Be Stars seen by space photometry

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October 24, 2017

Some Be stars. Credit: Robert Gendler via APOD (January 9, 2006)

Pleione, Alkyone, Electra, Merope

Disclaimer

Some words on what follows

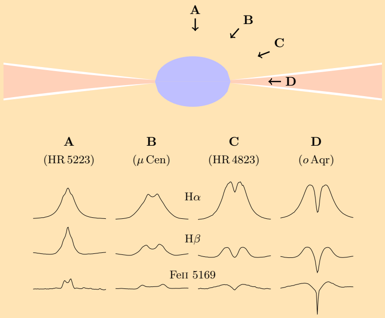
- Many of the following cases have been first published by others
- I have re-analysed Kepler, CoRoT, and SMEI data (but not MOST)
- Results below may not be fully endorsed by original authors
  - ➙ Any stupid blunder is surely mine, not theirs
- Unpublished BRITE results are from Dietrich Baade
- Graphs without reference are own work (but possibly by collaborators)

Content

Be star classification

Definition (Be stars)

A non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emission. (Jaschek et al., 1981; Collins, 1987)



Be star classification

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A non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emission. **(Jaschek et al., 1981; Collins, 1987)**

- **Problem:** Any dense gas will produce emission around B star

Still has its scope:

For classification data (in amount and quality), the above definition is the only practicable.

Physical properties of classical Be stars

Definition (Classical Be stars)

- Emission is formed in a disk
  - ➙ Evidence: Interferometry, polarimetry
- Disk is created by central star through mass loss
  - ➙ Evidence: Disk can come and go in weeks to decades, absence of mass-transferring companion

More physical definition, still based on observational properties, but hard to apply. Though necessary to understand different object types.

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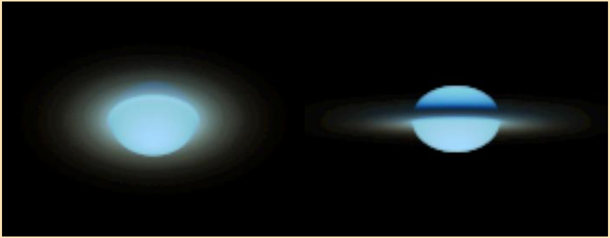
Observational corollary (Disk angular momentum & magnetic field)

- *Disk is rotationally supported (i.e. Keplerian)*
  - → *Evidence: Spectro-interferometry, spectroscopy of shell stars, time behaviour of perturbed disks*
- *No large-scale organized magnetic field (e.g. dipole)*
  - → *Evidence: None found down to few ten Gauss*

What do we observe

low incl. high incl.

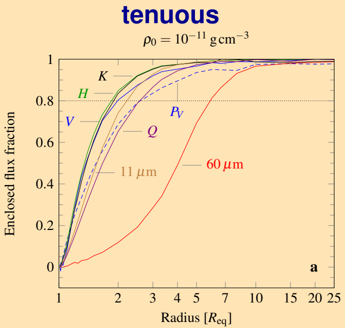


Faes & Carciofi, priv. comm.

Physical model

- HDUST radiative transfer model of Be star with disk
  - → High dynamic range, colour computed with model for human vision
- Star only one of several contributors to observational signature

Origin of continuum excess (pole-on case)

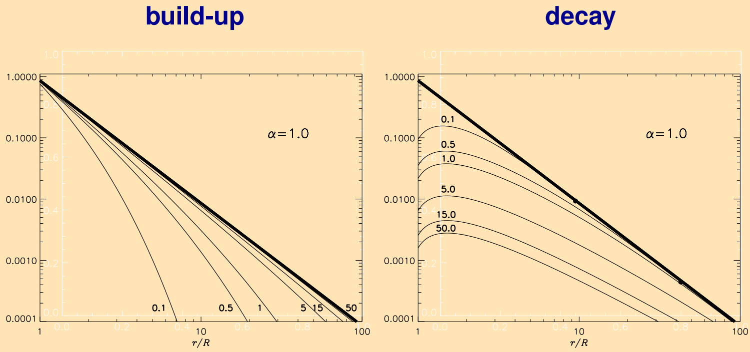


Rivinius, Carciofi, & Martayan, 2013

Formation region as function of disk density (pseudo-photosphere)

- Optically thin disk: blueish photometric bands have common formation region
- Optically thick disk: stratification, redder means further out

