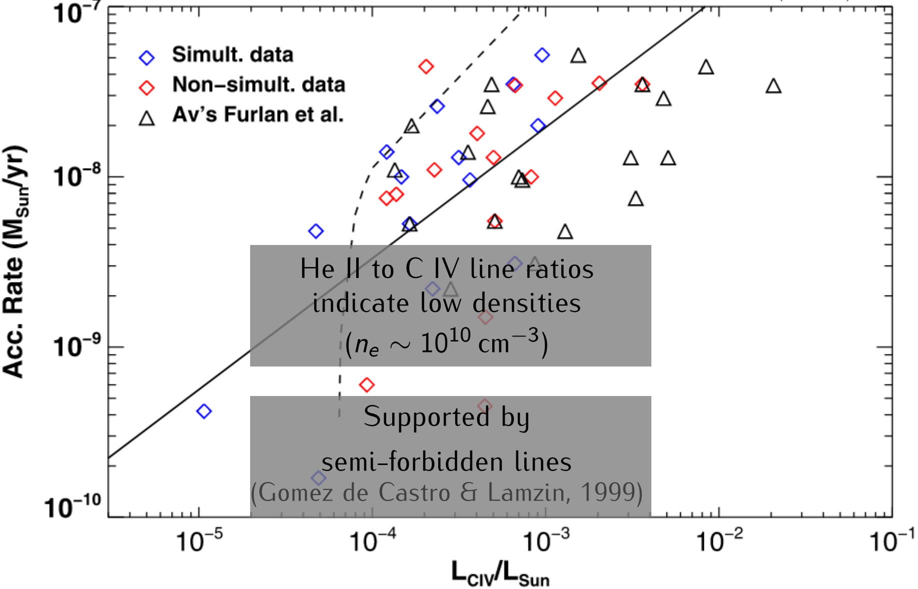
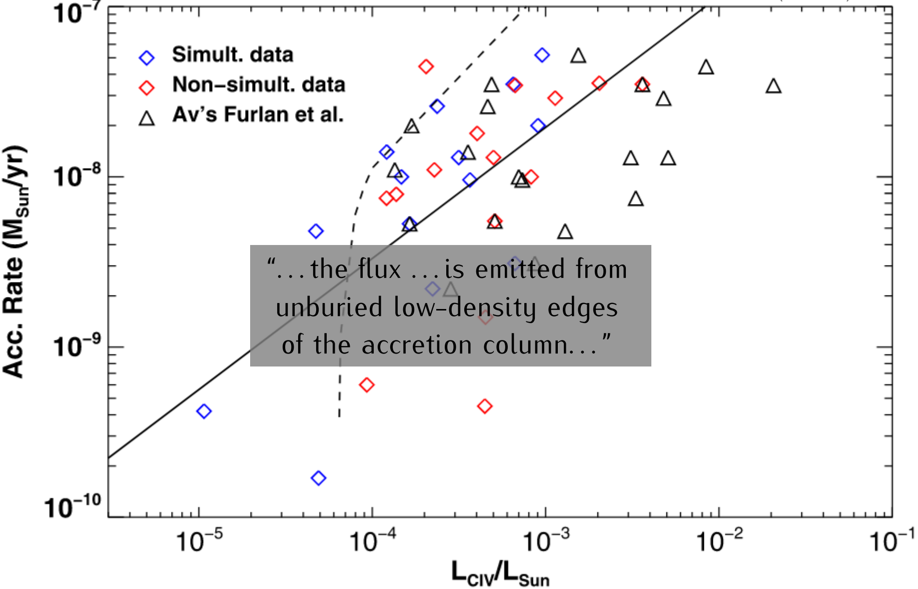


He II to C IV line ratios indicate low densities ($n_e \sim 10^{10}\,\mathrm{cm}^{-3}$)

Supported by semi-forbidden lines (Gomez de Castro & Lamzin, 1999)

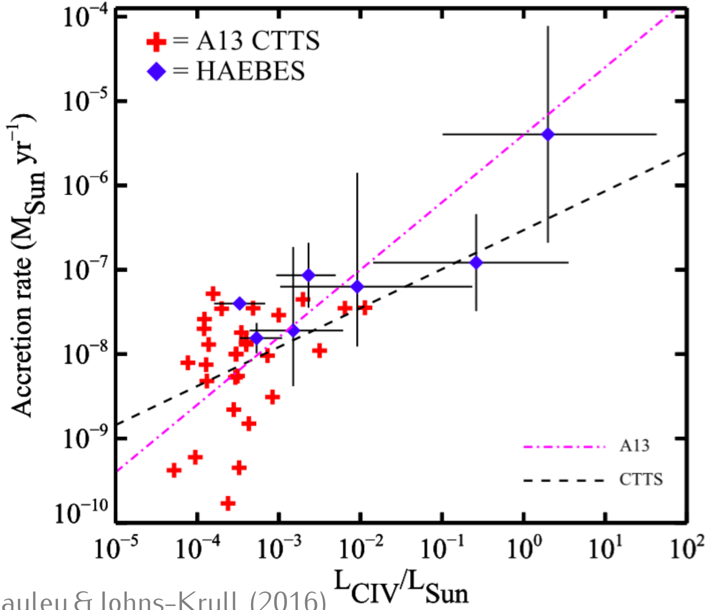
C IV vs accretion

Ardila et al. (2013)



"...the flux ...is emitted from unburied low-density edges of the accretion column..."

