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Nonlinear radial pulsations for hot 20-$M_\odot$ models

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Abstract. We present the results of calculations that predict a radial pulsation instability region for hot 20-$M_\odot$ stars within a narrow band around $T_{eff} = 22,000$ K. These models have exhausted core hydrogen and are undergoing shell hydrogen burning, and have luminosities similar to the most massive β Cephei stars, but are slightly cooler and more evolved. The pulsations grow to a radial velocity amplitude of $\sim$20 km s^{-1} with a period of $\sim$0.75 d. The amplitude increases for higher Z and lower Y models.

1. Introduction

This work is an ongoing project at Los Alamos National Laboratory, aimed at examining pulsations of higher-mass stars. We use both linear and nonlinear pulsation codes to investigate 20-$M_\odot$ stars and conduct a parameter study in Y, Z and T_{eff}.

The models are evolved using an updated version of the one-dimensional Iben (1963, 1965a,b) evolution code. The evolution and pulsation codes use the OPAL opacities (Iglesias & Rogers 1996) and Alexander & Ferguson (1995, private communication) low-temperature opacities. Full description of the updated physics in the codes can be found in Templeton et al. (2000) and in Guzik & Swenson (1997). The resulting evolutionary model is then processed using a model-building code similar to the one described by Cox (1983) that generates a more finely-zoned (1998-zone) model which can then be used for the pulsation calculations. We use the linear nonadiabatic code of Pesnell (1990) to test for pulsation instability.

Using an input model from the model-building code, we use the nonlinear radial hydrodynamics code of Cox (1990), Ostlie (1990), and Ostlie & Cox (1993) to examine the growth or damping of the pulsation amplitude. This code includes time-dependent convection but neglects rotation. For these hydro models, we use a 60-zone envelope model. To ensure the accuracy of such a model, we compared 60-zone and 1998-zone envelope models (that include more of the envelope) using the linear pulsation code. We find that the frequency differences for the fundamental mode using the two different zoning schemes are negligible,

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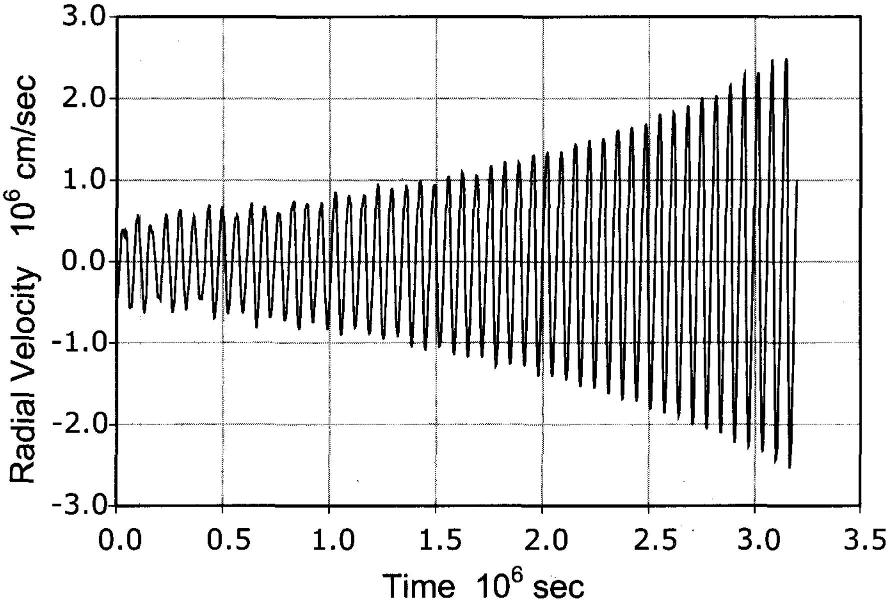

Figure 1. Radial velocity vs. time for model with Y = 0.28, Z = 0.02, $T_{eff} = 24,000\,K$

being of the order of 0.1%. The models used in the hydro code were started with an initial radial velocity of $5\,km\,s^{-1}$.

2. Results

We present the results for a parameter study of 20-$M_\odot$ models. These models are evolved through the blue hook, have exhausted core hydrogen, and are undergoing shell hydrogen burning. In the HR diagram this parameter study is just outside of the cool edge of Pamyatnykh's (2002) theoretical β Cep instability strip. Note the growth rates presented below are only estimates based on the early cycles. We estimated the growth rates by fitting an exponential to the amplitude of the radial velocity vs. time curve over about 50 cycles. The growth rates in Table 1 are the coefficient of the exponential fit. Fig. 1 shows an example radial velocity curve.

