The Impact of Large-Scale Surveys on Pulsating Star Research
ASP Conference Series, Vol. 203, 2000
L. Szabados & D. W. Kurtz, eds.

Metallicity Effects in Evolutionary Cepheid Models

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Abstract. Based on consistent stellar evolution and pulsation calculations for Cepheids, we analyse the effect of metallicity on period–luminosity relationships. We discuss the main uncertainties of the results inherent to stellar evolution calculations and linear stability analysis.

1. Introduction

The metallicity dependence of the period–luminosity relationship ($P{-}L$) is an old debate of fundamental importance for the use of Cepheids as distance indicators. Both observational and theoretical controversies exist (see Tanvir 1997 for a review). On the theoretical viewpoint, small or negligible effects are quoted by Chiosi, Wood, & Capitanio (1993) or Saio & Gautschy (1998), whereas a large effect, up to $\delta M_V \sim 0.77$ and $\delta M_K \sim 0.42$ between the Small Magellanic Cloud (SMC) and Galactic pulsators at a given P, is found by Bono et al. (1998; see also Marconi, Caputo, & Ripepi 2000).

Except for the work of Saio & Gautschy (1998), there is usually a lack of consistency between the stellar evolution calculations and the pulsation calculations, both based on different input physics. In this paper, we present stellar evolution calculations coupled to a linear non-adiabatic stability analysis (Baraffe et al. 1998; Alibert et al. 1999). We have performed a grid of evolutionary models covering a mass range characteristic of Cepheids ($3 - 12\ M_\odot$) and for metallicities representative of the SMC ($Z = 0.004$), the LMC ($Z = 0.01$) and the Galaxy ($Z = 0.02$). Different treatments of convection are used in the evolutionary calculations, such as a variation of the mixing length parameter and the use of core overshooting (see Alibert et al. 1999 for details).

2. Results

2.1. Evolutionary Effects

The first interesting result obtained from such self-consistent calculations is the explanation of most of the 1H/2H beat Cepheids observed in the Magellanic Clouds (MC) by first-crossing models (Baraffe et al. 1998).

These models correspond to the evolution toward the red giant branch after the star leaves the main sequence. This phase of evolution is relatively short, comparable to a thermal time scale. The time spent on the first crossing is $\sim$ 1/100 the time spent in the blue loop instability strip (IS). Our models predict a change of period in the first crossing IS of $\sim 10^{-6} - 10^{-5}$ d/yr, which may be detected by the long term surveys of microlensing experiments (EROS, MACHO, OGLE).

The second success of such models is the prediction of a change of slope at short periods, due to the reduction of the blue loop size as mass decreases (cf. Fig. 1). Such a trend has been observed in the EROS sample (Bauer et al. 1998) and in the OGLE sample (Udalski et al. 1999). This evolutionary scenario has been questioned by Bauer et al. (1998) since the change of slope should also be observed for 1H Cepheids in the frame of this scenario. As suggested by Alibert et al. (1999), the non-detection of the 1H change of slope may be attributed to a narrower IS, as predicted by the models, and to a higher contamination of first crossing models at low P, which do not show any change of slope (cf. Fig. 1). The combination of both effects should render the detection of a change of slope for 1H extremely difficult.

2.2. Period–Luminosity Relationships

Regarding metallicity effects, the present calculations show negligible effects of Z on the $P-L$ and $P-T_{\rm eff}$ relationships. This small dependence is not affected by variations of the mixing length parameter or by the use of core overshooting. We thus confirm the results found by Saio & Gautschy (1998). We stress however that caution must be taken at low P, since an increase of Z (as well as an increase of the amount of core overshooting) increases the minimum mass undergoing a blue loop. Thus the period at which the afore-mentioned change of slope is predicted increases with Z.

2.3. Period–Magnitude and Period–Colour Relationships

In order to transform the theoretical quantities (L, $T_{\rm eff}$) into observable quantities (colours, magnitudes) we have calculated a grid of atmosphere models and corresponding synthetic spectra in a $T_{\rm eff}$ range (7000 K – 4000 K) and gravity range ($\log g = 0 - 3.5$) representative of Cepheids. These models are performed with the spherically symmetric radiative code of Allard & Hauschildt (cf. Hauschildt, Allard, & Baron 1999).

