Stellar Structure and RR Lyrae Masses

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Abstract

I describe qualitatively the constraints on RR Lyrae masses that arise from consideration of the interior structure of Horizontal Branch (HB) stars. Briefly, the stellar models lying within the temperature range of the instability strip are slightly less massive than those with deep exterior convection zones. I discuss therefore what brings about the existence of these zones in the models.

1. Horizontal Branch Stellar Structure and the Instability Strip

The object of this paper is to present a simple argument showing how the masses of stellar models that appear in the instability strip depend on the physics of stellar interiors. The discussion here follows after a detailed treatment of HB stellar structure given in Dorman (1992a, hereafter D92). Recall first that the HB is understood to be a set of helium core-burning stars which have (to a good approximation) the same helium rich core masses and are inferred to have a range of total mass. This mass range is responsible for the colour spread to which the HB owes its name.

For fixed composition, models of decreasing mass are located successively further to the blue, and they are distinguished by successively less luminous hydrogen burning shells. In particular, for most compositions, the reddest models of each Zero Age HB sequence have exterior convection zones. These models also have the shortest blueward loops in the HR diagram because if the convection zone persists throughout evolution the surface temperature changes very little. The mechanisms thought to be responsible for RR Lyrae pulsations cannot operate in the presence of a stellar convection zone deep enough to engulf the H and He ionization zones. Hence the red edge of the instability strip lies at some point on the ZAHB blueward (*i.e.* on the less massive side) of the point beyond which these extensive exterior convection zones are not present. The figure shows HB evolutionary tracks from Dorman (1992b). The lines show, very schematically, the limit of models with exterior convection on the ZAHB (solid line), with the fundamental red edge slightly blueward of this limit. For sufficiently low envelope mass, the ZAHB model and most of its evolutionary track will be located blueward of the instability strip and its hydrogen burning shell will be much dimmer, the outer layers being hot and dense but strongly radiative. One therefore needs to understand what produces models with exterior convection zones, and how the masses of such models change with assumed composition.

An important exception to the argument presented here concerns stars which only enter the instability strip at a late stage of evolution, on the way to the AGB; no relevant constraints exist for their masses. For these stars there is also no mass-metallicity relationship.

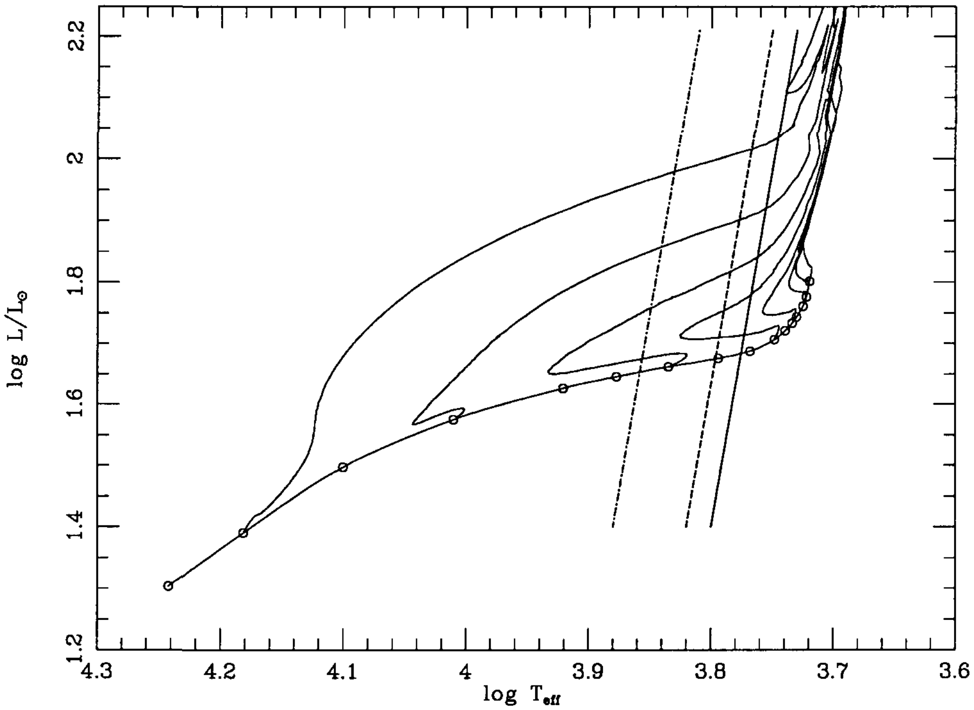

Figure. Evolutionary tracks are shown for [Fe/H] = −1.66, [O/Fe] = 0.63. The solid line represents the limit of models with convective envelopes; the dashed and dashed-dotted lines represent, roughly, the edges of the instability strip.

2. How to Obtain Exterior Convection Zones in Stellar Models

It is useful to separate the effects of the CNO elements, which act as nuclear catalysts, and other heavy elements which only contribute to the opacity. One can think of the CNO abundance as giving the hydrogen shell a potential to burn, whose magnitude is regulated by the opacity sources in the envelope above it. If the CNO abundance is increased, everything else being fixed, the most important things that happen to the deep interior are (i) the hydrogen burning shell (and thus the model luminosity) becomes brighter, and (ii) the temperature gradients in the hydrogen rich envelope become steeper, *lowering the temperature of the outermost layers*. This is demonstrated by explicit calculation (D92, Figure 4). The fact that at fixed mass the outer layers are at lower temperature of course implies a deeper convection zone, and from there we see easily that the models without convection zones will have lower masses as the CNO abundance is increased.

The D92 study also showed that if Z was high, the masses of models in the instability strip would also be small, irrespective of the CNO abundance. This occurs because the opacity clamps down the temperature of the hydrogen burning shell, regulating the luminosity but also ensuring that smaller masses have exterior convection zones (D92, Fig. 6). Clearly, however, this 'clamping' is an effect caused by the opacity at high temperature. The recent superior opacity treatments by the OPAL group and the Opacity Project have not so far produced large changes at these temperatures. Numerical experiments show that the properties of models are quite sensitive to small changes ($\sim$ 10%) in the opacity for $T > 10^6 K$. However for the most metal poor compositions the metal contribution is a small proportion of the total opacity, so that the remaining uncertainties are expected to be small.

3. Masses of Metal Poor Variables

The mass of RR Lyrae variables in the cluster M15 has been the subject of much debate in the last year (Kovács *et. al.* 1991, Cox 1991, Simon 1992). With the new OPAL opacities, the most recent pulsational estimates for the mass are around 0.80 $M_\odot$. Note that the model red-giant tip mass is about 0.80 $M_\odot$ for a cluster age of 15 Gyr. The pulsational masses are thus only compatible with the evolutionary models (a) if the abundances are in solar proportion and (b) if there are many stars which undergo little mass loss at the red-giant tip. The former is uncomfortable because of a large body of evidence suggesting that [O/Fe] $\sim 0.2 - 0.4$ in globular clusters. For M15 in particular, there are a set of apparently unevolved HB stars (Buonanno *et. al.* 1985; Stetson 1991) which are too red for the scaled-solar ZAHB. The latter (little mass loss) presents difficulties if it also implies that bright AGB stars which are indistiguishable from red giants in their exterior characteristics also may not lose mass. However, for [O/Fe] as high as 0.75, the inferred evolutionary masses are around 0.72 $M_\odot$. A smaller assumed oxygen enhancement gives an intermediate value, probably still discrepant with the new pulsational estimates by a few hundredths of a solar mass.

References:

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