SOME MASSES FOR POPULATION I AND II CEPHEIDS

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The masses of Cepheids can be obtained in several ways. If a Cepheid luminosity is known from membership in a galactic cluster, the mass-luminosity relation obtained from stellar evolution theory gives its mass. This evolution mass depends slightly on the composition, that is, the mass fraction of helium, Y, and on the the mass fraction of all the heavier elements, Z, but as we shall see later, the composition dependence is small.

A mass of a Cepheid that is based entirely on pulsation theory is called the pulsation mass. Here the needed observations are: the luminosity, the color (giving a surface effective temperature by use of a conversion formula), and the easily observed pulsation period. In this report the observed period is assumed to always be the fundamental mode for the classical Cepheids. The mass, M, the pulsation constant, Q, and the radius, R, are unknowns that are solved for using the three equations

$$L = 4\pi R^2 \sigma T_e^{\,4} \quad , \quad Q = P(M/R^3)^{1/2} \quad , \text{ and } Q = Q(M,R,L,T_e) \quad .$$

These equations are: the definition of the effective temperature, the period-mean density relation, and an expression fitting the pulsation theory values for the pulsation constant Q obtained from a large number of models covering a large range of stellar parameters.

A third mass can be derived based on both evolution and pulsation theories. The required observations are only the well determined period and a surface effective temperature. The above three equations, plus the evolution mass-luminosity relation, are used to simultaneously solve for the unknowns M, R, L, and Q. Due to the strong influence of the evolution theory mass-luminosity relation for the theoretical mass, this mass agrees to within a few % with the evolution mass for almost all Cepheids. The major value of the theoretical mass is its availability when a luminosity has not been observed, and one cannot get an evolution mass.

These three masses have been calculated for 29 Cepheids recently listed by Fernie and McGonegal (1983). The luminosities of these Cepheids have been uniformly set by assuming a distance modulus of 3.29 for the Hyades cluster. Table 1 gives our evolution, theoretical, and pulsation masses. Fernie and McGonegal have suggested that CS Vel and V810 Cen are not in the cluster as supposed, and therefore their luminosities are incorrectly stated. Due to the large discrepancy between the evolution and pulsation masses for V Cen, GY Sge, and S Vul, we have rejected them also. We find only a small difference between the masses for TW Nor, and therefore we do not reject this Cepheid even though there is a cluster membership question about it. The ratios of these masses relative to the theoretical masses average to the values at the bottom of the evolution and pulsation mass columns. The usual scatter in the pulsation masses is present, but on the average, the masses seem in accord with evolution theory.

Table 2 gives similar results with only the distance scale to the Hyades changed to 3.45, a value recently suggested by Vandenberg and Bridges (1984). With the increased luminosities, evolution masses increase a bit, while the luminosity-independent theoretical masses remain unchanged. However, pulsation masses are greatly increased so that the average is about 1.22 above the theoretical masses. For both these tables we have converted the dereddened (B-V) colors to effective temperatures by use of the Kraft (1961) formula. As discussed by Cox (1979) and many others such as Pel (1978) these temperatures may need to be cooled by 0.01 to 0.03 in log T_e. That would greatly alleviate the mass discrepancy. It appears that a distance scale which has the Hydade distance modulus at 3.45 is too large, but part of the change from the currently used 3.29 may be acceptable from the viewpoint of Cepheid masses.

Other recent data on Cepheid luminosities have been prepared for publication by Schmidt (1984). Table 3 shows at the top section the evolution, theoretical, and pulsation masses for 7 Cepheids using his luminosities and dereddened colors. The pulsation masses are so low that for conventional compositions, stars would not evolve into the instability strip. The possible cooling of the temperature scale is investigated in the second section. Even though we have reduced the log

