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Scanner Observations of the Classical Cepheids RT Aur and T Vul

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Abstract. The effective temperatures of the classical Cepheids RT Aur and T Vul have been determined by a comparison of their spectral scans with appropriate model atmospheres. The radii of the stars have been determined through the Wesselink method. Using these temperatures and the Wesselink radii, the luminosities of the stars have been determined. These radii estimates, including the radii of SU Cas (Joshi & Rautela 1980) and ζ Gem (unpublished) fit better in the theoretical period–radius relationship given by Cogan (1978), as compared to earlier determinations of Wesselink radii. The pulsation masses and evolutionary masses of the stars have been calculated. The pulsation to evolutionary mass ratio is derived to be 0.85.

Based on the effective temperatures obtained by us at different phases of the stars a $\theta_e - (B-V)_0$ relationship is found of the form,

$$\theta_e = 0.274\ (B-V)_0 + 0.637$$
$$\quad \pm 0.011 \qquad\qquad \pm 0.007$$

Key words: classical Cepheids—effective temperatures—mass discrepancy

1. Introduction

In two earlier papers (Rautela & Joshi 1976 and Joshi & Rautela 1980) we have given the effective temperatures for the Cepheids ζ Gem and SU Cas at several phases determined from scanner observations of these stars. In this paper we have determined similarly the effective temperatures for two more Cepheids namely RT Aur and T Vul at several phases of their light cycles. The radii of the stars have been determined by using the Wesselink method. Using the effective temperatures and radii thus determined, the luminosities, Wesselink-radii masses and evolutionary-theory masses for the stars have been estimated.

Table 1. Blanketing- and reddening-corrected magnitudes (i) along with the blanketing (ii) and reddening (iii) corrections for RT Aur at various phases.

	Phase	0.030		0.228		0.350		0.426		0.458	
λ (nm)	$1/\lambda$ (μm)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)
339.0	2.95	...	...	6.46	0.42	...	...	6.75	0.53	6.89	0.53
344.8	2.90	...	...	6.45	0.43	...	...	6.65	0.54	6.88	0.54
350.9	2.85	5.68	0.43	6.43	0.45	6.46	0.49	6.62	0.55	6.82	0.55
363.6	2.75	5.59	0.46	6.36	0.49	6.42	0.55	6.52	0.64	6.76	0.64
370.4	2.70	5.60	0.48	6.27	0.51	6.34	0.57	6.62	0.66	6.85	0.66
403.6	2.48	5.05	0.36	5.56	0.38	5.63	0.43	5.80	0.49	5.85	0.49
416.7	2.40	5.04	0.38	5.53	0.40	5.60	0.45	5.77	0.52	5.79	0.52
425.5	2.35	5.03	0.34	5.52	0.36	5.59	0.40	5.75	0.46	5.79	0.46
446.4	2.24	5.04	0.30	5.47	0.32	5.54	0.38	5.69	0.45	5.74	0.45
456.6	2.19	5.02	0.25	5.48	0.27	5.52	0.31	5.68	0.37	5.70	0.37
478.5	2.09	5.03	0.12	5.45	0.13	5.48	0.15	5.62	0.19	5.66	0.19
500.0	2.00	5.03	0.18	5.44	0.19	5.45	0.22	5.58	0.25	5.63	0.25
526.3	1.90	5.02	0.20	5.42	0.21	5.44	0.23	5.54	0.25	5.60	0.25
555.6	1.80	5.02	0.10	5.35	0.11	5.42	0.12	5.53	0.13	5.55	0.13
584.0	1.71	5.01	0.04	5.34	0.04	5.36	0.05	5.48	0.05	5.51	0.05
605.5	1.65	5.01	0.04	5.33	0.05	5.36	0.05	5.45	0.06	5.48	0.06
643.5	1.55	4.99	0.06	5.32	0.06	5.35	0.06	5.41	0.07	5.48	0.07
679.0	1.47	4.99	0.04	5.31	0.04	5.33	0.04	5.38	0.05	5.41	0.05
710.0	1.41	4.99	0.04	5.31	0.04	5.34	0.05	5.36	0.05	5.43	0.05

