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NONLINEAR MODELS OF THE BUMP CEPHEID HV 905 AND THE DISTANCE MODULUS TO THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Nonlinear pulsation models have been used to simulate the light curve of the LMC bump Cepheid HV 905. In order to reproduce the light curve accurately, tight constraints on the input parameters M, L, and $T_{\rm eff}$ are required. The results, combined with accurate existing V and I photometry, yield an LMC distance modulus of 18.51 ± 0.05, and they show that the luminosity of HV 905 is much higher than expected from the mass-luminosity relation of stellar evolution theory. If we assume that the pulsation models are accurate, this suggests that there is a larger amount of convective core overshoot during the main-sequence evolution of stars with $M \sim 5\ M_\odot$ than is usually assumed.

Subject headings: stars: oscillations — Cepheids — Magellanic Clouds

1. INTRODUCTION

The new opacities generated by the Livermore group (Iglesias, Rogers, & Wilson 1992) and by the Opacity Project (Seaton et al. 1994) have led to the alleviation of the long-standing disagreement (Rodgers 1970; Iben & Tuggle 1972; Cox 1980) between the pulsation, beat, and bump masses of Cepheids. Results obtained so far with the new opacities (Moskalik, Buchler, & Marom 1992; Simon & Kanbur 1994; Christensen-Dalsgaard & Petersen 1995; Sebo & Wood 1995) have largely used linear pulsation theory. A feature of the linear theory results is that they require a mass-luminosity relation for Cepheids that is considerably brighter at a given mass than predicted by current stellar evolution calculations.

Stobie (1969) showed that the mass-luminosity relation of bump Cepheids could be estimated by fitting light curves from nonlinear pulsation calculations to observed light curves. Since the new opacities and linear pulsation theory now appear to give consistent results provided that a bright mass-luminosity relation is used, it is worth looking at the results of nonlinear pulsation calculations with the new opacities. Indeed, some nonlinear pulsation calculations using the new opacities have already been performed by Moskalik et al. (1992), who were able to reproduce the general features of the Hertzsprung progression of light-curve shapes quite well, once again provided that a bright mass-luminosity relation was used. We note that since the general pattern of the Hertzsprung progression is strongly influenced by a resonance between P_2 and P_0 such that $P_{02} = P_0/P_2 = 2$ at $P_0 \approx 10$ days (Simon & Schmidt 1976; Simon & Lee 1981; Buchler & Kovács 1986), and since period ratios were not reliably predicted by the old opacities (Moskalik et al. 1992), the masses derived from nonlinear models of bump Cepheids using these old opacities were incorrect.

Here we present specific nonlinear pulsation simulations of the bump Cepheid HV 905 in the LMC bar for which accurate V and I photometry has been published by Sebo & Wood (1995). A particular feature of this bump Cepheid is that it is quite near the blue edge of the instability strip, so the convective energy transport in the stellar envelope should not be very important. Another important consequence of being near the blue edge is that the pulsation driving, and hence limiting amplitude, is very sensitive to the effective temperature of the model. Sebo & Wood (1995) examined constraints on the properties of HV 905 using linear theory and the assumption $P_{02} = 2$. The light curve generated for the best model with this assumption had the general characteristics of the HV 905 light curve, but the model was far from a good fit.

2. COMPUTATIONAL DETAILS

The nonlinear pulsation calculations described here were done with an updated version of the code described by Wood (1974), while the linear calculations performed to derive starting models were done with the fully compatible linear code described in Fox & Wood (1982) and Chiosi, Wood, & Capitanio (1993). The opacities used were those of Iglesias et al. (1992), supplemented for temperatures below 6000 K as described in Chiosi et al. (1993). Convective energy transport was included by means of mixing-length theory and a mixing length of 1.6 pressure scale heights. A form of time dependence of the convection was included by forcing the convective velocity to vary on a convective timescale (see Wood 1974). The convective velocity and enthalpy flux were limited to physical values as described in Chiosi et al. (1993). The differencing of the radiative transport equation in both the linear and nonlinear codes was done according to the prescription in Fox & Wood (1982). Artificial viscosity was included by using the formula of Stellingwerf (1975) with viscosity parameter $C_Q = 2$ and the velocity cutoff parameter $\alpha = 0.06$. Tests run with $C_Q = 4$ produced light curves that were essentially indistinguishable from those run with $C_Q = 2$. Models typically had 460 mass points outside an inner radius of $\sim 0.3\ R_\odot$.