Initially we examined the temperature dependence for our models with Y = 0.28 and Z = 0.02 (Table 1). Strong pulsation occurred only between 21,000 and 24,000 K. There is an entry missing from the 22,000 K model because, while the amplitude was growing slowly, not enough cycles had been completed to estimate the growth rate.

Next the composition dependence was investigated. For these models the temperature was kept constant at ~22,000 K. For Z = 0.02 we investigated the pulsation properties with varying Y (Table 2). As can be seen, decreasing Y

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increases pulsation instability, and increasing Y strongly damps the pulsations. This is because the envelope opacity decreases with increasing Y. For Y = 0.28 we then investigated variations in Z (Table 3). We note that decreasing Z strongly damps the pulsations, consistent with the decrease in κ-effect driving. This has important relevance for observational studies of these stars. While as yet there appears to be no observational evidence of pulsating 20-$M_\odot$ stars, this may reflect that the areas under close scrutiny for variable stars generally have low metallicity, in particular in the Magellanic Clouds.

Table 1. T_{eff} Dependence for models with Z = 0.02, Y = 0.28.

T_{eff} (K)	Frequency (μHz)	Period (d)	Growth Rate (s^{-1})
19 081	6.53	1.77	−2.42e-07
20 017	7.66	1.51	−7.43e-08
20 663	9.06	1.28	−8.68e-08
22 009	11	1.05	growing
24 107	15.0	0.77	6.88e-07
25 854	~15	0.77	−1.51e-07

Table 2. Composition dependence for models with Z = 0.02 and $T_{eff} \sim 22,000$ K.

Y	Frequency (μHz)	Period (d)	Growth Rate (s^{-1})
0.24	14.0	0.83	1.02e-07
0.28	11	1.05	growing
0.30	10.8	1.07	−6.40e-07

Table 3. Composition dependence for models with Y = 0.28 and $T_{eff} \sim 22,000$ K.

Z	Frequency (μHz)	Period (d)	Growth Rate (s^{-1})
0.005	12.1	0.96	−6.96e-07
0.01	12.3	0.94	−5.60e-07
0.02	11	1.05	growing
0.03	10.8	1.07	8.85e-07

Finally, we compared the radial fundamental mode period predicted by the nonlinear hydrodynamics code with the period predicted by the linear pulsation code. Note that while we were able to identify the radial fundamental modes in the nonlinear code, there was often multimodal pulsation predicted, and higher order modes were also excited. While the periods for the nonlinear models are consistently longer by several percent than those predicted by the linear code, this is expected as the hydrodynamics expands the envelope of the model during the pulsation cycle, and consequently decreases the mode frequencies.

3. Conclusions

These results represent an ongoing project, and further work is required. However, we can draw some preliminary conclusions from the models. We predict fundamental radial pulsations in hot 20-$M_\odot$ stars. These pulsations have a period of $\sim$0.75 − 1 d and a maximum radial velocity amplitude of $\sim$20 km s^{-1}. These pulsations are occurring in shell hydrogen burning stars, and are limited to a narrow T_{eff} range of 21,000 − 25,000 K. We predict that these pulsations are strongly damped by increasing Y and decreasing Z. Future directions of work include extending the mass range of the parameter study, including the effects of mass loss for higher-mass stars, further zoning and initiation studies, and investigating the sensitivity to the time-dependent convection treatment. Finally, we are interested in comparisons to any observational data for stars in this region of the HR diagram, particularly those with higher metallicity.

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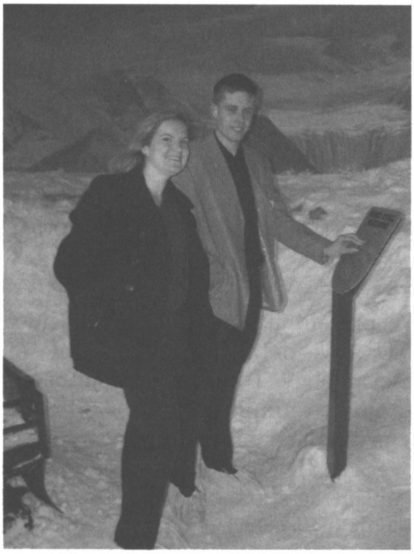

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