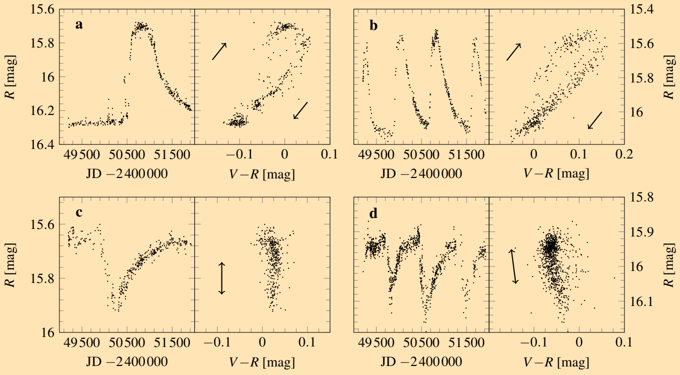
Disk cycles (density profiles)



Haubois et al., 2012, ApJ 756, 156

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

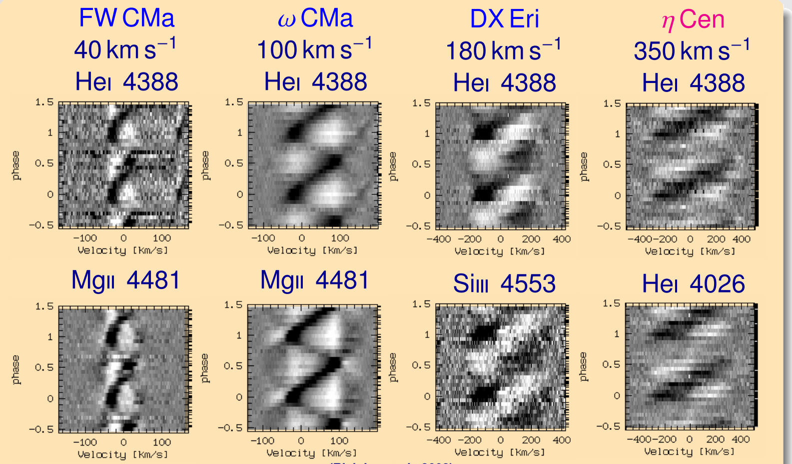
Photometric disk cycles (observed)



Rivinius, Carciofi, & Martayan, 2013

- Upper row: Low inclination Be stars
- Lower row: High inclination Be stars

Pulsation seen in many Be stars (spectra)



(Rivinius et al., 2003)

The questions

What we understand

- How the star behaves, at least at large
  - Rapid rotation
  - *g*-mode pulsation
  - no magnetic field
- How the disk behaves (non-disturbed)
  - Governed by viscosity (maybe plus ablation)
  - “forgets” how it was formed once in place

What not

- How does the matter get ejected?
- How is it circularized into a viscous disk?
- How the inner disk behaves dynamically when disturbed
- **Star-disk interface (and disk-star interface)**

The pre-BRITE spaceborne photometry view

Multiperiodic Be stars

Between a few and more than 30 periods found:

CoRoT 102719279, HD 175869, HD 51193, CoRoT 102761769, HD 181231, HD 50209, HD 51452, **HD 49330**, **ζ Oph**, HD 163868, HD 127756, HD 217543, β CMi, **Achernar**, KIC 6954726

Gutiérrez-Soto et al., 2010, 2009, 2011; Janot-Pacheco et al., 2011, Neiner et al., 2009, 2012; Diago et al., 2009; Huat et al., 2009; Walker et al., 2005; Saio et al., 2007; Cameron et al., 2008; Goss et al., 2011; Balona et al., 2011. Data from CoRoT, MOST, SMEI, & Kepler.

Red: Amplitude maxima coincide with outbursts.

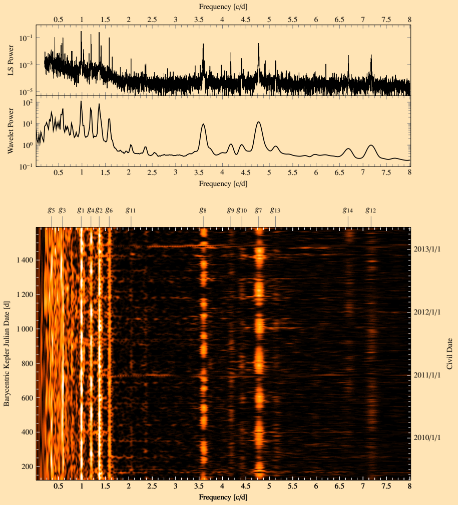
Semann et al., 2011

On 18 Be stars in the CoRoT exoplanet fields:

> “Generally the frequency spectrum shows a forest of frequencies around one or two main frequencies as well as several isolated frequencies.”

