Wolf-Rayet Stars
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Instabilities in the envelope of Wolf-Rayet stars

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Wolf-Rayet stars are very hot stars close to the Eddington limit. In the conditions encountered in their radiation pressure dominated outer layers several instabilities are expected to arise. These instabilities could influence both the dynamic of their optically thick winds and the observed spectral lines introducing small and large scale variability. We investigate the conditions in the convective envelopes of our helium star models and relate them to the appearance of a high number of stochastic density inhomogeneities, i.e. clumping in the optically thick wind. We also investigate the pulsational stability of these envelope, considering the effect of the high stellar wind mass loss rates.

1 Introduction

The late stages of the evolution of galactic massive stars are characterized by a very high mass loss via stellar wind (Chiosi & Maeder 1986; Langer 2012). During the helium burning stage massive stars become very hot and their stellar wind is so dense that it can enshroud the hydrostatic layers and dominate the spectra of these objects with broad emission lines. Wolf-Rayet stars (WR) of the subclass WNE are thought to be helium burning stars that, due to their high mass loss rate have lost almost all their hydrogen rich envelope (Chiosi & Maeder 1986; Langer 2012). While the energy production due to the 3-α process makes their core convective, most of the WR envelope is expected to be radiative (see Fig.1). In the very outer layers at the base of their optically thick wind a convective zone is expected to arise.

This convective zone (FeCZ) is due to the recombination of iron and iron-group elements, which significantly increase the opacity at the temperature $\log(T) \approx 5.3$ which is thought to be of crucial importance for the driving of the wind (see Fig.1, Hamann et al. 2006; Owocki 2015). The FeCZ is characterized by the proximity to the Eddington limit (cf. Langer et al., this volume), a density inversion (Gräfener et al. 2012; Sanyal et al. 2015) and a very small convective flux. Cantiello et al. (2009) and Grassitelli et al. (2015) argued that the propagated effects of turbulent convection in the subsurface convective zones is likely the origin of the observed small and large scale velocity fields at the photosphere of massive main sequence stars, namely the micro- and macro-turbulence.

It has been observed that WR spectra show the presence of systematic variability in the form of emission sub-peaks. These emission sub-peaks are thought to be the signature of a high number of density inhomogeneities, or clumps, in the wind of WR stars (Moffat et al. 1988; Lépine & Moffat 1999). Given the stochastic nature of the phenomenon and the fact that it is thought to originate at the base of the wind (Owocki 2015), we investigate the connection between the conditions in the outer hydrostatic layers and the small-scale variability of the spectral lines, in order to connect the effects of convection to the appearance of wind clumping.

In addition to this, according to theoretical works we can expect another kind of periodic variability to appear in the low density envelope of WR stars, the *strange mode* pulsations (Glatzel et al. 1993). However there is no observational evidence for pulsations in WN stars so far, except for WR123 (Chené & Moffat 2011) which presents a 10 h period which is by far larger than the expected periods. We investigate the so far neglected influence of mass loss onto the pulsational stability of our WR models.

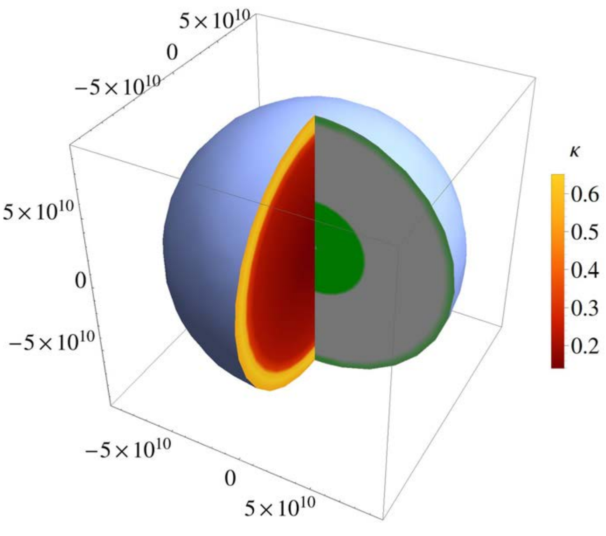

Fig. 1: 3D spatial projection (in cm) of the interior of a 1D 16 $M_\odot$ helium star. The right section shows in green the convective zones and in gray the radiative one, while the left section shows color coded the opacity of stellar matter according to the color bar on the right.

