Be Stars and Rotational Mixing

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With many thanks for discussions to make things clearer to myself to

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

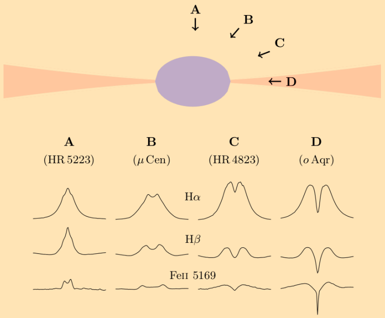
Pleione, Alkyone, Electra, Merope

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 solar masses, 10 000 to 28 000 K)



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: Disks 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 physics.

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Observational corollary (Disk angular momentum)

- *Disk is rotationally supported (i.e. Keplerian)*
  - → *Evidence: Spectro-interferometry, spectroscopy of shell stars, time behaviour of perturbed disks*

Astrophysical relevance

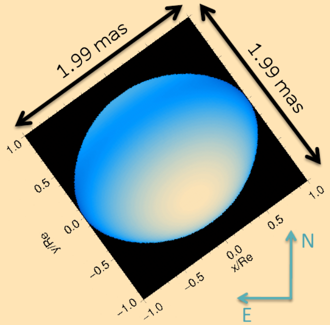
Most rapid massive rotators

- How did they evolve? How will they evolve?
- **Differences vs. slower rotators in structure, chemistry etc.?**
- Will the most massive ones become GRBs?
- Do they have magnetic fields? **No!**

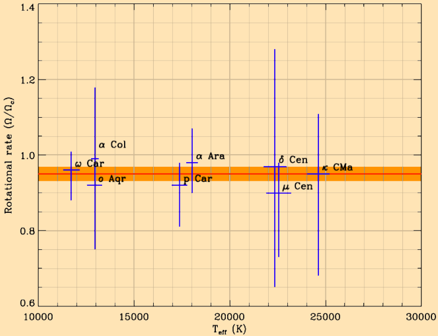
Disk physics

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

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)
- Cases in which inclination could be determined point to 80 to 90% critical (75 to 85% of Keplerian vel. above equator).

Two thresholds!

Survey results

- Mean rotation rate 75 to 85% Keplerian, independant of subtype
- Huang et al. (2010) studied clusters, find only Be stars above certain rotation rates (no more B stars).

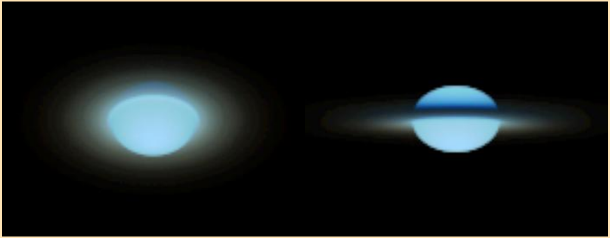
A B star can become a Be star

- If it rotates above about 70% of the equatorial Keplerian velocity
- This does not depend on spectral type.

A B star must become a Be star

- For early type B stars:
  - → If it rotates above about 70% of the equatorial Keplerian velocity
- For late type B stars
  - → If it rotates above about 95% of the equatorial Keplerian velocity
- This does depend on spectral type.

What do we observe?



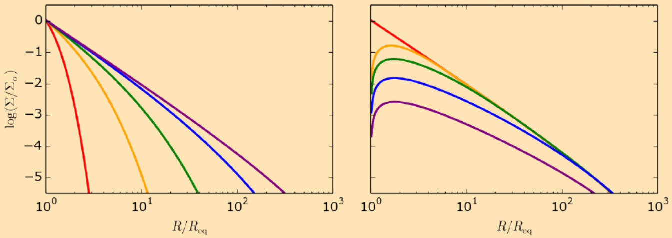
Faes & Carciofi, priv. comm.

Physical model

- Disk structure analytically out of dynamical viscous model
- HDUST Monte Carlo radiative transfer model of Be star
  - ➙ High dynamic range, colour computed with model for human vision

Content

Disk density profiles during build-up and decay

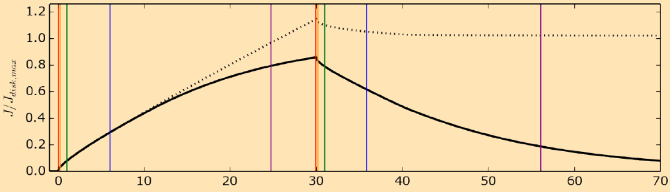


Rimulo, Carciofi et al, submitted

Disk formation and decay

- Disks are formed and decay inside out
- Disk evolves assuming standard viscuous disk processes
  - ➙ Viscous disks cannot be stable
- Mass and AM lost in an individual event can be measured
  - ➙ Outer radius is set by $v_{\rm orb} = v_{\rm sound}$ (e.g., Krtička, Owocki, & Meynet, 2011)

