Be Stars and their Viscous Disks

Th. Rivinius, L.R. Rímulo & A.C. Carciofi

European Southern Observatory, Chile

IAG, São Paulo, Brasil

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

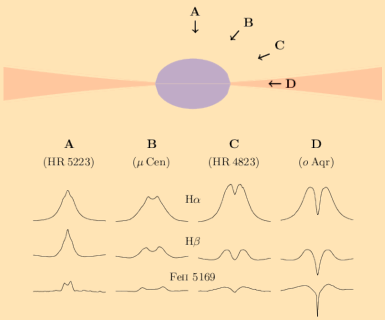
Pleione, Alkyone, Electra, Merope

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)
(Non-sg B star: 3 to 15 $M_\odot$, 10 000 to 28 000 K)



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- **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
  - ➙ Interferometry, polarimetry
- Disk is created by central star through mass loss
  - ➙ 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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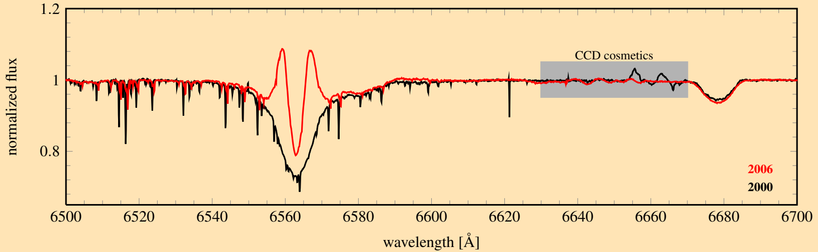
Observational corollary (Disk angular momentum)

- *Disk is rotationally supported (i.e. Keplerian)*
  - ➙ *Spectro-interferometry, spectroscopy of shell stars, time behaviour of perturbed disks*
- *These disks do not contain dust*
  - ➙ *IR and radio SED pure gas ff and bf*

Spectra of disk variability



Stories of disk gain and loss

- Disks can both form from zero and decay into nothing in short to medium times (weeks to years).
  - → No significant disk feeding since early 2000s

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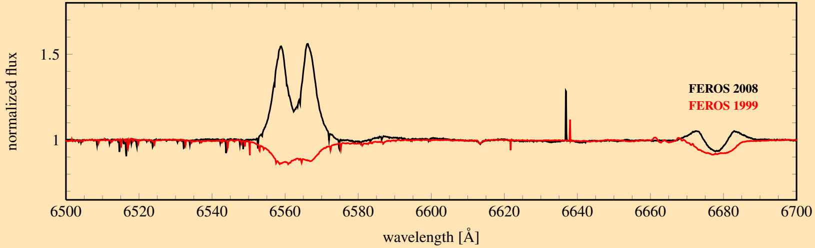

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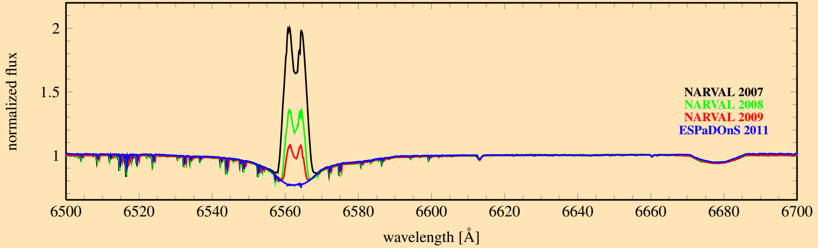

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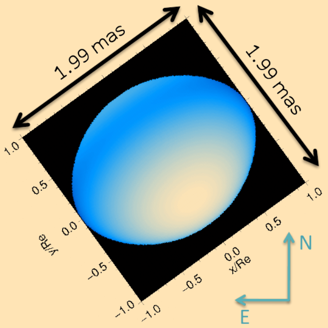
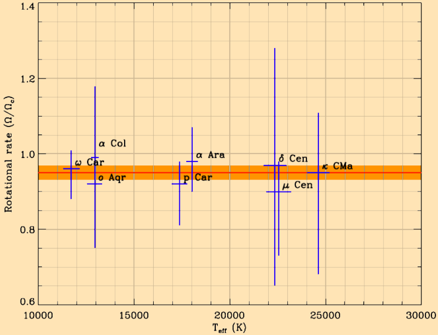
How rapid is rapid rotation?





