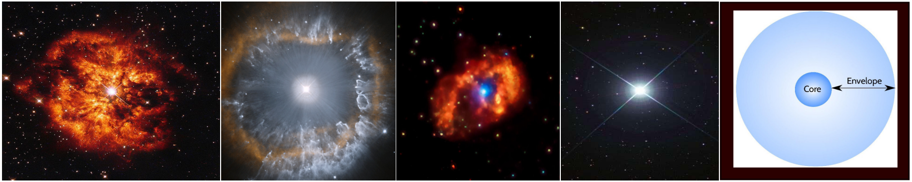

Instabilities and mass-loss in massive stars

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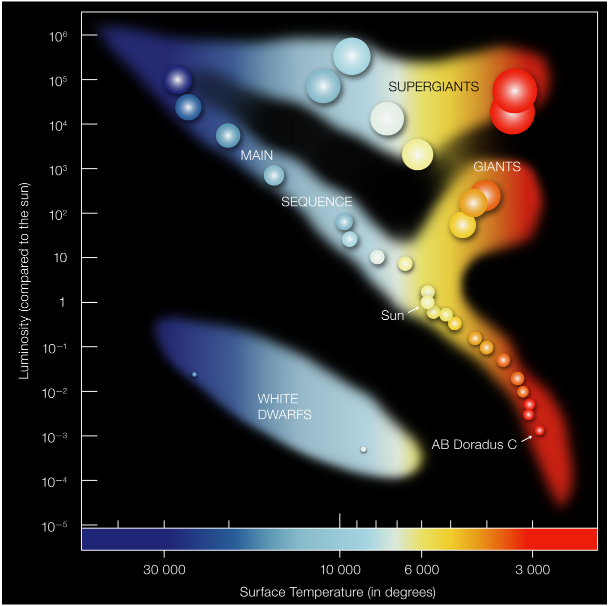

10^6
10^5
10^4
10^3
10^2
10
1
10^−1
10^−2
10^−3
10^−4
10^−5
Luminosity (compared to the sun)
SUPERGIANTS
MAIN
SEQUENCE
GIANTS
Sun
WHITE
DWARFS
AB Doradus C
30 000
10 000
6 000
3 000
Surface Temperature (in degrees)

Why stars are variable?
Due to internal instabilities...

Present work is on the stellar instabilities and their final consequences.

Overview

1. Basic equations and methods
2. Results
    - Main sequence and post main sequence stars
    - Primordial stars
3. Ongoing/Future Work
    - B-type supergiant: HD 2905
    - δ - scuti stars under Nainital-Cape Survey
    - Study of LBVs using BINA network
4. Summary

1. Basic equations and methods

Basic equations and methods

Theoretical description of stellar structure and dynamics:

- Rotation and magnetic fields are disregarded.
- Spherical symmetry, Lagrangian description.
- Independent coordinates: m and t

Physical Principles

- **(i) Mass conservation**
- **(ii) Momentum conservation**
- **(iii) Energy Conservation**
- **(iv) Energy Transport**

Basic equations and methods

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- **(iv) Energy Transport**

Equations

$$\begin{aligned}
\frac{\partial r}{\partial m} &= \frac{1}{4\pi r^2 \rho} \\
\frac{\partial P}{\partial m} &= -\frac{Gm}{4\pi r^2} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2} \\
\frac{\partial L}{\partial m} &= \epsilon - C_p \frac{\partial T}{\partial t} - \frac{\delta}{\rho}\frac{\partial P}{\partial t} \\
\frac{\partial T}{\partial m} &= -\frac{G}{4\pi r^4} \nabla \frac{T}{P}
\end{aligned}$$

Basic equations and methods

Linear stability analysis

- Consider small perturbation of variable $x(m, t)$ around the time independent hydrostatic configuration.
- Decomposition of hydrostatic(x_0) and perturbation part (x'):

$$x(m, t) = x_0(m) + x'(m, t)$$

where $x' << x_0$.

- Separation of variables

$$x'(m, t) = x_1(m) . e^{i\sigma t}$$

- Linearization leads to a boundary eigenvalue problem with $\sigma = \sigma_{\mathrm{r}} + \mathrm{i}\ \sigma_{\mathrm{i}}$ as complex eigenfrequency.
- Normalization by the global free fall time;
  $\sigma_{\mathrm{i}} > 0$: damping, $\sigma_{\mathrm{i}} < 0$: instability.
- Fourth order boundary eigenvalue problem solved by the Riccati method.