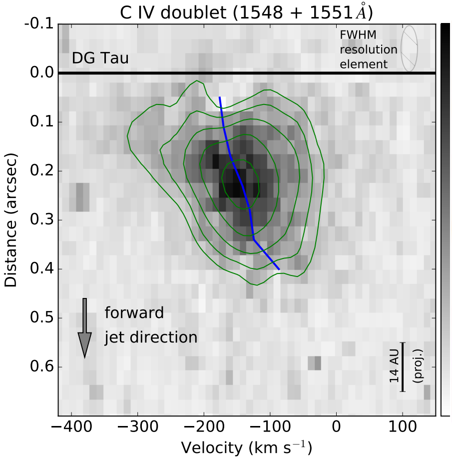
C IV emission in HAeBEs



Cauley & Johns-Krull (2016)

- ~half show C IV in emission
- Those extend $M_{acc} \sim L_{CIV}$ relation
- Kinematic features → optically thin *stellar* winds

Caution: Spatially Extended C IV emission



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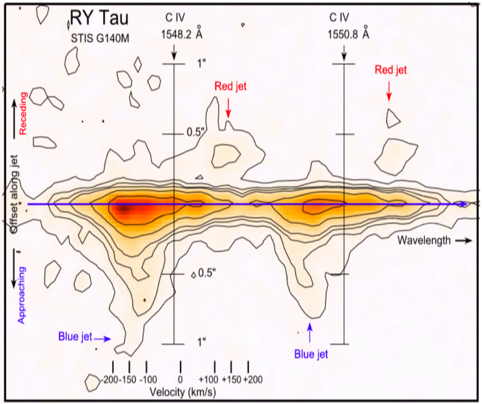


Skinner et al. (2018)

- Jet emission from shock heated plasma
- Subject to different extinction than star

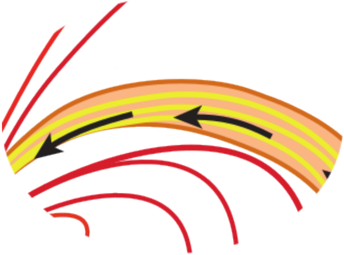
Hot Line Summary

- Excess emission in several FUV lines (10^5 K)
- Extinction corrected fluxes correlate with M_{acc}
- Indicate low densities ($n_e \sim 10^{10}\,\mathrm{cm}^{-3}$)
  C IV to He II, Semi-forbidden Lines
- Differ between CTTS and HAeBe
- Kinematic properties often incompatible with accretion shocks
- BUT (at least) some objects show clear outflow/jet emission!

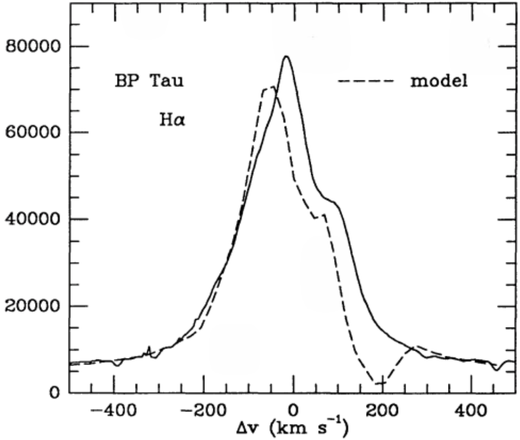
X-rays and FUV lines correlate with $\dot{M}_{acc}$, but show features incompatible with dipol-like, single uniform column accretion

$\Rightarrow$Diagnostics of additional/new processes like hot stellar winds(?)

