Massive Star Rotation – Observations

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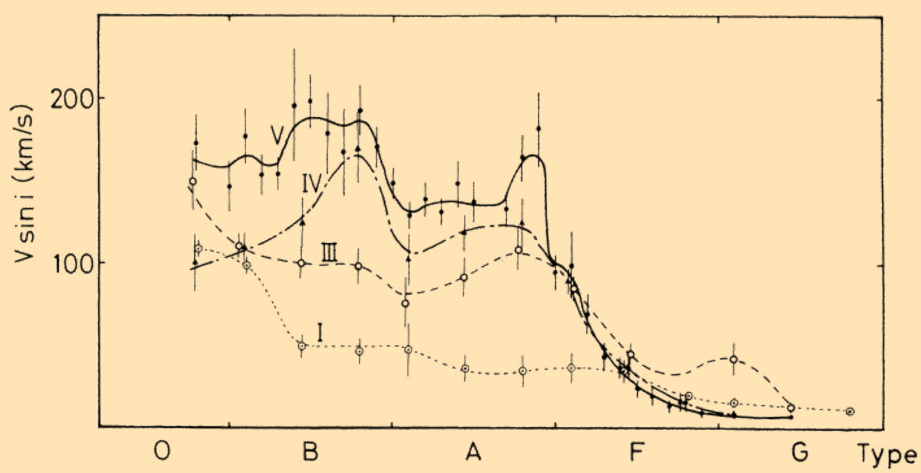
March 2, 2017

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

Pleione, Alkyone, Electra, Merope

Content

Rotation in early type stars

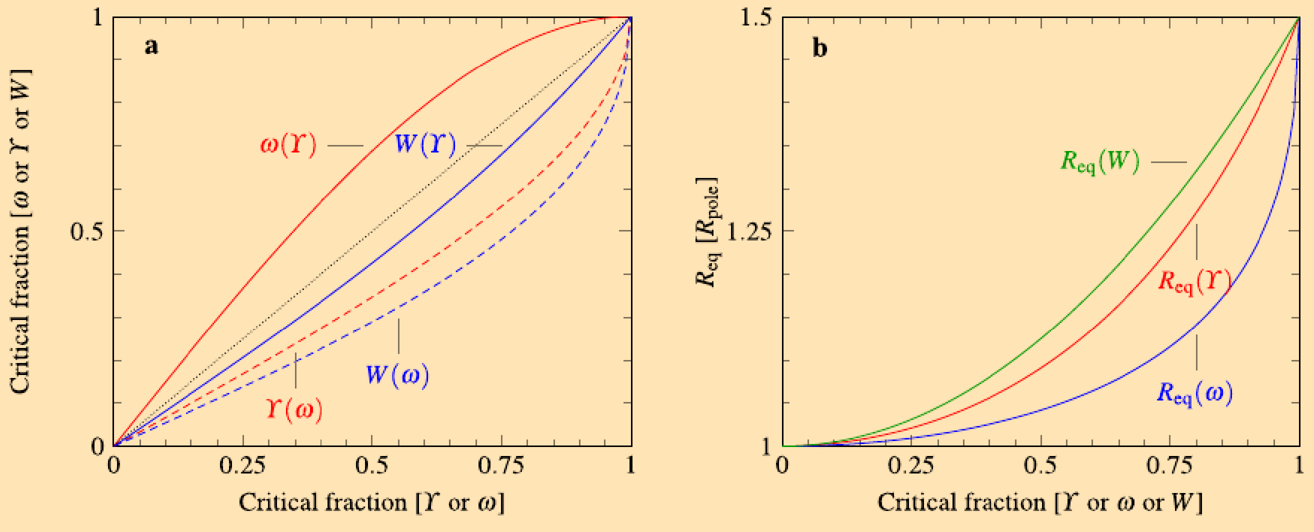


Fukuda, 1982, PASP 94, 271

Statistics of $v \sin i$

- Radiative envelope stars hardly brake on the MS
  - ➛ Some braking in O stars by strong winds
- The line width, $v \sin i$, is not straightforwardly rotation
  - ➛ Additional broadening important for O stars in particular

Rotation defined



Rivinius, Carciofi, & Martayan, 2013

Statistics of $v \sin i$

- In theory, often expressed as angular velocity $\Omega = \Omega_{\rm rot}/\Omega_{\rm crit}$
- Observers prefer linear velocity $\Upsilon = v_{\rm rot}/v_{\rm crit}$
- For problems involving circumstellar dynamics $W = v_{\rm rot}/v_{\rm orb}$

von Zeipel theorem

A rapidly rotating star

- Can not be in static equilibrium
- Can not have a uniform surface temperature.
- Must have a meridional flow
  - ➙ that re-juvenates the core
  - ➙ and enriches the surface
- Will be deformed from spherical shape
- With the pole hotter than the equator

