Pulsation, rapid rotation, mechanical mass ejection, and disks: Be stars with TESS + contemporaneous spectroscopy

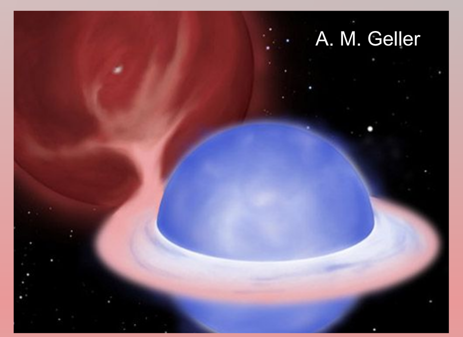
Jonathan Labadie-Bartz, Alex Carciofi, André Luiz Figueiredo, Tajan Henrique de Amorim, Amanda Rubio, Pedro Ticiani dos Santos

Universidade de São Paulo, Brazil

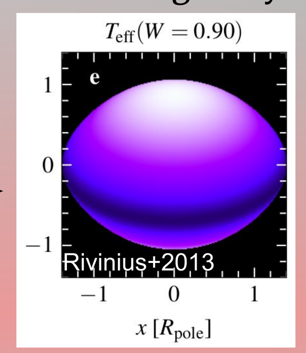
Classical Be stars: Main sequence B-type stars with circumstellar "decretion" disks

Key Ingredients

Binary mass transfer -> spin-up of *eventual* Be star



Near-critical rotation (≥80%). Low equatorial surface gravity.



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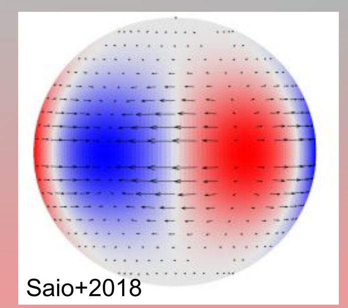
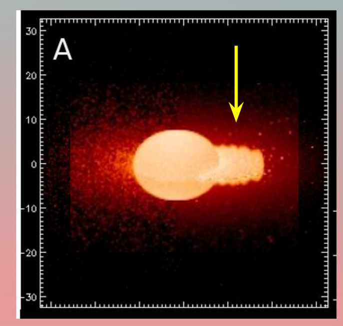
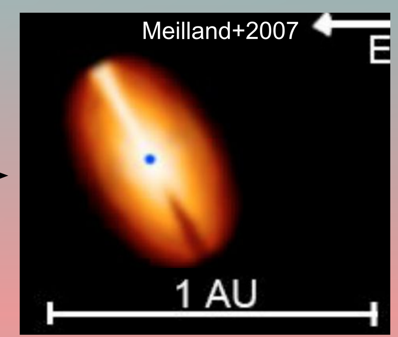
Multi-mode non-radial pulsation.



Mechanical mass ejection (not winds)



"Decretion" disk is formed (hot, gas, Keplerian, viscosity)



Physical parameters

- Binary parameters
- M + AM transfer rates
- efficiency of mass transfer

- Rotation rate
- Oblateness
- Surface gravity + T_{eff}
- Gravity darkening

- Waves carry energy + momentum
- Temperature + velocity perturbations
- mode coupling

- Density + temperature + velocity distribution
- Behavior of ejecta
- What drive mass ejection?

- Transport of mass and angular momentum outward
- Role + strength of viscosity
- Slow oscillations
- Tidal interaction with companion

Timescale

P_{orb} ~ 10 - 40 d

P_{rot} ~ 0.5 - 2 d

P_{pulse} ~ 0.2 - 2 d

P_{orb} ~ 0.5 - 3 d

t_{disk} ~ 10 d - 100 yr

Observables

- binary RVs
- **Brightness at P_{orb}**
- Emission + **phot. var.** from accretion + disk