Accretion funnel



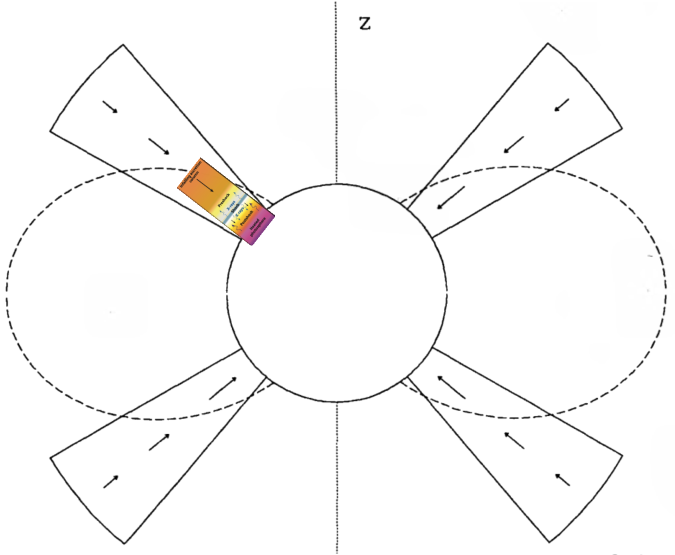
Optical (hydrogen) emission lines



Calvet et al. (1992)

- Initially tought to originate in (spherically symmetric) winds, because
  - blueshifted absorption in optically thick lines,
  - blueshifted emission in optically thin lines,
- but
  - lines are generally centrally peaked,
  - some lines feature redshifted absorption.

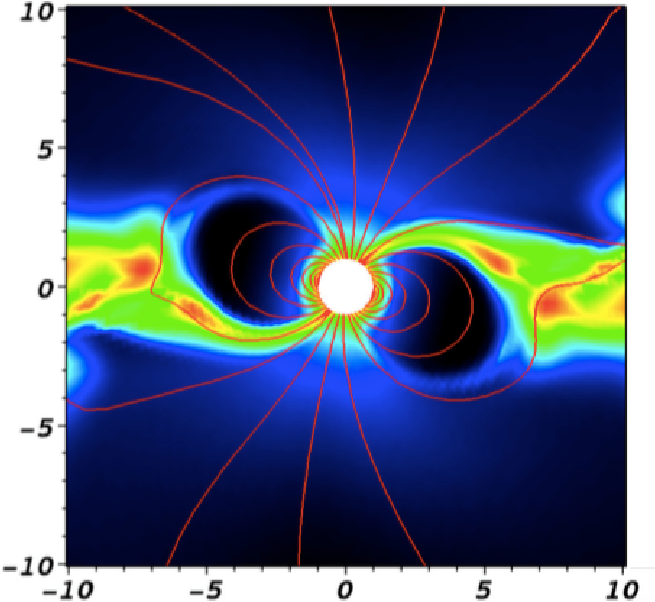
(Kinematic) Emission Line Models



- Axisymmetric, steady state
- Ballistic infall ($v_{shock} \approx 300\,\mathrm{km\,s^{-1}}$)
- Density such that $\log M_{acc} = -7.8 \cdots - 6.6$
- Isothermal columns ($T = 7,000\,\mathrm{K}$) (higher $T \rightarrow L > L_{acc}$)

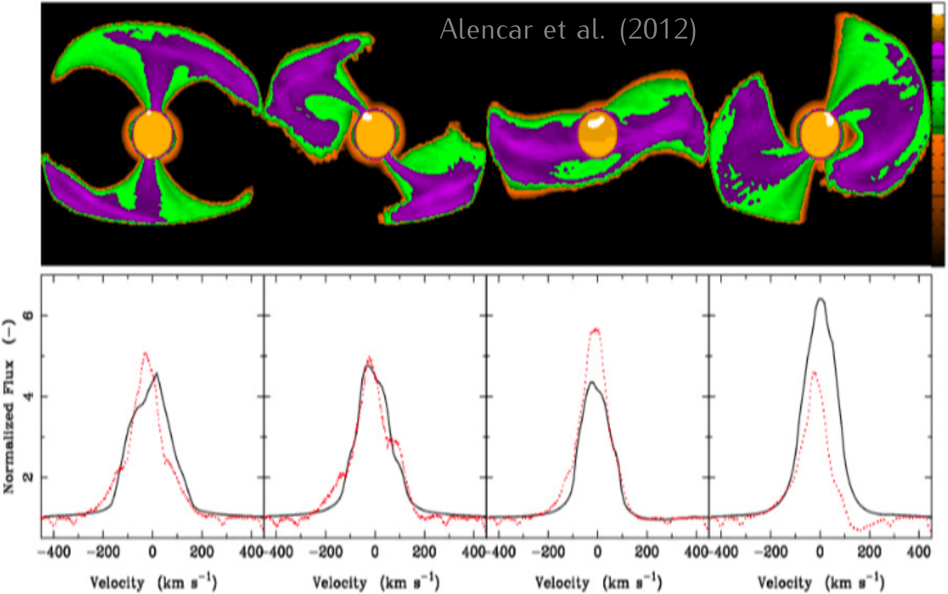
Calvet et al. (1992)

20 years later



Alencar et al. (2012)

