Evolution of massive stars constrained by supergiant pulsations

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Semi-periodic variations in luminous ($>10^5L_\odot$) SG B stars

Strange modes and Strange-mode instability

Evolution of massive stars ($\geq 25 \, M_\odot$) with mixing & winds
Semi-periodic light variations in most massive stars

Micro-variations in S Dor stars (LBVs)
Alpha Cygni variables

Humphreys and Davidson (1994)
S Dor variables (LBVs) show semi-regular micro variations.

Periods: 10 -- 100 days

\[ \log L = 5.7 \]

R71 (LMC)
α Cyg variables – Periods are similar to S Dor stars but no S Dor (LBV) phases

van Leeuwen et al. (1998)
Hipparcos supergiant variables (LMC)

α Cyg (Deneb) Richardson et al. (2011)

Log L = 5.4, $T_{\text{eff}}$ = 8500

P = 17.8 days

Log L = 5.2

P = 13.4 days

Log L = 5.8

P = 105 days

B3 Ia

A3 Ia

14.65 days

105 days
Rigel \( T_{\text{eff}} = 12100 \) K, \( \log L = 5.1 \) (possible member)

Moravveji et al. (2012)
Blue supergiants in NGC 300

Bresolin et al. (2004)

Kudrizuki et al. (2008)

50 days

NGC 300

α-Cygni var. (NGC300)

D12
A10

Log $L/L_\odot$

Log $T_{eff}$

C16

mag

18

18.2

18.55

18.6

18.65

18.75

18.7

18.8

18.85

18.9

18.95

V

19.05

Phase

0

0.5

1

1.5

2

D12

P = 72.5 d

A10

P = 96.1 d
Semi-regular variations in S Dor (LBV) and alpha-Cygni variables

periods; 10 days ---- $10^2$ days

Light-curves are simple --- probably radial pulsations

Both groups similarly distributed in HRD

Bounded by luminosity

$log L > 5$ \quad (M_i > 20)

but no color boundary

They should be excited by strange-mode instability
Strange modes

The first appearance of “Strange mode” in the literature

PULSATIONS OF THE R CORONAE BOREALIS STARS

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ABSTRACT

The radial pulsations of very luminous, low-mass models (L/M ~ 10^4, solar units), which are possible representatives of the R CrB stars, have been examined. These pulsations are extremely nonadiabatic. We find that there are in some cases at least one extra ("strange") mode which makes interpretation difficult. The blue instability edges are also peculiar, in that there is an abrupt excursion of the blue edge to the blue for L/M sufficiently large.

Proceedings of the Los Alamos Conference in 1980
Strange modes in very luminous stars \((L/M > 10^4)\)

Strange modes are trapped in a cavity where \(P_{\text{gas}}/P_{\text{tot}} < 0.1\)

Frequencies of strange modes vary as a function of a parameter differently from ordinary modes

\[P_{\text{rad}}/P_{\text{gas}} \gg 1 \quad (L/M > \sim 10^4)\]
Why L/M > 10^4 :

\[
\frac{dP_{\text{gas}}}{dr} = -\frac{GM_r \rho}{r^2} \left(1 - \frac{\kappa L_r}{4\pi c GM_r}\right) \approx -g \rho \left(1 - \frac{\kappa}{1.3 \times 10^4} \frac{L / L_{\text{sun}}}{M / M_{\text{sun}}}ight)
\]

Extensive density inversion is formed in the envelope (around He II ionization zone), where \( P_{\text{rad}} \gg P_{\text{gas}} \)

--- Oscillations are trapped \( \rightarrow \) strange modes
Strange mode instability \((L/M > 10^4)\)

In extremely nonadiabatic limit; \(\tau_{th} \to 0\)

\[
\left( T \frac{\partial s}{\partial t} = \varepsilon_n - \frac{\partial L_r}{\partial M_r} \right) \Rightarrow \quad i\sigma \tau_{th} \frac{\Delta s}{C_p} = \Delta \varepsilon_n - \frac{d\Delta L_r}{dM_r} \to 0; \quad \text{i.e.,} \quad \frac{d\Delta L_r}{dM_r} \approx 0 \quad \text{in the envelope}
\]

Plane-parallel approximation (for strange modes trapped in outer layers)

\[
\frac{\Delta L}{L} \approx \frac{\Delta F}{F} = -\frac{\kappa_T}{4} \frac{\Delta P_R}{P_R} - \kappa_\rho \frac{\Delta \rho}{\rho} - \frac{c}{\kappa F} \frac{\partial \Delta P_R}{\partial m} = 0, \quad \text{(cf. adiabatic relation;)} \quad \frac{\Delta P}{P} = \Gamma_1 \frac{\Delta \rho}{\rho}
\]