- Vsini
- polarimetry + interferometry
- **asteroseismology**

Periodic signals in:
- **brightness**
- line profile shape + RV

- **Continuum brightness**
- Variable emission features
- Polarimetry

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- Interferometry

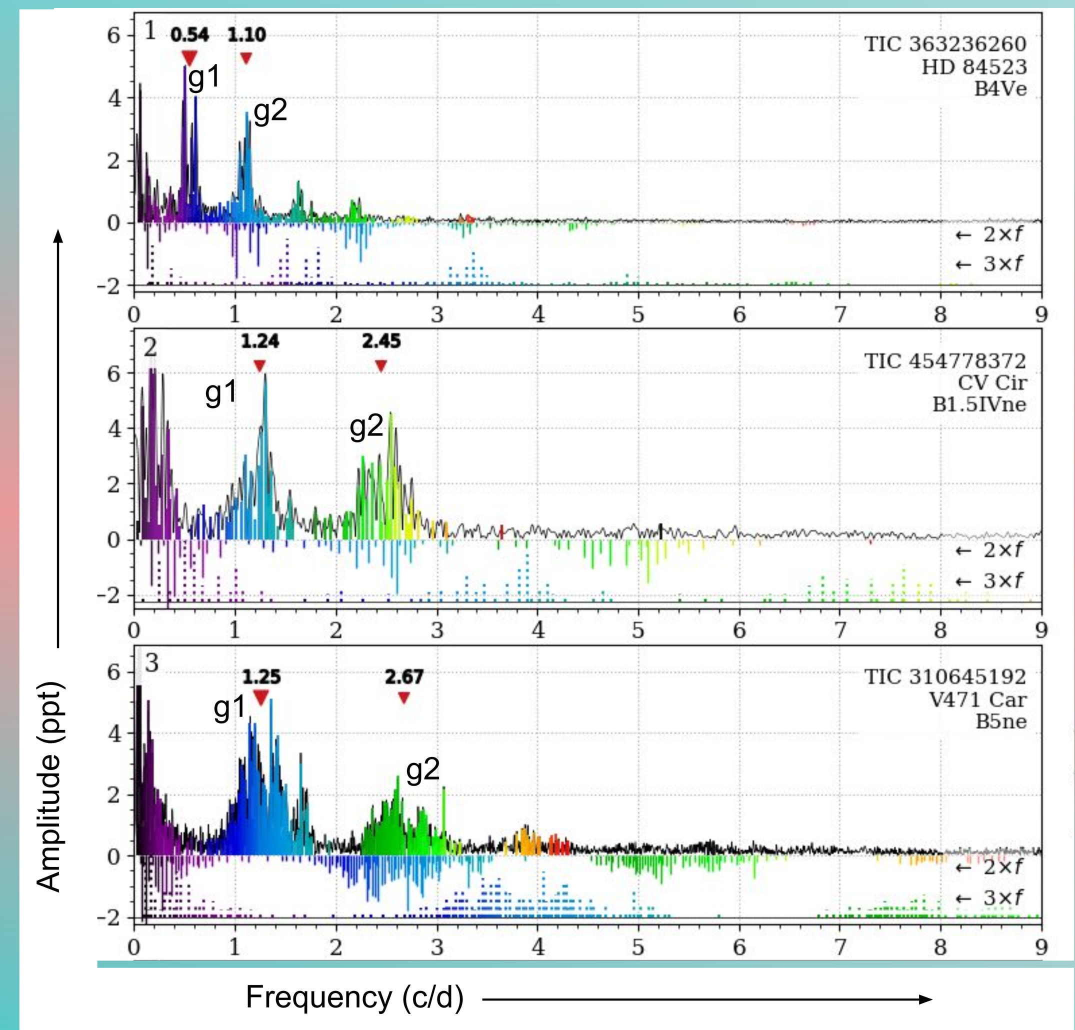
Pulsation + frequency groups

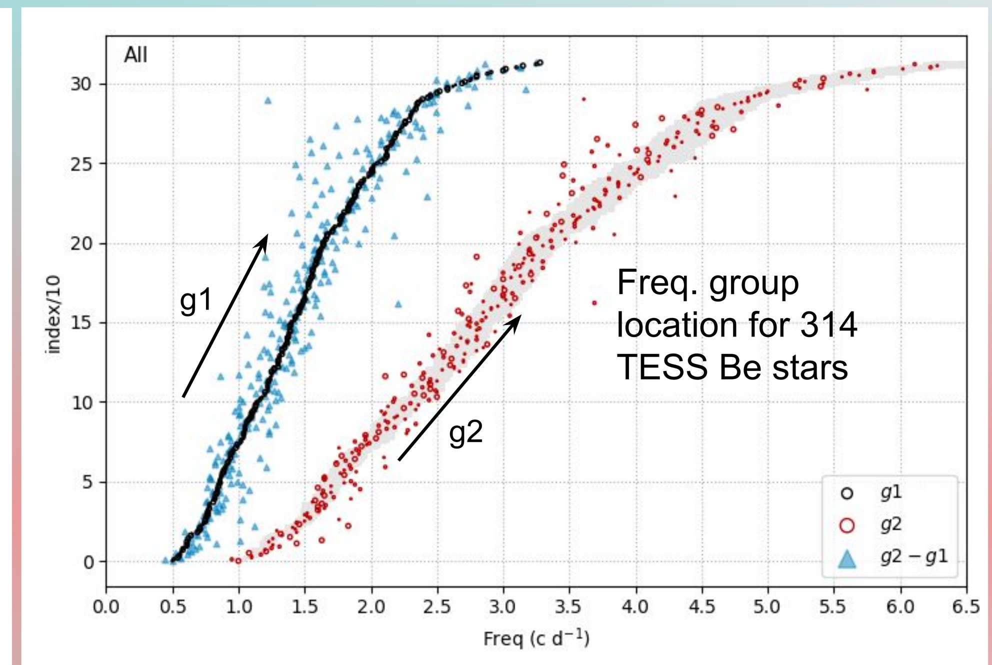
Main results from 430 Be stars with TESS (Labadie-Bartz+2020):

- All Be stars pulsate (98% detected in TESS), always multi-mode (many freqs)
- Freq. groups are very common (87%)