Gravity darkening

For geometrically thin and radiative atmospheres

$$T(\vartheta) = T_{\mathrm{p}} \frac{g(\vartheta)^{\beta}}{g_{\mathrm{p}}} \; ; \quad \beta = 0.25$$

von Zeipel theorem

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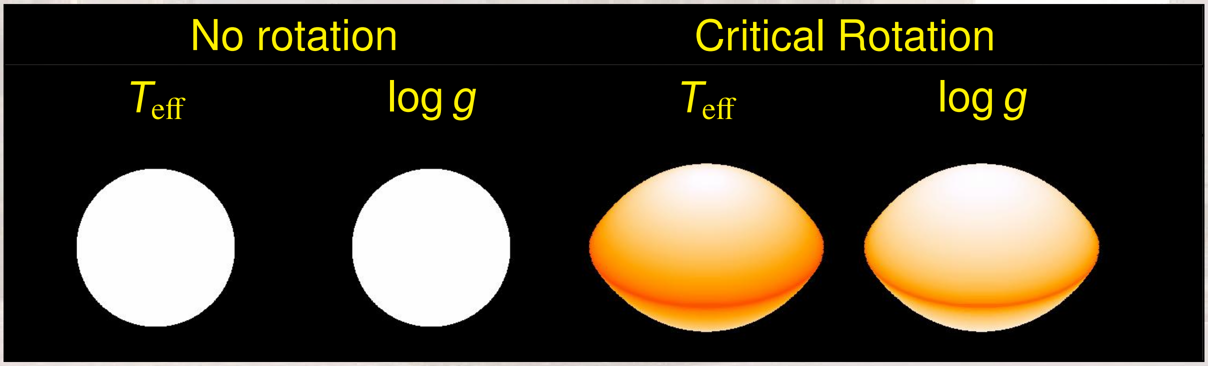
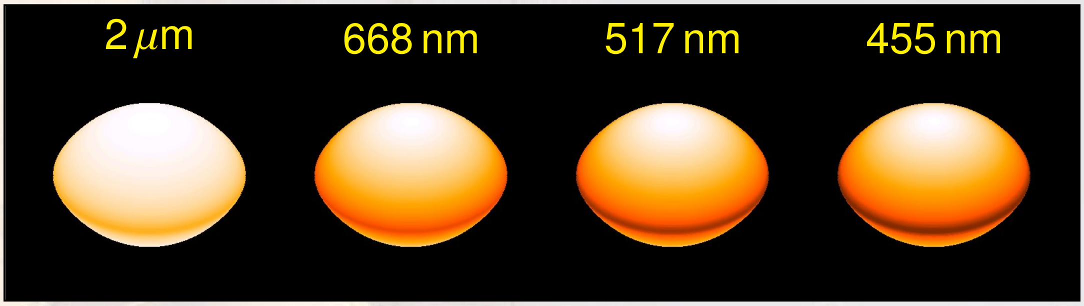
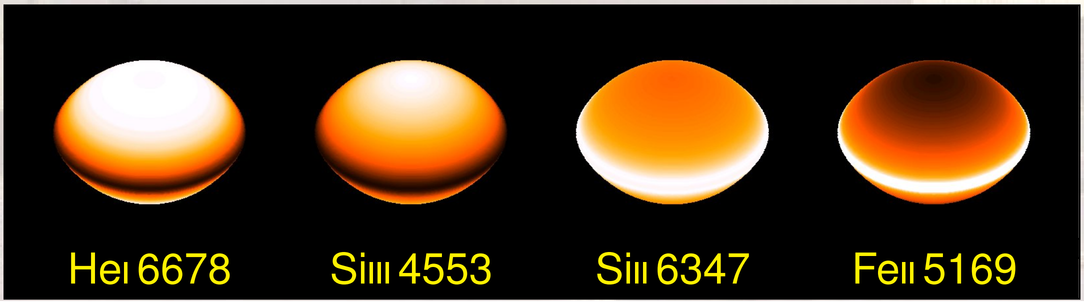


GD for continuum vs. lines



Systematics due to used method

- Gravity darkening stronger at shorter wavelengths
- Continuum fades out bluewards
  - ➛ such methods will derive a lower temperature
- For spectroscopy, depends on lines used



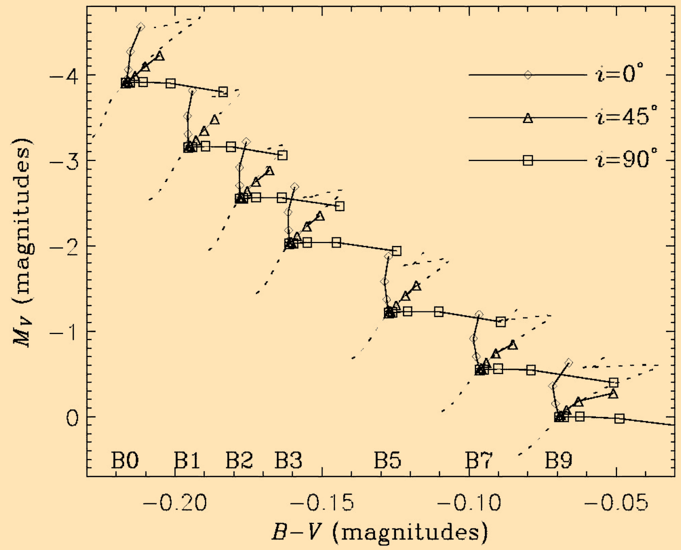
GD for a convective atmosphere

A similar mechanism acts for cooler stars

- Leon Lucy, 1967, derives $\beta = 0.08$ for convective case
- Why care?
  - ➙ Convective stars rotate slowly
- But what happens to the equator of a hot star?
  - ➙ Becomes cool
  - ➙ Possibly cool enough for onset of convection

Content

The rotating HR-diagram



Townsend et al., 2004, MNRAS 350, 189

Treating stellar flux as isotrope

- Causes apparent position in HRD to move
  - ➛ Path direction depends on inclination
  - ➛ Path distance depends on critical fraction

What are the stellar parameters (first order)?