In order to convert the theoretical quantities L and $T_{\rm eff}$ into V and $V - I$ (Cousins system), model atmospheres of Kurucz (1993) with an appropriate abundance and gravity were used. The filter bandpasses of Bessell (1990) were convolved with the model atmospheres to produce V and I magnitudes. The zero point of color came from assuming that $V - I$ for Vega is -0.005 (Bessell 1983), while the zero point of the bolometric

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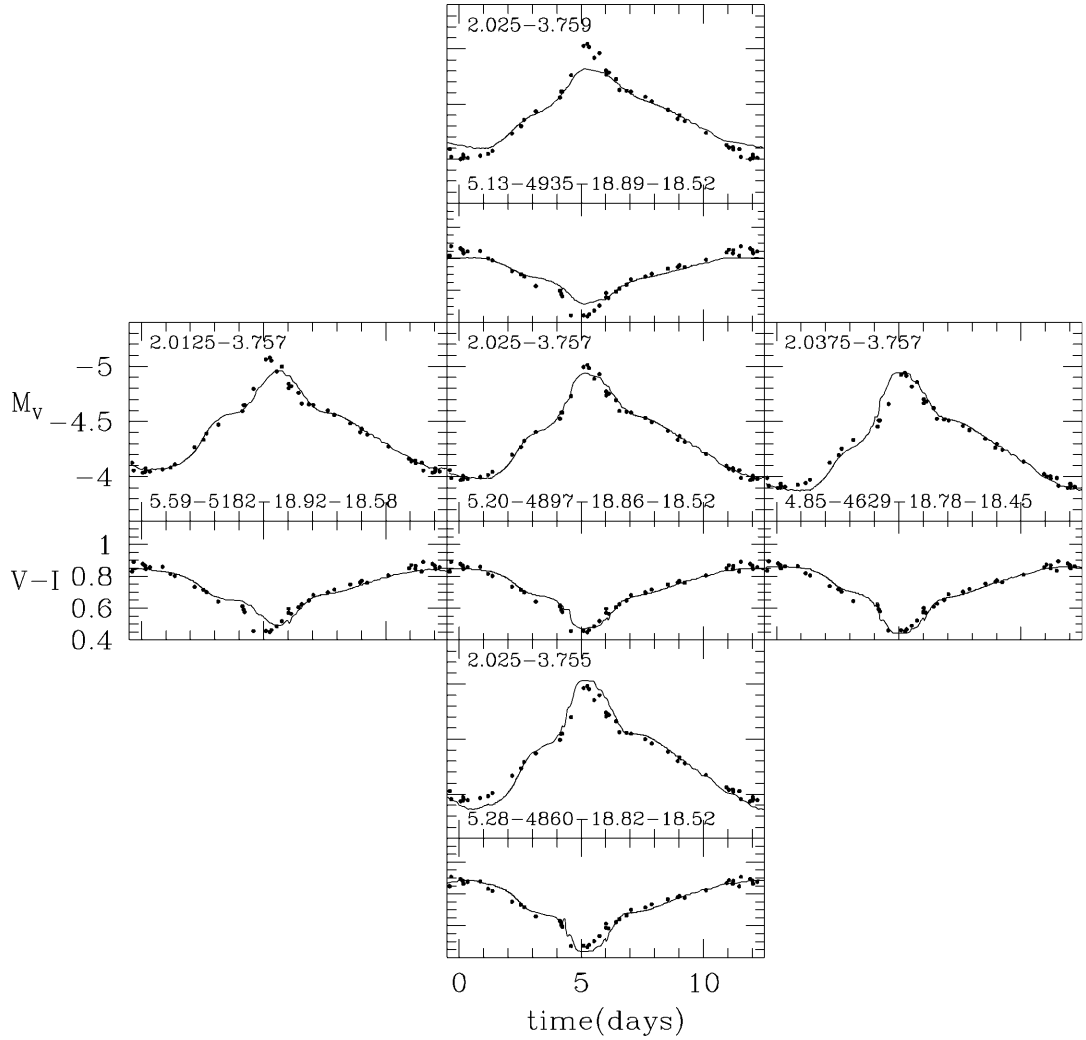