- Low-frequency pulsation (g- and/or r-modes) ubiquitous even in the hottest B stars
- All stars with mass ejection have freq. groups
- Temporarily high amplitudes correlated with mass ejection episodes
- Non-rapidly rotating B stars do not have frequency groups (Burssens+2020)

Measurements from TESS freq. spectrum:

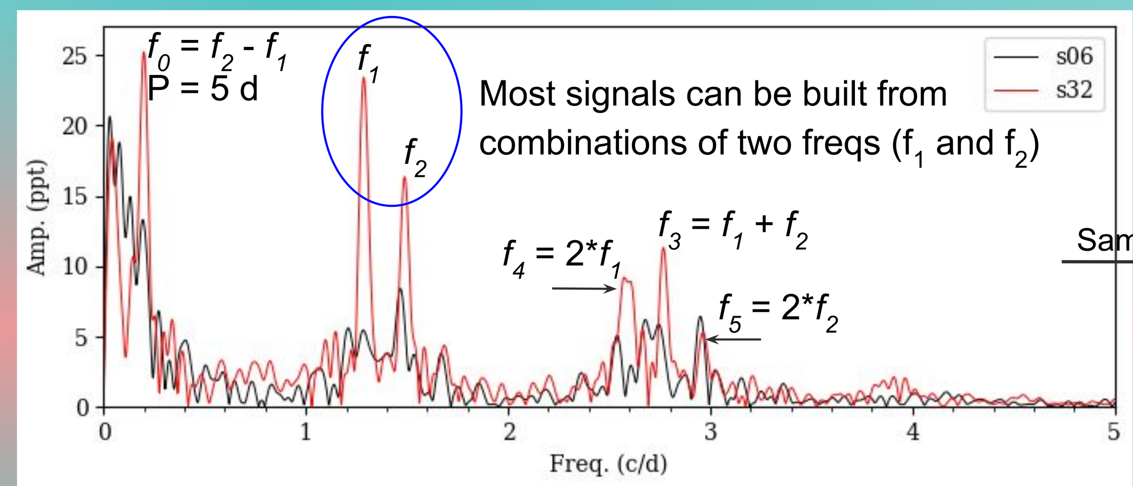
- All individual frequencies (including in groups)
- Weighted central frequency of each group
- Relative amplitude of each group
- All isolated signals (not in groups)
- Red noise level (low-freq stochastic var.; not related to groups)