Basic equations and methods

Strange modes and associated instabilities

- Found in models having high luminosity to mass ratio ($> 10^3$ in solar units).
- Examples: ZAMS, HdC, AGB, Wolf-Rayet stars.
- Present for radial as well as nonradial perturbations.
- Also found in models of accretion disks around stars and within galaxies.

Basic equations and methods

Strange modes and associated instabilities

- Strange modes are formed by mode pairing from ordinary acoustic modes.
- Mode pairing process indicates acoustic origin.
- NAR approximation: Disregard the time derivative of the entropy in the energy equation; Equivalent to vanishing heat capacity.
- NAR Consequences: Thermodynamics is disregarded, Carnot type processes are excluded.
- Existence in NAR approximation: Not related to Carnot type mechanisms.

Strange modes and associated instabilities have mechanical origin.

Basic equations and methods

Results of instabilities need to be determined by following their evolution into nonlinear regime.

Nonlinear simulations

- Shock waves are treated using artificial viscosity.
- Correct energy balance is crucial.
- Scheme intrinsically conservative.
- Consequence of conservativity: Scheme has to be implicit with respect to time.

Basic equations and methods

In order to follow instabilities in nonlinear regime:

$$\frac{d}{dt}\left(\frac{1}{\rho}\right) = \frac{\partial}{\partial m_r}\left(4\,\pi\,r^2\,v\right);\ \textit{Mass Cons.} \tag{1}$$

$$\frac{dv}{dt} = -\frac{G\,m_r}{r^2} - 4\,\pi\,r^2\,\frac{\partial\,p}{\partial m_r} - v_Q;\ \textit{Momentum Cons.} \tag{2}$$

$$\frac{d\epsilon}{dt} = -p\,\frac{\partial}{\partial m_r}\left(4\,\pi\,r^2\,v\right) - \epsilon_Q - \frac{\partial}{\partial m_r}\left(4\,\pi\,r^2\,F_{con}\right) - \frac{\partial}{\partial m_r}\left(4\,\pi\,r^2\,F_{rad}\right);\ \textit{Energy Cons.} \tag{3}$$

$$F_{rad} = -4\,\pi\,r^2\,\theta\,\frac{\partial\,p_{rad}}{\partial m_r};\ \textit{Energy Trans.} \tag{4}$$

2. Results: Part I

Massive main and post main sequence stars

(Yadav & **Glatzel; MNRAS 2017a, 2017b)**

Results I: Massive main sequence stars

Linear stability analysis

- Models having masses above than 58 $M_\odot$ are unstable.
- Fundamental mode is only weakly unstable.

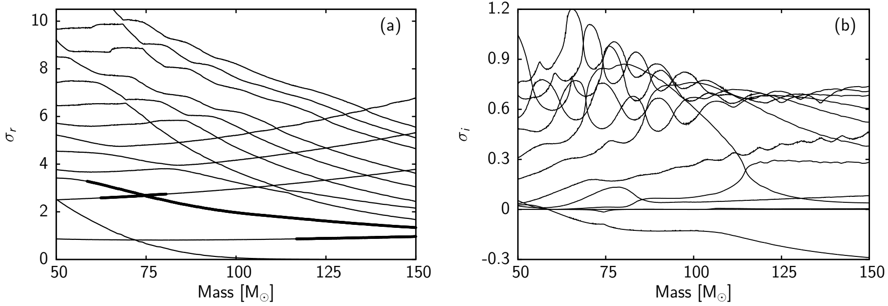


Figure : Eigenfrequencies as a function of mass along the ZAMS.

Results I: Post main sequence stars

ZAMS models having masses above 58 $M_\odot$ are unstable (Yadav & Glatzel, 2017a).

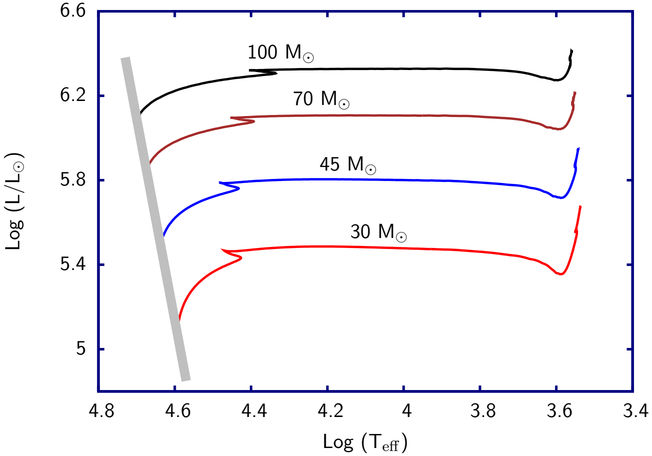


Figure : Evolutionary tracks for solar chemical composition

Results I: Post main sequence stars

Outcomes of the post main sequence stars

- Models in the mass rage of 23 and 100 $M_\odot$ have been analyzed.
- Instabilities lead to envelope inflation and pulsations. (Periods of hours to 100 days).
- Estimated mass-loss rates are in the range of 10^{-9} and 10^{-4} $M_\odot$/yr.
- Mass-loss of the order of 10^{-4} $M_\odot$/yr can affect the stellar evolution.