FIG. 1.—Plots of M_V and $V - I$ against time for five models. Solid lines show the results of the theoretical calculations, and filled circles are the observed values for HV 905, except that V and $V - I$ have been shifted vertically to give the best fit to the theoretical models in each case. The two numbers at the top of each panel are P_{02} and log $T_{\rm eff}$; the four numbers near the middle of each panel are $M/M_\odot$, $L/L_\odot$, apparent visual distance modulus and true distance modulus. The three horizontal panels show the effect of varying P_{02}, while the three vertical panels show the effect of varying $T_{\rm eff}$.

correction came from assuming the bolometric correction for the sun of -0.08, $L_\odot = 3.90 \times 10^{33}$ ergs s^{-1}, and $M_{\rm bol,\odot} = 4.75$.

For each model computed, a composition was first adopted. Having adopted the composition, there were three parameters of the model that could be adjusted independently: M, L, and $T_{\rm eff}$. A constraint that all models were required to satisfy was that the fundamental mode pulsation period according to the linear nonadiabatic code was 11.858 days, the observed period of HV 905. After satisfying this constraint, there were two parameters that we could vary independently in order to try to reproduce the light-curve shape. We chose $T_{\rm eff}$ and P_{02} as the independent parameters, although this choice is not essential. The reason for our choice was that pulsational driving is sensitive to the position ($T_{\rm eff}$) of a model relative to the edge of the instability strip, so the the amplitude of pulsation should act as a strong constraint on $T_{\rm eff}$. On the other hand, Simon & Schmidt (1976) demonstrated that bump phase depended on P_{02}, so matching the model bump phase to the observed phase should constrain P_{02}. Furthermore, Simon & Lee (1981) demonstrated that the bump phase was essentially independent of pulsation amplitude, suggesting that our two parameters $T_{\rm eff}$ and P_{02} could map independently to the two observational quantities, pulsation amplitude and bump phase, respectively.

At the beginning of the model construction process, values for $T_{\rm eff}$ and the period ratio P_{02} were specified. The model parameters L and M were then iterated until the linear period P_0 and the ratio P_{02} had the required values. At the conclusion of the iteration procedure, the model parameters were completely determined. The static model was then perturbed with the eigenfunction of the linear adiabatic fundamental mode and let to run until the kinetic energy of pulsation reached an asymptotic limit. The magnitude of the initial velocity perturbations was adjusted in separate calculations so that the limit was reached from above and below as a test that a true limit had been attained.

3. RESULTS

Figure 1 shows how varying $T_{\rm eff}$ and P_{02} affect the light curve. First, varying $T_{\rm eff}$ causes a change in the amplitude of pulsation. This is because HV 905 is near the blue edge of the instability strip where pulsational driving is a strong function of $T_{\rm eff}$. The