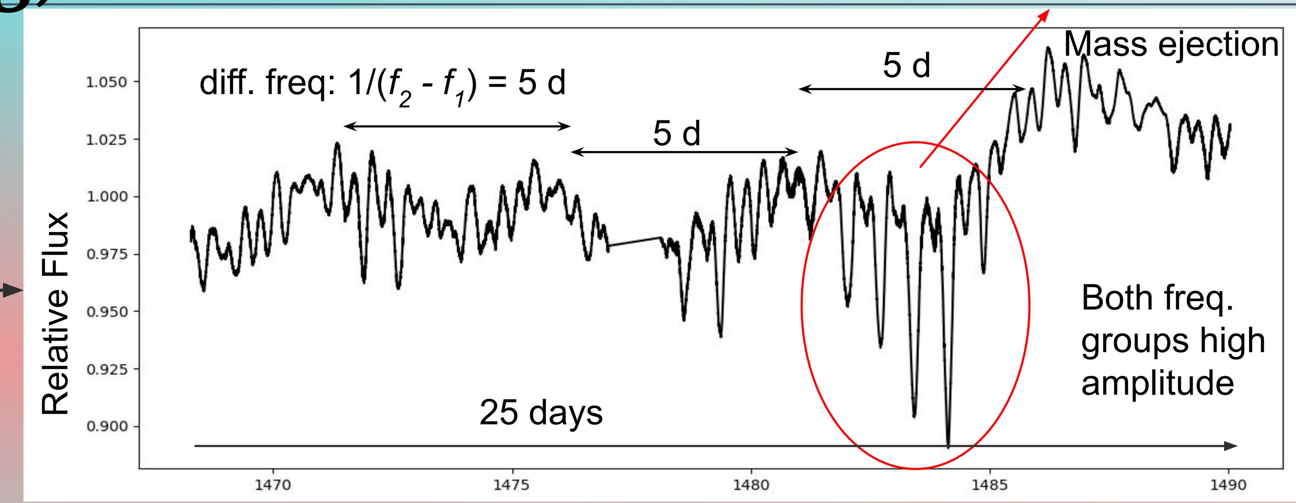




- On average, g2 is located at 2x g1
- g2 - g1 seems related to the stellar rotational frequency (Semaan+2018)
- g1 usually stronger than g2. But, in stars with 'flickers', g2 is usually stronger

Combination freqs. (mode coupling)