Yet to be done !

- Extending the nonlinear simulations for $M > 100$ $M_\odot$.
- Non-radial linear stability analysis.
- Implementation of the extended opacity tables to follow highly inflated models.

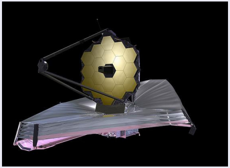
2. Results: Part II

Primordial stars: Science with the models

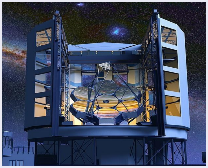
(Yadav, Biavati & Glatzel; MNRAS 2018)

Results II: Primordial stars

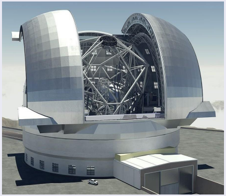
Primordial stars are not yet observed!



JWST ~ 2020



GMT ~ 2022



E-ELT ~ 2024

TMT ~ 2027

Common science objective

Study of first stars

Results II: Primordial stars

Models of Pop III stars can be used to study their properties

Objectives of this study:

- Identify instabilities
- Final consequences
- Determination of mass-loss rates

Models properties

- Masses in the range between 150 and 250 $M_\odot$
- $X = 0.77$, $Y = 0.23$ and $Z = 0$
- $6.60 < \log L/L_\odot < 6.88$
- $3.62 < \log T_{\mathrm{eff}} < 4.80$

Results II: Primordial stars

Stability analyses and nonlinear simulations in Pop III models

Strange mode instabilities discovered in models having log $T_{\rm eff} < 4.5$

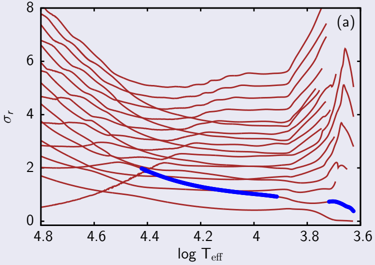


Figure : Modal diagram for models having $M = 250\ M_\odot$ and log $L/L_\odot = 6.88$

Presence of instability in several primordial models

Instabilities getting stronger in heavier models

Results II: Primordial stars

Outcomes for primordial stars

- First time, strange mode instabilities identified in primordial stars.
- Final consequences: finite amplitude pulsations (4 to 26 days).
- Estimated mass-loss rates 10^{-4} and 10^{-7} $M_\odot$/yr.

Yet to be answered !

- How massive can be a primordial star, 1000 $M_\odot$?
- Other mass-loss mechanisms
- Final fate of the primordial stars: Black holes or detonation

3. Ongoing/Future Work

Ongoing/Future Work: HD 2905

HD 2905 is a B-type supergiant with M ≈ 33 $M_\odot$ and $T_{\rm eff} = 24600$ K.

Recent observations of HD 2905 by Simón-Díaz et al. (2018)

- Variabilities between 2.5 to 10 days
- A pronounced period of 2.7 days

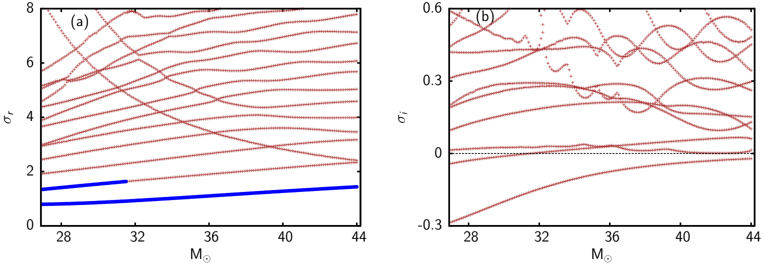
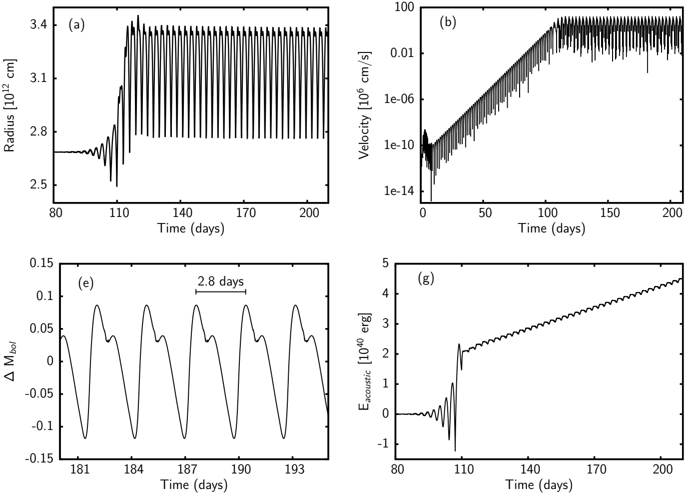


