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Study of Instabilities and Outbursts in the Luminous Blue Variables *AF And* and R 127

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Abstract

Luminous blue variables (LBVs) are evolved massive stars close to the Eddington limit, exhibiting distinct spectroscopic and photometric variability having unsteady mass-loss rates. These stars undergo considerable changes in their surface temperature from quiescent to outburst phases. The cause of this irregular variability and unsteady mass-loss rate is not fully understood. Here, we present the results of a linear stability analysis in two LBVs *AF And* and R 127 during their quiescent and outburst phases. We observe that several modes are unstable in the models of the considered LBVs, with mode interactions being common in the modal diagrams for the models of both LBVs. For *AF And*, the number of instabilities increases in models with temperature below 15000 K. These found instabilities may be linked to the observed irregular variabilities and surface eruptions. The observational facilities of the BINA network will be highly beneficial for studying the spectroscopic and photometric behaviour of the considered LBVs.

Keywords: Massive stars, Luminous blue variables, Instabilities in stars, Mass-loss in stars

1. Introduction

Luminous blue variables (LBVs) represent the late evolutionary transient phase of most massive stars exhibiting pronounced photometric and spectral variability at time scales ranging from months to years (Humphreys and Davidson, 1994; van Genderen, 2001). Generally stars with masses equal to or greater than 21 $M_\odot$ undergo this temporary yet influential phase of evolution (Weis and Bomans, 2020). During this phase, stars experience significant mass loss through surface eruptions and other unsteady mass-loss processes. LBVs are believed to be the progenitor of Wolf–Rayet stars (e.g., Groh et al., 2014). However, recent studies also suggest that some LBVs may be the progenitors of peculiar supernovae (Kotak and Vink, 2006; Groh et al., 2013; Smith, 2017). Irregular variabilities and surface eruptions are the primary characteristics of LBVs, yet the origins of these phenomena remain poorly understood. In this context, the present work is a preliminary step in studying instabilities in models of two well-known LBVs, *AF And* and R 127.

AF And is one of the most luminous stars in Andromeda. Between 1917 and 1953, at least five major eruptions were observed. Joshi et al. (2019) noted that the surface temperature of this star varies within the range of 30000 K to 7000 K. During the quiescent phase, *AF And* exhibits a mass-loss rate of $2.2 \times 10^{-4} M_{\odot}\,\mathrm{yr}^{-1}$, with a wind terminal velocity ranging from 280 to 300 $\mathrm{km\,s}^{-1}$.

Radcliffe (R) 127 is another LBV situated in the evolved cluster NGC 2055 of the Large Magellanic Cloud (Walborn et al., 1991; Heydari-Malayeri et al., 2003). During the transition from the quiescent to the outburst phase, the surface temperature of R 127 undergoes a change from approximately 30000 K to 9000 K.

The method and parameters used to construct the models of *AF And* and R 127 are described in Sect. 2. The results of the linear stability analysis are presented in Sect. 3, followed by discussion and conclusions in Sect. 4.

2. Models of *AF And* and R 127

To construct models of the considered stars, parameters such as mass, luminosity, range of surface temperature, and chemical compositions are required. However, for several luminous blue variables (LBVs), the uncertainty in distance measurement leads to inaccuracies in determining luminosity. Similarly, the masses of several LBVs remain uncertain as many of them are single field stars. Without precise values for mass and luminosity, modeling LBVs and other very massive stars becomes challenging. To address this issue, instead of relying on a single model, a sequence of models is generally used (Yadav and Glatzel, 2016; Yadav et al., 2021). To account for the quiescent and outburst phases, we have adopted a sequence of models for both *AF And* and R 127, spanning surface temperatures ranging from 32000 K to 9000 K.

For model construction, we integrated the stellar structure equations as an initial value problem from the surface to the interior, where temperatures of 10^7 K are reached. We utilized Stefan–Boltzmann's law and the photospheric pressure as boundary conditions for the inward integration up to $T = 10^7$ K. To simplify the modeling problem, rotation and magnetic fields were disregarded. The onset of convection was determined using the Schwarzschild criterion. For all the considered models, we utilized OPAL opacity tables (Rogers and Iglesias, 1992; Rogers et al., 1996). Convection was accounted for by using the mixing length theory (Böhm-Vitense, 1958), with mixing length parameter $\alpha = 1.5$.

The models of *AF And* and R 127 were constructed with a solar chemical composition ($X = 0.70$, $Y = 0.28$ and $Z = 0.02$, where X, Y and Z represent the mass fractions of hydrogen, helium and heavier elements, respectively) utilizing the mass, luminosity and the range of surface temperature as specified in Table 1. Figure 1 illustrates the density as a function of

Table 1: Mass, luminosity and surface temperature range for the considered LBVs. The luminosity values are adopted from Jiang et al. (2018).