Traditional fundamental parameters

- Effective temperature T_{eff}
- Surface gravity log g

Enough to place star in HRD, gives evolutionary path

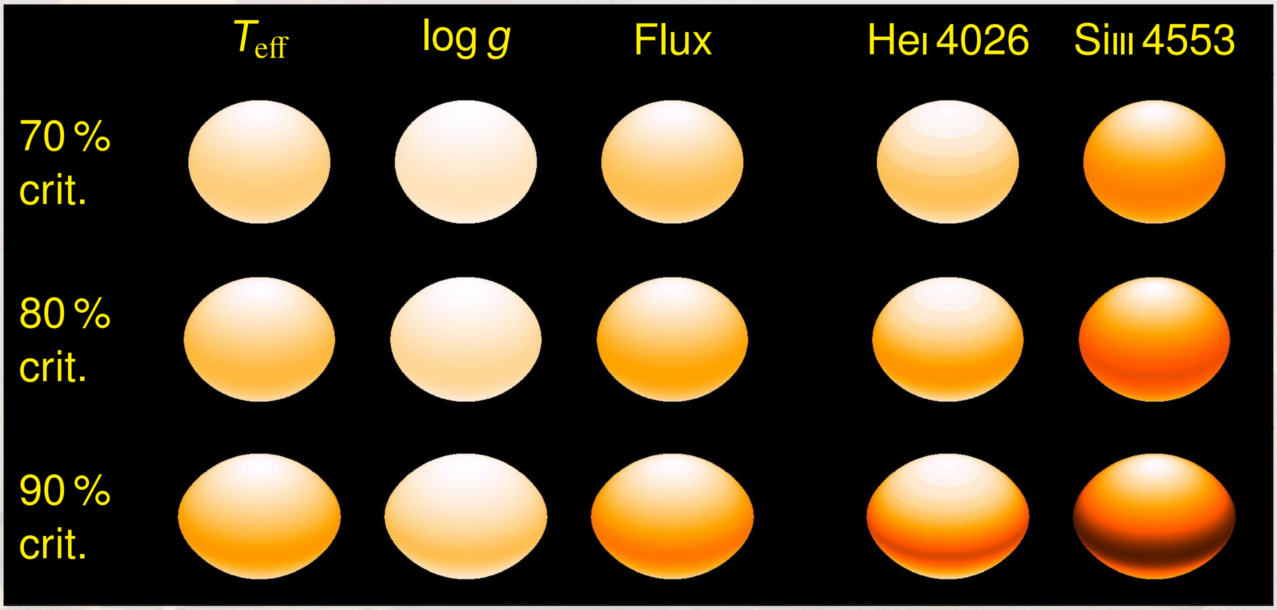
Fundamental parameters for rotating stars

- Effective temperature $T_{\text{eff,pole}}$ at pole
- Surface gravity log g_{pole} at pole
- Critical fraction Ω
- Radius R_{pole} at pole

In addition, to translate observations to those quantitites:

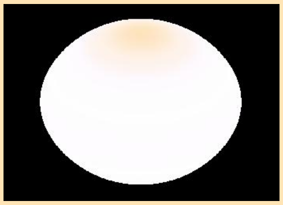
- Inclination angle i

Rotation and spectral line formation

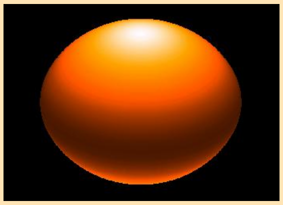


Rotation and spectral line shapes

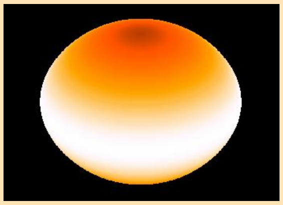
“normal”



“hot”



“cool”



		2					3					1		
	2	2	2			2	2	2			2	2	2	
2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	2	2	2			2	2	2			2	2	2	
		2					3					1		

Rotation and spectral line shapes

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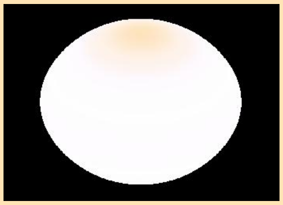

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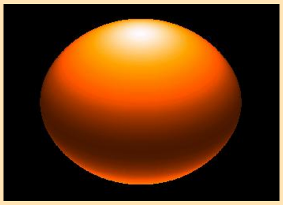

