Pulsations as a common mass-loss trigger in evolved massive stars?

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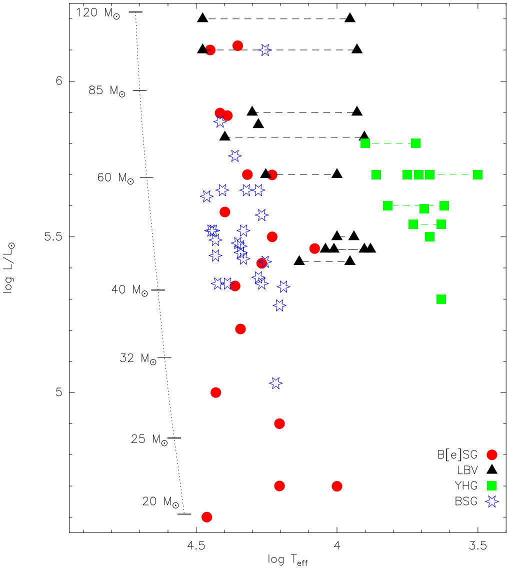
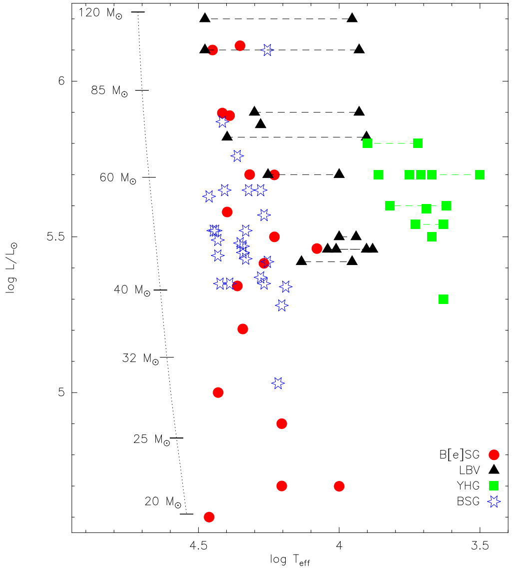


- Crucial transition phases in the evolution of massive stars: BSGs, B[e]SGs, LBVs, and YHGs

Main research goals:

- what is their evolutionary state and connection to each other?
- which physical mechanism causes enhanced mass-loss and outbursts?
- what ist the structure and evolution of the ejected material?
- how much mass is lost and on which timescales?



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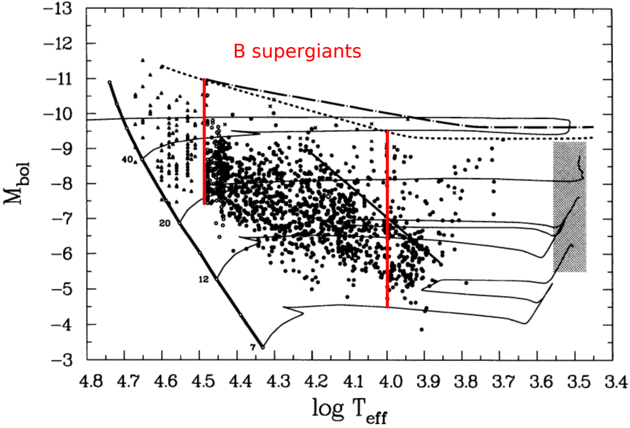
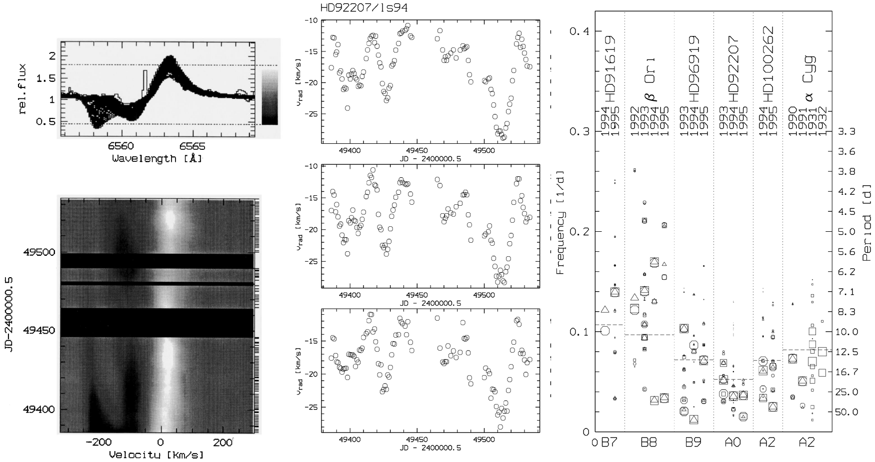


