Radial and Nonradial Pulsations as Probes of Stellar Physics
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Pulsation in Cool Hydrogen Deficient Stars

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Abstract. Models for hydrogen deficient stars are presented for different L/M-ratios and temperatures typical for RCB and HdC. Initially, we searched for unstable pulsation modes and identified their character using a simple linear code based on matrix methods. In a second step, we employed our fully-implicit Radiation-Hydro-Dynamics code to obtain amplitudes, radial velocities and lightcurves. For small L/M-ratios, nonlinear periods are close to the linear ones. Cooler models show strong shock-waves, which are suggested to play a key role in the dust formation of RCB stars which will be our ultimate goal.

1. Introduction

Among the hydrogen deficient stars, the R Corona Borealis stars (RCB) show a very spectacular feature: dropping their visual magnitude by up to 9 mag in a few weeks. The general accepted theory for this is the condensation of a carbon-rich dust cloud directly in the line of sight. Observed infrared excess supports this (for a review see Clayton, 1996). RCB are closely related to Hydrogen deficient Carbon stars (HdC) and extreme Helium stars (EHe). While the first two groups are similar in abundance (H is underabundant by a factor of $\approx 10^{-5}$), the EHe cover a great range in H abundance and also in temperature. HdC pulsate with much smaller amplitudes than RCB. Currently, no detailed abundance analyses (like Asplund, 2000 and Pandey, 2001) are available for HdC. For the origin of luminous Hydrogen deficent stars there are two scenaria employed: the double degenerate (DD) and the final Helium flash (FF). While Clayton (2001) outlines reasons for the FF, Pandey (2001) favours the DD, which is also supported by recent calculations of Saio & Jeffery (2000).

Little is known about the physical parameters of these stars. Pulsation can help constrain these. Additionaly some RCB show a correlation between pulsation phase and the onset of the declines.

2. Method

We calculated both nonlinear and linear models with the Vienna Radiation Hydro Dynamic code. Following Asplund et al. (2000), we chose OPAL opacites and an EOS by Wuchterl (1990) resembling a chemical composition of the majority group of RCB's ($X_{\rm H} = 0, X_{\rm Z} = 0.05$). Additionaly we used Alexander opacities for low temperatures, but for a slightly different composition.

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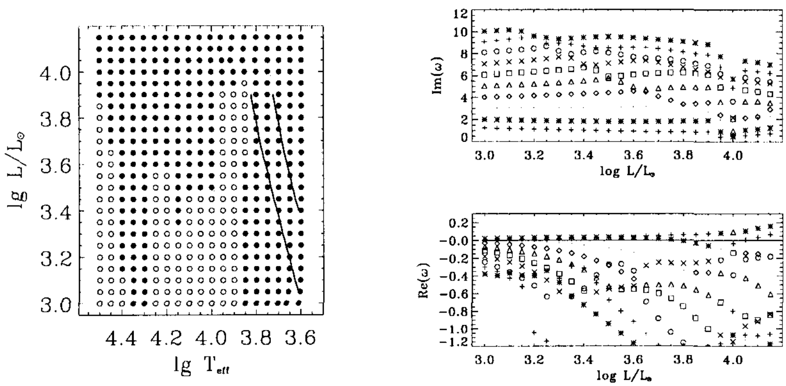

Figure 1. Linear analysis: left: HRD: Linear overstable models are shown by filled circles. Two lines of constant period (40 and 100 days) are displayed. The upper end of the lines end in the region where strange modes invade the frequency regime typical for the fundamental mode, which makes an automated detection of the fundamental mode in the frequency spectrum hardly feasible. Right: Modal diagram: L is the control parameter. $T_{\rm eff}$ is held constant (6310 K) and all models are overstable, allthough different modes/overtones dominate. The upper panel shows the imaginary part of the dimensionless frequencies (ω), the lower gives the real part (the "damping" if < 0). Mode crossing is clearly visible in the oscillatory part.

The linear analysis we employ (see Feuchtinger, 2000) is simple. By perturbing the equations of motion and energy and the grid equation, we end up with a linear non-adiabtic radial pulsation code. The eigenvalues and -functions are determined with the Castor method and checked by directly analysing the matrix with standard tools from a linear algebra package (`lapack`). The interpretation of the linearized problem allows the investigation of a large range of parameters. Fig. 1 shows a HRD for 1 $M_\odot$ models. The agreement with Saio (1995) is good, but we notice an additional instability region for temperatures of 10 000 K and higher. Modal diagrams suggest that this is due to strange modes with $n = 6$. The instability is supported by nonlinear models with small amplitudes. Changing the mass to 0.7 $M_\odot$ leaves the pattern in the HRD unchanged, if L/M is used instead of L. Constraining the stellar parameters by matching typical observed periods and temperatures, and assuming a model mass of 1 $M_\odot$, we derive that luminosities are around 9000 $L_\odot$ for a warm (7000 K) RCB.

