Be Star Spectroscopic Observables

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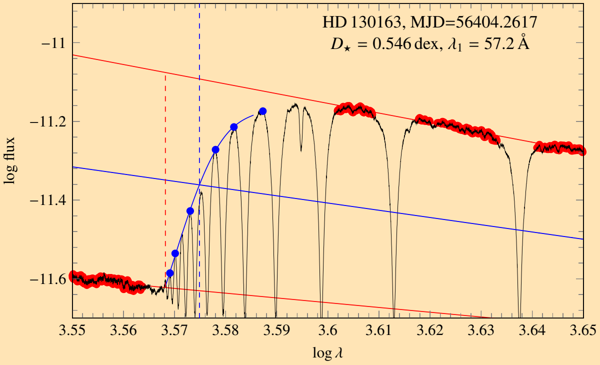
SED at Balmer discontinuity



see Shokry et al, A&A submitted, for details of procedure

- Provides fundamental stellar parameters (log g and $T_{\rm eff}$)

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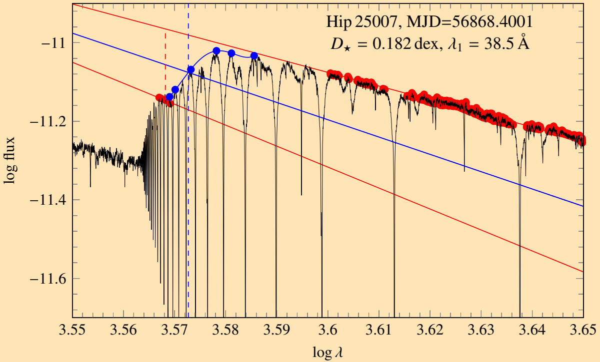

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- Provides fundamental stellar parameters (log g and $T_{\rm eff}$)

Equivalent width (Monitoring!)

Measurement

- Local re-nornalization wioth linear function
- Base points/intervals for this well outside line.
- If scripted, repeat this $\sim$ 100 times with different base points/intervals
- will provide statistics of measrement. Use median as value and RMS scatter as 1-σ error.

Tellurics?

- Should not matter much (very nrarrow, even if strong)
- However, can be tested:
  - ➙ Take very dry and very wet spectrum of normal B star.
  - ➙ Compare difference in median to scatter in individual measurement.

Equivalent width (f-test, time series)

Simple way to test for variability

- Jones, C. E., Tycner, C., & Smith, A. D. 2011, AJ, 141, 150
- Basically, divide RMS scatter of sample by RMS individual uncertainty.
- If larger than one, the smaple is intrinsically variable.

Search for periods etc.

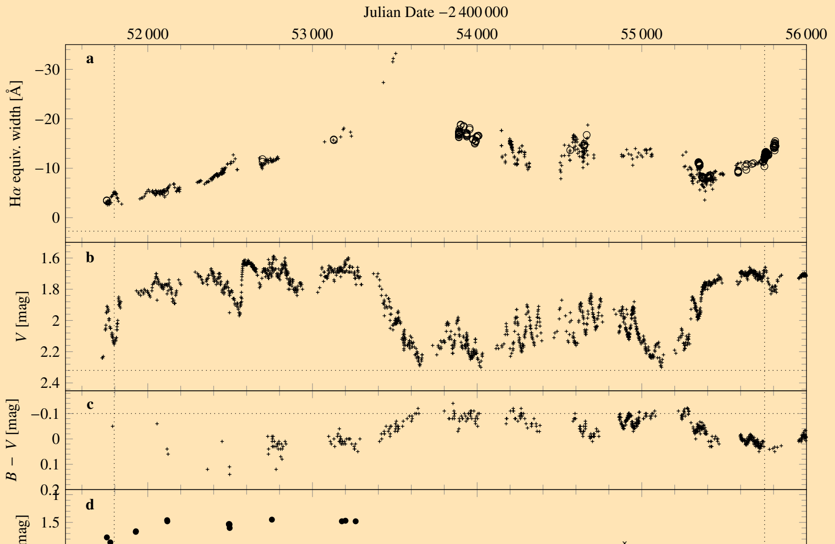
- "vartools" is an analysis package for time series data
- Free, available for all major op. systems, incl. windows
- http://www.astro.princeton.edu/~jhartman/vartools.html