- Surface temperatures $T_{\rm eff} = 10\,000 - 30\,000\,{\rm K}$
- Luminosities $L = 10^4 - 10^6\,L_\odot$
- Mass-loss rates $\dot{M} = 10^{-7} - 10^{-5}\,M_\odot {\rm yr}^{-1}$
- Line-driven stellar winds with terminal velocities $v_\infty = 200 - 3500\,{\rm km\,s}^{-1}$

Characteristics of B supergiants from spectroscopy:

1. line profile variability (Kaufer et al. 1996, 1997)



2. “macroturbulent” line-broadening in excess to rotation

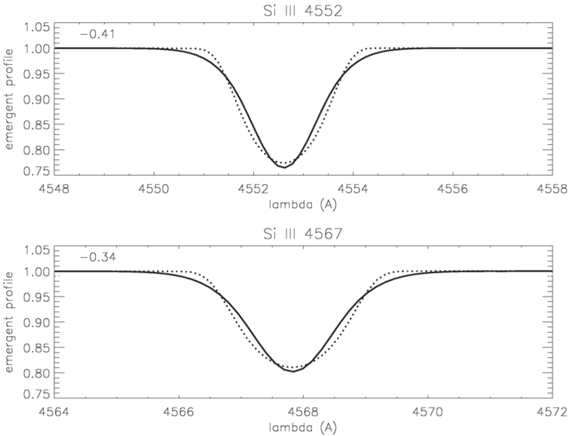
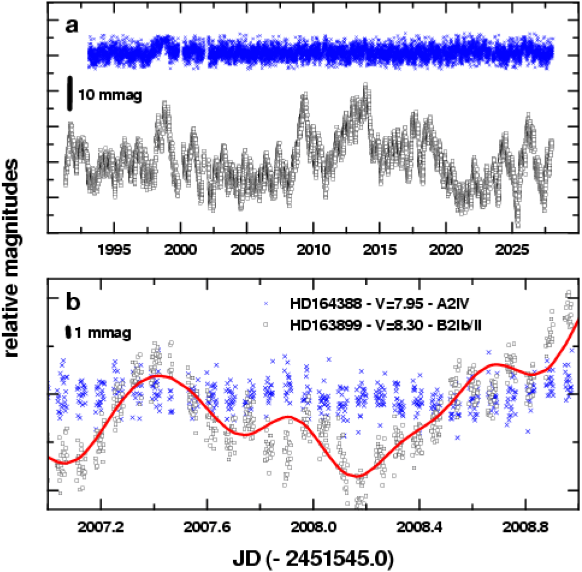


Figure 4. High resolution Si III spectra from HD 89767 (B0Ia), observed with CES@CAT (R = 70,000, S/N ≈ 250). Dotted: Best fitting profile with rotational broadening alone ($v \sin i = 80$ km s^{-1}). Large discrepancies are visible in the wings and cores. Solid: Perfect fit using $v \sin i = 47$ km s^{-1} and $v_{\rm mac} = 80$ km s^{-1} in parallel. Observations and data from Lefever *et al.* (2007).

Line-profile variability + macroturbulence are strong indications for pulsations



Photometric variability:

- Photometric observations of HD 163899 with MOST over 37 days

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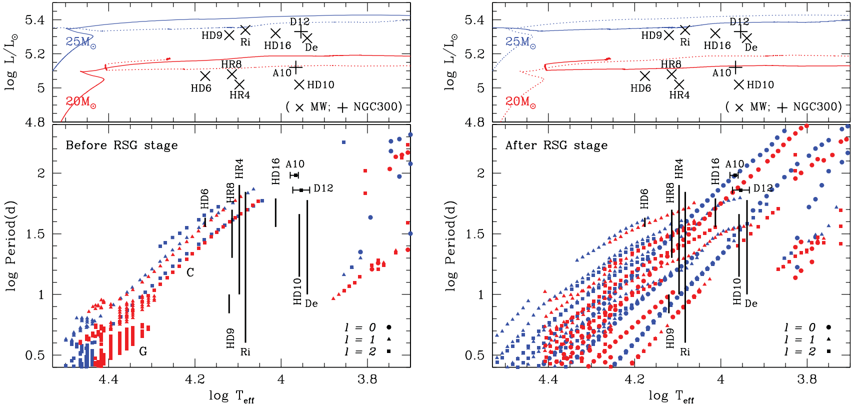
  Discovery of 48 periods from 10 h to 25 d