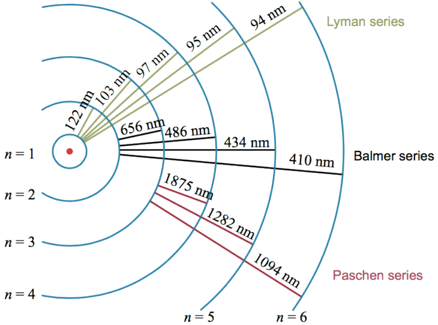
20 years later



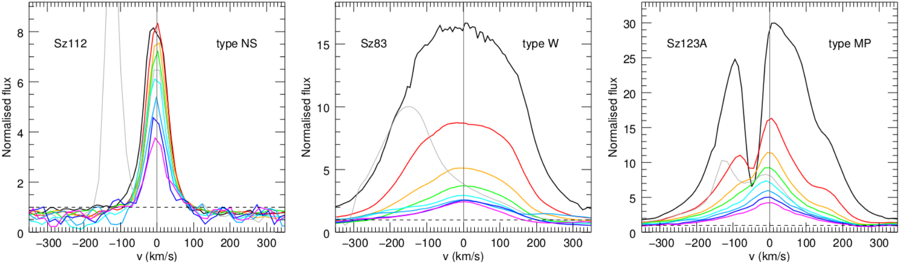
Hydrogen Line Modelling

- Profiles can be well reproduced
  - using prescriptions of the accretion funnel
  - using independent accretion geometry information (B-field form ZDI)
- predict/assume $\log n_e \approx 12 \dots 13$
- Contribution by outflows negligible for $\dot{M}_{acc} \lesssim 10^{-9}\, M_\odot\, \mathrm{yr}^{-1}$

Can H lines also inform us about the **densities** and **temperatures**?



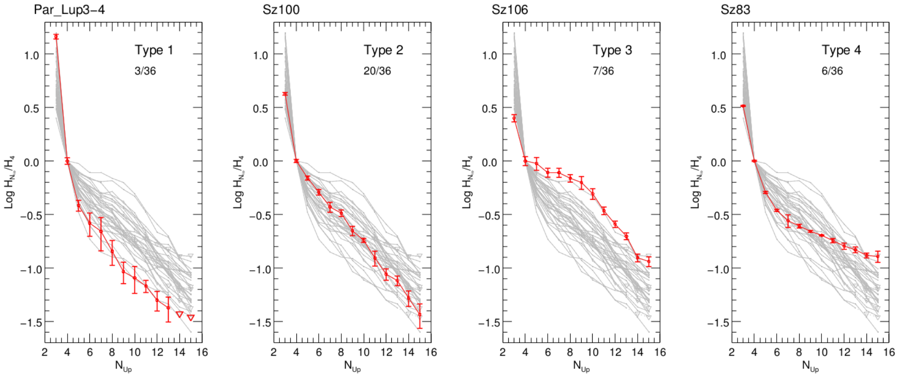
Line Profile Categories



Antoniucci et al. (2017, 2011)
also, e.g., Bary et al. (2008), Edwards et al. (2013)

- More and more symmetric in higher lines (lower opacities of these lines with respect to Hα and Hβ)
- Paschen lines tend to be more symmetric profile than lower Balmer lines
- Paschen and Brackett probably better diagnostics (weaker extinction and opacity effects)
- Stars with higher veiling have broader line profiles

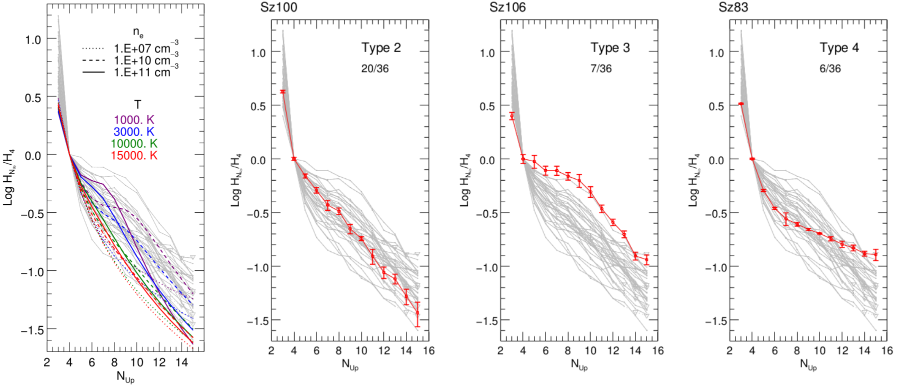
Balmer Decrements



Antoniucci et al. (2017)

- Four (empirically defined) categories
- Lines become optically thick for $\log n_H > 11$ ($\rightarrow$ L-shape decrement, type 4)
- Some profile may be compatible with Case B models
- More advanced models (e.g., Kwan & Fisher, 2011)