Some words on S/N

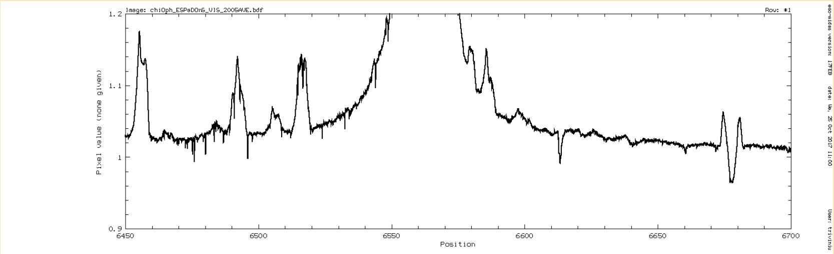
How to measure and to compare SNR values

- Be stars have lots of continuum, 1/RMS method is fully ok:
  - ➙ In a normalized (or at least flat) region, make statistics
  - ➙ SNR=value/RMS
- For comparison purpose:
  - ➙ Agree on wavelength range for all (e.g. red if Hα lots of continuum)
  - ➙ SNR is always per resolution element!
  - ➙ SNR of 100 at R=1000 is different from SNR 100 at R=10 000

Example: Del Sco



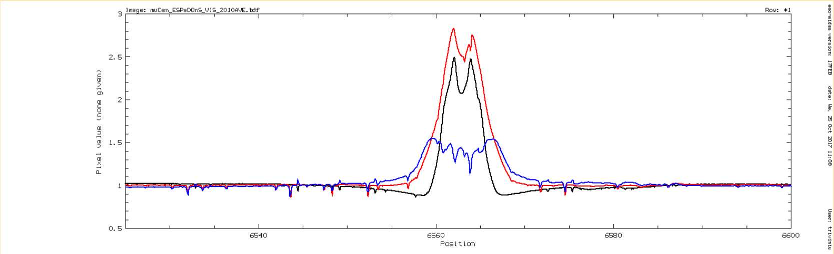
Example for scattering wings: chi Oph



Scattering wings and normalization

- Electron scattering wings are extremely wide
- Width is due to temperature (kinetic energy)
- Very light particles (electrons) means high velocity

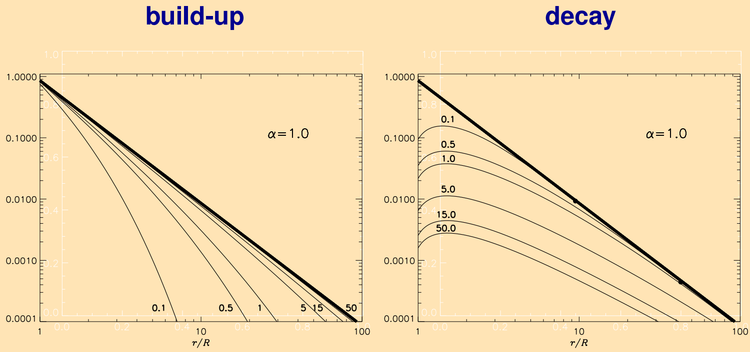
Example for scattering wings: mu Cen



Scattering wings and disk state

- 2006 FEROS (red), disk dense down to star
- 2010 ESPaDOnS (blk), disk central part depleted by decay
- Difference in blue

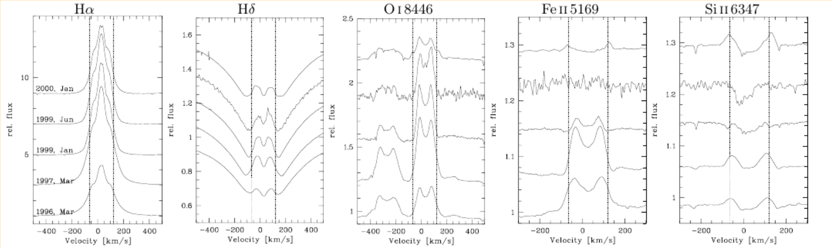
Disk cycles (density profiles)



Haubois et al., 2012, ApJ 756, 156

- Disk grows **and** decays both **inside out**
- Inner part of the disk reacts most quickly

Peak separation



Huang's law (Huang, S. S., 1972, ApJ 171, 549)

- Relates peak sep to disk size
- Ok for optically **thin** lines, **very** wrong for optically thick
- See OI8446 vs. Hα and Hβ.