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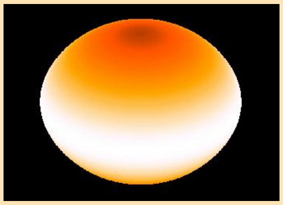
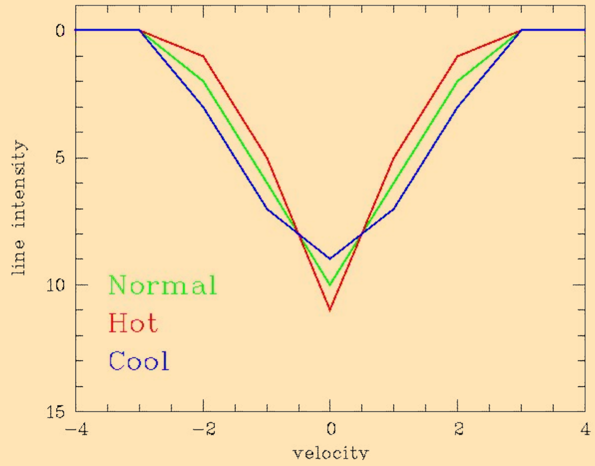
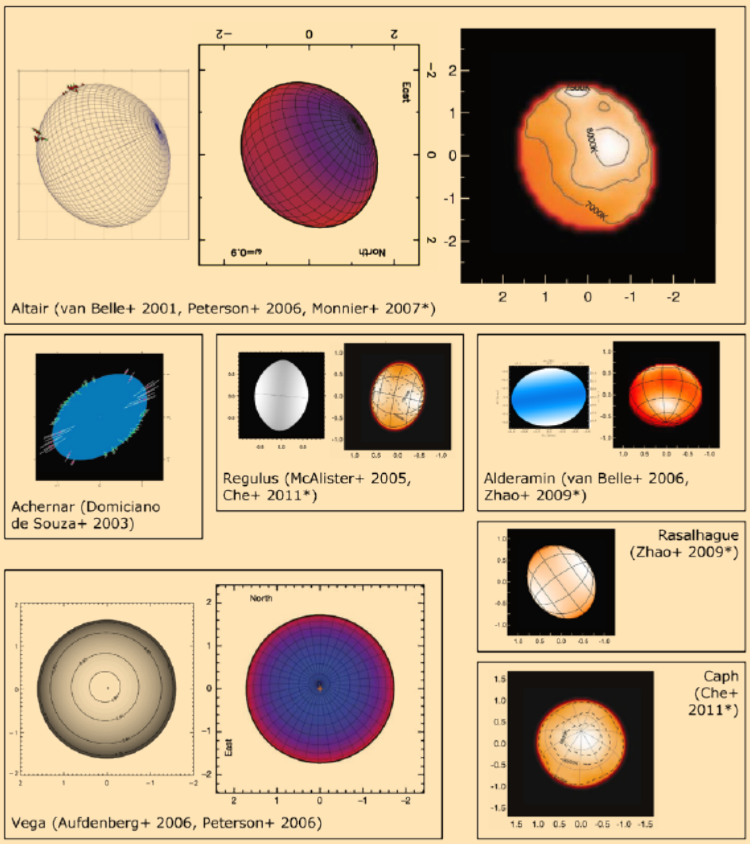




Content

Most direct: Stellar shape



van Belle, 2012

Interferometric image reconstruction

Sample not that great for massive star purpose

- Only very bright and large stars
- B4 III star Achernar the most massive so far
- Sepctral types:
  - ➙ $2 \times$ B (B4 & B8), $4 \times$ A, $1 \times$ F

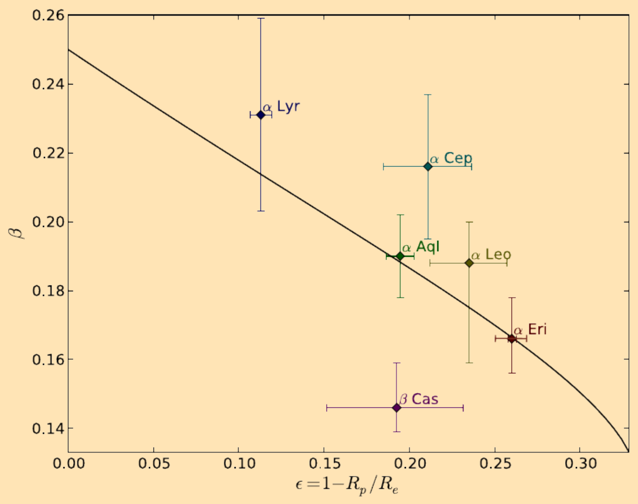
Regularization, even if called "model-free"

- Image reconstruction does require assumptions
- Typical cases:
  - ➙ Shape, size, PA etc. might be forced to acceptable values
  - ➙ No flux allowed from outside that shape

Assuming Roche model

- Direct measuerements of
  - ➙ Critical fraction Ω
  - ➙ Gravity darkening parameter β

Measured GD parameter β



de Souze et al., 2014

Becomes lower with faster rotation

- Are these stars still fully radiative?
  - ➙ Curve by Espinoza-Lara & Rieutord, 2011
- Or does Lucy’s convective GD already play a role?