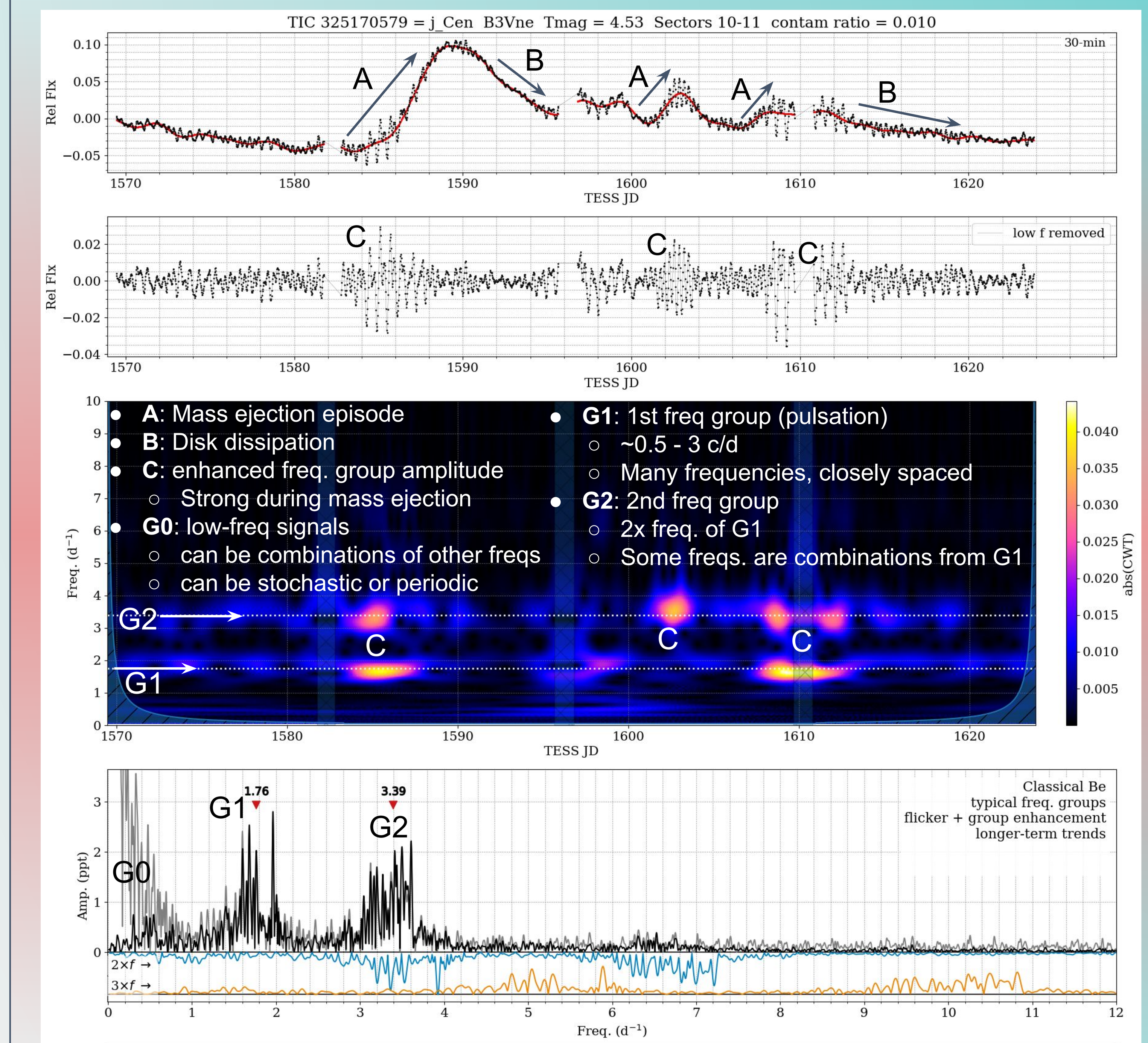




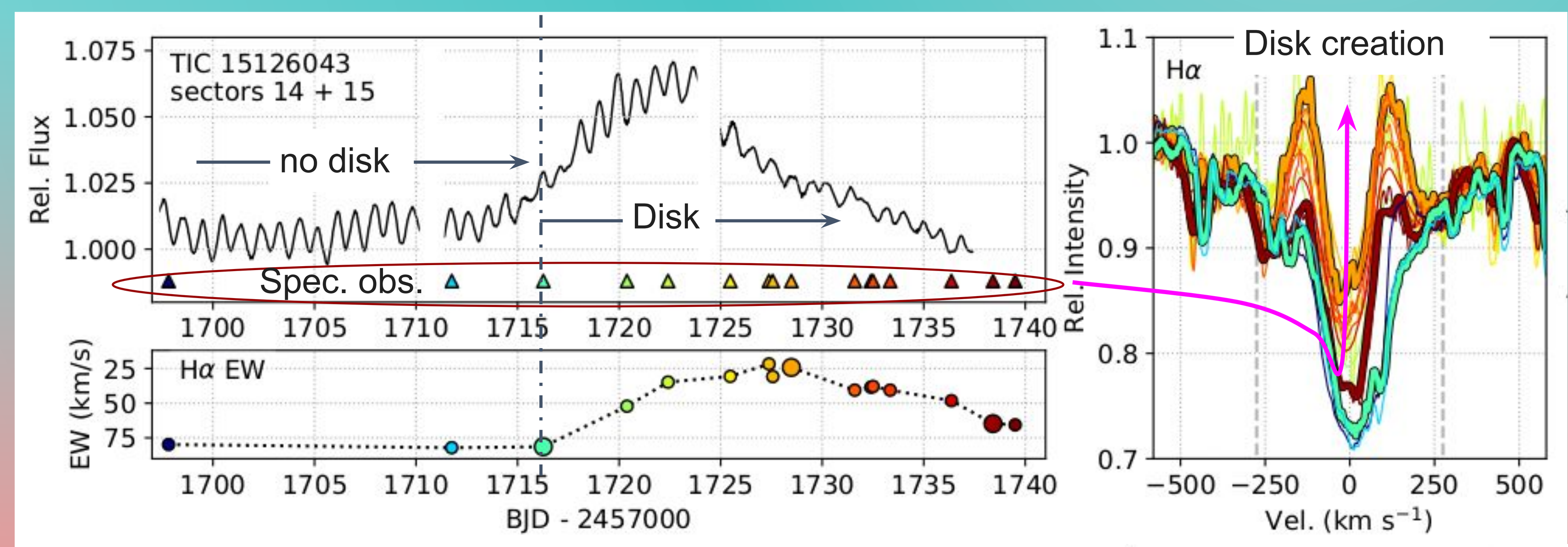
- Pulsation modes can couple in stellar envelope (combination frequencies; Kurtz+2015, Baade+2018)
- Physical non-linear coupling -> high amp., not simply a beat pattern

- Non-linear mode coupling can trigger mass ejection (sometimes). But…
  - Some Be stars have no freq groups, yet build up disks
  - Some Be stars have freq groups + mode coupling, yet at times have no disk
- Some (unknown) slower 'clock' also modulates mass loss.