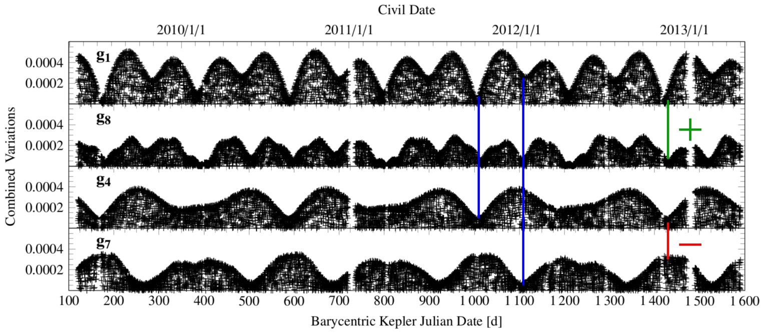
Content

Inactive: KIC 8057661, 21 kK



Rivinius, Baade, & Carciofi, 2016

Inactive: KIC 8057661, 21 kK



Rivinius, Baade, & Carciofi, 2016

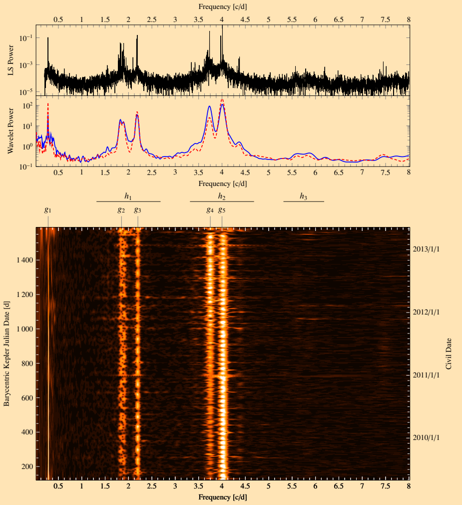
- Reconstructed absolute variability of some groups
- Minima and maxima are intedependent with complicated pattern

Inactive: KIC 8057661, 21 kK

Early type, but inactive Be star

- Kepler data, full time span over 4 yrs
- **No outbursts, probably not even a circumstellar disk during run**
- Many frequencies
  - → Either hundreds in a dozen groups
  - → Or a dozen frequencies with variable amplitude
- Correlations and anti-correlations between different groups
  - → Resonant coupling?
- **Looks like a normal pulsating star**

Beginning or low activity: KIC 11971405, 12 kK



Rivinius, Baade, & Carciofi, 2016

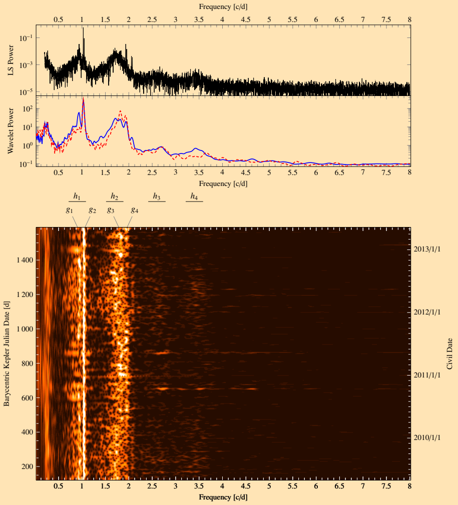
Beginning or low activity: KIC 11971405, 12 kK

Late type, low activity Be star

- **A few minor outburst in second half of run**
- Many frequencies
  - → Either many dozens in five or six groups
  - → Or a few frequencies with variable amplitude
- Correlations and anti-correlations between different groups
  - → Resonant coupling?
- **So far looks like a normal pulsating star**

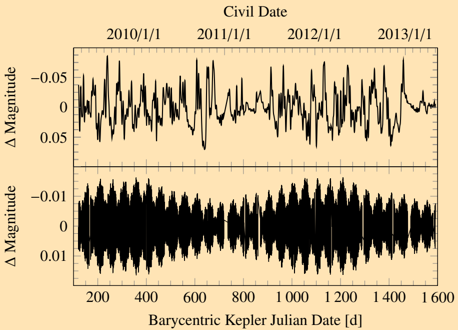
- **Broad bumps in power spectra**
- Stronger when more active (second half of run)
- An additional frequency (group) becomes apparent in the second half of the run
- **Be specific properties**