Balmer Decrements



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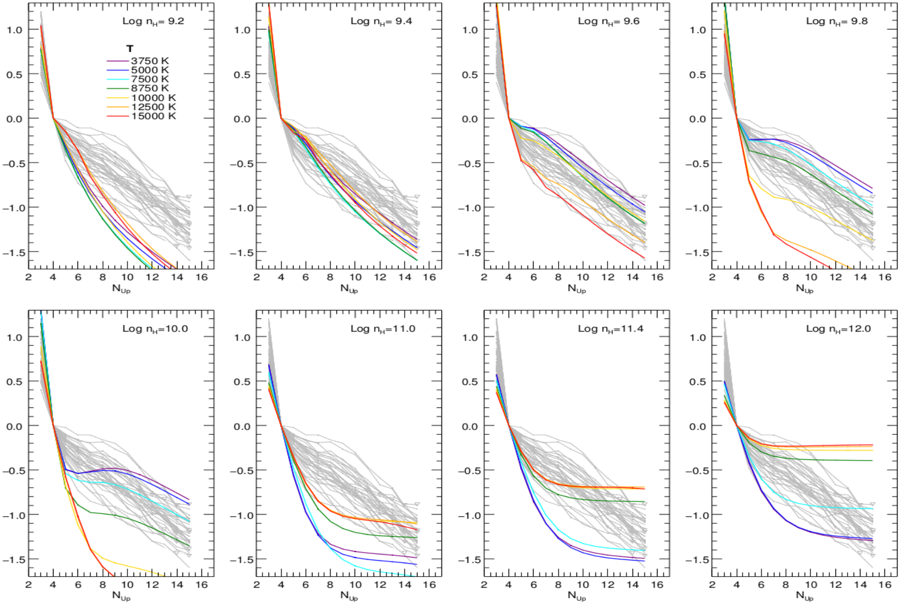


Conditions in the H-Line Emitting Region

- Two (main) groups identified:
  1. narrow symmetric lines, type-2 Balmer decrement:
     $\rightarrow \log n_H = 9 - 10,\ T = 5,000 - 10,000\,\mathrm{K}$
     Optically thin emission, tend to have lower accretion rates ($\log \dot{M}_{acc} \lesssim -9$), perhaps simple geometries
  2. type-4 decrements
     $\rightarrow \log n_H > 11,\ T \lesssim 9,000\,\mathrm{K}$ (from KF-type modelling)
     Lines (partially) optically thick, wide profiles ($\rightarrow$ high kinematic velocities), high accretion rates
     Similar conditions derived for stars in Taurus-Aurigae (Edwards et al., 2013, $n_H \sim 10^{11}\,\mathrm{cm}^{-3}$)
- These densities are somewhat lower than Muzerolle and collaborator models ($\log n_H \sim 12$)
- Channeling of the funnel flow $\rightarrow$ higher pre-shock densities

Hydrogen Line Summary

The hydrogen line

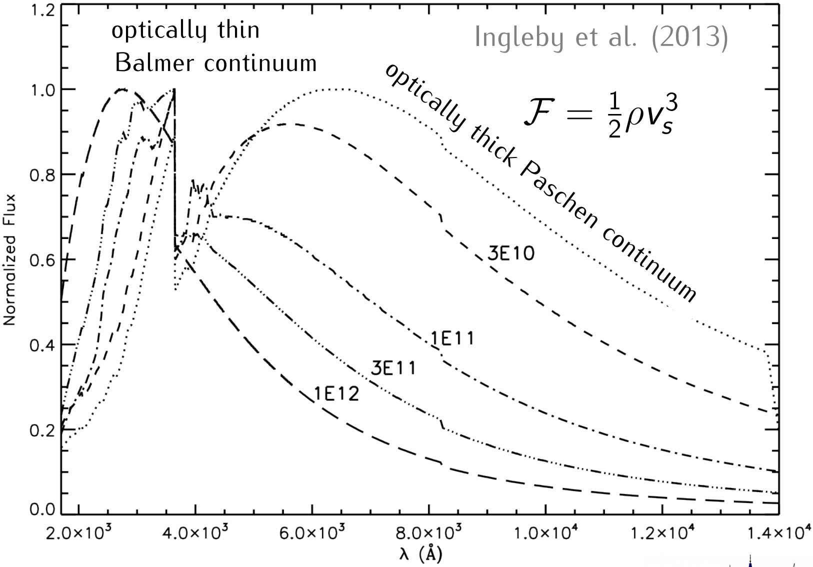
- profiles $\sim$match model expectations
- fluxes $\sim$match model expectations, but heating not well understood
- density estimates may be below expectations BUT compatible with UV diagnostics (and partly with X-ray densities)
- likely have outflow/wind contributions