- Periods can be explained by a combination of p and g mode pulsations (Saio et al. 2006)

Pulsation behavior during the evolution of massive stars

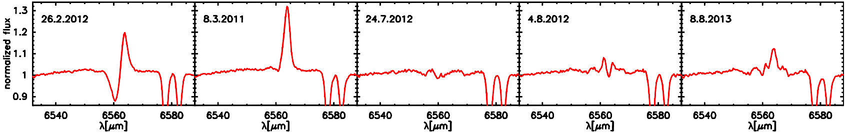


- **Pre-RSGs:** Non-radial g-modes (G) + oscillatory convection modes (C)
- **Post-RSG:** Numerous excited modes + radial strange modes, consistent with periods found in α Cygni variables (Saio et al. 2013)
- Study of pulsation behavior to pin down evolutionary stage of BSGs
- Strange mode instability can lead to pulsationally driven mass-loss in massive stars (Glatzel 1994)

Selected results from our spectroscopic observing campaign

1. HD 198478 = 55 Cyg

- Total of 344 medium-resolution observations distributed over 64 nights (08/2009 to 08/2013, Perek 2 m telescope at Ondřejov) in the Hα region.
- 41 high-resolution echelle spectra (Poznan spectroscopic Telescope at the Winer Observatory in Arizona)



- Analysis of wind via FASTWIND code (Puls et al. 2005)
- stellar ($T_{\rm eff}$, $\log g$, R_*, $v \sin i$, $v_{\rm macro}$) and wind ($\dot{M}$, v_∞, β) parameters are obtained from fitting profiles of photospheric (He, Si) and Hα lines.

Pulsation – mass-loss interaction in B Supergiants

- Stellar parameters:
  - T_{eff} ranges from 18 570 K to 19 100 K
  - $R = 57 \pm 1\,R_{\odot}$ but varies from 52 to 65 $R_{\odot}$
  - $\log L/L_{\odot} = 5.57 \pm 0.03$
  - $M = 34 \pm 4\,M_{\odot}$
  - $L/M > 10^4\,L_{\odot}/M_{\odot}$, suitable to excite strange mode pulsations
  - $v_{\text{rot}} \sin i = 50 - 60$ km/s; $v_{\text{macroturbulence}} = 10 - 50$ km/s
- Wind parameters:
  - v_{∞} varies between 230 km/s and 350 km/s, with exceptions of 600 km/s and 700 km/s when also the mass-loss rates were increased
  - $\dot{M}$ varies between $1.5 \times 10^{-7} M_{\odot}\text{yr}^{-1}$ and $4.6 \times 10^{-7} M_{\odot}\text{yr}^{-1}$

    $\Longrightarrow$ more than a factor of 3 !
- Pulsations:
  - Multiple periods (2.7 h to 22.5 d) derived from HeI $\lambda 6678$ radial velocity variations $\Longrightarrow$ star pulsates in p-, g- and strange modes

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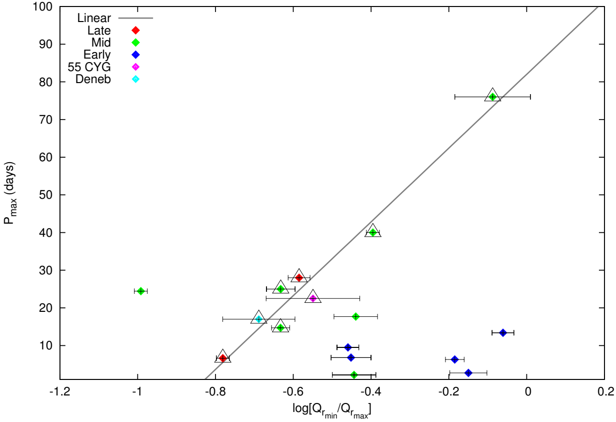
- Change in radius and variable wind conditions, in agreement with phases of enhanced mass-loss (Kraus, Haucke, Cidale et al. 2015)
- **Non-linear simulations** by Yadav & Glatzel (2016) proof strange mode instabilities in 55 Cyg with triggered mass-loss rates in agreement with observations