For a given $T_{\rm eff}$ and g, we find the following metallicity effects when Z decreases from 0.02 to 0.004: since the dominant metallic line absorption decreases with Z, this yields an increase of the B-flux by at most 0.1 mag, depending on $T_{\rm eff}$. Consequently, there is a decrease of the VI fluxes by at most 0.05 mag and of the JK fluxes by at most 0.03 mag. This translates in a metallicity effect *at a given P* of less than 0.12 mag in the $VIJK$ bandpasses, without systematic effects. We find systematic bluer $B-V$ colours by 0.1 – 0.12 mag at a given P between $Z = 0.02$ and 0.004.

We therefore conclude that excluding the B-band, the effect of Z on P–mag and P–colour relationships is found to be small and less than 0.1 mag (excluding the short period region $P \lesssim 4$ d which may be affected by the change of slope). The generally good agreement between the present models and observations in P–mag, as illustrated in Figure 2 for the Galaxy, P–colour and P–radius diagrams (see Alibert et al. 1999 for details) adds credibility to the present models and the conclusions regarding the metallicity effects.

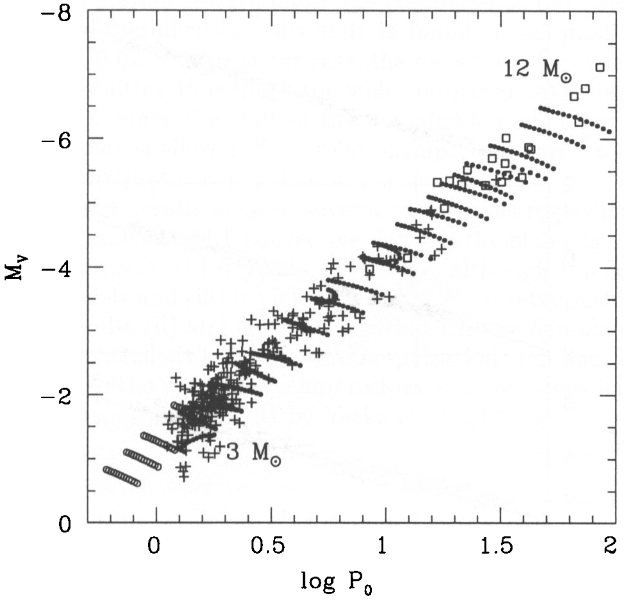

Figure 1. Period–magnitude diagram (P in days) for the SMC fundamental pulsators. Observations are from EROS1 (plus symbols, Sasselov et al. 1997) and Laney & Stobie (1994, open squares). The models correspond to a metallicity $Z = 0.004$ and different masses from 3 $M_\odot$ to 12 $M_\odot$: first crossing models (open circles) and core He-burning unstable models (dots).

3. Uncertainties

Our present standard models (without core overshooting in the evolutionary calculations) agree extremely well with the lowest period $P_{\rm min}$ observed in the SMC, but they underestimate $P_{\rm min}$ in the LMC, predicting log $P_{\rm min} = 0.25$ (1.8 d) compared to the observed value log $P_{\rm min} = 0.4$ (2.5 d). A better agreement is found with the observed LMC $P_{\rm min}$ if core overshooting is taken into account. This problem is illustrated in the poster of Alibert & Baraffe (2000). Since there are no indications and no physical arguments for assuming that the amount of overshooting increases with Z, this discrepancy may be due to specific properties of the LMC. A spread of metallicity could solve the problem, given the sensitivity of $P_{\rm min}$ to Z. Alternative solutions are given by Alcock et al. (1998), invoking some kind of exotic Cepheid population resulting from binary coalescence. Work is in progress to understand this puzzle in the LMC.