Domiciano de Souza et al., 2014 A&A

Meilland et al., 2012, A&A 538, A110

- Achernar at 88% of critical velocity (84% of Keplerian velocity)
  - → Very typical case
- Rest of ejection work is done by pulsation (don't know how)

Astrophysical relevance

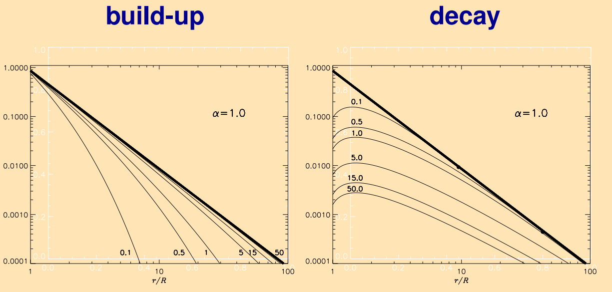
Most rapid massive rotators

- How did they evolve? How will they evolve?
- Are they different from slower rotators in structure, chemistry etc.?
- Will the most massive ones become GRBs?
- Do they have magnetic fields?

Disk physics

- Brightest example pieces to study disk physics, with potential impacts on all scales:
  - Catcalysmic variables
  - Star & planet formation
  - Our own Galactic Center
  - AGNs .....

Disk density profiles during build-up and decay

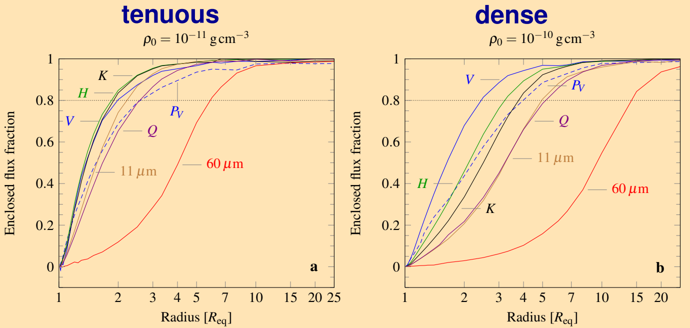


Haubois et al., 2012, ApJ 756, 156

Disk evolution

- Disk grows and decays inside out
  - → SINGLEBE code by Okazaki
- Inner region reacts quickest
- This is where most photometric bands are formed

Origin of continuum excess (pole-on case)

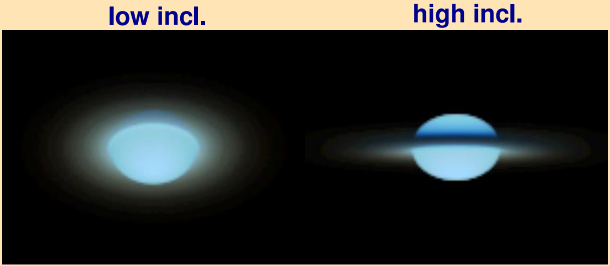


Rivinius, Carciofi, & Martayan, 2013

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

- Redder means further out
- Computed with MC code HDUST (SED, polarimetry, Balmer lines)

What do we observe

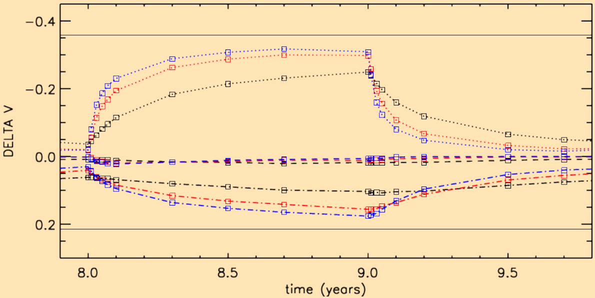


Faes & Carciofi, priv. comm.

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

Photometric signature of disk formation and decay



Haubois et al., 2012, ApJ 756, 156

Disk evolution

- →
-
-

The questions

What we understand

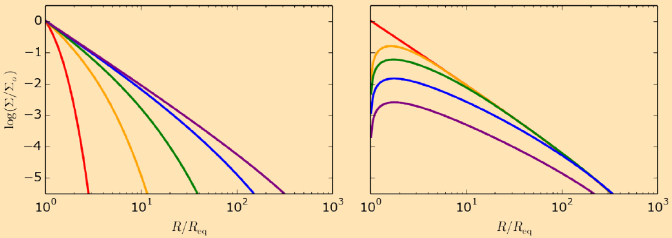
- How the star behaves, at least at large
  - Rapid rotation
  - *g*-mode pulsation, plays a role in mass ejection
  - no magnetic field
- How the disk behaves (non-disturbed)
  - Governed by viscosity (maybe plus ablation)
  - “forgets” how it was formed once in place

What not

- How did/will a Be star evolve?
  - Did binarity play any role?
- Star-disk interface (and disk-star interface)
  - How does the matter get ejected?
  - How is it circularized into a viscous disk?
  - How the inner disk behaves dynamically when disturbed