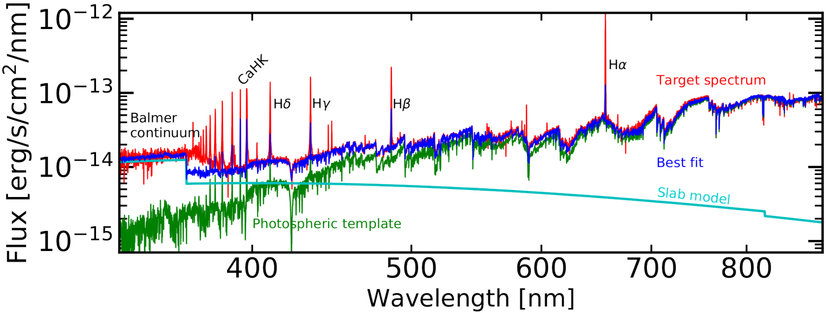
Accretion Rate

$$\dot{M}_{acc} \approx L_{acc} \frac{R_\star}{M_\star}$$

Accurate stellar parameters are important, too!
Gray extinction (edge-on disks)

Accretion Continuum





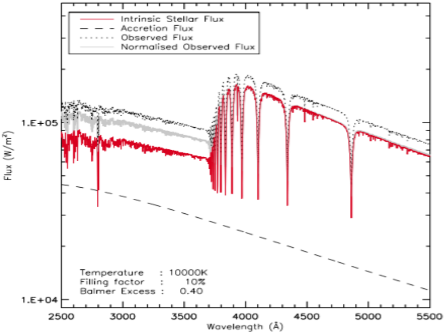
Manara et al. (2017)

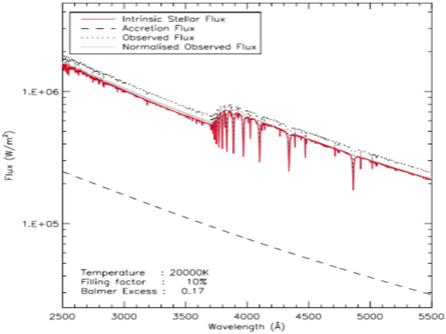
What observers do:

- absolute fluxes (spectra/photometry)
- combine/fit
  - spectral template (T_{eff}, $\log g$) (chromospheric emission variable)
  - accretion flux model(s)
  - extinction (A_V)

$\Rightarrow L_{acc}, M_\star, R_\star$

Deriving Accretion Rates





What observers do:

Fairlamb et al. (2015a)

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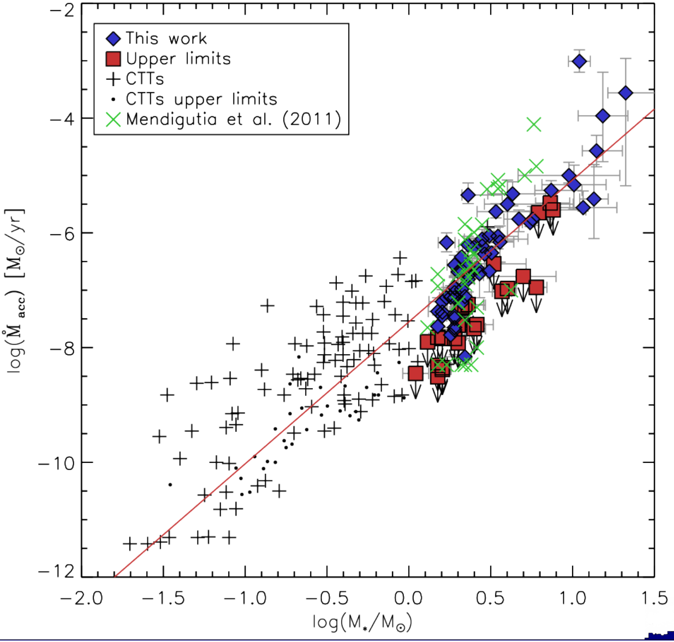
- combine/fit
  - spectral template (T_{eff}, $\log g$)
    (chromospheric emission variable)
  - accretion flux model(s)
  - extinction (A_V)