Peak height and V/R

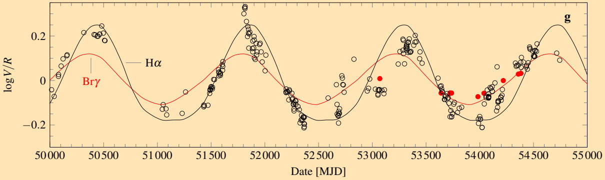
V over R measurement

- Historically, several conventions were used:
- V/R
- $V-1/R-1$
- $V - \text{supposed stellar profile}/R - \text{supposed stellar profile}$
- It does not really matter: Best publish both V and R individually, but **always** define **how** you compute it.

E over C measurement (aka intensity)

- Subject to same normalization issues as EW
- Sensitive to resolution (EW is not)

Cyclic Global V/R Oscillations (zet Tau)



Adapted from Carciofi et al., 2009

Stable cycles for about 15 years

- Cycle time scale stable at ~1500 d for four cycles
- Enables steady-state model, angle ϕ only variable parameter.
  - ➙ Physically understood as precessing density waves in the disk

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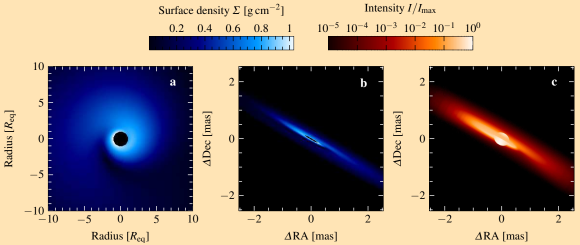

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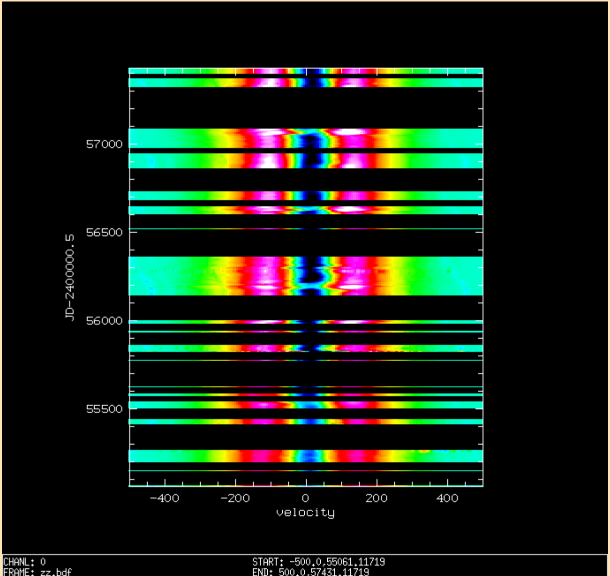
- Enables steady-state model, angle ϕ only variable parameter.
  - ➙ Physically understood as precessing density waves in the disk
- Surface density is turned to intensity by MC-RT code HDUST
  - ➙ Polarimetry is as well modeled

Pleione binary cycle (219 d)