Content

Disk density profiles during build-up and decay

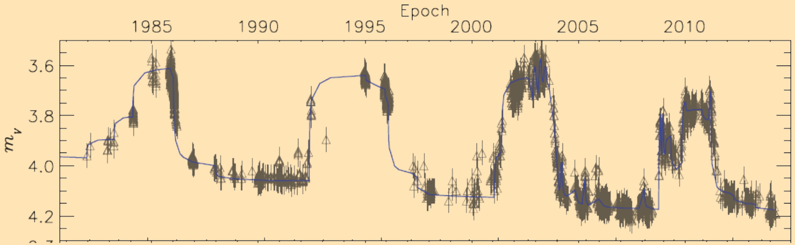


Rimulo, Carciofi et al, submitted

Disk formation and decay

- Disks are formed and decay inside out
  - ➙ Disk evolves assuming standard viscuous disk processes
  - ➙ Viscous disks cannot be stable
- TImesclaes are controlled by viscosity (so we think)

The disk life-cycle

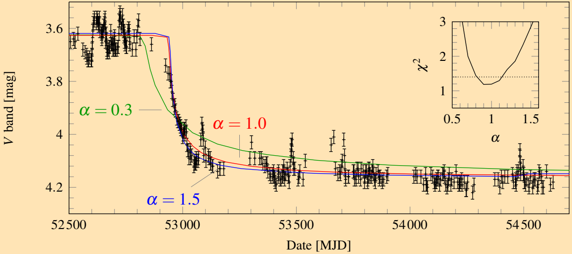


from Ghoreyshi et al., 2016, ASPC 506, 315

Long- and mid-term disk evolution

- Medium term disk outburst/decay cycle
  - ➙ Formation and decay of viscous decretion disk (VDD) close to star
  - ➙ Or just forms as VDD, but decays differently (radiative ablation?)
- Long-term underlying dimming
  - ➙ Hα emission always there, but decaying as well.
  - ➙ If VDD, too, why timescale so different?

A large viscosity parameter

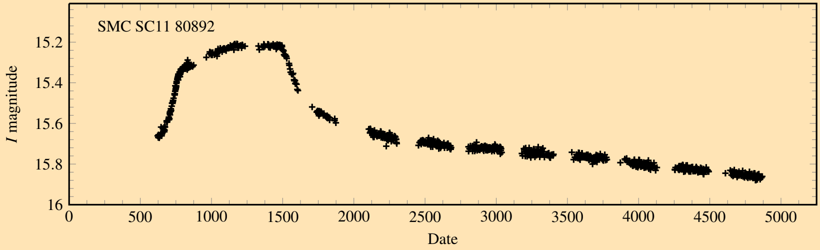


from Carciofi et al., 2012, ApJ 744L, 15

Decay of the disk

- Very rapid disk decay: High viscosity?
  - ➙ Model fits best with $\alpha \approx 1$ (turbulent over sonic speed)
  - ➙ More recent value w/ better understanding a bit lower
  - ➙ Still high: about 0.3
  - ➙ Method can be applied to large set of lightcurves

Generalizing the viscosity determination



OGLE II and OGLE III data

A viscosity survey

- OGLE, MACHO etc. provided hundreds of such light-curves
  - → Enables determination of α in a survey

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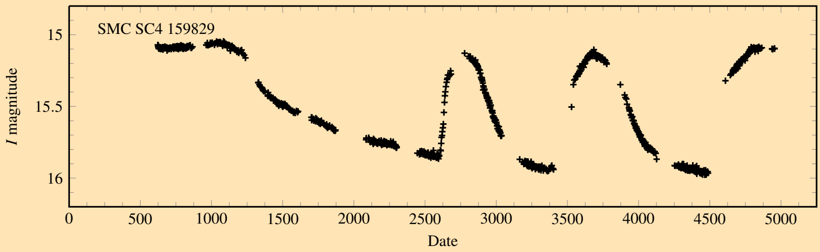

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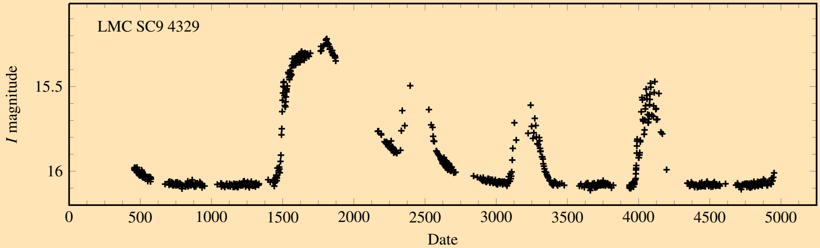

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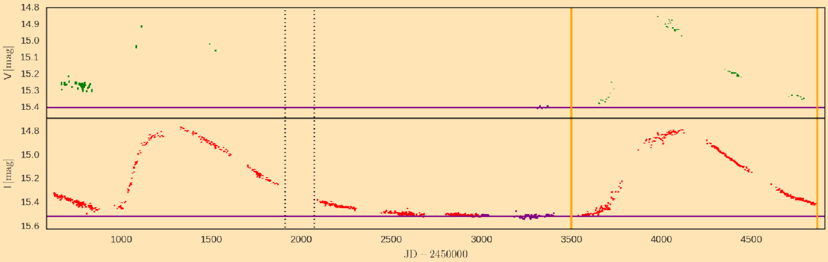
Finding well isolated events