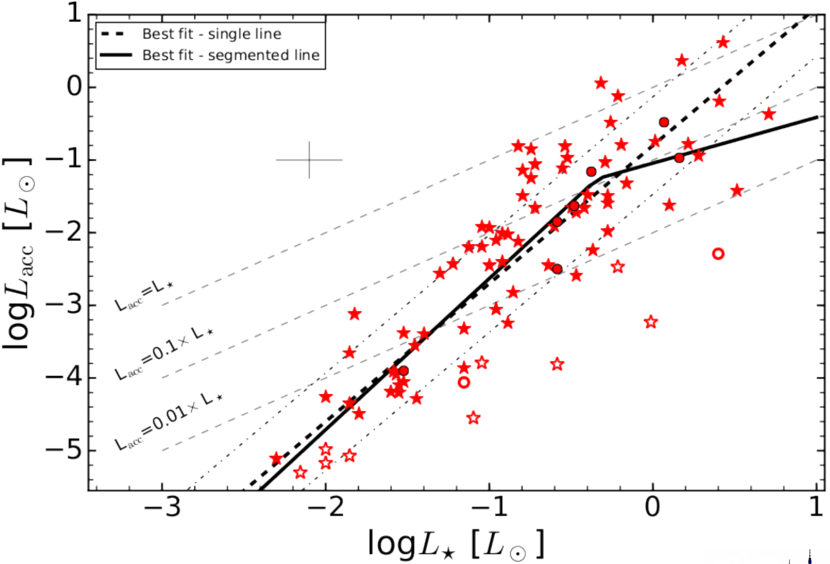
$\Rightarrow L_{acc}, M_\star, R_\star$

Mass accretion vs stellar mass



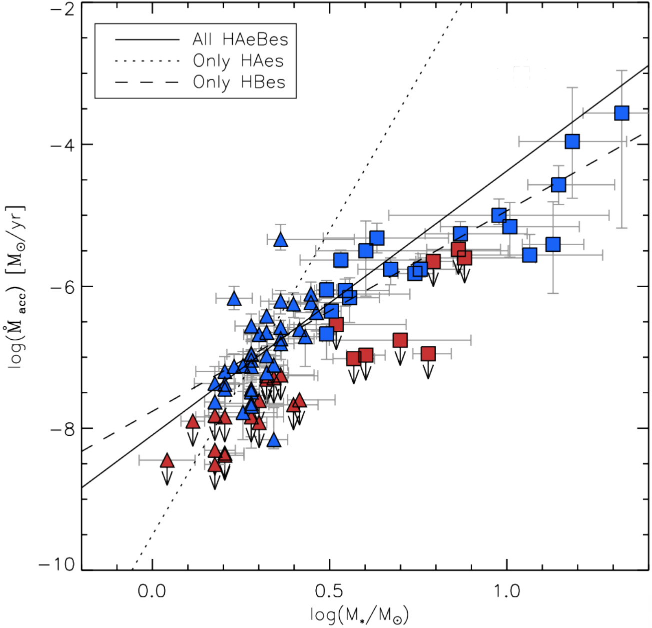
Fairlamb et al. (2015)

Mass accretion vs stellar mass

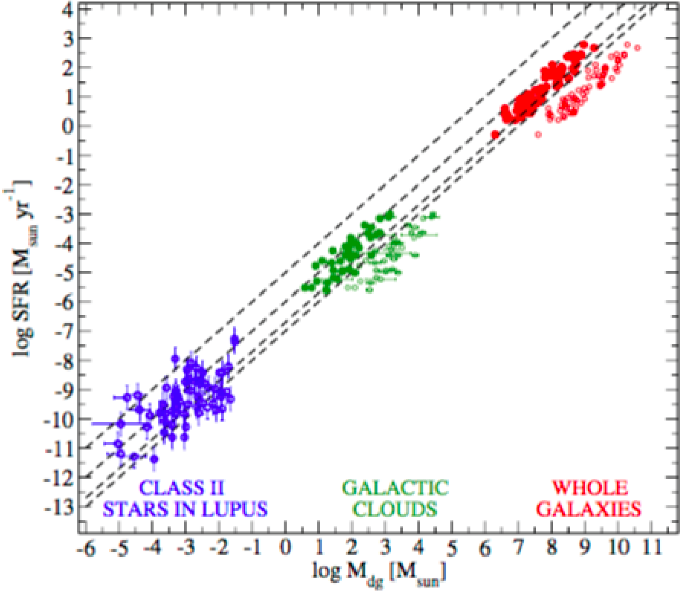


Manara et al. (2017)

Mass accretion vs stellar mass



Fairlamb et al. (2015)



Mendigutía et al. (2018)

Mass accretion summary

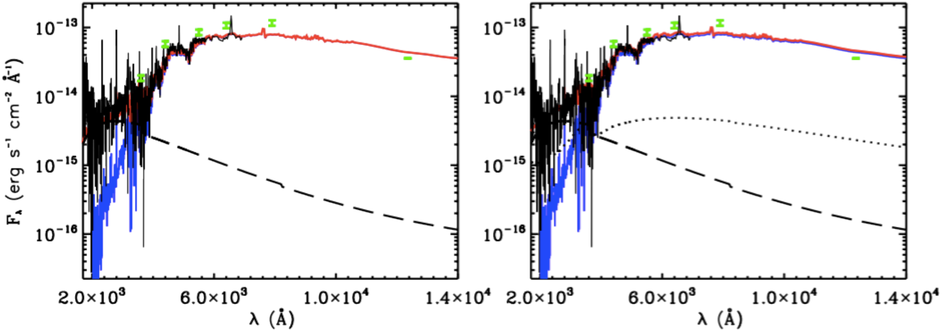
Accretion rates derived from continuum excess emission

- increases with stellar mass
- may deviate for the lowest stellar masses,
- may not be well reproduced by MA accretion (uncomfortably large filling factors)

Immediate question:

- Unrecognized/unsee accretion luminosity?

