WHAT "MASSES" FOR CEPHEIDS?

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ABSTRACT

To understand the evolution of giant stars, it is important to pin down the masses for Cepheids. The 7- to 10-day "bump" Cepheids imply lower than evolutionary mass (60%). Recent theoretical work, though, indicates that for Cepheids with periods of 15 to 16 days, the best understanding of the light curves results from using evolutionary masses.

I. INTRODUCTION

To test the theories of evolution in the yellow giant region of the Hertzsprung-Russell diagram, it is important to pin down the masses of Cepheids. The question of mass loss arises in attempts (Christy 1965; Tayler 1970; and Davis 1977) to explain the discrepancy between the "bump" Cepheid masses and evolutionary masses. We will discuss the present status of Cepheid masses utilizing results from a new dynamic zoning hydrodynamic nonlinear pulsation code. This new technique produces improved light curves that can be compared directly to the observations. Because of computational problems, previous investigators calculated velocity curves and compared these results to the observed light curves, the Hertzsprung sequence. We should note that the light curve is not a mirror image of the velocity curve. This study utilizes models for 7-, 10-, and 16-day Cepheids with masses ranging from the evolutionary masses to 60% of the evolutionary masses. The comparison Cepheids are η Aquilae (7.15 days), β Doradus (9.8 days) or S. Normae (9.75 days), and X Cygni (16.4 days). In Sec. II we discuss Cepheid masses; in Sec. III, the models, and in Sec. IV, our conclusions.

II. CEPHEID MASSES

In Bamberg (Davis 1977), we discussed the various mass discrepancies between pulsation theory masses and evolutionary theory masses for Cepheids. Since then, with the new distance scale for the Hyades (Iben and Tuggle 1972; and Hanson 1977), with the improved reddening corrections of Pel (1978) and Dean, Warren, and Cousins (1978), linear pulsation theory (L, T_{eff} and $\pi \cdot \sqrt{\rho}$) now gives the evolutionary masses for Cepheids. Some questions can still be raised about evolutionary

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theory and the processes of semi-convection, imposed magnetic fields, and the occurrence and physics of the blue loop. As yet, no evolutionary tracks for Cepheids with pulsation included have been done. To study the "bump" Cepheid masses in more detail, we have developed a nonlinear pulsation code that resolves the light curve in deference to those calculations made by Christy, Stobbie, and others. In their method only the velocity curve could be resolved and the velocity "bumps" related to those observed on the light curves. The present method relies on a non-Lagrangian formulation of the hydrodynamic equations coupled with the equations of radiative diffusion. The hydrogen ionization region, which moves very rapidly in mass during this period, is continuously rezoned using as fine a zoning as necessary to resolve the light curve. This method is completely implicit.

III. THE CEPHEID MODELS STUDIED

Our initial study centered around the so-called Goddard model of a 10-day Cepheid ($L = 3187\ L_\odot$, $T_{eff} = 5700°K$, $M = 4.0\ M_\odot$), which is the most detailed nonlinear intercomparison on record. Our results using DYN (Castor, Davis and Davison 1977) are displayed in Fig. 1 for luminosity versus phase for the Goddard model, 5, 6, and 7.4 solar masses. Table I lists the important parameters for these models and the 7-day models that will be discussed later. A comparison of these ∿ 10-day models to the observations of S. Normae (9.75 days) (Davis and Davison 1978), shows that the mass must be reduced to some 60% of the evolutionary mass to get good agreement (Fig. 2).

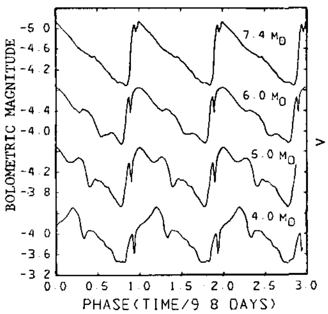

Figure 1. M_{bol} Vs Phase.

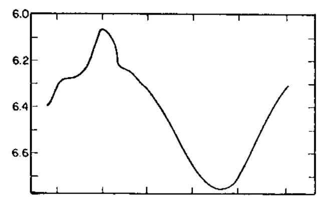

Figure 2. V Vs Phase S. Normae.

TABLE I

MODEL PARAMETERS

Model Number	Period (days)	Mass ($M_\odot$)	Luminosity ($L_\odot$)	Effective Temp. (K)	M_{evol}* ($M_\odot$)	M/M_{evol}*
6A	7.52	6.70	3587	5700	6.70	1.00
6B	7.55	4.00	2404	5717	5.97	0.67
6C	7.56	3.40	2105	5717	5.75	0.59
5A	9.78	7.40	5210	5682	7.46	0.99
4A	9.79	6.00	4421	5687	7.11	0.84
3A	9.78	5.00	3849	5690	6.84	0.73
1B†	9.79	4.00	3187	5700	6.48	0.62

*$\log (L/L_\odot) = 3.48 \log (M_{evol}/M_\odot) + 0.68$.