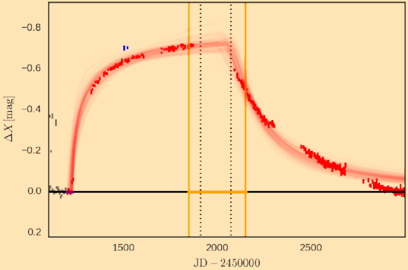


Rimulo, Carciofi et al, submitted

SMC, OGLE II and III data, 12 years

- Total of ~ 1000 Be star candidates, 54 of those:
  - Show clear, well isolated events, plus stretches of inactivity
  - Only events with at least 15 days build-up time chosen
  - Total of 81 events

Modeling the viscosity

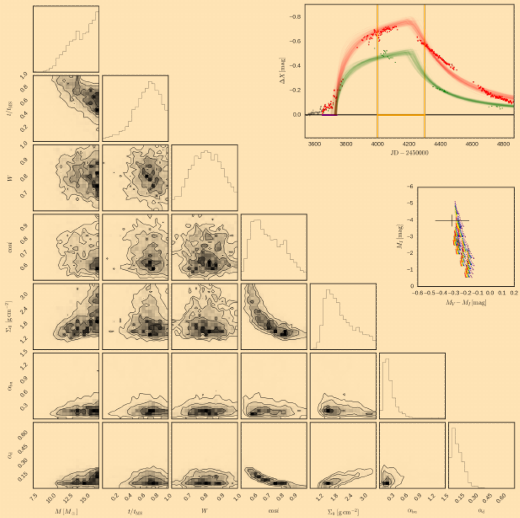


Rimulo, Carciofi et al., yesterday, unpublished

Monte-Carlo radiative transfer modeling of lightcurves

- Large grid of models for each event (54 stars, about 80 events)
- Probablilty density functions found with Markov-Chain method

Results for a single event



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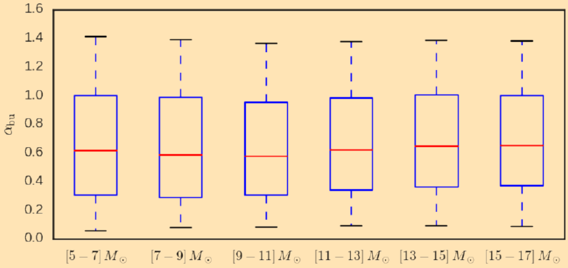
Viscosity when building and destroying a disk (SMC)

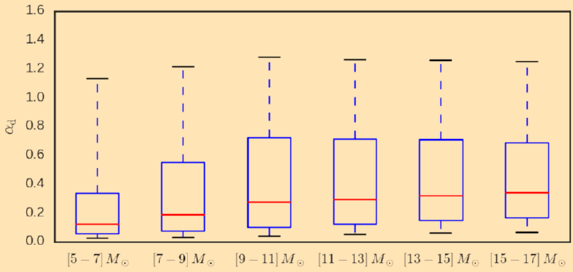


Rimulo, Carciofi et al., yesterday, unpublished

Building a disk

- Viscosity high, mean about 0.6
- Does not depend on Sp. type of central star
- Mechanically driven viscosity, by outbursts?

Viscosity when building and destroying a disk (SMC)



Rimulo, Carciofi et al., yesterday, unpublished

Destroying a disk

- Viscosity lower, mean about 0.25, closer to CV derived values
- Does depend on Sp. type of central star
- Radiatively driven viscosity, via opacity?

Late type Be & Herbig stars, β Pic like objects

VDDs (viscous decretion disks) cannot be stable

- Late type Be stars often look as if
- Extremely similar to YSOs like 51 Oph
  - → Solution one: Mass los rates constant over long times
  - → Solution two: Viscosity parameter drops radically

SMC data not available for late-type Be stars (too faint)

- However, trends point to:
  - → Lower base densities Σ_0!
  - → Longer time scales for disk variability!
  - → Lower viscosity in decay?

What changes?

- Radiation field
  - → Radiative ablation may mimick viscosity.
  - → Radiation pressure induces turbulence

Viscosity in Be star disks

Where we are:

- α high in outburst in all Be stars.
- α "low" in decay in all Be stars.
- α even lower in decay in mid to late-type Be stars.

Stuff to be done

- Play same game for LMC and MW: α vs. metallicity?
- Could different viscosities be a radial effect?
  - → Outbursts take place in inner disk only
  - → Decay takes place in entire disk
- Can it be measured?
  - → Dynamical response to outburst: inner disk
  - → Dynamical response to binary tidal effects: outer disk