Angular momentum loss through a Be star disk cycle

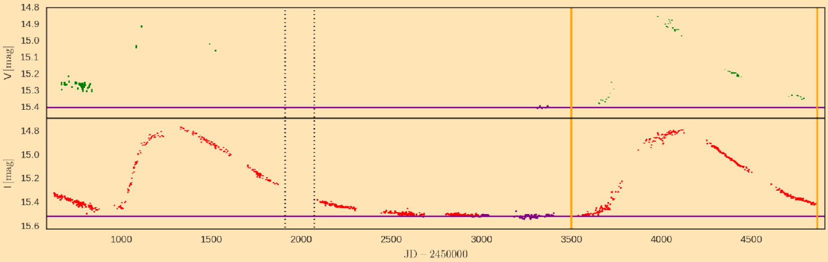


Rimulo, Carciofi et al, submitted

Measuring Am loss through outer disk edge

- Bold: AM of current disk
- Dotted: AM that is not in star
- Difference: AM lost from system
  - → Disk forms, AM is lost to ISM when outer edge of disk reached
  - → Disk decays, part of AM is re-accreted, but still most is lost
  - → Vertical lines: Time snapshots from last slide

Finding well isolated events

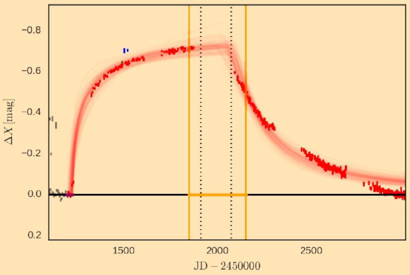


Rimulo, Carciofi et al, submitted

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 event

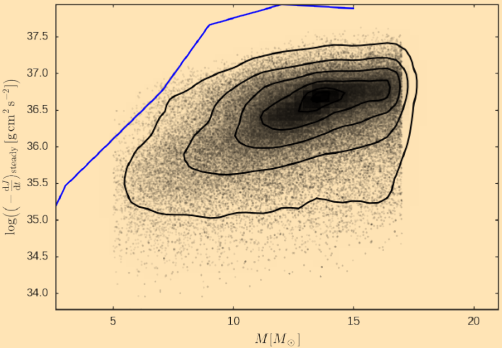


Rimulo, Carciofi et al., submitted

Monte-Carlo radiative transfer modeling of lightcurves

- Large grid of models for each event
- Probablilty density functions found with Markov-Chain method

The AM-loss rate



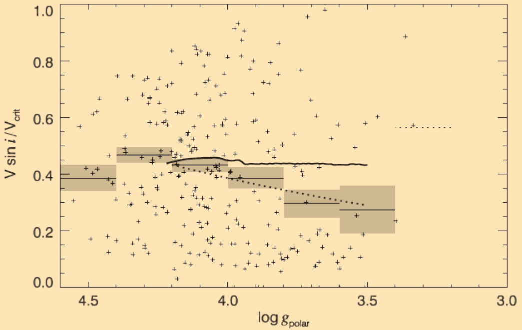
Rimulo, Carciofi et al., submitted

Say for a 10 solar mass star:

- $\dot{J} \approx 5 \times 10^{36} \mathrm{g\,cm^2\,s^{-2}}$, $0.5\tau_{\rm MS} = 3 \times 10^{14}$ s, 30% duty cycle
- $\Delta J = 5 \times 10^{50} \mathrm{g\,cm^2\,s^{-1}}$, (2.5% for critical solid body rotation)

The evolving rotation of Main Sequence B stars

2 to 4 solar masses

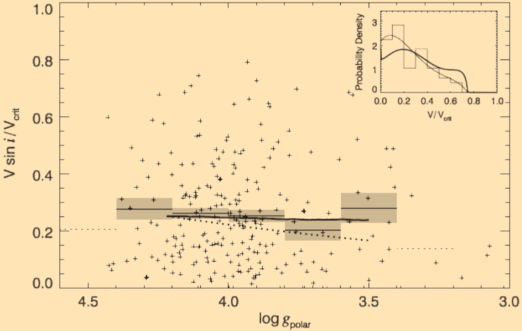


Huang et al., 2010, ApJ 722, 605. $v \sin i / v_{crit}$ **vs.** $\log g$

- Bold: Geneva code prediction (Ekström et al., 2008)
- Dotted: No AM mixing at all
- Obvious issue for late B stars, inconclusive for early ones

The evolving rotation of Main Sequence B stars

7 to 13 solar masses



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Is there MA mixing at all?