†The "Goddard model".

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A similar study for 7.5-day Cepheids is shown in Fig. 3. In Fig. 4 we indicate how the calculated velocity differs from the calculated luminosity. A dip occurs in the light curve when a "bump" occurs on the velocity curve. In comparison to the Cepheid η Aquilae (7.15 days) in Fig. 5, the mass must be reduced to some 60% of the evolutionary mass to gain agreement. These results therefore are in agreement with Christy, Stobbie, and Fadeyev (1979). They support Christy's conclusion that results in the so-called mass discrepancy.

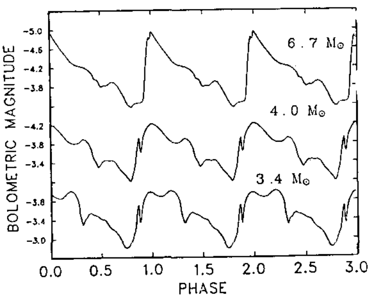

Figure 3. M_{bol} Vs Phase.

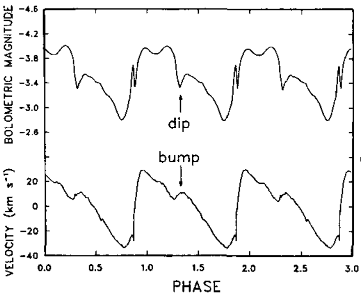

Figure 4. Vel & M_{bol} Vs Phase.

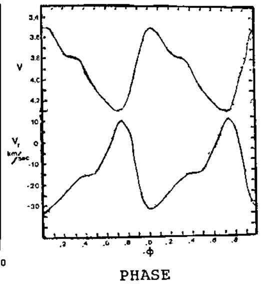

Figure 5. V & Vel Vs Phase η Aquilae.

Our final study was done in conjunction with an experimental observation of T. Barnes and T. Moffett on the 16.4-day Cepheid X Cygni (Davis, Barnes, and Moffett 1980). The models of X Cygni were developed like those described above for the 7- and 10-day Cepheids. The parameters are listed in Table II. The effective temperature in this case, though, was held at 5300°K, based on Pel's observations. The red edge of the instability strip is estimated to be near 5100°K in this region of the Hertzsprung-Russell diagram (Pel 1978).

Table II:

$M/M_\odot$	$\log (L/L_\odot)$
6	3.785
8	3.890
9	3.932

The results for the model that agrees best with the observations is shown in Fig. 6. To avoid "bumps" on the light curve, the mass in these models is near the evolutionary mass, i.e., 9 $M_\odot$. The dip in the model light curve is related to the occurrence of the increase in optical depth as a compression wave transits the atmosphere at a phase near 0.85. The compression or shock front is treated by using the method of pseudo-viscosity; therefore a question arises as to the artificial nature of the shock treatment. The phase of the calculated dip agrees with the Barnes and Moffett observations (0.85) in Fig. 7, and with an increase in the H_α velocity as observed by Abt.

IV. CONCLUSIONS

At present, nonlinear pulsation theory gives us an ambiguous estimate for the masses of Cepheids. The theory predicts that for stars

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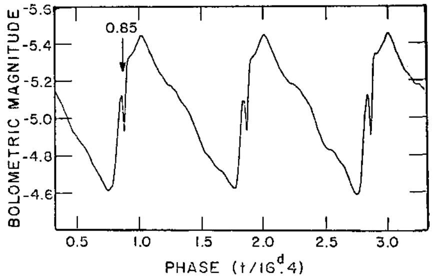

Figure 6. M_{bol} Vs Phase.

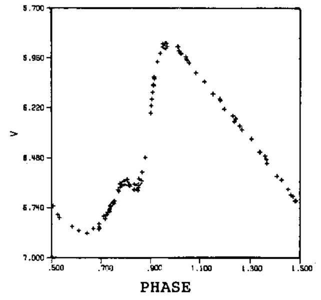

Figure 7. V Vs Phase X Cygni.

pulsating in their fundamental radial mode, the mass must be reduced to 60% of the evolutionary mass in the period range from 7 to 10 days. For 16-day Cepheids, X Cygni, in particular, it is necessary to have nearly the evolutionary mass (9 $M_\odot$) in order to obtain light curves where no "bumps" are observed.

Either nonlinear pulsation theory is wrong, for 7- to 10-day Cepheids, or mass loss and/or changes in evolutionary theory must be invoked. It is possible that changes in the stars' surface structure, say, from Helium enhancement (Cox et al. 1977) or tangled magnetic fields (Stothers 1979), could explain the discrepancy.

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