Star Name	**Mass ($M_\odot$)**	**Luminosity ($\log L/L_\odot$)**	**Surface Temperature Range (K)**
AF And	75	6.25	32000 to 9000
R 127	55	6.15	32000 to 9000

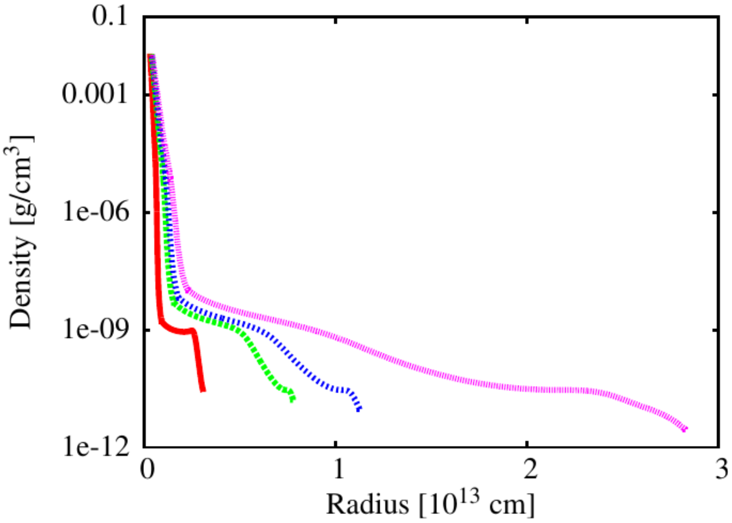

Figure 1: Density profile of the models of *AF And* with a mass of $75 M_\odot$ and $\log L/L_\odot = 6.25$. Density inversion can be noticed in the small region of the envelopes.

radius for four different models of *AF And*. It is observed that models with lower surface temperature exhibit significantly extended envelopes compared to those with surface temperatures ≥ 25000 K. Additionally, the presence of density inversion can be noted in Fig. 1.

3. Linear stability analysis and results

For a radial perturbation, the linearized pulsation equations constitute a fourth-order boundary eigenvalue problem. In this study, we have adopted the standard form of pulsation equations as outlined by Baker and Kippenhahn (1962) and Gautschy and Glatzel (1990a). For a detailed discussion on the pulsation equations and boundary conditions used here, readers are referred to Gautschy and Glatzel (1990a). To solve this boundary eigenvalue problem, the Riccati method is employed. The obtained eigenfrequencies are complex ($\sigma = \sigma_r + \mathrm{i}\sigma_i$) where the real part ($\sigma_r$) is linked to the pulsation period and the imaginary part (σ_i) indicates excitation or damping. Modes with negative σ_i are excited while the modes with positive σ_i are damped. In this study, the eigenfrequencies are normalized with the global free-fall timescale, $\sqrt{R^3/3GM}$,

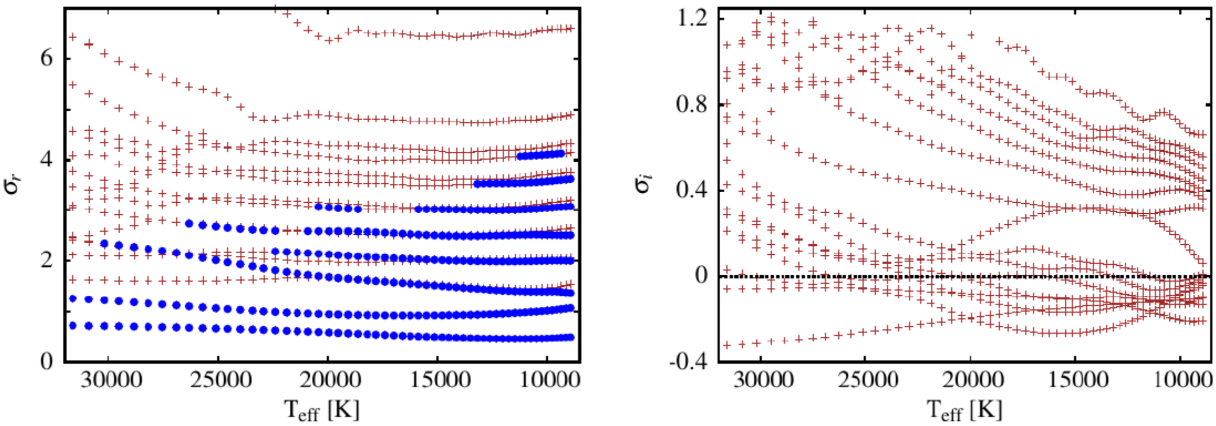

Figure 2: Result of linear stability analysis in models of *AF And*. The real (*left*) and imaginary (*right*) parts of the eigenfrequencies are displayed as a function of surface temperature. Eigenfrequencies have been normalized with the global free-fall timescale. Negative imaginary parts indicate unstable modes. Blue dots in the real part of eigenfrequency correspond to unstable modes. Several modes become unstable in models with lower surface temperature.

where R, G and M represent the stellar radius, gravitational constant and stellar mass, resp. This normalization renders the eigenfrequencies dimensionless.