2. Observations

Spectrophotometric observations of RT Aur and T Vul have been obtained during 1976–79 on the 52-cm and 104-cm reflectors of Uttar Pradesh State Observatory. The instrumental set-up was the same throughout as has been described in an earlier paper (Rautela & Joshi 1976). The observations have been obtained using a bandwidth of 5 nm in the wavelength region 339–710 nm at nineteen selected 'line-free' wavelengths suggested by Oke (1965). α Lyr, ξ^2 Cet and η UMa were observed as standard stars. The observations, after being corrected for atmospheric extinction, were converted to absolute fluxes with the help of standard stars observed each night. These absolute values conform to the calibration of α Lyr as given by Hayes & Latham (1975).

The observation for different nights were grouped together according to the phases of the respective star. The phases have been calculated with the help of the following ephemerides (Kukarkin *et al.* 1969),

$$\text{Phase (RT Aur)} = \frac{\text{JD} - 2420957.466}{3.728261} \tag{1}$$

and

$$\text{Phase (T Vul)} = \frac{\text{JD} - 2437939.60}{4.435578} \tag{2}$$

The observations have been corrected for interstellar reddening. The colour excesses for this purpose have been taken from Dean, Warren & Cousins (1978), who give $E\,(B-V) = 0.06$ for RT Aur and $E\,(B-V) = 0.07$ for T Vul.

0.496		0.686		0.850		0.896		0.921		0.990		
(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(iii)
6.82	0.53	6.98	0.59	...	...	6.52	0.42	6.47	0.42	...	...	0.30
6.78	0.54	6.91	0.59	...	...	6.44	0.43	6.47	0.43	...	...	0.29
6.87	0.55	6.94	0.60	6.67	0.49	6.39	0.45	6.47	0.45	6.21	0.43	0.29
6.69	0.64	6.81	0.69	6.51	0.55	6.24	0.49	6.22	0.49	5.77	0.46	0.28
6.86	0.66	6.98	0.71	6.31	0.57	6.17	0.51	6.18	0.51	5.53	0.48	0.27
5.88	0.49	6.08	0.57	5.69	0.43	5.34	0.38	5.26	0.38	5.04	0.36	0.26
5.86	0.52	6.02	0.60	5.66	0.45	5.33	0.40	5.24	0.40	5.03	0.38	0.25
5.83	0.46	5.99	0.55	5.65	0.40	5.33	0.36	5.25	0.36	5.03	0.34	0.25
5.81	0.45	5.93	0.49	5.61	0.38	5.31	0.32	5.24	0.32	5.02	0.30	0.24
5.77	0.37	5.90	0.41	5.61	0.31	5.30	0.27	5.23	0.27	5.03	0.25	0.23
5.74	0.19	5.89	0.22	5.58	0.15	5.28	0.13	5.22	0.13	5.03	0.12	0.22
5.68	0.25	5.82	0.26	5.56	0.22	5.28	0.19	5.21	0.19	4.99	0.18	0.20
5.66	0.25	5.77	0.26	5.54	0.23	5.27	0.21	5.20	0.21	5.02	0.20	0.19
5.60	0.13	5.71	0.13	5.50	0.12	5.28	0.11	5.20	0.11	5.02	0.10	0.18
5.57	0.05	5.80	0.05	5.47	0.05	5.25	0.04	5.19	0.04	5.01	0.04	0.17
5.54	0.06	5.67	0.06	...	...	5.24	0.05	5.18	0.05	...	...	0.16
5.53	0.07	5.60	0.07	...	...	5.24	0.06	5.19	0.06	...	...	0.15
5.53	0.05	5.58	0.05	...	...	5.25	0.04	5.18	0.04	...	...	0.14
5.54	0.05	5.58	0.05	...	...	5.26	0.04	5.18	0.04	...	...	0.13

With the help of the reddening law given by Whitford (1958) and using $A_v = 3E(B-V)$, the reddening corrections for each observed wavelength have been determined.