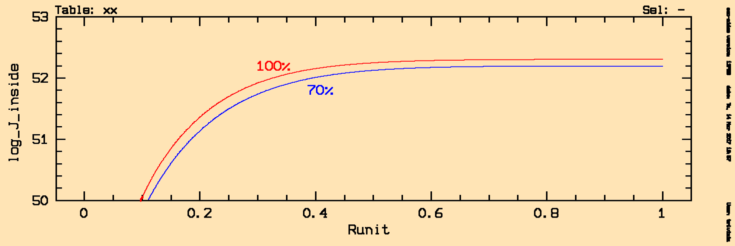
Binaries?

- If no AM mixing, all Be stars must be binary products
  - ➙ Because then there is no evolutionary spin-up
- How long can a Be star remain above rotational threshold?
  - ➙ Both evolutionary spin-down and disk spin down work against you
  - ➙ E.g., if 25% of B stars are Be stars, but can be Be stars only for 1/4 of their min sequence life...

Definition (Spin-up and spin-down)

Spin-up: A star gets closer to the critical limit
Spin-down: A star moves away from the critical limit

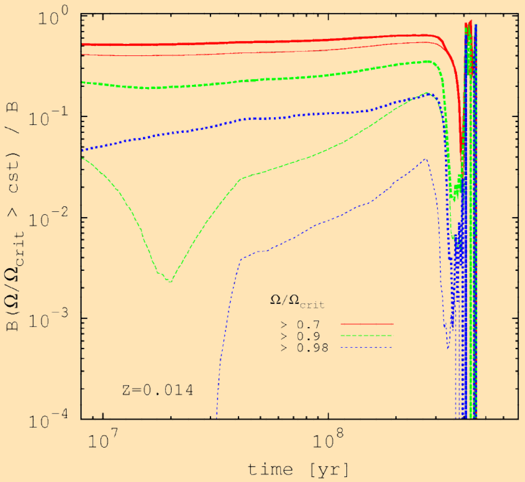
The no-AM transfer hypothesis



At least some AM transfer is required to explain Be stars

- Two rigidly rotating models, 100% and 70% critical
- This much ΔJ (5×10^{50} g cm^2 s^{-1}) comes from 0.5 to 1 R_{eq} if the star has to remain above 70% on surface.

Evolutionary spin-up



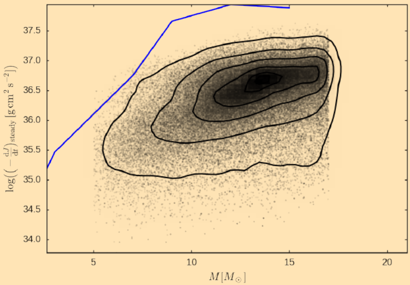
Granada & Haemmerlé, 2014 A&A 570, A18

Are Be stars inevitable?

If there is spin-up then

- Number of stars above Be star threshold will increase
- AM needs to be removed to keep star stable
- The most efficient way to remove AM
  - ➙ is an equatorial viscous **disk**, not a wind.
- Be stars are a natural consequence of evolutionary spin-up
- AM lost through the disk equals AM transported to surface
  - ➙ Critical fraction remains about the same once Be-phenomenon started

AM removed from the system, $\dot{J}$ vs. $M_\star$

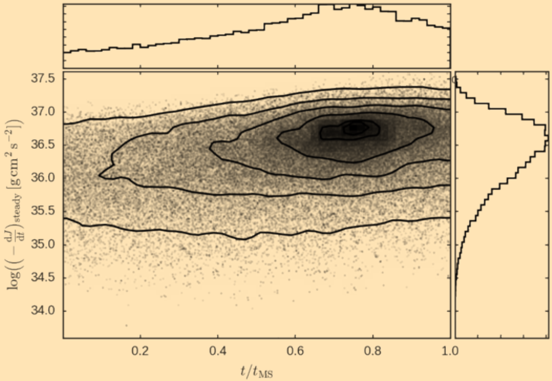


Rimulo, Carciofi et al., submitted

But how much AM transfer?