High activity: KIC 6954726, 17 kK



Rivinius, Baade, & Carciofi, 2016

High activity: KIC 6954726, 17 kK



Rivinius, Baade, & Carciofi, 2016

- Top: Reconstructed long term variations (outbursts)
- Bottom: Reconstructed behaviour of group at $\sim$ 1 c/d

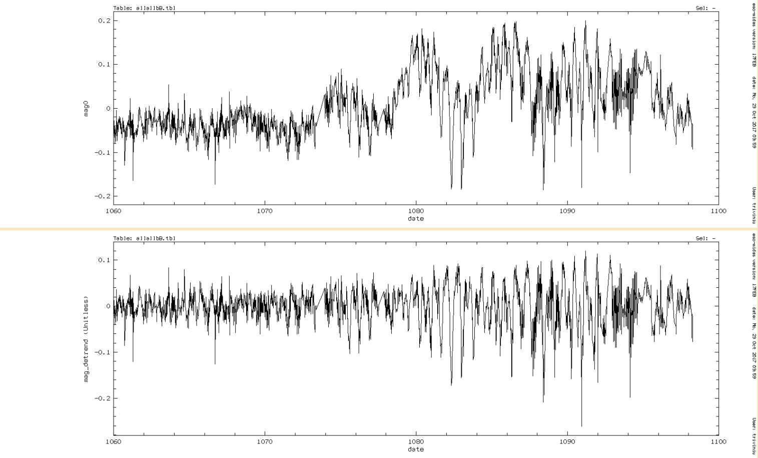
High activity: KIC 6954726, 17 kK

Mid type, high activity Be star

- **Many outburst; almost continuously**
- Nearly infinte number of fequencies
  - → Thousands needed to explain strong bumps
  - → Or a few frequencies in groups plus non-periodic varibility on typical timescales
- **Very different from a normal pulsating star**

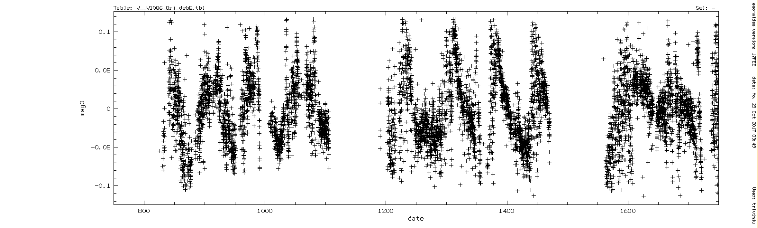
- Strength of broad bumps correlate with outburst activity
- As well correlation between **pulsation group 1** and **outbursts**
- Additional frequency group present when more active
- Bumps have many higher harmonics
- **Be specific properties**

Bright BRITE star: ψ^1 Ori, B1 Vne



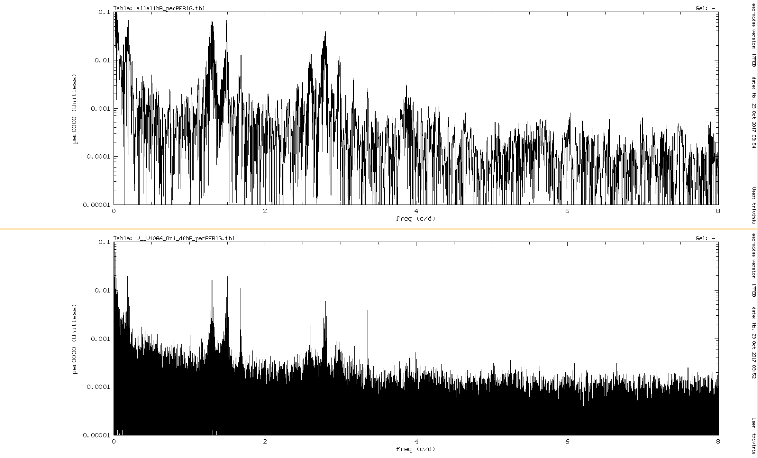
BRITE data: Baade et al., in prep.

Bright BRITE star: ψ^1 Ori, B1 Vne



SMEI data: Baade et al., in prep.

Bright BRITE star: ψ^1 Ori, B1 Vne



SMEI data: Baade et al., in prep.