Rotational periods

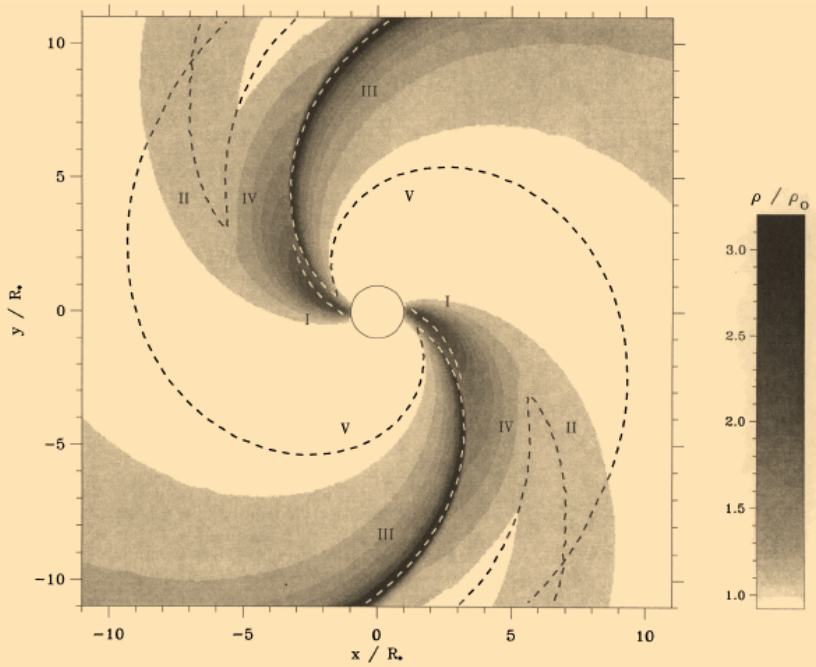
Clock is clear, but what is ticking?

- Magnetic fields, spots, magnetosphere etc.
  - Mostly late B and A stars
  - Very few really rapid rotators (Two above 50% critical)
  - All magnetic O stars rotate sloooowly (very efficient braking)
- Winds
  - Corotating Inetraction Regions (CIR)
  - Star is having alternating sectors w/ slow and fast wind
  - Winds running into each other create garden sprinkler type wind-density

Other parameters needed to get to Ω

- Equatorial radius
- Stellar mass

The CIR model



Cranmer & Owocki, 1996

- “IR” part well confirmed
- “C” part more tricky: lack of long-term coherence

In terms of massive stars, the best we have

HD 64760, B0 Ib

- Seemed to be a clear case with P=4.12 d, but detailed modeling...
  - E.g.: "... 2 unequally bright equatorial spots that rotate 5 times slower..." (Lobel, 2013)

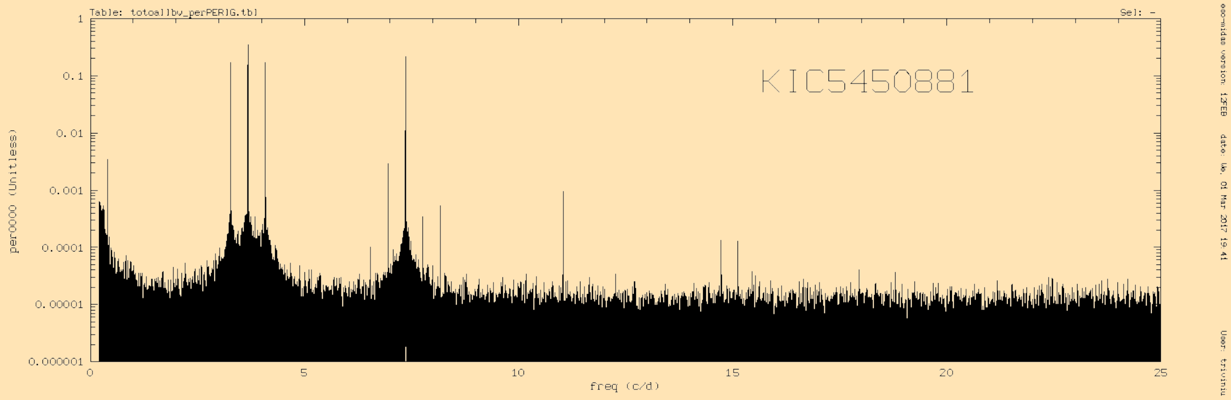
Probably many stars like this

- In the B0-range with rapid rotation, luminosity classification blurry
  - The spectroscopic twin of HD 64760 (B0 Ib) κ Aql, is listed as B0.5 IIIn
- There might be a dozen or more such stars with HD-numbers

Rotational periods from mode splitting

Frequency difference large for rapid rotation

- Easiest to find in moderate rotators
  - ➙ No danger of confusing splitting with amplitude changes
  - ➙ Sequences of modes easily identified even by eye
- Example below KIC5450881
  - ➙ Looks like $\ell = 1$ triplet, $\ell = 2$ quintuplet
  - ➙ $P_{\mathrm{rot},\ell=1}$ =2.44646 d, $P_{\mathrm{rot},\ell=2}$ =2.44913 d



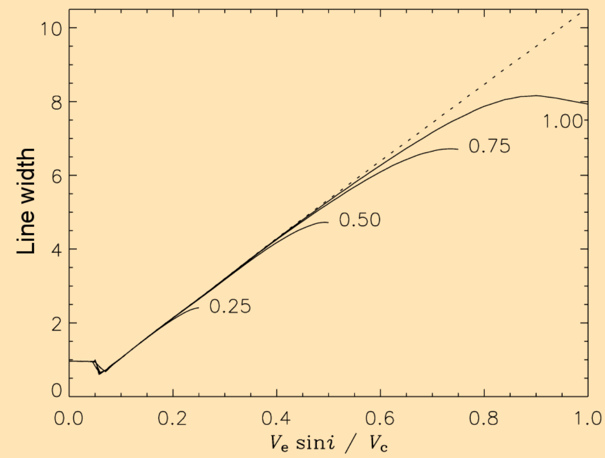
But even in this case...