Table 1

Fernie and McGonegal Data
$(m-M)_{Hyades}=3.29$

Cepheid	P(d)	T_e(K)	$L/L_\odot$	M_{ev}	M_{th}	M_Q
SU CAS	1.95	6288	791	4.6	4.6	4.8
EV SCT	3.09	6212	1176	5.1	5.4	4.1
CE CAS B	4.48	6086	2447	6.3	6.2	6.6
CF CAS	4.86	5848	2276	6.1	6.0	6.5
CE CAS A	5.14	5896	2673	6.4	6.3	7.1
UY PER	5.37	5848	2568	6.3	6.3	6.5
CV MON	5.38	6113	2676	6.4	6.7	5.4
V CEN	5.50	6138	2061	6.0	6.6	3.7
VY PER	5.53	5895	3690	7.0	6.4	9.6
CS VEL	5.90	5991	828	4.7	6.8	1.3
V367 SCT	6.30	6138	3484	6.9	7.2	5.9
U SGR	6.75	5801	3566	6.9	6.8	7.3
DL CAS	8.00	5824	3723	7.0	7.4	5.8
S NOR	9.75	5685	4233	7.3	7.7	5.8
TW NOR	10.79	5594	4444	7.4	7.9	5.6
VX PER	10.89	5731	5012	7.6	8.2	5.8
SZ CAS	13.61	5872	8400	8.7	9.2	7.2
VY CAR	18.92	5309	11369	9.5	9.1	10.9
RU SCT	19.66	5685	15067	10.2	10.2	10.4
RZ VEL	20.42	5549	14532	10.1	10.0	10.6
WZ SGR	21.83	5266	8000	8.6	9.6	6.0
SW VEL	23.44	5549	14532	10.1	10.6	8.7
T MON	27.04	5181	17763	10.7	10.1	13.3
KQ SCO	28.71	5058	19950	11.1	10.1	15.8
RS PUP	41.40	5224	28161	12.1	12.1	12.1
SV VUL	44.98	5099	33526	12.7	12.1	15.3
GY SGE	51.05	4898	41139	13.5	12.0	20.7
S VUL	67.61	4819	71024	15.6	13.1	32.4
V810 CEN	130.32	6068	154420	19.3	23.1	10.4
				.993		.999
				±.052		±.247

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T_e by only 0.01, it is apparent that more than three times this amount is needed to reconcile Schmidt's low pulsation masses. With the use of the Becker, Iben and Tuggle (1977) fits for the second crossing luminosities as a function of composition and mass, we give the lower two sections for, respectively, higher Y and lower Z. These extreme composition changes for population I Cepheids do not lower the evolution masses enough to match the Schmidt pulsation masses. We feel that his luminosities are very much too low.

Anomalous Cepheids have periods like RR Lyrae variables, but they are typically 5 times more luminous. Zinn and King (1982) have proposed that variable V19 in NGC 5466 at 0.82 day is pulsating in the first radial overtone mode, but even with that mode, its mass is about 1.4 $M_\odot$. This is surprising for a population II star because it is believed that stars

Table 2

Fernie and McGonegal Data
$(m-M)_{Hyades}=3.45$

Cepheid	P(d)	T_e(K)	$L/L_\odot$	M_{ev}	M_{th}	M_Q
SU CAS	1.95	6288	917	4.6	4.6	5.9
EV SCT	3.09	6212	1362	5.3	5.4	4.9
CE CAS B	4.48	6088	2836	6.5	6.2	8.1
CF CAS	4.88	5848	2640	6.4	6.0	7.9
CE CAS A	5.14	5895	3097	6.7	6.3	8.7
UY PER	5.37	5848	2976	6.6	6.3	8.0
CV MON	5.38	6113	3100	6.7	6.7	6.6
V CEN	5.50	6138	2389	6.2	6.8	4.4
VY PER	5.53	5895	4276	7.3	6.4	12.2
CS VEL	5.90	5991	959	4.6	6.8	1.5
V367 SCT	6.30	6138	4038	7.2	7.2	7.1
U SGR	6.75	5801	4132	7.2	6.8	9.0
DL CAS	8.00	5824	4314	7.3	7.4	7.0
S NOR	9.75	5685	4905	7.6	7.7	7.0
TW NOR	10.79	5594	5149	7.7	7.9	6.9
VX PER	10.89	5731	5808	7.9	8.2	7.0
SZ CAS	13.61	5872	9734	9.1	9.2	8.7
VY CAR	18.92	5309	13198	9.9	9.1	13.3
RU SCT	19.68	5665	17462	10.7	10.2	12.7
RZ VEL	20.42	5549	16839	10.6	10.0	12.9
WZ SGR	21.83	5266	9270	9.0	9.6	7.2
SW VEL	23.44	5549	16839	10.6	10.6	10.5
T MON	27.04	5161	20583	11.2	10.1	16.3
KQ SCO	28.71	5058	23118	11.5	10.1	19.5
RS PUP	41.40	5224	32632	12.6	12.1	14.7
SV VUL	44.98	5099	38849	13.3	12.1	18.6
GY SGE	51.05	4898	47671	14.0	12.0	25.6
S VUL	67.61	4819	82302	16.2	13.1	42.7
V810 CEN	130.32	6088	178939	20.1	23.1	12.3
				1.036		1.216
				±.054		±.312