Assume \(\kappa_T = 0\) for simplicity

\[
\frac{\partial \Delta P_R}{\partial m} = -\frac{\kappa_\rho \kappa F}{c} \frac{\Delta \rho}{\rho}
\]

\(P_R \gg P_{\text{gas}}\); \(\frac{\partial \Delta \rho}{\partial m} = -\frac{\kappa_\rho \kappa F}{c} \frac{\Delta \rho}{\rho}\)

\(\Delta P \propto \exp(i\sigma - ik_z)\)

\[
\Delta P = i \frac{\kappa_\rho \kappa F}{k_z c} \Delta \rho
\]

Large phase difference between \(\Delta P\) and \(\Delta \rho\)

\(\quad \Rightarrow\) Strong instability

(Glatzel 1994; Saio, Baker, Gautschy 1998)
Instability boundary for low-order radial-modes

- Extremely nonadiabatic
  \[ \frac{P_{rad}}{P_{gas}} \gg 1 \]

- Strange-mode instability
  \[ \frac{\partial \Delta P}{\partial m} \approx \frac{\kappa \kappa' c}{\rho} \Delta \rho \]

- Kappa-mechanism excitation

- Nearly adiabatic
  \[ \frac{\Delta P}{P} = \Gamma \Delta \rho/\rho \]

- Cepheid blue edge

- Beta Cep variables

- \( Z = 0.015 \) (GS98)

- LBVs

- \( \alpha \)-Cygni var.

- \( \alpha \)-Cygni var. (NGC300)

- R71

- D12

- A10

- \( \alpha \)Cyg

- \( \log \frac{L}{L_0} \)

- \( \log T_{\text{eff}} \)
Variable supergiants must have lost significant mass

--Two important facts in massive star evolution

Wind mass loss (hot & cool winds)
Mixing in radiative layers (overshooting & rotation)

Exploratory models using MESA (Paxton et al. 2010):

Wind mass loss rates are adopted from
  Vink et al.(2001) for $T_{\text{eff}} > 10^4$ K
  Nieuwenhuijzen & de Jager (1990) for $T_{\text{eff}} < 10^4$ K
with possible enhancement of cool wind
  by a factor $f_{\text{cw}}$ for $\log(T_{\text{eff}})<3.70$

Extent of mixing in radiative layers – Overshooting factor $f_{\text{OV}}$

$$D_{\text{OV}} = D_0 \exp \left( - \frac{2z}{f_{\text{OV}} H_p} \right)$$ (Herwig 2000)
$$\alpha_{\text{OV}} \sim 10f_{\text{OV}}$$
If extensive mixing is assumed, He-burning occurs in the blue region after losing significant mass in the red supergiant phase.

Central He abundance

$30 \, M_\odot \quad X = 0.716 \quad Z = 0.0040$

$pulsations \, excited$

$f_{OV} = 0.05 \quad (\alpha_{OV} \approx 0.5)$

$f_{CW} = 10$

no overshooting

$\alpha_{OV} \approx 0.5$
Z = 0.015:
Less extensive mixing is needed for metal rich stars

\[ f_{\text{OV}} = 0.03 \ (\alpha \approx 0.3) \]

\[ f_{\text{CW}} = 10 \]

25 \( M_\odot \)
\( X = 0.705 \quad Z = 0.0150 \) pulsations excited
Periods of excited radial pulsations are comparable to those of R71 in LMC
Micro (αCyg-type) variations of LBVs in SMC

αCyg Variables in SMC

Excited radial pulsations

$X = 0.716$, $Z = 0.0040$

$M_i = 35$, $f_{ov} = 0.05$

$M_i = 40$, $f_{ov} = 0.0$

R40
NGC 300

Parameters taken from Urbaneja et al. (2005) and Kudritzki et al. (2008))
Conclusions

Blue supergiant pulsators underwent a **Blue ---> Red ---> Blue** evolution and lost substantial mass during Red SG stage.

Surface CNO: \( \frac{X_C}{X_N} \approx 0.02 \) & \( \frac{X_O}{X_N} \approx 0.3 \)

Substantial mixing in radiative layers (overshooting and/or rotation mixing)

Cool wind mass-loss may be enhanced