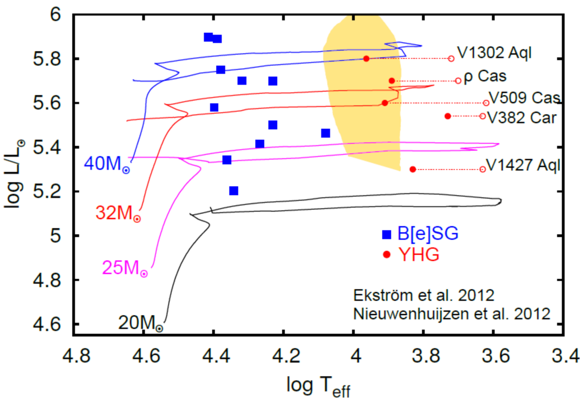
2. Sample of 19 BSGs with reported photometric variability

- Determination of wind parameters from CASLEO echelle spectra
- Combination with literature values to compute the optical-depth invariant parameter $Q_r = \dot{M}/R_*^{1.5}$ and comparison with longest recorded period
- The longer the period the higher the mass-loss variation



(Haucke et al. 2018)

Yellow Hypergiants

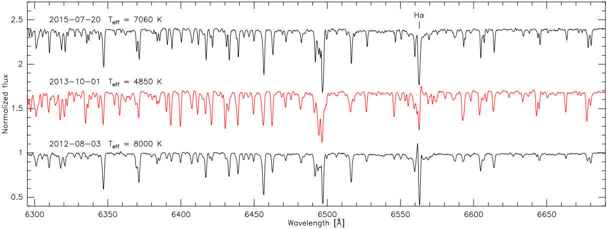


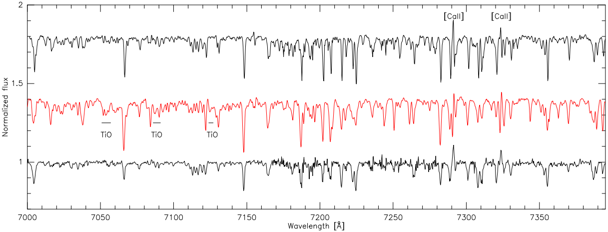
- Progenitor stars in the range 25 – 50 $M_\odot$
- Surface temperatures $T_{\rm eff} = 4000 - 9000\,$K
- Luminosities $L = 10^{5.3} - 10^{5.8}\,L_\odot$
- When star reaches $\sim 7000\,$K, atmosphere becomes dynamically unstable (Nieuwenhuizen & de Jager 1995; Stothers & Chin 2001)

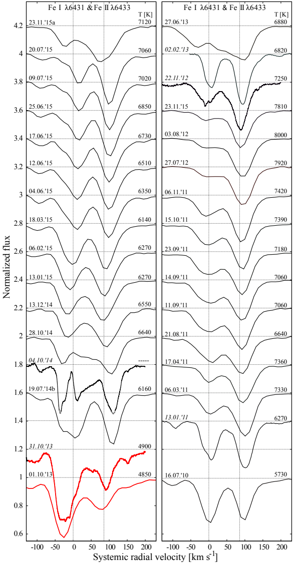
- Outburst along with strong inflation of radius creates a pseudo- photosphere mimicking a much cooler temperature
- When ejected material dilutes and star contracts (months to years), it appears hot again
- Process is called bouncing at the Yellow Void
- Stars typically surrounded by multiple dusty shells/rings

Spectroscopic monitoring of Yellow Hypergiants:

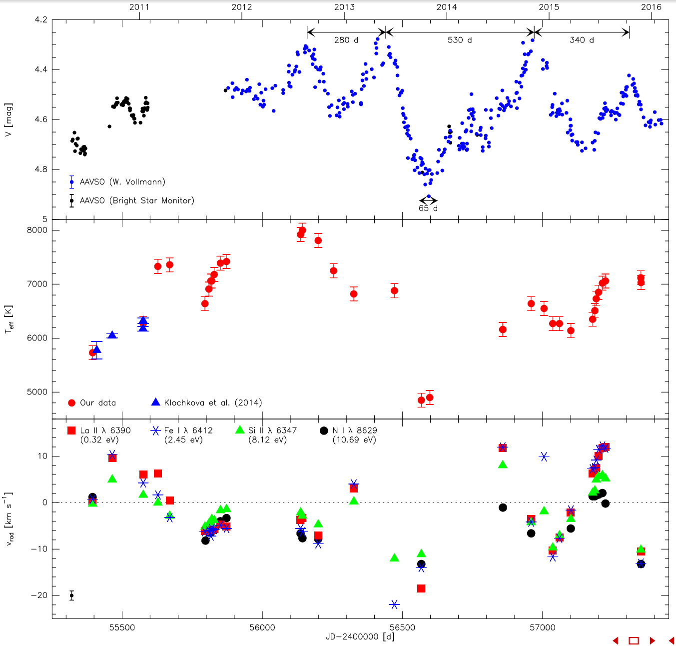
Discovery of a new outburst in ρ Cas in 2013





