Wolf-Rayet Stars
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A new mechanism for long long-term pulsations of hot stars?

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We suggest several ideas which when combined could lead to a new mechanism for long-term pulsations of very hot and luminous stars. These involve the interplay between convection, radiation, atmospheric clumping and winds, which collectively feed back to stellar expansion and contraction. We discuss these ideas and point out the future work required in order to fill in the blanks.

1 Introduction

The current understanding of stellar pulsations is based on the following scenario: a star contracts, the opacity of a certain layer increases, and radiation is trapped beneath. If sufficient radiation pressure manages to build up, the star will begin to expand, thus reducing the opacity and releasing the radiation. Due to the reduction in radiative pressure, the star will contract and so on.

The κ-mechanism is a well know example of such opacity related pulsations.[1] The link between the stellar contraction and increase in opacity is found in partially ionised layers, whose opacity is proportional to the temperature (as opposed to inversely proportional, which is usually the case). If there exists such a layer with a sufficient heat capacity, pulsations could occur.[2] The timescale for such pulsations is the dynamic timescale, $1/\sqrt{G\rho}$.

In very hot, massive stars, the partially ionised layers are either absent altogether or very close to the surface, in which case the density is very low and so is the heat capacity. Any κ-mechanism oscillations are therefore expected to be damped.[3] These stars may also exhibit pulsations of much longer timescales – the S-Dor pulsations, see e.g. Vink (2012).

In attempt to understand years-scale pulsations of very hot stars, we propose a new mechanism for stellar pulsations, which falls into the previously described generalised class of opacity related pulsations. It is depicted in Fig. 1.

The suggested mechanism, as this note, consists of several components. First is the coupling between convection and radiation, reviewed in Sect. 2. Second is the coupling between radiation and opacity, presented in Sect. 3. Third, and most important, is the connection between opacity and winds, proposed in Sect. 4. Finally, in Sect. 5 we point out well defined questions and the future toolbox required in order to answer them.

2 Between convection and radiation

As argued by Shaviv (2000), even if a region is unstable to convection – as is expected in atmospheres of super Eddington stars – if the radiative flux is *too* high the convective efficiency might be significantly lower than the mixing-length-theory (MLT; Vitense 1953, Böhm-Vitense 1958) prediction. Simply put, if the thermal energy flux is lower than the radiative flux, convection will be effectively choked.

Consider a gas element with a specific energy ε and height H. The energy density gradient, which scales as $\nabla E \sim \rho\varepsilon/H$ gives rise to a radiative flux given by

$$\mathbf{F}_{\rm rad} = -\frac{1}{3}\frac{c}{\kappa\rho}\nabla E \sim \frac{c\varepsilon}{\kappa H}, \tag{1}$$

which exceeds the maximal convective flux

$$\mathbf{F}_{\rm conv} = v_{\rm sound}\rho\varepsilon \tag{2}$$

when

$$H\rho\kappa \equiv h < c/v_{\rm sound}. \tag{3}$$

Here we defined h to be the *optical width* of the layer. Above the surface which satisfies relation (3), which we refer to as the *last convective surface* (LCS), convection could be safely ignored.

3 Between radiation and opacity

The only known explanation for stable super-Eddington states is that radiation can force the atmosphere to become inhomogeneous due to hydrodynamical instabilities, which operate at Eddington

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[1] For a review see, e.g., Maeder (2009); Cox (1974).

[2] Admittedly, this is a rather simplified description. Even if the thermodynamical conditions for amplification of pulsations are locally satisfied, a careful analysis should weigh in the damping effect of the surroundings.

[3] An exception to this statement is the strange mode instability which "enhances" the κ-mechanism, but relevant to short-term variations – see e.g. Saio et al. (2013).