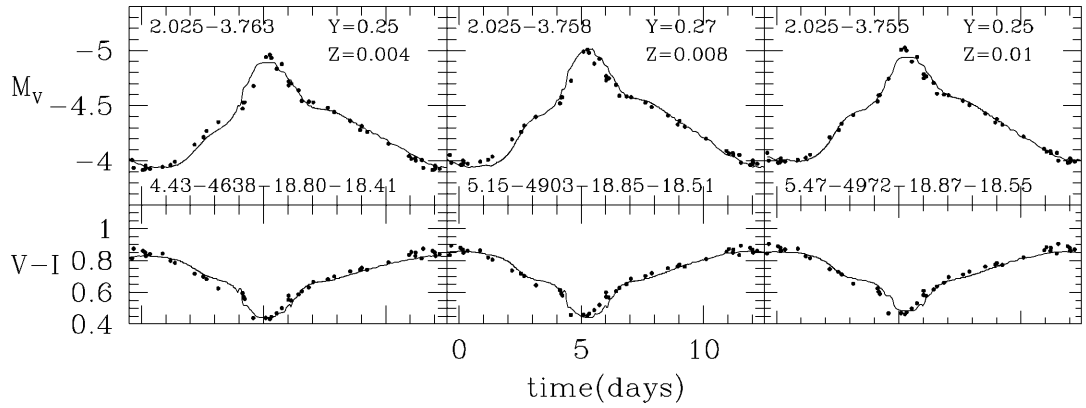

FIG. 2.—Same as Fig. 1, except that abundance varies between the panels as indicated. Each plot shows the best-fit model for that abundance.

kind of analysis carried out here is dependent on modeling stars near the blue edge. Second, varying P_{02} changes the position of the bump on the light curve. Although only five models are shown in Figure 1, light curves were constructed for models with a much wider range of parameters than shown, and the effects of $T_{\rm eff}$ and P_{02} remained the same.

In each panel of Figure 1, the observational V magnitude has been shifted vertically to give the best least-squares fit to the theoretical M_V light curve. The size of the shift gives the apparent visual distance modulus of HV 905. At the same time, the observed $V - I$ color curve has been shifted to match the theoretical curve, the offset required being the reddening E_{V-I}. This was converted to the extinction A_V with $E_{V-I} = 1.3E_{B-V}$ and $A_V = 3.1E_{B-V}$. The visual extinction was then used to derive the true distance modulus to HV 905. The parameters of each model are displayed on the corresponding panel of Figure 1. In this fitting sequence, the only assumed parameter is the abundance: M, L, $T_{\rm eff}$, E_{B-V}, and distance modulus are all derived solely by fitting the shape and amplitude of the light curve.

The model in the central panel of Figure 1 gives the best fit to the observed light curve. Note that the P_{02} value of this model (2.025) does not identically satisfy the resonance condition $P_0/P_2 = 2$. Decreasing P_{02} by 0.0125 from 2.025 causes the bump on the theoretical curve to start too late. Similarly, increasing $T_{\rm eff}$ by 0.002 from the nominal value of 3.757 causes the amplitude of the V light curve to become too small. We take the uncertainty in the parameters of the best model to be half the change between the panels in Figure 1. The errors are dominated by the uncertainty in P_{02} rather than that in $T_{\rm eff}$. For models with helium abundance $Y = 0.25$ and metallicity $Z = 0.008$, the best-fit parameters of HV 905 and their errors are $M = 5.20 \pm 0.2\ M_\odot$, $L = 4897 \pm 140\ L_\odot$, $\log T_{\rm eff} = 3.757 \pm 0.001$, $E_{B-V} = 0.11 \pm 0.005$, and distance modulus $= 18.52 \pm 0.03$.

The one assumed parameter in the above modeling is the abundance. The adopted metallicity $Z = 0.008$ is typical of that for young stars in the LMC (Russell & Bessell 1989), while the adopted helium abundance $Y = 0.25$ is similar to the observed value in LMC H II regions (Dufour 1984). Since Cepheids have undergone first dredge-up, they would be expected to have $Y \approx 0.27$ for masses around 5 $M_\odot$ (Fagotto et al. 1994). In order to see the effect of Y and Z on the model calculations, models were constructed with $Y = 0.27$ and $Z = 0.004$ and 0.01. Although an attempt was made to make models at $Z = 0.016$, it was not possible to create a model with a large enough amplitude. The metal abundance $Z = 0.01$ is near the maximum possible metallicity for HV 905.