Bright BRITE star: ψ^1 Ori, B1 Vne

Early type, high activity Be star

- **Regular outbursts over last ten years!**
- Many high frequencies
  - → Some difference values between those have own life, not only beating
- Frequency differences govern outburst behaviour
- **In many other BRITE stars, too. Published: 28 Cyg, η Cen**

Joint campaign planned on λ Pav

- BRITE would observe March to September, alert to outbursts
- Southern amateurs to follow in spectroscopy
- ESO-VLTI to follow in interferometry
- Brazilian LNA to follow in polarimetry
- **Technical difficulties prevented BRITE to observe**

Observational summary I

Štefl frequencies

- In outburst (when matter is ejected) a distinct frequency group becomes active
- Always at about same value, but with ~10% scatter
- Clearly **associated with circumstellar environment** (spectroscopy)
- Either freshly ejected matter, or ejection process itself

Frequency groups

- Many frequencies are
  - ➙ either intrinsically variable in strength and value
  - ➙ or consist of large number of subfrequencies, creating the vriable appearance via beating
- Sometimes, frequency differences within or between these groups are seen in the power spectra, too (see talk Baade)
- Could this reflect the root cause of the ejection?

Observational summary II

Power bumps

- Not well defined frequencies, but very broad
- Present when star has disk, stronger in outburst
- Large number of harmonics (strongly non-sinusoidal)
- Stochastic variation, but with a typical timescale
- Most obvious (and common) feature in Be star power spectra
  - → SMEI, CoRoT, Kepler: Between 1/3 and 2/3 of stars show bumps.
- Probably arises from transition region star-disk (or disk-star?)

Delta frequencies

- Very low frequencies
- Values equal to difference of two shorter frequencies
- High to very high amplitude
- These are actual outbursts. At least in some stars.

Content

What we observe and what we understand

Observed variability

- **The star**
  - Notwithstanding details, pulsational appearance is in principle clear
  - Can easily extrapolated from non-Be stars (such as SPB, β Cep)
- **The disk**
  - Viscous Decretion Disk (VDD) model explains long term variations
  - But only in quasi-equilibrium state.
  - Disturbed inner disk (aka outburst) not covered by current VDD
- **The rest**
  - Assumption: What is left comes from star-disk interface region

Mass ejection mechanism

η Cen type mechanism

- Dominant mechanism of mass ejection
- Observationally, we may be ready to identify all we need
  - → Need **in-depth observations of well-known stars**, not statistics
- Next steps have to do with
  - → physical interpretation of various components
  - → modelling

Other mechanisms?

- Some very early type Be stars show “amorphous” power spectrum
  - → **Stochastic pulsation?**
- Very late type Be stars show “almost rotational” power spectrum
  - → **Rotation plus something?**
  - → **Something else entirely?**

Mass accretion mechanism

Accretion?

- Way viscosity works **requires** large fraction of material to be re-accreted.
  - ➞ Only then gas disk can transport angular momentum outwards
- It is unknown if this has an observational signature
- It is unknown how such signature might look like
- **Have we already observed it?**

Content

Comparison of missions wrt. Be stars

Mission	Time base	Data quality	Statistics	Context
MOST	several weeks	very high	bad	ok
Kepler	4 yrs	very high	bad	bad
K2	several weeks	very high	ok	bad
CoRoT	1–3 months	very high	ok	bad
SMEI	9 yrs	what's that?	good	good
BRITE	months to years?	high	ok	good
TESS	several weeks	very high	ok	ok

- **BRITE** has a unique position in the above table:
  - → Observes many stars
  - → For which we know a lot of context
  - → Precision high enough to analyze individual outbursts (and sometimes even cycles of a frequency)
  - → Timebase can be extended by re-observing fields.
  - → **Only mission without a red entry in the Table!**

Conclusions

- BRITE data promise giant leap in understanding
  - ➛ Bright targets mean they are well studied already
  - ➛ Further supporting data can be acquired with modest equipment
  - ➛ **For few selected targets get closer to Kepler time base**
- We know enough to make sense of what we do not know
  - ➛ **Stellar pulsation** and **long-term disk behaviour** identifiable
  - ➛ What remains is likely signature of **disk formation process**
- Have to be very careful in interpretation for modelling
  - ➛ Is any frequency a **photospheric** mode at all, **or circumstellar**?
  - ➛ Is any frequency group a **real group** or just the Fourier representation of a **single, variable mode**?
    - ➘ Resonant mode coupling in Be (and SPB, β Cep) stars