The Bump Cepheid Mass Discrepancy Laid to Rest (?)

P. Moskalik[1] and J. R. Buchler[2],

[1]*Copernicus Astronomical Center, Warsaw, Poland,* [2]*University of Florida, Gainesville, USA*

1. New Opacities

The beat and bump mass discrepancies have been a long standing, unsolved difficulty in the Cepheid modelling (Cox 1980). The new opacities of Rogers & Iglesias (1992) has provided a partial solution to the problem, bringing the beat masses into good agreement with other mass determinations (Moskalik, Buchler & Marom 1992; herafter MBM). The discrepancy for the bump masses has also been greatly reduced, nevertheless it has not been eliminated entirely.

Recently, the new version of the Livermore tables has been released (Iglesias, Rogers & Wilson 1992). The new calculations take into account previously disregarded spin-orbit coupling in the iron atoms. The inclusion of this effect leeds to a further enhancement of the "metal opacity bump" around 2-5$\times 10^5$K. In the following we repeat the calculations of MBM to assess the consequences of this enhancement for the bump mass calibration.

2. New Bump Masses

The Cepheid bump progression has its origin in a 2:1 resonance between the fundamental mode and the second overtone (Simon & Schmidt 1976; Buchler, Moskalik & Kovács 1990). The requirement of placing the center of the progression at $10^d(\pm 0\overset{d}{.}5)$ is equivalent to the requirement of placing the resonance at this period. Thus, the bump mass problem can be studied with the linear models alone.

Following MBM we start from determining the luminosity of a 10^d Cepheid. Averaging four independent $P-L$ relations (Caldwell & Coulson 1987; Gieren 1988; Walker 1988; Fernie 1992) we obtain $M_V = -4\overset{m}{.}11$. The largest difference between this value and a prediction of any particular $P-L$ relation (at 10^d) is $0\overset{m}{.}04$, but we feel that $0\overset{m}{.}10$ is a more realistic error estimation. Adopting the bolometric correction scale of Gieren (1989) we find $L = 3800L_\odot \pm 10\%$. Next, we construct the period ratio diagram (Petersen diagram) of P_2/P_0 *vs.* P_0 for models with $L = 3800L_\odot$ and with different masses. From that diagram we find that the resonance condition ($P_2/P_0 = 0.5$ at 10^d) is satisfied for $M = 5.90 \pm 0.15 M_\odot$ if Z = 0.02 is assumed, or for $M = 6.65 \pm 0.15 M_\odot$ if Z = 0.03 is assumed (quoted errors correspond to the adopted error in luminosity). These are our new bump masses.

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3. Baade-Wesselink Masses

Gieren's (1989) average Baade-Wesselink mass of a 10^d Cepheid is $6.52 \pm 0.9 M_\odot$. This value, however, was obtained using the period-radius-mass relation derived with the older Los Alamos opacities. The models constructed with the new opacities have slightly longer periods, and the resulting $P-R-M$ relation (for Z = 0.02) is

$$P_0 = 0.026(M/M_\odot)^{-0.68}(R/R_\odot)^{1.70} \tag{1}$$

Repeating Gieren's (1989) procedure with Eq. (1) we find the average trend of the Baade-Wesselink masses with period, which for a 10^d Cepheid gives $M = 6.81 \pm 0.9 M_\odot$. The same excercise repeated for Z = 0.03 (slightly different P–R–M relation) leads to $M = 6.92 \pm 0.9 M_\odot$.

4. Conclusions

Our results are summarized in the table below, where we also present the evolutionary masses inferred from the standard $M-L$ relation of Becker, Iben & Tuggle (1977). The new bump masses *do agree* within the error bars with the Baade-Wesselink masses for both Z = 0.02 and for Z = 0.03, with a better agreement for higher Z. There is still a disagreement, however, between the bump and the evolutionary masses. The increase of metallicity does not help here, because the evolutionary masses also grow quickly with Z. This discrepancy can be reduced, though, by placing the resonance at a longer period, as shown in the last row of the table.

	metallicity	$M_{bump}/M_\odot$	$M_{BW}/M_\odot$	$M_{EV}/M_\odot$
$P_{rez} = 10^d_.0$	Z = 0.02	5.90 ± 0.15	6.81 ± 0.9	7.04
	Z = 0.03	6.65	6.92	8.20
$P_{rez} = 10^d_.5$	Z = 0.02	6.21	6.94	7.15

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Discussion

Simon: 1) Evolutionary tracks with OPAL have been done by Stothers & Chin and they find little difference from standard tracks. 2) Using Baade-Wesselink masses is very tricky; they are notoriously uncertain.

Moskalik: I agree that Baade-Wesselink masses usually have large errors. However, they are the closest to the "observational" masses we can get, depending only on the rather well established pulsational $P-R-M$ relation. The evolutionary masses have small formal errors, but they heavily depend on the theoretical $M-L$ relation. Comparing bump masses with evolutionary masses we compare one theory with another. In my mind, the comparison with the Baade-Wesselink masses, which are based primarily on observed quantities, is more fundamental.

Sreenivasan: How can you be certain that there has been no mass loss and that in fact no discrepancy exists between evolutionary masses and pulsation masses (mass loss produces overluminous stars for their mass as compared to conservative mass evolution) ?

Moskalik: I cannot be certain, this is why I prefer the comparison with Baade-Wesselink masses. Another uncertainity in the evolutionary models is the precise amount of convective overshooting. Our bump masses are already higher than the full-overshooting evolutionary masses of Chiosi.

Cox: Do you use convection in your models ? Poster 72 shows that convection in deep layer changes the structure and gives bump masses about $7M_{\odot}$.

Moskalik: Our models are purely radiative.

Percy: Although you and other theorists construct models with $Z=0.02$ and $Z=0.03$, those who measure abundances of Pop. I objects prefer $Z=0.02$ (actually $Z=0.016-0.020$).

Moskalik: Well, theorists will do anything to make their models pulsate right. Seriously, I think, that it tells us that the true metal opacities are still a little bit higher.

Pel: In relation to the high Z-sensitivity of your bump masses, it would be important to compare the Hertzsprung progression for Galactic and Magellanic Cloud Cepheids. It is known that the "resonance period" of the Hertzsprung progression of Cloud Cepheids has a slightly different value with the respect to the Galactic Cepheids. This way you could make a nice differential check on the Z-dependence of your bump masses.

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