Outlook



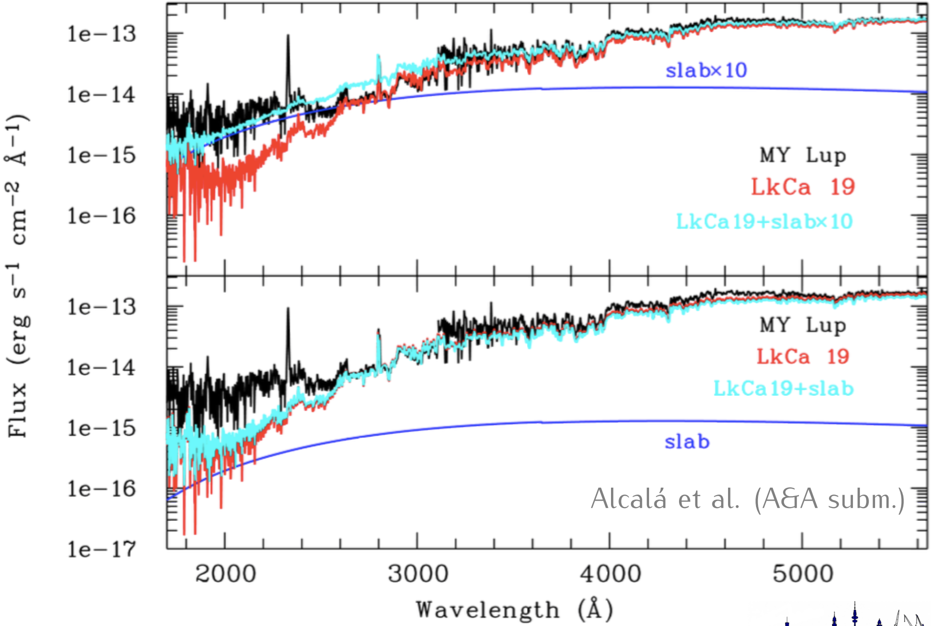
Ingleby et al. (2013)

see also Robinson & Espaillat (2019)

Inlcuding columns with low $\mathcal{F}$ may

- enhance accretion rates (factor of ∼two)
- gratly increase filling factors
  (more compatible with density estimates?)

Low/High Accretion Rates



ULLYSES

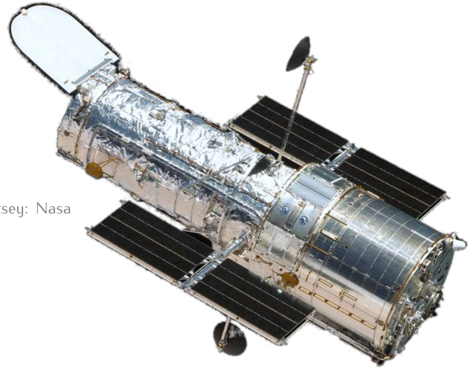
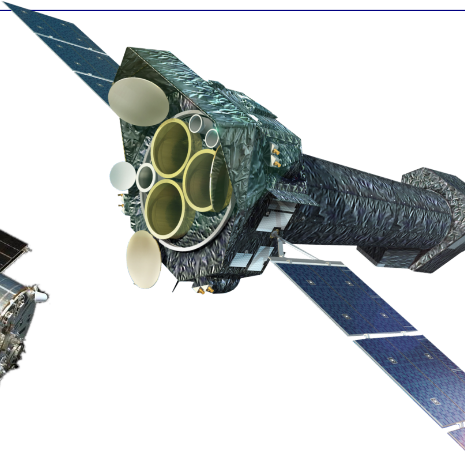


Image courtsey: Nasa



HST legacy program

- UV-NIR Atlas of Accreting Stars
- Multi-Epoch Monitoring
- Hopefully w/ Simultaneous X-ray Data (XMM-Newton)

Summary

Summary

Accretion produces excess emission in

- X-rays
  - Not (or only partly) associated with direct shock emission
  - No (strong) correlation with $\dot{M}_{acc}$
  - Only low-mass stars show high densities expected for accretion shock plasma
- hot lines
  - Thin plasma and kinematic properties challenging
  - Rough correlation with $\dot{M}_{acc}$
  - HAeBe show different morphologies, but fall on same $L_{line} \propto L_{acc}$-relation if C IV is in emission
- hydrogen lines
  - Well explained by models (perhaps incl. densities)
  - Good correlation with $\dot{M}_{acc}$
  - HAeBe vs CTTS?