Kurtz et al., 2015

- Accept only two frequencies as genuine
  - Construct all the rest by addition/subtraction with integer factors
- Which one is harder to believe:
  - Combination frequencies mimicking rotational splitting?
  - Rotational splitting mimicking combination frequencies?

Labels	Frequency (d^{-1})	Amplitude (mmag) ± 0.001	Phase (rad)
$-\nu_1 + \nu_2$	0.408 7346	0.110	0.9693 ± 0.0107
$-2\nu_1 + 2\nu_2$	0.817 4692	0.007	1.4095 ± 0.1584
ν_1	3.269 9899	0.768	1.4283 ± 0.0015
ν_2	3.678 7245	1.117	2.5033 ± 0.0011
$-\nu_1 + 2\nu_2$	4.087 4591	0.779	-0.8178 ± 0.0015
$2\nu_1$	6.539 9798	0.013	0.0892 ± 0.0921
$\nu_1 + \nu_2$	6.948 7144	0.103	-0.4452 ± 0.0115
$2\nu_2$	7.357 4490	0.886	-2.6611 ± 0.0013

Line width (aka v sin i)

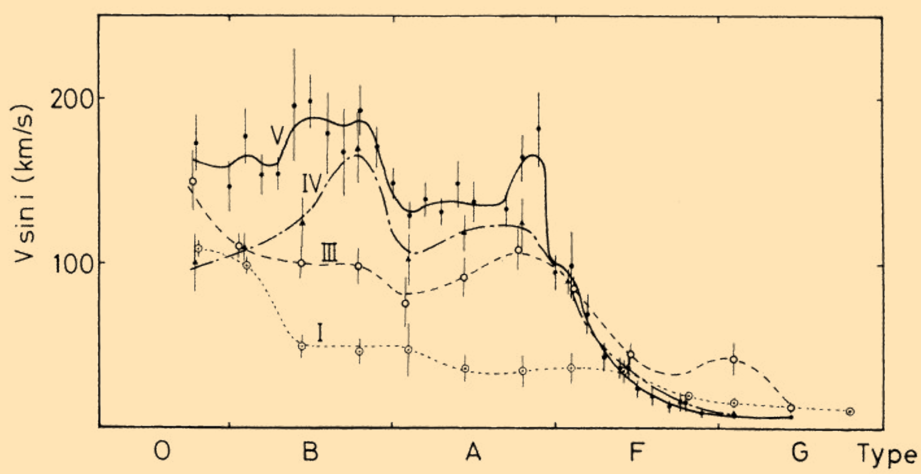


Townsend, Owocki, & Howarth, 2004

Gravity darkening strikes

- Measure $v \sin i$ → statistics → case settled? **Not quite!**
- Line width independent of rotation above $\approx 0.8w$ $\left(w \equiv v_{\rm rot}/v_{\rm crit}\right)$
- Not to mention non-rotational broadening

Remember the funny shape?

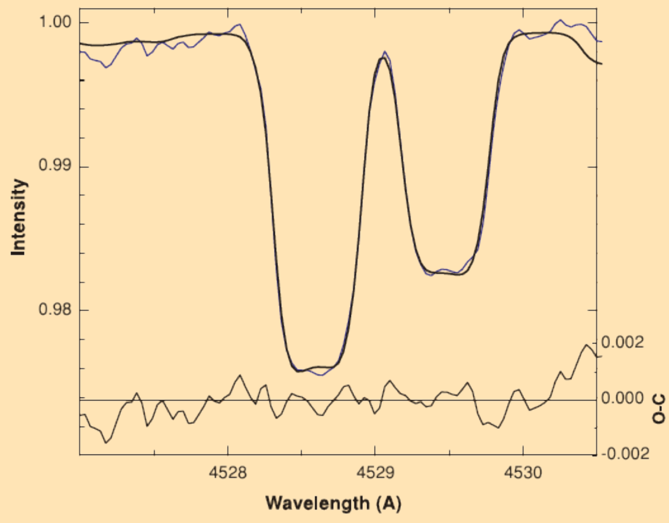


Fukuda, 1982, PASP 94, 271

Statistics of $v \sin i$

- High $v \sin i$ in supergiant O star not rotation
- Some other broadening

Funny line shapes



Hill et al., 2010

Pole-on rapid rotator Vega

- Shows flat-bottomed profiles
- Only equatorially formed, high Ω
- Incredibly high S/N needed

Content

Rotational periods with $\Delta\Omega(\theta)$?

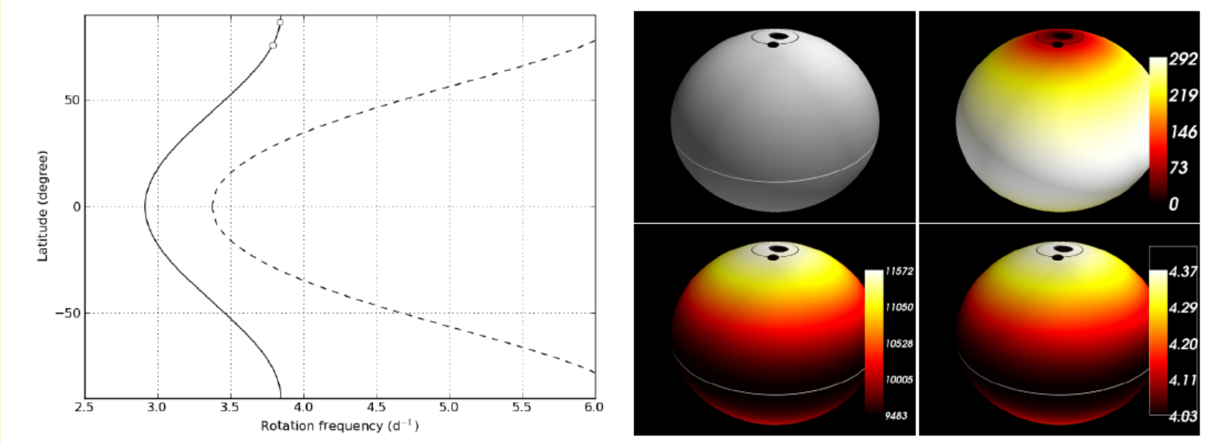
Subset of stars with rotational modulation