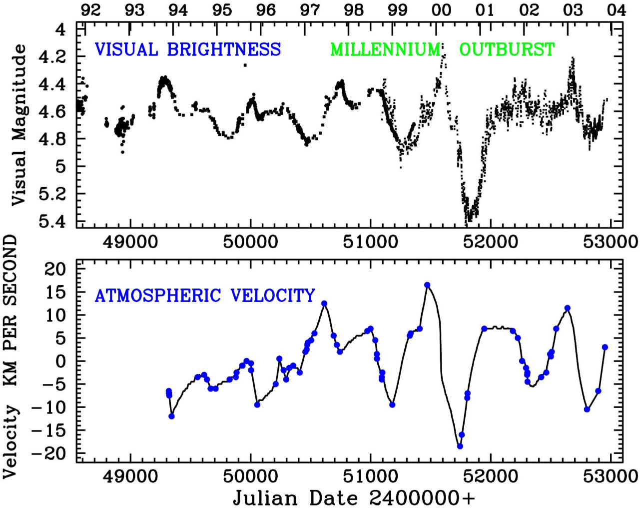


Yellow Hypergiants – ρ Cas



- Temperature follows the lightcurve trend
- Highly dynamical atmosphere
- Previous outbursts:
  - 1945-1947
  - 1985-1986
  - 2000-2001
- Decrease in time interval between outbursts: is ρ Cas passing through the Yellow Void?

(Kraus et al., MNRAS, submitted)



Increase of radial velocity amplitude in FeI

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enhanced pulsation activity prior to outburst

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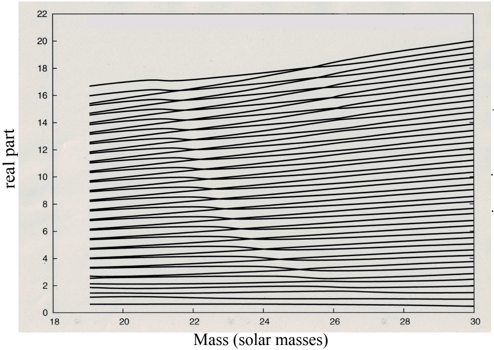
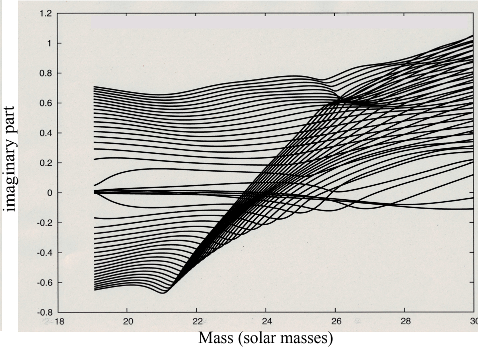
Outburst activity caused by strange mode instabilities?

(Lobel et al. 2003)

Linear stability analysis for ρ Cas

- Stellar parameters:
  $T_{\rm eff} = 7000 \pm 1000\,$K; $\log L_*/L_\odot = 5.7 \pm 0.1$; $M_* = 24 \pm 5\,M_\odot$
  $\Longrightarrow \log L_*/M_* > 4$





(Glatzel & Kraus, in preparation)

B Supergiants

- B supergiants in post-RSG phase can pulsate in many different modes, including radial strange modes
- Strange mode instability can trigger phases of enhanced mass loss as seen in 55 Cyg
- Detailed analysis and non-linear simulations required to search for strange mode instabilities in a larger sample of post-RSGs

Yellow Hypergiants

- Pulsational instabilities also seen in YHGs on their blue-ward evolution (bouncing at the Yellow Void)
- It needs to be tested (work in progress) whether strange mode instabilities can cause the observed outbursts

Work in progress

- Campaigns to acquire long-term photometric (BRITE, STEREO, SMEI) and spectroscopic data to analyze the pulsation and mass-loss behavior of a large sample of BSGs and YHGs.