The energy distribution curves for the stars were then corrected for line-blanketing effect. The line-blanketing corrections for both the stars have been taken from Ardeberg & Virdefors (1975) where we have assumed the stars to be of luminosity Class I. The spectral types at intermediate phases of these stars have been assessed by interpolation between the spectral types given for the respective maximum and minimum of these stars. The reddening- and blanketing-free magnitudes of RT Aur and T Vul along with the respective reddening and blanketing corrections are listed in Tables 1 and 2 respectively.

The standard deviation of an individual measurement does not exceed ± 0.03 mag shortward of wavelength 370.4 nm and ± 0.02 mag above wavelength 403.6 nm.

3. Effective temperature

The absolute energy distribution curves of RT Aur and T Vul corrected for interstellar extinction and line blanketing as described in previous section were then compared with model stellar atmospheres computed by Parsons (1969). The procedure for the determination of effective temperatures has been described in an earlier paper (Rautela & Joshi 1976).

For RT Aur and T Vul we have used models of Parsons (1969) with $\log g = 1.8$. This value of $\log g$ adopted for these stars is based on Parsons (1971) and Parsons & Bouw (1971). The temperatures thus obtained are listed in Table 3 and are plotted in Figs 1(a) and 2(a). The effective temperature of RT Aur during a pulsation cycle varies

Table 2. Blanketing- and reddening-corrected magnitudes (i) along with the blanketing (ii) and reddening (iii) corrections for T Vul at various phases.

λ (nm)	$1/\lambda$ $(\mu m)^{-1}$	Phase 0.036 (i)	(ii)	0.120 (i)	(ii)	0.262 (i)	(ii)	0.305 (i)	(ii)	0.470 (i)	(ii)
339.0	2.95	6.28	0.39	6.38	0.42	6.43	0.46	6.49	0.46	...	...
344.8	2.90	6.30	0.40	6.36	0.43	6.48	0.47	6.49	0.47	...	...
350.9	2.85	6.40	0.41	6.47	0.45	6.47	0.49	6.50	0.49	6.73	0.60
363.6	2.75	6.28	0.44	6.35	0.49	6.45	0.55	6.50	0.55	6.65	0.69
370.4	2.70	6.28	0.46	6.37	0.51	6.46	0.57	6.55	0.57	6.72	0.71
403.6	2.48	5.55	0.34	5.64	0.38	5.90	0.43	6.04	0.43	6.23	0.57
416.7	2.40	5.52	0.36	5.65	0.40	5.92	0.45	5.97	0.45	6.20	0.60
425.5	2.35	5.52	0.32	5.63	0.36	5.91	0.40	6.00	0.40	6.14	0.55
446.4	2.24	5.50	0.28	5.61	0.32	5.88	0.38	5.92	0.38	6.10	0.49
456.6	2.19	5.51	0.23	5.62	0.27	5.87	0.31	5.93	0.31	6.09	0.41
478.5	2.09	5.49	0.11	5.59	0.13	5.81	0.15	5.90	0.15	6.04	0.22
500.0	2.00	5.47	0.17	5.56	0.19	5.81	0.22	5.89	0.22	6.03	0.26
526.3	1.90	5.47	0.19	5.55	0.21	5.81	0.23	5.84	0.23	5.96	0.26
555.6	1.80	5.45	0.10	5.54	0.11	5.75	0.12	5.88	0.12	5.94	0.13
584.0	1.71	5.44	0.04	5.52	0.04	5.72	0.05	5.80	0.05	5.90	0.05
605.5	1.65	5.43	0.04	5.52	0.05	5.71	0.05	5.76	0.05	5.84	0.06
643.5	1.55	5.42	0.06	5.50	0.06	5.68	0.06	5.74	0.06	5.83	0.07
679.0	1.47	5.43	0.03	5.51	0.04	5.67	0.04	5.73	0.04	5.79	0.05
710.0	1.41	5.44	0.04	5.49	0.04	5.66	0.05	5.71	0.05	5.77	0.05

from 5925 K to 6690 K, giving a mean temperature of 6235 K. This value of mean temperature is in excellent agreement with the mean temperature 6276 K obtained by Schmidt (1972) through H_α profile studies. The effective temperature of T Vul during a pulsation cycle varies between 5920 K to 6565 K giving the mean effective temperature of 6240 K. This value is also in excellent agreement with the mean effective temperature of 6222 K estimated by Schmidt (1972) through H_α profile.