- Need spots in radiative atmosphere
  - Spots arising from strong global magnetic fileds won't do
  - Recall Norbert's talk yesterday
- Do we have others? Some claim so:
  - Böhm et al. 2015 for Vega
  - Balona & Abedigamba, 2016, for several Kepler T=10 kK stars
  - Ramiaramanantsoa et al. 2014 for ξ Per
  - Balona & Abedigamba, 2016, for several Kepler T=10 kK stars
    - Give results for differential rotation!

Polar spots with a slower equator??

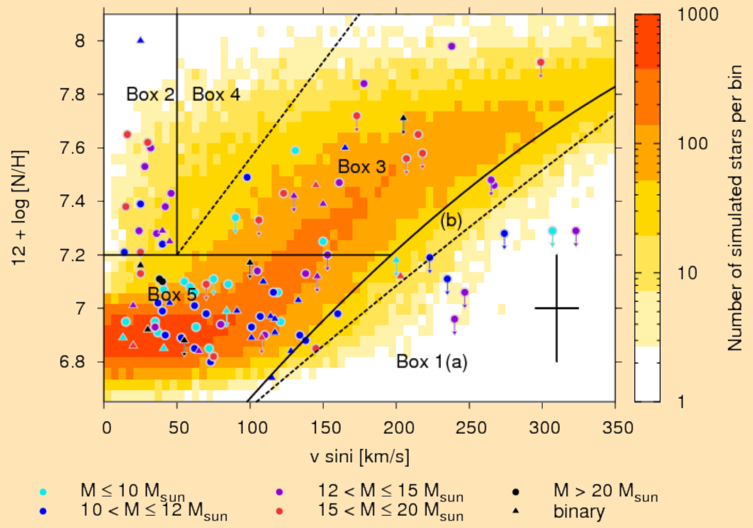
Degroote et al., 2011

- B8/B9 star HD 174648
- Two spots, both at polar latitudes
- Strong differential rotation
- Polar rotation faster than equator



Content

Rotational Mixing on Main Sequence

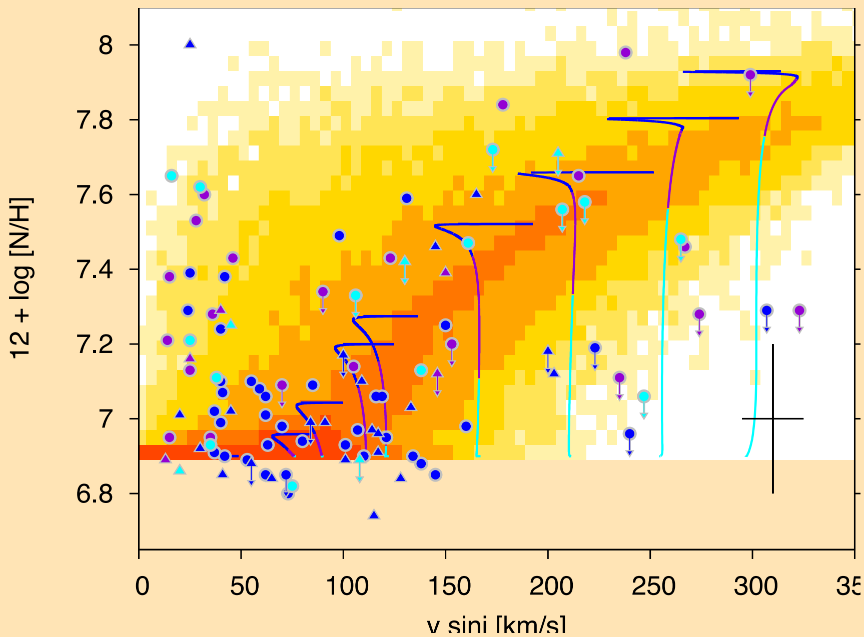


from Brott et al., 2011, A&A 530, A116

Agreement Obs. vs. Theory only for box 5

- Boxes 3 and 4 underpopulated (4 not really an issue)
- Boxes 1 and 2 overpopulated
  - ➙ Binarity cannot solve Boxes 1 and 2 simultaneously

Theoretical considerations on Hunter diagram



from Brott et al., 2011, A&A 530, A116

Theoretical [N/H] enhancement pattern (for LMC)

- MS-enrichement paths are plotted
- Stellar age indicated

Rotational mixing coefficients

There is an observational calibration!