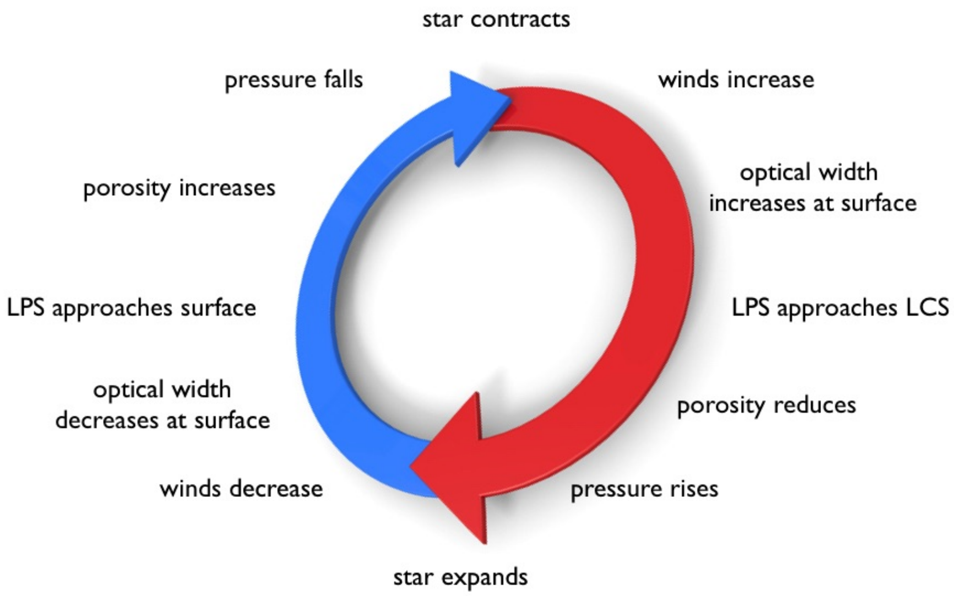

Fig. 1: The proposed pulsation mechanism consists of this cycle of events.

ratios of $\Gamma \gtrsim 0.8$. These were first predicted in Shaviv (2001) and seen in recent simulations (Takeuchi et al. 2013).

The clumping of the atmosphere reduces the opacity on macroscopic distances.[4] Due to the mixing nature of convection, the hydrodynamical instabilities could result in clumping only above the last convective surface.

At very low optical depths, the clumps will "smear" as radiation could easily escape. Therefore, the *last porous surface* (LPS), is located where $h \sim 1$. In steady state winds, the sonic surface and last porous surface will coincide.

A necessary condition for the existence of clumps is that the last convective surface and last porous surface be separated by at least a few scale heights.[5] Since

$$-\int_{LCS}^{LPS} \frac{dr}{H(r)} = \ln\left(\frac{P|_{LCS}}{P|_{LPS}}\right) > \text{a few}, \qquad (4)$$

the pressure at the LPS must be significantly lower than at the LCS. Therefore, a change in pressure at the sonic surface will effect the opacity beneath it. Such changes of pressure are expected to follow changes in mass loss.

4 Between opacity and winds

Consider a contraction of a star with thick continuum driven winds – the mass loss is expected to increase. This would reflect in the conditions at the sonic point; an increase in mass loss would increase the pressure, and push the sonic point towards higher optical depths. The LPS would approach the LCS, eventually closing the window for porosity. The subsequent rise in opacity will translate to a rise in pressure, followed by expansion.

There are two regimes which are usually dealt with separately; one where the winds reach infinity with a velocity comparable to the escape velocity at the sonic surface, and the other where the winds stagnate and fall back down (the "photon tired" regime). The pulsations we aim to describe here reside in the transition between the two regimes, where the energy in the winds is comparable to the luminosity. As every super-Eddington star with heavy winds necessarily passes through this stage, such pulsations

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[4] In this case, macroscopic stands for "of the order of the scale height".

[5] The length scale of the smearing of the clumps, at both the last porous surface and last convective surface, is of the order of a scale height.

are rather generic.

Whether or not these oscillations are damped or not, depends on the height of energy barrier due to the column depth of the cumulative winds. The amount of mass which must accumulate above the sonic surface in order to have significant feedback to the structure of the star, dictates the time scale of the pulsations. As this amount is proportional to the luminosity of the star, so will be the period of the pulsations.

A modulation of the pulsations could be due to hysteresis in the porosity phase transition of the atmosphere. We do not yet know how this phase transition depends on radial velocity.

5 Summary

In this wonderful conference, we proposed several ideas that may eventually assemble the long-term pulsations mechanism behind the S-Dor phenomena.

In order to further investigate these ideas, several questions should be answered:

1. What is the dependence of the convective efficiency on the radiative flux?
2. How does the atmosphere clump; what are the parameters of the porosity phase transition, hysteresis etc.?
3. What is the profile of interaction between clumping and convection?
4. How do the boundary conditions at the surface depend on mass loss? and finally,
5. What region of parameter space supports pulsations?

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Norbert Langer: I cannot see how you could obtain periods much longer than the dynamical timescale.

Tomer Shacham: The wind intensity is coupled to the amount of ejected mass, which accumulates during timescales much longer than the dynamical timescale.

Stephen Ro: Your illustration shows an efficiently convective region smoothly transitioning into an inefficient region. In more massive WR stars, the iron convection zone is inefficient and exists above a radiative envelope. How do these instabilities apply here?

Tomer Shacham: The instabilities exist only above the last convective surface, and only when the profile of the gamma factor can support them. Once they begin to operate, the convective structure of the outer layers changes (and winds start blowing).