2 Method

We computed a set of chemically homogeneous helium zero age main sequence (He-ZAMS) stellar models from 2 to 17 $M_\odot$ with BEC, the Bonn 1-D hydrodynamical stellar evolution code (Heger et al. 2000; Petrovic et al. 2006; Brott et al. 2011). It includes up-to-date physics, adopts the Mixing-Length Theory (MLT) for convection (Böhm-Vitense 1958), mass loss via stellar wind according to Nugis & Lamers (2000) and a metallicity Z=0.02. The models were computed with outer boundary conditions given by the assumption of a plane parallel gray atmosphere.

Goldreich & Kumar (1990) considered the interaction between the convective eddies and the overlying radiative layers as a possible driving mechanism for travelling gravity-waves. Cantiello et al. (2009) applied this concept to the sub-surface convective zones of massive main sequence stars introducing an estimate of the upper limit of the induced velocity field at the surface, based on a conservation of energy argument. This writes:

$$v_s \leq \langle v_c \rangle \sqrt{M_c \frac{\rho_c}{\rho_s}} \quad , \tag{1}$$

where v_s is the upper limit for the expected velocity field at the surface, M_c is the Mach number, ρ_c and ρ_s are the densities at the outer convective border and at the surface, respectively, and $\langle v_c \rangle$ is the averaged convective velocity in the last mixing-length λ_p of the FeCZ. We consider the isothermal sound speed in defining the Mach number because of the small ratio between the thermal and dynamical time scales.

3 Results

All the computed He-ZAMS models in the mass range 2−17 $M_\odot$ have a convective region close to the surface. Starting from the 6 $M_\odot$ model, all the more massive helium star models are inflated with $\Gamma \approx 1$ and a density inversion (Sanyal et al. 2015). The radial extent of the inflated region increases in the more massive models and, despite its small mass, typically of the order of 10^{-8} $M_\odot$, it can account 6% of the total radius in the 17 $M_\odot$ model.

3.1 Sub-surface convection

The convective velocities within the FeCZ are low ($\lesssim$ 5 km/s) for the less massive ($\leq$ 10 $M_\odot$) helium star models. As the luminosity-to-mass ratio increases in the more massive models, the convective velocities become of the order of the local sound speed, i.e. 10 − 20 km/s. Consequently the averaged convective velocities in the last mixing-length sharply increase in the models with $M > 10$ $M_\odot$, inducing therefore a turbulent velocity field at the surface that approaches the local sound speed in the more massive models (see Fig.2). Such a surface turbulent velocity field induced by convection is thought to be able to trigger the formation of clumps in the WR wind.

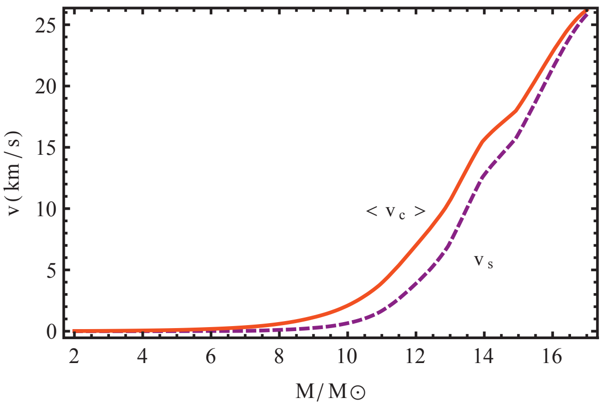

Fig. 2: Average velocity (red solid line, $\langle v_c \rangle$) of the convective elements at the top of the convective zone and expected surface velocity fluctuations (purple dashed line, v_s) as a function of stellar masses.

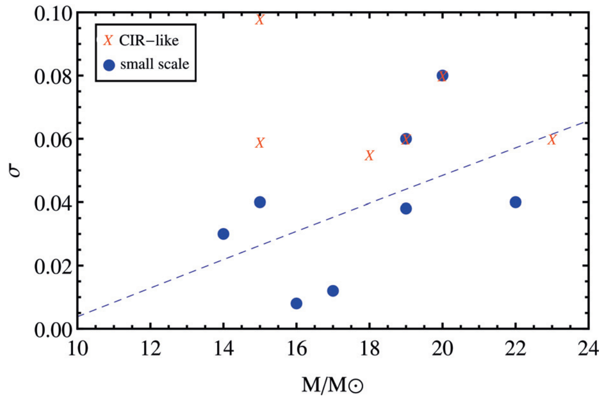

Fig. 3: Rms variability relative to the line strength σ as a function of mass of the Galactic H-free WN stars. Red crosses correspond to CIR-type variability, while the blue dots correspond to the small-scale variability in WN stars. Data are taken from St-Louis et al. (2009); Chené & St-Louis (2011); Michaux et al. (2014). The linear fit in blue dashed is computed considering only the blue dots.