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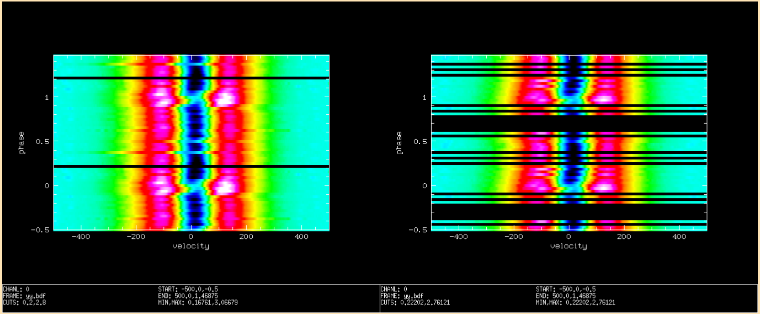
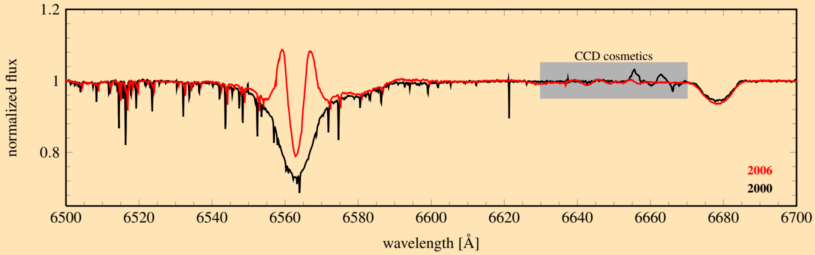


Pleione (early 2016)

- Left: Hα monitoring, right: echelle monitoring. Consistent!
- Many new profiles in last periastron (Nov 2016), in addition to
  - ➞ FORS polarimetry, X-shooter spectra, GRAVITY interferometry

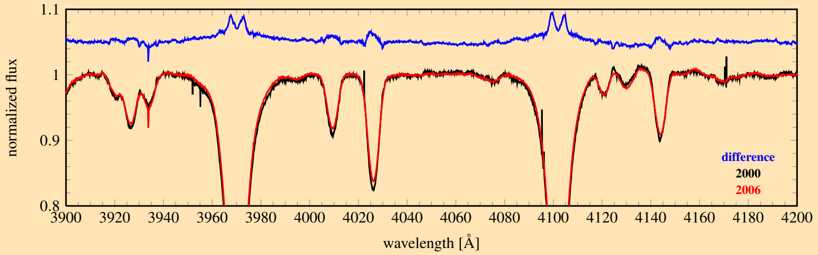
Quiescent vs. active phase (Achernar, 2000 vs. 2006)



Differences quiescent vs. active phase

- Balmer lines have emission contribution

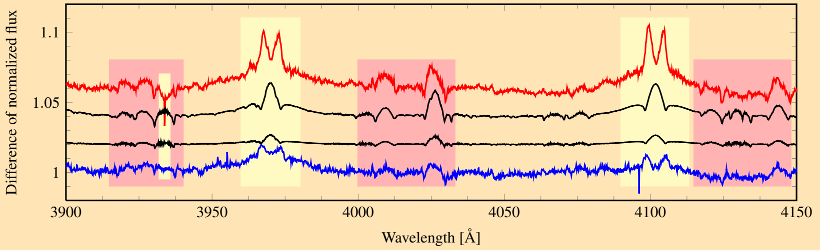
Quiescent vs. active phase (Achernar, 2000 vs. 2006)



Differences quiescent vs. active phase

- Balmer lines have emission contribution
- “abs-emi-abs” residual signature in most spectral lines
- sometimes “abs-abs-abs”

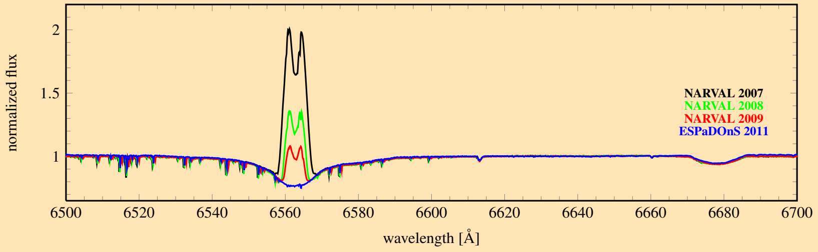
Modelling the variations



Variable $v \sin i$ parameter

- Residuals of two seasons (1999, 2006) vs. diskless state (2000)
- Model residuals of $\Delta v \sin i$=+10 and +35 km s^{-1} vs. $v \sin i$ =250 kms
- Varying any of (L, $T_{\rm eff}$, β, $v_{\rm rot}/v_{\rm crit}$) does not reproduce residuals