The nonlinear part of the code is descibed by Feuchtinger (1998). Its main advantages are its implicity and the adaptive grid (Dorfi, 1998). In our first attempt we neglected convection and chose a luminosity of a few 10^3 $L_\odot$ to check our code. We start the simulation by computing a hydrostatic initial

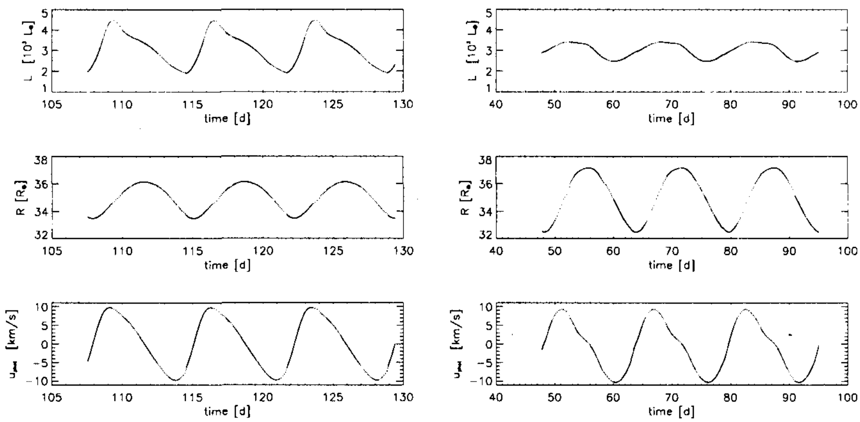

Figure 2. Nonlinear Pulsation: Lightcurve and radial variation for models with $M = 1M_{\odot}$ and $L/L_{\odot} = 3000$. Left: radiative Model: $T_{\rm eff} = 7268$ K, first overtone, P = 7.16 d, Right: convective Model: $T_{\rm eff} = 7238$ K, fundamental mode, P = 13.8 d

model, to which we apply a small perturbation in the gas velocity to start the pulsation. After reaching a stable limit cycle (see Fig. 2), we derive the period and the amplitudes for the change in radius, $T_{\rm eff}$ and luminosity.

Allthough turbulent convection does not change the stellar structure a lot, through its dissipative nature it has a strong influence on pulsation. We used the modified Kuhfuß convection model. It is a time-dependent, one-equation model based on the Boussinesq-approximation. The model is described in Wuchterl & Feuchtinger (1998) and Feuchtinger (1999a,b). The influence of the parameters on pulsation was investigated by Feuchtinger et al. (2000). We neglected overshooting, the flux limiter, radiative cooling, turbulent viscosity and pressure. The adopted set of parameters reduces the model in the local static limit to the mixing length model. We set the mixing length to 1.5 $H_{\rm p}$ (pressure scale heigth) and the turbulent viscosity parameter to $\alpha_{\mu} = 0.33$. Again we scanned for a wide range in stellar parameters using the linear code, but including convection. We note that there is only little difference. Convective energy transport occurs where it is more efficent than by radiation. This happens where the opacity is high and in the ionisation zones. These are also the regions where the driving of the pulsation via the κ-mechanism is taking place. For the models investigated here, convection lowers the driving and therefore cool, low-luminosity models are stable against pulsation, in contrast to the radiative models. In Fig. 2 we compare a radiative to a convective model, which have almost the same parameters. The radiative model pulsates in the first overtone, while the convective model pulsates in the fundamental mode. This is predicted by the linear models and confirmed by the nonlinear RHD results. The nonlinear periods agree with the linear ones to better than 1% in both cases.

Typical periods for RCB are longer than the ones presented. With increasing luminosity, periods get longer, the driving of the modes gets stronger, radiation energy becomes the dominant source of energy in the envelopes and nonlinear effects get more important. For high-luminousity models we did not reach stable limit cycles, because at the outer simulation boundary (where the pressure equals 1% of the photospheric pressure) the temperature gets so low that we have to include adequate opacity and EOS tables.

During the post-AGB evolution, models will enter the instability region somewhere. Pulsation, which is intrinsically a nonlinear process, can also change the evolution, by eg. means of levitation of the atmosphere or by triggering mass loss.

3. Conclusions and future work

Time-dependent convection is necessary for good models, although it introduces a set of free parameters. The detailed chemical composition of RCB plays an important role for the stability and finally decides if carbon-rich dust can condensate. With improved opacities and an EOS we are currently investigating the high-luminosity part of the HRD and the amplitude limiting mechanismum. In a next step we will model the dust formation self-consistently together with the pulsation.

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Discussion

A. Cox : What did you do about convection ? It may often affect your solutions.

H. Pikall : It's a general belief, that for high-luminousity models the energy transported by convection is neglible. For this reason we switched it off, but we will have a look at it in future work.