In order to test this hypothesis, but being unable to directly observe the hydrostatic layers veiled by the optically thick winds, we have to rely on indirect evidences. Therefore we compare our prediction of an increased turbulent velocity field at the surface in the more massive models to the observed small-scale variability in a sample of H-free single WN stars. We collect the results of St-Louis et al. (2009), Chené & St-Louis (2011), and Michaux et al. (2014), in particular the rms variability across the HeII spectral lines relative to the local line strength σ, which is considered as an indication of the intensity of clumping, and investigate σ as a function of the WR mass estimated by Hamann et al. (2006).

We note however that spectra showing a dominant large-scale variability, the so called corotating interaction regions (Dessart & Chesneau 2002; St-Louis et al. 2009), have been excluded, assuming for this kind of periodic variability an origin not directly related to the convective motion.

Our results, plotted in Fig.3 show that an increased variability as a function of mass is found. Moreover, the zero point of the linear fit matches our prediction of an increased variability occurring only above M $\approx$ 10 $M_{\odot}$. However these results have to be taken with cautious due to the small sample and the relatively small number of spectra available to derive the values of σ (St-Louis et al., in prep.).

3.2 Pulsations

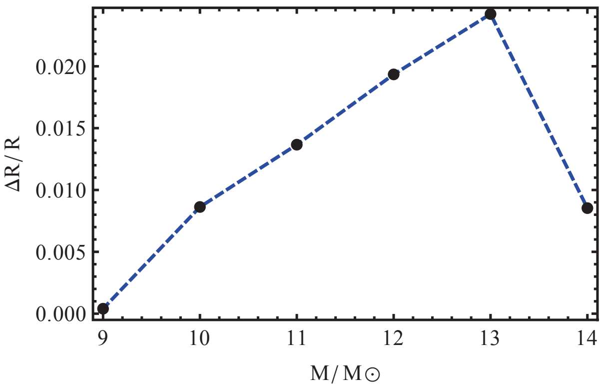

Fig. 4: Amplitude of the saturated pulsations appearing in the helium star models. The decreasing amplitude above 13$M_{\odot}$ is believed to be an effect of the increased mass-loss rate.

A sub-sample of our He-ZAMS model shows instability to pulsations. The small ratio between the local thermal-to-dynamical time scale in the envelope of WR stars rules out thermal mechanisms (as the κ-mechanism) as the origin of these pulsations, but refer to strange modes (Glatzel et al. 1993). These pulsations appear in the mass range 9 – 14 $M_{\odot}$ in our models, and their periods match well those of the lowest unstable order in the models of Glatzel et al. (1993).

Their normalized radial amplitudes $\Delta R/R$ are shown in Fig. 4, where we can see an increase in the pulsational amplitude from the 9 $M_{\odot}$ to the 13 $M_{\odot}$ model, followed by a decrease in the case of the 14 $M_{\odot}$ models, after which the models are stable. However Glatzel et al. (1993) predict also the more massive models to be unstable to pulsation, and indeed the more massive models do show instability to pulsations, but only in the computations in which mass loss was neglected. In fact, the 14 $M_{\odot}$ model does show higher amplitudes (of the order of $\Delta R/R \approx 0.03$) when mass loss is not included in the calculations. The same works for the higher mass models, which are unstable to also higher order modes only when mass loss via stellar wind is not included.

We therefore conclude that the high mass loss rates have a stabilizing effect on these pulsations, starting from the 14 $M_{\odot}$ model. This may help to understand the lack of observational evidences for pulsations in the very late stage of the evolution of stars with high luminosity-to-mass ratio. Furthermore, the computed luminosity variation due to pulsations is very small, typically $10^{-2}\,L_{\odot}$, which could be masked by the small and large scale variability present in the winds of WR stars. It is important to note that the velocities associated to these pulsations are significantly supersonic, up to 140 km/s, therefore an observational spectroscopical signature could be expected.

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Gloria Koenigsberger: In a binary system, oscillations can be excited. So, can we speculate that these oscillation modes in your talk can subsist even if the star has a high mass-loss rate?

Luca Grassitelli: It could, although I am not aware of neither theoretical nor observational evidences of pulsations for binary systems. The message that, however, we can take from these results is that these pulsations have high surface velocities that could be detected even in the case of optically thick winds. I think that the lack of observational evidences favours a stabilizing effect of the wind scenario.