Other stars? 66 Oph



66 Oph – Story of a disk loss

- Disk decayed for about 10 years, diskless state reached ~ 2010
  - ➙ No significant disk feeding since early 2000s

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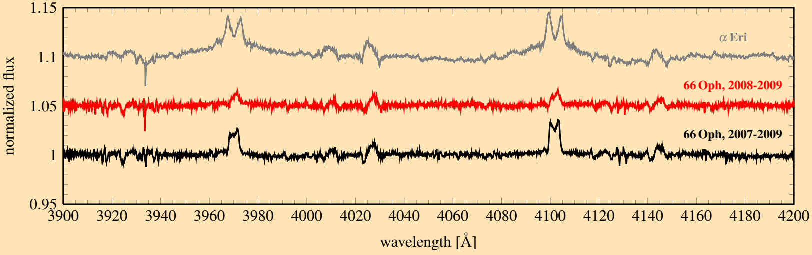
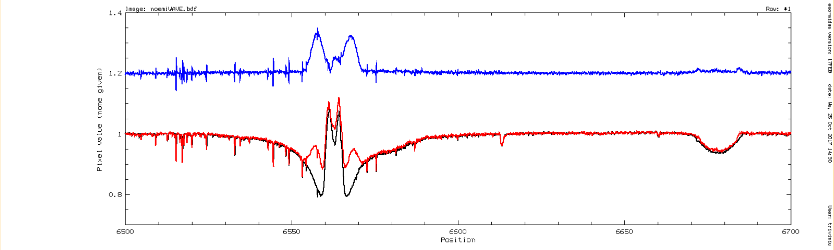


66 Oph – Story of a disk loss

- Disk decayed for about 10 years, diskless state reached ∼ 2010
  - ➙ No significant disk feeding since early 2000s
- But still significant excess wings until ∼ 2008
- Does excess $v \sin i$ correlate with re-accretion *rate*?

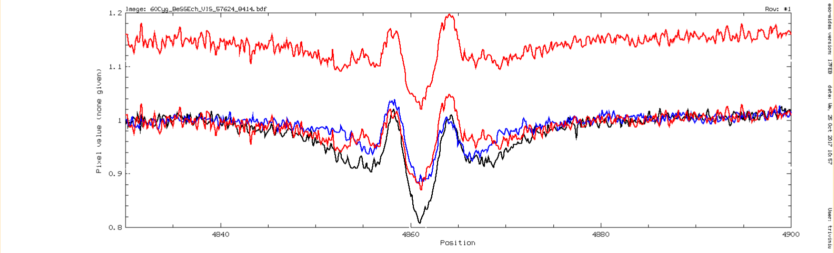
A double disk story



66 Oph (2009, NARVAL)

- perfectly normal profile in March 2009 (blk)
- 40 days later, something had happened
- The inner part of the disk had been replenished, then decayed again

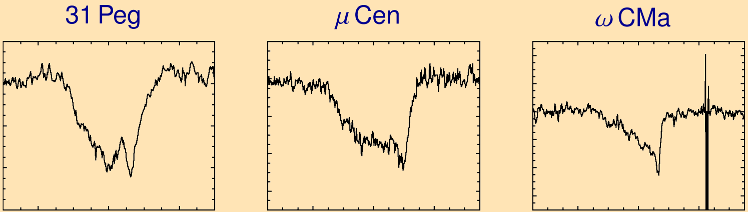
And with BeSS?