Table 3

Schmidt Photometry and Kraft Temperatures

Cepheid	P(d)	T_e(K)	$L/L_\odot$	M_{ev}	M_{th}	M_Q
		Y=0.28 Z=0.02				
EV SCT	3.09	6364	1176	5.1	5.6	3.6
CF CAS	4.88	5685	997	4.9	5.8	2.6
CV MON	5.38	5824	1352	5.3	6.3	2.9
U SGR	6.75	5943	2682	6.4	7.1	4.5
DL CAS	8.00	5848	3233	6.7	7.4	4.8
S NOR	9.75	5572	2786	6.5	7.5	3.8
TW NOR	10.79	5395	1568	5.5	7.5	2.0
		T_e cooler by 0.01 in $\log T_e$				
		Y=0.28 Z=0.02				
EV SCT	3.09	6219	1176	5.1	5.4	4.0
CF CAS	4.88	5556	997	4.9	5.6	2.9
CV MON	5.38	5692	1352	5.3	6.1	3.3
U SGR	6.75	5806	2682	6.4	6.8	5.0
DL CAS	8.00	5715	3233	6.7	7.2	5.4
S NOR	9.75	5445	2786	6.5	7.3	4.3
TW NOR	10.79	5272	1568	5.5	7.2	2.2
		Y=0.35 Z=0.02				
EV SCT	3.09	6364	1176	4.3	4.6	3.6
CF CAS	4.88	5685	997	4.1	4.7	2.6
CV MON	5.38	5824	1352	4.5	5.1	2.9
U SGR	6.75	5943	2682	5.5	5.9	4.5
DL CAS	8.00	5848	3233	5.8	6.2	4.8
S NOR	9.75	5572	2786	5.6	6.3	3.8
TW NOR	10.79	5395	1568	4.7	6.2	2.0
		Y=0.28 Z=0.01				
EV SCT	3.09	6364	1176	4.3	4.5	3.6
CF CAS	4.88	5685	997	4.1	4.7	2.6
CV MON	5.38	5824	1352	4.5	5.1	2.9
U SGR	6.75	5943	2682	5.5	5.8	4.5
DL CAS	8.00	5848	3233	5.8	6.1	4.8
S NOR	9.75	5572	2786	5.5	6.2	3.8
TW NOR	10.79	5395	1568	4.7	6.2	2.0

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more massive than about 0.8 $M_\odot$ should have long ago died. We here confirm the proposal that this star is the result of a coalescence of two stars in a binary system that had an initial separation smaller than the red giant radius of the more massive star.

Figure 1 gives the work done in each of the 195 zones over each pulsation cycle to cause pulsations in each of the three lowest radial modes. The mass used for this nonadiabatic pulsation analysis is 1.4 $M_\odot$, and the luminosity is the observed 257 suns. The typical population II composition used is the King Ia table with Z=0.001. Here at 7500K, hotter than NGC 5466 V19, all modes are stable because the radiative damping of the interior (lower zone number) layers is greater than the hydrogen and helium driving in the surface layers.

Figure 2 gives the same plot for the effective temperature of 6500K. In this case it is apparent that the first and second overtone modes are driven more than they are damped, and linear theory predicts growing pulsations. Actually the first overtone is driven the strongest, and at the observed effective temperature of 7000K, probably only the first overtone is unstable to pulsations.

Fig. 1. The work per pulsation cycle to drive pulsations in a NGC 5466 V19 model at 7500K is plotted for each of the 195 zones.

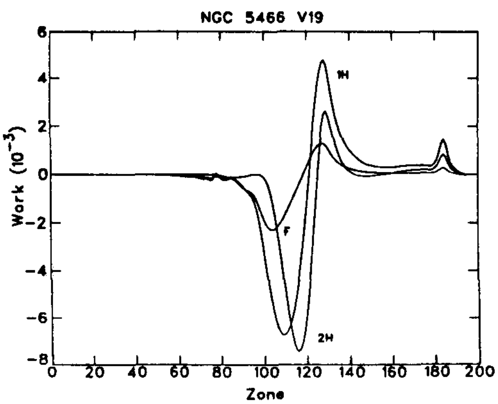
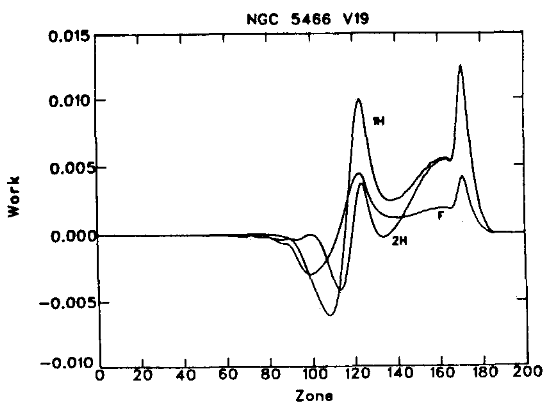


Fig. 2. The work per pulsation cycle to drive pulsations in a NGC 5466 V19 model at 6500K is plotted for each of the 195 zones.



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