The light curves for the best-fit models with $Z = 0.004$, $Z = 0.01$, and $Y = 0.27$ are shown in Figure 2. It is clearly possible to create models that fit the observations well with each of these abundances. As in Figure 1, the model parameters M, L, $T_{\rm eff}$, and distance modulus are shown in the figure. Comparison with Figure 1 shows that changing the helium abundance from $Y = 0.25$ to 0.27 makes very little difference in the model parameters. Varying the metal abundance from $Z = 0.004$ (typical of the SMC) to 0.01 does change parameters by a modest amount.

The results shown in Figures 1 and 2 demonstrate that the models cannot be used to determine the abundance of HV 905. We therefore adopt the values $Y = 0.27$ and $Z = 0.008$ as the best guess for the reasons given above. We also adopt Y and Z ranges based on likely errors in these values. If the abundance of HV 905 is assumed to lie in the range $Z = 0.006$–0.01, then the errors in the derived parameters of HV 905 resulting from uncertainty in the metal abundance are similar to the errors resulting from the uncertainties in P_{02} and $T_{\rm eff}$. If the most appropriate helium abundance is assumed to be $Y = 0.27 \pm 0.02$, then the distance modulus to HV 905 (and the LMC bar) is 18.51 ± 0.05, where the errors due to uncertainty in Y, Z, P_{02}, and $T_{\rm eff}$ have been added in quadrature.

4. DISCUSSION

The fits to the light curve of HV 905 have allowed the determination, to high accuracy, of all the parameters of this bump Cepheid, apart from abundance. Only stellar pulsation and stellar atmosphere theory have been used in the calculations—no stellar evolution theory was used. A complete determination of the star's properties was possible because the nonlinear pulsation calculations provide one extra constraint (essentially the amplitude of pulsation) that linear calculations involving the beat and bump Cepheids do not have available. (The beat Cepheids have two known quantities, P_0 and P_0/P_1, while the condition used for bump Cepheid modeling is that $P_0/P_2 = 2$ when $P_0 \approx 10$ days. With the linear pulsation calculations, it is necessary to adopt one other constraint in order to make models, usually $T_{\rm eff}$ or the M–L relation from stellar evolution theory.)

The reddening and distance modulus derived here are in good agreement with other determinations. Observational estimates of the reddening in the vicinity of HV 905 range

from $E_{B-V} = 0.09$ to 0.18 (Sebo & Wood 1995), consistent with the value 0.11 derived here. Recent determinations of the LMC distance modulus that are not based on Cepheids include the values 18.50 ± 0.13 from SN 1987A (Panagia et al. 1991) and 18.48 ± 0.19 (Alcock et al. 1997) and 18.54 (Simon & Clement 1993) from double-mode and RR*c*-type RR Lyraes, respectively, in the LMC. Once again, these values are consistent with the distance modulus of 18.51 ± 0.05 derived here.

The other important parameters derived for HV 905 are $M = 5.15\ M_\odot$ and $L = 4903\ L_\odot$, with the assumption that $Y = 0.27$. The mass-luminosity ratio implied by these values can be compared with current mass-luminosity relations derived from stellar evolution theory. Taking the luminosity above, stellar evolution calculations without convective overshoot during the main-sequence phase (Alongi et al. 1993) predict an evolution mass of 7.14 $M_\odot$, while evolution calculations with currently favored mild overshoot (Schaerer et al. 1993; Fagotto et al. 1994) predict an evolution mass of 6.38 $M_\odot$. Both these values are higher than the mass derived in this paper. In order to bring the evolution mass into agreement with the mass derived here, the amount of overshoot required in the evolution calculations needs to be roughly double the currently used values. This finding is in agreement with recent results from linear pulsation theory that all find that evolution masses based on current calculations are significantly higher than masses based on pulsation theory (Moskalik et al. 1992; Sebo & Wood 1995; Buchler et al. 1996). It seems that the new opacity calculations have not cured the discrepancy between the evolution and pulsation masses. Whether the cause of the discrepancy lies with evolution or pulsation theory, or both, remains to be determined. However, the calculations in this paper show that current pulsation theory can reproduce the quite complicated light curve of a bump Cepheid, and the theory yields secondary quantities such as reddening and distance modulus that are in good agreement with independent determinations.

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