- Georges mentioned it yesterday
- Until very recently, reliable results only up to moderate $v \sin i$
- High $v \sin i$ mixing region extrapolated
- Look for most rapidly rotating massive stars: Be stars
  - ➙ Problem: Come with emission, line & continuum, which may affect results
  - ➙ Benefit: even if low $v \sin i$, rapid rotation at 80% critical is certain

Single star results: Unmixed Be stars

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

- Two Be stars in NGC 330 lack any sign for rotational mixing
  - ➙ Narrow lined Be stars with strong emission, systematic problem?

Peters, 2011, IAUS 272, 101

- IUE spectra of eight low $v \sin i$ Be stars
- Little to no rotational mixing found
  - ➙ IUE data quality does not allow strong constraints

Hardorp et al, 1986, ESA-SP 263, “8 years of IUE”, 377

- Carbon abundances of Pleiades Be vs. B stars
- All consistent with local contemporary B star values
- No depletion, i.e. no mixing
  - ➙ Again, IUE data quality does not allow strong constraints

Single star results: Mixed Be stars

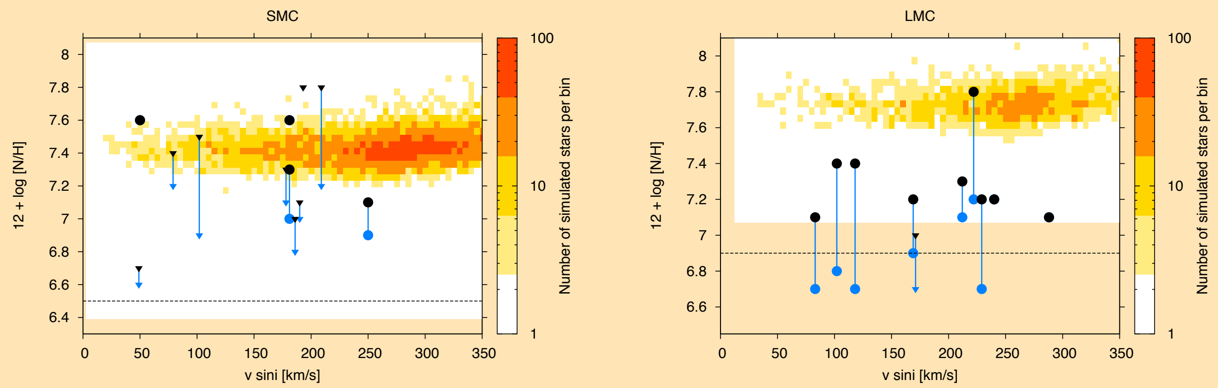
Levenhagen & Künzel, 2011, New Ast. 16, 307

- HD 171 054 is enriched, but even more than possible by evolution
  - ➙ Some enriched elements shouldn't even form in a star of that mass
  - ➙ Rather some binary evolution product

Villamariz & Herrero, 2005, A&A 442, 263

- ζ Oph is enriched
- Enrichment also higher than expected for evolutionary state
  - ➙ ζ Oph seems to be a runaway star
  - ➙ As well binary evolution product?

A survey of N in SMC/LMC Be stars



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

- Be stars are from FLAMES survey
- 30 Be stars in LMC and SMC, incl. correction for emission (blue points)
- Abundances inconsistent with rotational enrichment at given $v \sin i$

First MW results

M.F. Nieva, unpublished

- A number of Be stars analyzed by Fernanda
- All have solar values

Where to go?

Observer's task

- Bring that result home: Be stars are not mixed
- Requires best current model vs. best current data
- **If result (no mixing) turns out to be robust:**

Hypothesis 1: Be stars rotate slowly most time on the MS

- Must be as low as 35 to 45% critical to be in line w/ mixing model
- Does rapid rotation occur quickly?
- Critical rotation phase short? All B stars become Be stars?

Hypothesis 2: Inhibition of mixing at highest $v \sin i$

- Somewhere above model calibration $v \sin i$, things go wrong
- A shell/layer inside the star which blocks mixing?
  - Core dynamo inhibits overshooting?
  - Or enforces rigid rotation in chemically enhanced region?

Content

Stuff that didn't fit anywhere else

Turn-off broadening

- In many clusters, MS turn-off is broader than single age paradigm demands
  - ➙ Broadening could be due to pulsation
  - ➙ Broadening could be due to rotation
- Currently open discussion (my money is on pulsation, though)

Stellar winds

- Original wind-compressed disk is not happening
- Instead winds are focussed above pole, i.e., prolate

Spin-up in binary evolution

- Yep, surely happens in many stars
- Exact consequences depend on when and how
- Pften invoked when other explanations fail (see above on mixing)

Content

Rotation

Measuring rotation

- Measuring rotation isn't easy, but after all we understand the problem...
- ...at least good enough to make do with it.

Are the most rapidly rotating stars different?

- All studies point to unexpected result wrt. to CNO abundances
- Inhibition of rotational mixing for most rapid rotators?
- Could have wide implications outside Be stars
  - ➙ Detailed and careful studies needed to get well-understood cases
    - ➘ E.g. get high S/N, high-resolution spectrum of inactive Be stars
  - ➙ Make local (MW) equivalent to FLAMES survey analysis

Stellar pulsation and seismology

Asteroseismilogical modeling

- Kepler, CoRoT and others provided fantastic data
- Asteroseismology is extremely successful
- Is there a tendency to apply it beyond its validity region?
  - ➙ Sometimes, I can't help the impression of data being over-interpreted