Figure : Real (a) and imaginary (b) parts of the eigenfrequencies.

Ongoing/Future Work: HD 2905

Instability in nonlinear regime: A period of 2.8 days for model with 34 $M_\odot$.



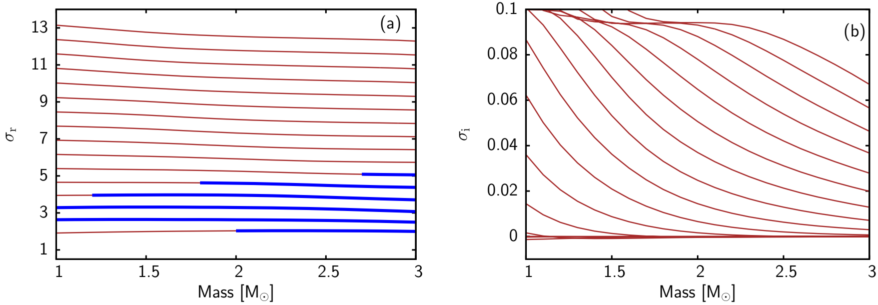
Yadav et al. (in preparation)

Ongoing/Future Work: δ - scuti stars

Nainital-Cape Survey: Study of chemically peculiar stars

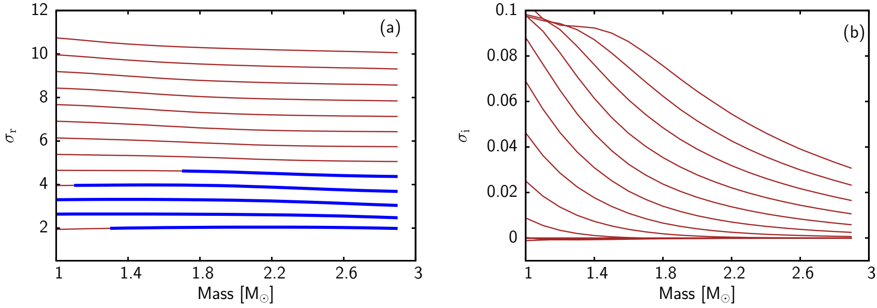
- Pulsational variabilities have been found in 8 stars
- Asteroseismic modeling had not been performed!

Modal diagram for HD 113878, where $T_{\rm eff} = 7000$ K and $\log L/L_\odot = 1.53$



Ongoing/Future Work: δ - scuti stars

Modal diagram for HD 98851, where $T_{\text{eff}} = 7000$ K and $\log L/L_{\odot} = 1.43$



Challenges

- Proper treatment of convection-pulsation interaction: TDC theory
- Incorporation of chemical composition

Ongoing/Future Work: Luminous Blue Variables (LBVs)

Instabilities and mass-loss in LBVs

- Variabilities of the order of hours and days
- Surface eruptions
- Episodes of enhanced mass-loss

To enhance our present understanding of LBVs

- A systematic linear stability analysis in models of LBVs
- Final consequence of instabilities
- Comparison of these predictions with observations
- Monitoring of LBVs using BINA observing facilities

We can detect the predicted strange modes in LBVs !

4. Summary

Summary

Instabilities in stellar models lead to:

- Finite amplitude pulsations (hours to days) & pulsationally driven mass-loss (10^{-9} to 10^{-4} $M_\odot$/yr).
- Re-arrangement of stellar structure.
- Surface eruptions.

Current involvement

- Variabilities and mass-loss in massive stars.
- Asteroseismic modeling of chemically peculiar/δ-scuti stars.
- Strange modes in luminous blue variables.

Looking forward for collaboration.
Please feel free to write me: **abhaypratapbhu@yahoo.com**

Thank you very much for your attention!