NONLINEAR RR LYRAE MODELS WITH NEW LIVERMORE OPACITIES

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Abstract. A. N. Cox recently showed that a 20% opacity decrease in the 20,000-30,000 K region as indicated by the new Livermore OPAL opacities reconciles the discrepancy between pulsation and evolution masses of double-mode RR Lyrae variables. Nonlinear hydrodynamic calculations were performed for RR Lyrae models of mass $0.75M_{\odot}$, $51L_{\odot}$, and $Z = 0.0001$ (Osterhoff II type) including this opacity decrease. The Stellingwerf periodic relaxation method was used to converge the models to a limit cycle, and the Floquet matrix eigenvalues calculated to search for a tendency of the fundamental mode to grow from the full-amplitude overtone solution, and the overtone mode to grow from the full-amplitude fundamental solution, thereby predicting double-mode behavior. Models of $T_{\rm eff} < 7000$ K with the opacity decrease have positive fundamental-mode growth rates in the overtone solution, in contrast to earlier results by Hodson and Cox (1982), and models with $T_{\rm eff} > 7000$ have positive 1st overtone growth rates in the fundamental-mode solution, but double-mode behavior was not found.

A. N. Cox (1991) recently showed that the 20% opacity decrease of the new Livermore (1991) opacities compared to the Los Alamos opacities for $T < 100,000$ K removes the discrepancy between pulsation and evolution masses of double-mode RR Lyrae variables. This conclusion was verified by Petersen (1992). This paper presents nonlinear calculations for RR Lyrae models of $0.75M_{\odot}$, $51L_{\odot}$, and $Z = 0.0001$ (Osterhoff II type) with this opacity decrease to search for a tendency of the fundamental mode to grow from the full-amplitude overtone solution, and the overtone mode to grow from the full-amplitude fundamental solution, thereby predicting double-mode behavior.

The 60-zone radiative models have envelope masses 4 to 8×10^{30} g, with temperature at the base $\sim 600,000$ K, and initial radial velocity amplitudes 20–40 km/s. The Stellingwerf (1975a, b) analytical fit to the Cox-Tabor (1976) opacity tables is modified by an opacity ramp decreasing from unity to 0.8 between 10,000 and 20,000 K, remaining constant at 0.8 between 20,000 and 30,000 K, and increasing to unity again by 100,000 K. Comparisons of the Stellingwerf fit to the OPAL opacities show that the fit is adequate for other temperatures (Iglesias and Rogers 1991). The nonlinear code described by Ostlie (1990, see also review by Cox and Ostlie 1992) is used to run several hydrodynamic cycles, to converge to a periodic limit cycle via the Stellingwerf periodic relaxation method, and to check for instability of other modes by analysing the Floquet matrix. The models use artificial viscosity parameters $C_Q = 4$, and $\alpha = 0.02$. The results do not seem to be sensitive to the choice of these parameters, in contrast to the findings of Kovacs

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TABLE I

Period, radial velocity amplitudes, and growth rates from Floquet matrix for RR Lyrae models.

1st Overtone Solutions

T_{eff} (K)	Period (d)	V_{min} (km/s)	V_{max} (km/s)	F in 1H (per period)
6800	0.3487	−21.4	20.6	0.000955
6900	0.3309	−20.7	20.5	0.000687
7000	0.3183	−20.9	24.1	−0.000476
7100	0.3009	−20.5	21.6	−0.000990

Fundamental Mode Solutions

T_{eff} (K)	Period (d)	V_{min} (km/s)	V_{max} (km/s)	1H in F (per period)
6800	0.4721	−34.1	41.4	−0.060858
6900	0.4487	−31.3	38.0	−0.035650
7000	0.4273	−27.8	31.8	−0.015758
7100	0.4063	−20.2	23.2	0.004022
7150	0.3963	−2.9	2.8	0.015353

(1992) and Kovacs and Buchler (1988). Table I summarizes the results for the fundamental and 1st overtone limit cycles for a grid of models with $T_{eff} = 6800$–7150 K.

In their nonlinear investigation of RR Lyrae models, Hodson and Cox (1982) did not find an effective temperature region with positive fundamental growth rates in the first overtone solution. We find that the 20% opacity decrease for $T < 100,000$ K indicated by the OPAL opacities causes the fundamental mode growth rates in the first overtone solutions to becomes positive for models with T_{eff} less than 7000 K. Still, we find no overlapping effective temperature region where the overtone mode is predicted to grow from the fundamental mode solution. Opacity adjustments such as widening or deepening the ramp on the Stellingwerf fit do change the growth rates somewhat. For example, widening the temperature range with the full 20% decrease to between 10,000 and 40,000, makes the 1H in F growth rate/period at 7000 K slightly less negative (−0.00037), and the F in 1H growth rate/period positive (0.0023). Additional studies are in progress.

In this study and in the analysis of Cox (1991), it appears most promising to search for double-mode RR Lyrae models just redward of fundamental blue edge, at $T_{eff} \sim 7000$ K, whereas Kovacs and Buchler (1988) and Kovacs (1992) find double-mode behavior for much cooler models ($T_{eff} = 6100$–6500 K).

References

Cox, A. N.: 1991, *Astrophysical Journal* **381**, 171.

Cox, A. N. and Ostlie, D. A.: 1992, "A Linear and Nonlinear Study of Mira," *Nonlinear Phenomena in Stellar Variability*, IAU 134, Mito, Japan, Jan. 7–10.

Cox, A. N. and Tabor, J. E.: 1976, *Astrophysical Journal, Supplement Series* **31**, 271.

Iglesias, C. A. and Rogers, F. J.: 1991, *Astrophysical Journal* **371**, L73

Kovacs, G.: 1992, "Double-Mode Stellar Pulsation," *Nonlinear Phenomena in Stellar Variability*, IAU 134, Mito, Japan. Jan. 7–10.

Kovacs, G. and Buchler, J. R.: 1988, *Astrophysical Journal* **324**, 1026.

Ostlie, D. A.: 1990, "Time-Dependent Convection in Stellar Pulsation," in *proceedings of conference* in Les Arcs, France.

Petersen, J. O.: 1992, "Kappa-Effect Functions for Period Ratios," preprint.

Stellingwerf, R. F.: 1975a, *Astrophysical Journal* **195**, 441.

Stellingwerf, R. F.: 1975b, *Astrophysical Journal* **199**, 705.