- Blue line: Geneva models by Granada et al. 2013, $\dot{J}$ at surface
- One order of magnitude more than actual Be disks remove
  - ➙ Even with 100% duty cycle, 30% are more typical

AM removed from the system, $\dot{J}$ vs. $\tau/\tau_{\rm MS}$

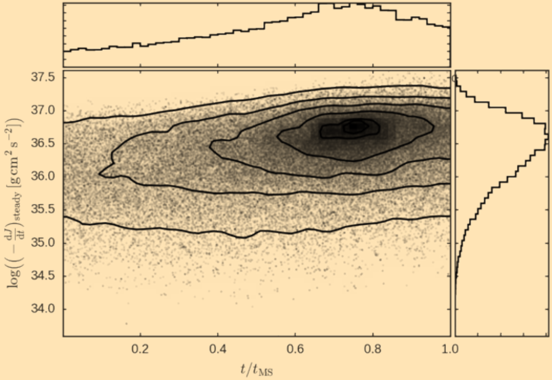


Rimulo, Carciofi et al., priv. comm.

When is the AM transfered?

- Be stars more likely to exist in later stages of the MS evolution

AM removed from the system, $\dot{J}$ vs. τ/τ_{MS}

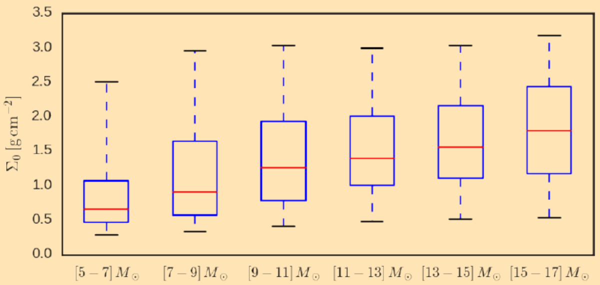


Rimulo, Carciofi et al., priv. comm.

When is the AM transfered?

- AM loss rate increases with time

Other disk quantities



Rimulo, Carciofi et al., submitted

- Typical mass loss rate $\sim 10^{-10} M_\odot/\mathrm{yr}$
- But both $\dot{M}$ and Σ_0 scale inversely with MS-lifetime
- Expected behaviour if AM mixing is controlled by nuclear timescale, but not for binary transfer products

Angular momentum mixing in rapid rotators

(Some) Angular momentum mixing is required

- Otherwise Be-star phase too short to explain ~20-25% incidence in
  - → Disk removes AM from surface layers

Predicted AM mixing too strong?

- AM removed from surface by disk measured for many (54) stars
  - → One to two orders of mag below Granada et al.

Be stars as binary evolution products

- Not touching mixing parameters:
  - → Overwhelming majority of Be stars then must come from binaries
  - → Strong constraints on post-interaction structure (rotation profile)
- Scaling down mixing:
  - → Leaves open fraction of single vs. binary produced Be stars.
  - → Weaker contraints constraints on post-interaction structure
  - → Naturally explains observed correlations with B subtype
  - → **However:** Still sufficent spin-up to make enough Be stars?

Content

Single star results: Unmixed Be stars

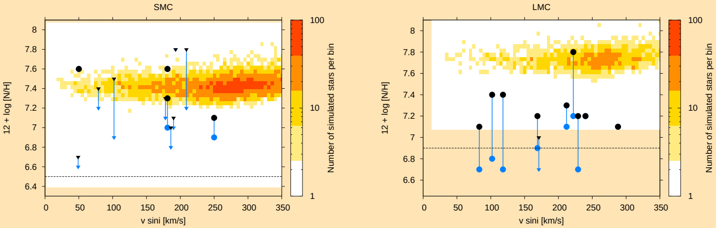
Lennon et al. 2005, A&A, 438, 265

- Two Be stars in NGC 330 (SMC) lack any sign for rotational mixing
- No Nitrogen enhancement at all
- Other B stars in NGC330 do show enhancement

Nieva & Rivinius, in progress

- Three out of three MW Be stars analyzed in detail
- Fully consistent with ZAMS B star values
- More stars to be analyzed in the near future

A survey of N in SMC/LMC Be stars



Dunstall et al., 2011, A&A 536, A65

- 30 Be stars from FLAMES survey in LMC and SMC
- Analysis included correction for emission (blue points)
- Abundances inconsistent with expected rotational enrichment

Content

Rotational mixing in the most rapid rotators

Angular momentum and chemical mixing in Be stars

- Disk AM loss measured for a large sample of stars in SMC
- Abundances measured for a large sample of stars in LMC/SMC
  - → SMC means wind effects probably not important
- Disagreement with current predictions for rapidly rotating stars
  - → If binary products, chemical results may be more easily explained.

Future work

- Inhibition of rotational mixing (for most rapid rotators)?
- Extend AM loss measurement to LMC and MW
- Make local (MW) equivalent to LMC/SMC abundance analysis