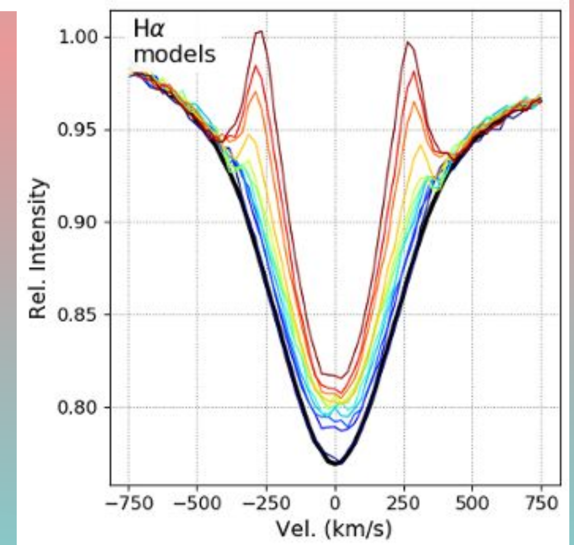
Anatomy of TESS data for a Be star



Mass ejection + disk formation : 'flickers'



- Time-series spectroscopy simultaneous with TESS reveals changes in the circumstellar environment (from mass ejection turning on/off + disk evolution)
- Mass ejection -> more circumstellar material -> emission lines + increased continuum brightness
- Simultaneous photometry + spectroscopy breaks degeneracies, allowing mass ejection events + disk evolution to be modeled on short (orbital) timescales for the first time
- 18% of Be stars observed with TESS have these mass ejection episodes ('flickers') during the short TESS baseline.
  - More common in early-type (>B3): 31%
  - All stars with flickers have frequency groups
  - 83% of stars with flickers see temporarily enhanced freq. group strength during mass ejection
- Not related to large-scale magnetic fields



Labadie-Bartz et al. 2020 (arXiv:2010.13905)
Semaan et al. 2018 (2018A&A...613A..70S)
Baade et al. 2018 (2018pas8.conf...69B)
Kurtz et al. 2015 (2015MNRAS.450.3015K)
Meilland et al. 2007 (2007A&A...464...73M)
Saio et al. 2018 (2018MNRAS.474.2774S)
Rivinius et al. 2013 (2013A&ARv..21...69R)
Burssens et al. 2020 (2020A&A...639A..81B)

Other relevant works:
Rivinius et al. 2013 (2016A&A...593A.106R) : Kepler's view of 3 Be stars
Neiner et al. 2020 (2020A&A...644A...9N) : AM transport, asteroseismology, pulsation of a Be star
Naze et al. 2020 (2020MNRAS.498.3171N) : Study of 13 Be stars (gamma Cas analogs) with TESS
Wade et al. 2016 (2016ASPC..506..207W) + ud-Doula et al. 2018 (2019MNRAS.487..304D) : no large-scale mag. fields in Be stars

We know (in part thanks to TESS):

- All Be stars pulsate
  - Frequency groups are by far the most common feature in Be star space phot.
- Non-linear mode coupling seems key for the (still unknown) mass ejection mechanism(s)
  - Many cases with links between photometric freqs, groups, combination freqs., and mass ejection
- Mass ejection often not smooth, symmetric, or periodic
- Pulsational phot. and spec. freqs often differ

Questions:

- What exactly do phot frequency groups represent (g and/or r modes?)?
- What is the role of the main spectroscopic frequency?
- How to explain diversity of Be star behavior?
- Multiple mass ejection mechanisms?
- Are internal gravity waves relevant (deposit AM in envelope)?
- TESS alone is not enough - need spectroscopy

Works in progress:

- Freq. group spacing seems related to rotation rate -> determine rot. rate independent of inclination angle. Verify with UV + optical spec. analysis.
- Simultaneous fitting of red noise profile + periodic signals (~1000 Be stars)
  - Determine low-freq. stochastic variability properties
  - Compare to non-rapid rotators. Is stochastic var. a key ingredient in Be star physics?
  - Better quantify combination freqs.
- Intensive (100+ spec.) monitoring simultaneous with TESS
  - pulsation from photospheric line-profile variability
  - kinematics, density profile, timing of mass ejection, relations to phot. signals
- Hydrodynamic + radiative transfer models of days-long mass ejection episodes and disk evolution (bottom-middle fig.)