Hβ of 60 Ori (a few days ago)

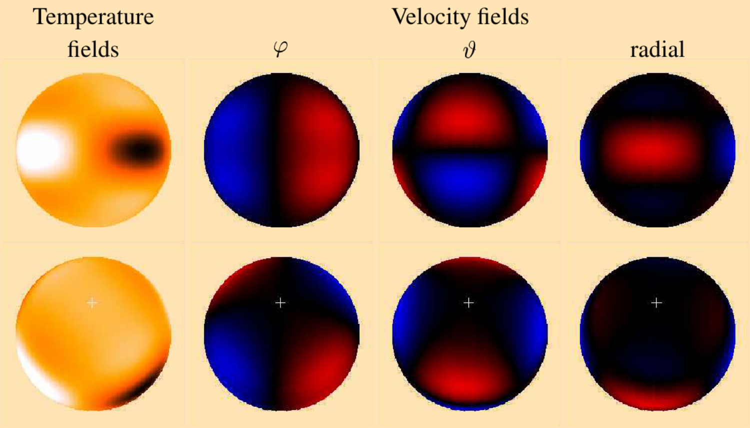
- A year ago (blk), a month ago (blue)
- And a week ago (red)
- Initial ejection must have been around the blue time
- Then circularized

Spectroscopy of non-radial pulsation: Spikes



- "Spikes" normal part of pulsation cycle in low $v \sin i$ Be stars
- A non-Be star, HR 4074, shows them, too
  - ➙ **Not** due to circumstellar material
  - ➙ HR4074 is a non-Be pulsational twin of ω CMa

Observational signatures: Spike formation



Rivinius et al., 2002

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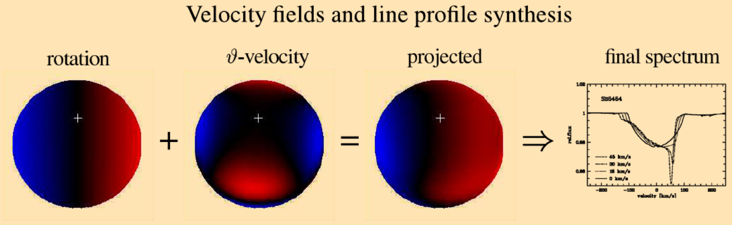
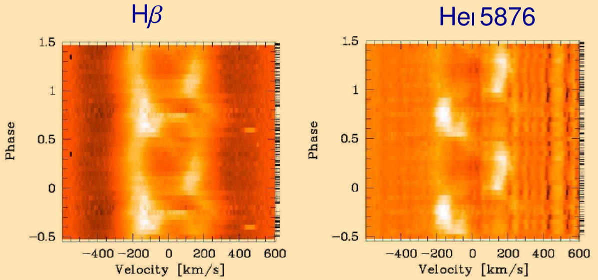


Rivinius et al., 2002

- At low *i*, $v \sin i$ and projected ϑ-amplitude comparable.
- Spikes occur naturally for:
  - ➙ **Rapid rotators** seen pole-on, **pulsating** in ℓ 2, m 2 g-mode
- Prograde modes did not produce spikes
- **But:** Other possibilities (Rossby etc.) not tested.

Tomography: Be+sdO Binaries

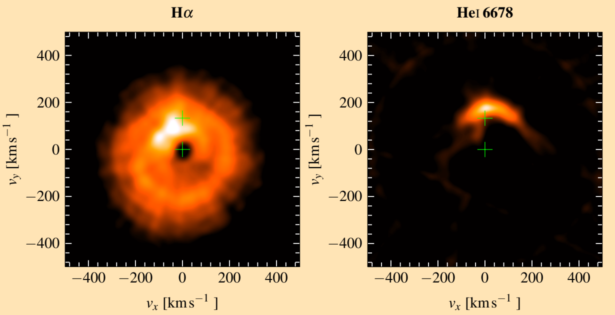


59 Cyg, Maintz, PhD thesis, 2003

Potential target systems

- ϕ Per, 59 Cyg, FY CMa, *o Pup, HD 161306*
  - ➙ Periods 28-130 d, all bright systems, 3×SB2, *2×SB1*, 2 shell stars.
- Optically thin?
  - ➙ Hα certainly not, Balmer lines more-or-less, other likely yes.