The error in temperature determination, on account of the deviation in slopes of the observed energy-distribution curves, does not exceed $\pm$ 60 K. We have adopted a constant value of log g for temperature determination; on this account, the total error in temperature estimates can reach a maximum of $\pm$ 100 K. The line-blanketing corrections applied by us (from Ardeberg & Virdefors 1975) are reported to be in error by about 10 per cent in the case of stars later than F. This error in the blanketing corrections could lead to a further error of about $\pm$ 120 K. Thus the overall maximum error in the temperatures determined by us could be about $\pm$ 220 K. We have compared the models given by Kurucz (1979) with the models given by Parsons (1969). Kurucz's models give lower temperatures near 5400 K and higher temperatures near 6600 K. The difference is about 100 K, which is well within the range of the error of our temperature estimates.

We have also estimated the effective temperatures for ζ Gem at some more phases than given earlier by Rautela & Joshi (1976); these are also listed in Table 3.

The effective temperatures of these stars at different phases of their pulsation cycles including the temperatures of SU Cas derived by Joshi and Rautela (1980) have been correlated with the intrinsic $B-V$ colours of the stars at the corresponding phases. The intrinsic colours have been obtained by dereddening the $B-V$ colours given by Mitchell *et al.* (1964) with the help of the reddening corrections given by

0.575		0.631		0.750		0.817		0.920		
(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(iii)
7.06	0.65	...	...	6.51	0.59	6.48	0.46	6.03	0.39	0.35
7.07	0.64	...	...	6.48	0.59	6.33	0.47	6.03	0.40	0.34
7.03	0.63	...	...	6.38	0.60	6.28	0.49	6.08	0.41	0.34
7.01	0.74	...	...	6.35	0.69	6.26	0.55	5.96	0.44	0.33
7.09	0.77	...	...	6.37	0.71	6.17	0.57	5.97	0.46	0.32
6.32	0.65	6.33	0.65	5.99	0.57	5.78	0.43	5.43	0.34	0.30
6.28	0.68	6.35	0.68	6.00	0.60	5.74	0.45	5.43	0.36	0.29
6.29	0.64	6.27	0.64	5.98	0.55	5.73	0.40	5.42	0.32	0.29
6.23	0.53	6.22	0.53	5.93	0.49	5.72	0.38	5.42	0.28	0.28
6.20	0.45	6.20	0.45	5.92	0.41	5.71	0.31	5.40	0.23	0.27
6.19	0.24	6.18	0.24	5.86	0.22	5.68	0.15	5.40	0.11	0.25
6.12	0.28	6.13	0.28	5.82	0.26	5.67	0.22	5.39	0.17	0.24
6.07	0.28	6.06	0.28	5.78	0.26	5.63	0.23	5.37	0.19	0.22
6.01	0.14	6.02	0.14	5.77	0.13	5.60	0.12	5.35	0.10	0.21
6.00	0.05	5.98	0.05	5.72	0.05	5.59	0.05	5.35	0.04	0.19
5.97	0.06	5.95	0.06	5.69	0.06	5.57	0.05	5.34	0.04	0.18
5.92	0.07	5.89	0.07	5.67	0.07	5.55	0.06	5.33	0.06	0.17
5.89	0.05	5.89	0.05	5.65	0.05	5.54	0.04	5.33	0.03	0.16
5.87	0.06	5.83	0.06	5.63	0.05	5.51	0.05	5.32	0.04	0.15

Dean' Warren & Cousins (1978). We thus obtained a $\theta_e - (B-V)_0$ relationship of the form,

$$\theta_e = \underset{\pm 0.011}{0.274}\,(B-V)_0 + \underset{\pm 0.007}{0.637} \tag{3}$$

4. Radius

The radii of observed stars have been estimated with the help of Wesselink (1946) method as described in an earlier paper (Joshi & Rautela 1980). The radial-velocity curves for this purpose have been taken from Bappu & Raghavan (1969) for RT Aur and from Lüst-Kulka (1954) for T Vul. The V light curves have been taken from Mitchell *et al.* (1964) for both the stars. The displacement and radii values at different phases are listed in Table 3. An average value of $35.2 \pm 2.4\ R_\odot$ and $41.1 \pm 1.3\ R_\odot$ have been obtained for RT Aur and T Vul respectively.