The results of the performed linear stability analysis for the models of *AF And* and R 127 are presented in the form of 'modal diagrams' in Figs. 2 and 3, respectively. n these diagrams, eigenfrequencies are plotted as a function of stellar parameters such as mass or surface temperature. For detailed discussions on modal diagrams, readers are referred to Saio et al. (1998) and Gautschy and Glatzel (1990b). In Fig. 2, the real and imaginary parts of the eigenfrequencies as functions of surface temperature are displayed for models of *AF And*. Blue dots in the real part (Fig. 2, *left*) and negative imaginary parts (Fig. 2, *right*) are representing the unstable or excited modes. It is noteworthy that all considered models of *AF And* within the surface temperature range of 32000 K to 9000 K are unstable. Specifically, two low-order modes are excited in all models. Moreover, models with surface temperatures close to 32000 K have only two unstable modes, whereas models with a surface temperature of 9000 K have at least eight of these. Models with lower surface temperatures tend to exhibit more unstable modes. Several mode interactions in terms of avoided crossings as well as instability bands are observed in this modal diagram.

Similarly to the case of *AF And*, eigenfrequencies as a function of surface temperature are given in Fig. 3 for R 127. In these models we also find several unstable modes. Analogous to *AF And*, all models of R 127 in the considered surface temperature range are unstable. Specifically, four modes are found to be unstable in all models. Mode interaction phenomena are also evident in the modal diagram of R 127 (Fig. 3).

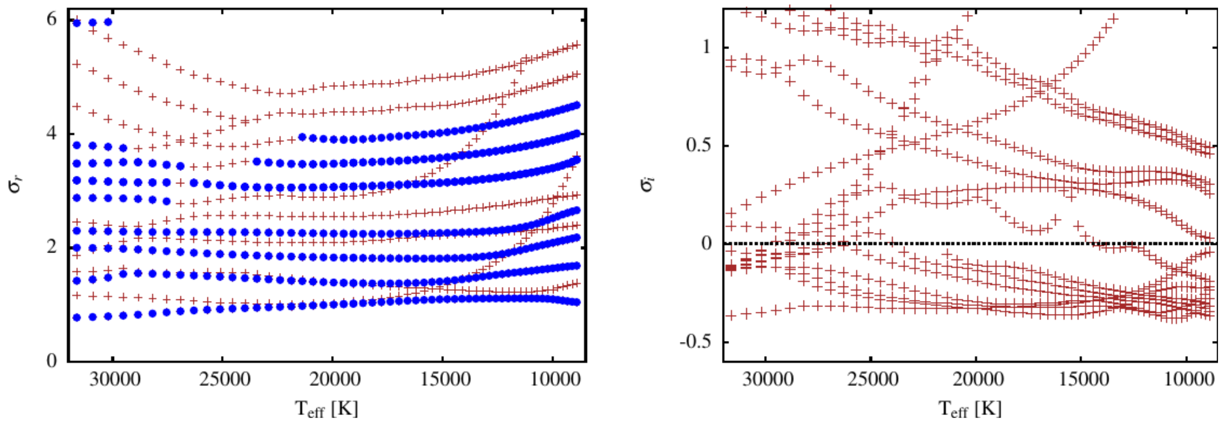

Figure 3: Same as Fig. 2, but for models of R 127.

4. Discussion and conclusion

Unsteady mass-loss, irregular variability, and surface eruptions have been observed in many LBVs. It has been pointed out in several studies that LBV models are susceptible to dynamical instabilities, which may contribute to the observed irregular variabilities and surface eruptions (see, e.g., Glatzel and Kiriakidis, 1993). In the present analysis, we considered models of two LBVs, *AF And* and R 127. Linear stability analyses were performed on a model sequence with temperatures ranging from 32000 K to 9000 K. Models with surface temperatures close to 32000 K represent LBVs in the quiescent phase, while models with surface temperatures close to 9000 K correspond to the outburst phase. In the case of *AF And*, we find more unstable modes in models with surface temperatures of 9000 K. This finding suggests that as the star approaches lower temperatures (below 15000 K), more instabilities emerge, potentially leading to irregular variabilities and surface eruptions. However, the final fate of instabilities cannot be determined solely by linear stability analysis. Nonlinear numerical simulations are required to ascertain the final outcome of the instabilities detected in the considered models. For R 127, the strength of the instabilities for some of the unstable models increases as the surface temperature of models are approaching 9000 K. Hence, it will be worthwhile to explore the consequences of these instabilities further. From the mode interactions observed in both modal diagrams (Figs. 2 and 3), we infer that the several unstable modes are strange modes, consistent with earlier studies of massive stars (see e.g., Saio et al., 1998; Glatzel et al., 1993; Glatzel and Kiriakidis, 1993).

The present work represents a preliminary study aimed at exploring the role of instabilities in models of two LBVs. The ongoing work aims to conduct a more extensive linear stability analysis considering a wide range of stellar masses and chemical compositions, followed by nonlinear numerical simulations for these two LBVs. The outcomes of this ongoing research will be presented in the near future. Observational studies of LBVs, using facilities of Belgo-Indian Network for Astronomy and astrophysics (BINA), combined with modeling, have the potential to significantly enhance our current understanding of LBVs.

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Conflicts of interest

The authors declare no conflict of interest.

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