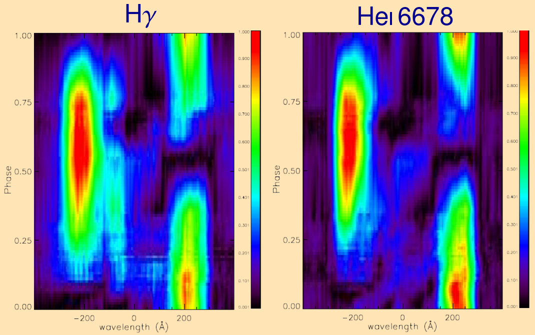
Tomographic view on 59 Cyg



A first result (by Jason Grunhut)

- He I 6678 shows radiative interaction, plus some faint features
- Hα shows persistent disk and radiative interaction, but at to low *v*
  - ➙ Consequence of optical thickness (c.f. "non-coherent scattering broadening", Hummel & Vrancken)
  - ➙ At higher *v* in Hβ (not shown)

Orbital Variability

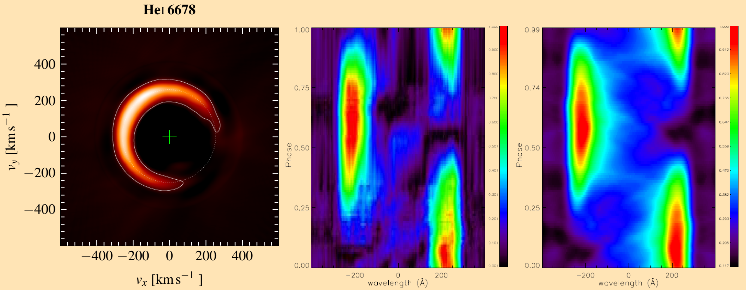


Difference vs. minimum

Short-term cyclicity in ω Ori

- Stable for $\sim$ a dozen cycles, $P \approx 1$ to 2 d
  - ➙ Probably newly ejected material before circularization
- Exceptional dataset for tomography (originally for magnetometry)

Tomographic Reconstruction



Tomograms and data reconstruction

- Left: tomogram, middle: data, right: reconstructed data
  - ➙ Balmer and He-lines remarkably similar (but not identical)
  - ➙ Emission already stretches over most of orbit

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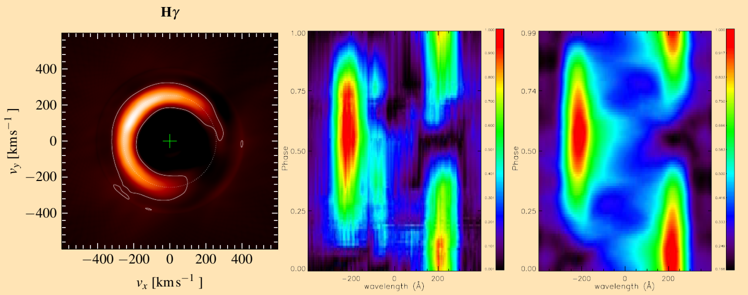

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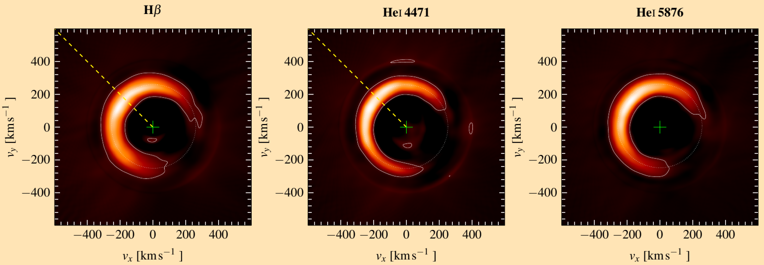
Similarities and Differences Between Lines



Short-term cyclicity

- Probably newly ejected material before circularization
  - ➙ Phase offset between Balmer and He lines in bulk of emission
  - ➙ Possibly some contribution at lower velocities.

Some unrelated remarks

What: Exploit synergies proactively

- Keep an eye on what is observed by e.g. satellites
  - ➙ BRITE, K2, TESS
- and just put it on your lists.

How: Every spectrograph has its space

- LR: EW monitoring, BD stellar parameters, find Be stars
- HR-Hα: Profile and EW monitoring, find Be stars
- Echelle: See above, and “alerted/requested” observations
- Echelle or special λ-regions: For well defined projects and tasks
  - ➙ Ca II, quiescent Be stars in very high SNR, etc.