As mentioned previously, uncertainties in the evolutionary calculations (mainly due to the treatment of convection) barely affect the present results and conclusions regarding metallicity effects. The main uncertainty in the present

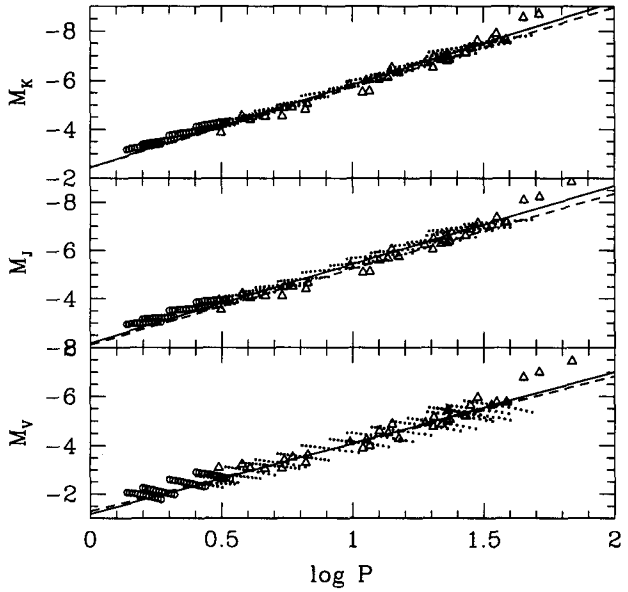

Figure 2. Period–magnitude diagrams for solar metallicity models $Z = 0.02$. The symbols for the models are the same as in Fig. 1. Observations (open triangles) are from Gieren, Fouqué, & Gómez (1998). The solid line corresponds to the mean relationship derived from the present models and the dashed line corresponds to the observed relationships derived by Gieren et al. (1998).

calculations is due to the neglect of convection–pulsation coupling in our linear stability analysis. Convection is frozen-in and an arbitrary criterion is used to define a red edge for the instability strip (see Alibert et al. 1999 for details).

A time dependent non-local theory of convection is required to take into account its effect on the pulsation. Such a theory is lacking and the current recipes include several free parameters (cf. Yecko, Kolláth, & Buchler 1998 and Buchler 2000). Yecko et al. (1998) have recently shown the high sensitivity of the position of the IS to these parameters.

In order to appreciate the effect of convection on pulsation, we have preliminarily adopted an extremely simplified approach where the convective flux given by the mixing length theory (MLT) is perturbed. This is equivalent to setting to zero several free parameters used in the Yecko et al. formalism, neglecting turbulent diffusion and turbulent stress and assuming that the convective flux adapts instantaneously to the pulsation.

Although very primitive, this approach will give us an idea of the sensitivity of our previous results when introducing some convection–pulsation coupling. We find a very small effect on the location of the blue edge, independently of

Z. This is expected given the limited role of convection in the stellar structure toward the blue edge. Interestingly enough, this very simplified treatment gives a red edge, which is shifted toward lower $T_{\rm eff}$ compared to our previous results. For SMC and LMC metallicities, this shift is found to be small and is more pronounced for $Z = 0.02$. In this latter case, the red edge is located at extremely small $T_{\rm eff}$ and the resulting IS is much too wide compared with observations (up to 1500 K in width). Since the shift of the red edge toward lower $T_{\rm eff}$ is larger at longer P, this yields shallower $P-L$ relationships, compared to our previous results and to observations.

These preliminary results suggest several conclusions regarding the perturbation of the instantaneous MLT convective flux: (i) the blue edge is almost not affected by this treatment, (ii) it yields a red edge, although too cool in $T_{\rm eff}$ for solar metallicity models and (iii) it yields shallower $P-L$ relationships compared to observations. Results (ii) and (iii) indicate that this oversimplified treatment is not appropriate to deal with the convection–pulsation coupling, but illustrate the high sensitivity of the red edge to *any* recipes and the necessity to calibrate them to observations, as emphasised by Yecko et al. (1998).

4. Conclusion

We have performed self-consistent stellar evolution and pulsation calculations for different masses and chemical composition. We do not find significant effects of metallicity on $P-L$ relationships, except at low periods ($P \lesssim 3-4$ d). These results are not affected by uncertainties inherent in stellar evolution calculations (mixing length parameter, overshooting, initial abundance of He, etc.). Even though the perturbation of the convective flux is neglected and an arbitrary criterion is used to define the red edge of the instability strip, we find excellent agreement between predicted and observed P–magnitude, P–colour and P–radius relationships in SMC, LMC and the Galaxy. An oversimplified treatment of the convection–pulsation coupling shows the robustness of the location of the blue edge and the extreme sensitivity of the position of the red edge. For distance calibrations, our results overstress the use of $P-L$ relationships in the K-band, which are the less affected by uncertainties inherent in stellar evolution and pulsation calculations, and the use of the blue edge as suggested also by Gautschy (1999).

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