Using the radial-velocity curve given by Abt & Levy (1974) and V light curve given by Mitchell *et al.* (1964) we have also estimated the radii for ζ Gem. The displacement and radii values at different phases are listed in Table 3. A mean radius of $70.7 \pm 3.8\ R_\odot$ has been obtained for the star.

5. Luminosity

Using the radii and temperatures determined above, the luminosities of these stars have been calculated. We obtain $M_{bol} = -3.32$ mag for RT Aur, -3.66 mag for T Vul

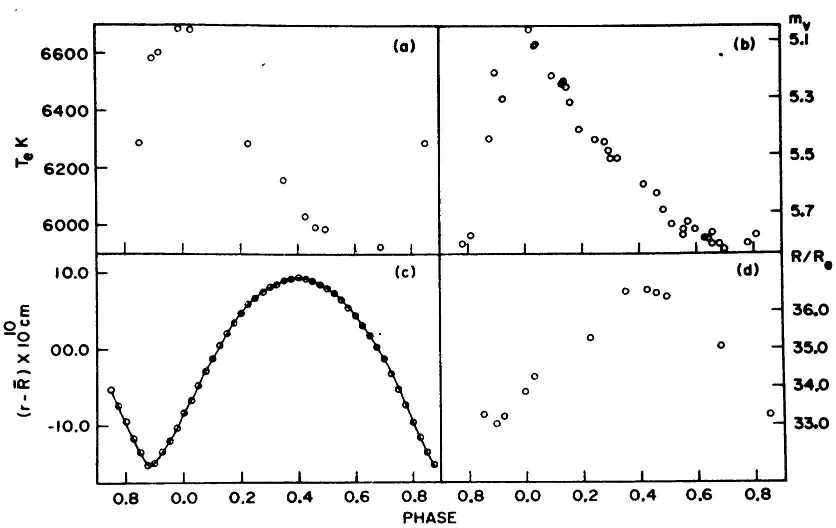

Figure 1. Variation with phase in some parameters of RT Aur.

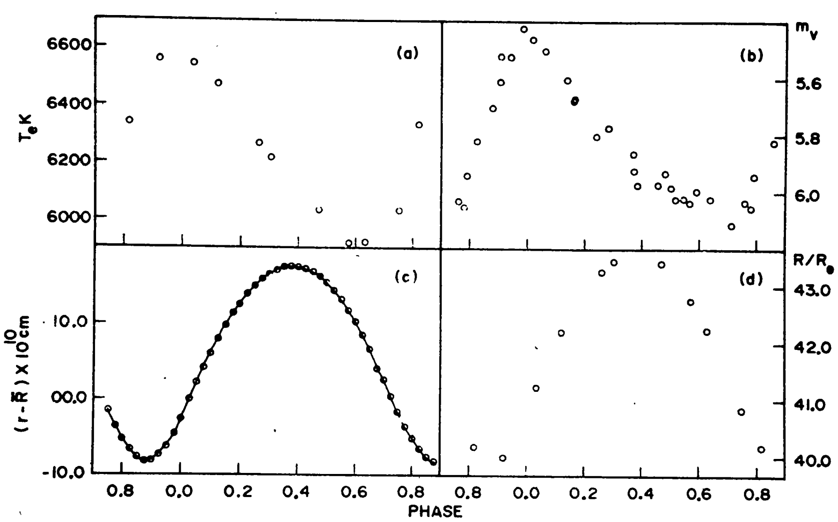

Figure 2. Variation with phase in some parameters of T Vul.

and − 4.62 mag for ζ Gem, corresponding to log $L/L_\odot$ = 3.23, 3.36 and 3.75 respectively. Our estimated bolometric magnitudes differ by about 0.1, 0.3 and 0.5 mag for RT Aur, T Vul and ζ Gem respectively, compared to the bolometric magnitudes obtained using *P-L-C* relationship given by Parsons & Bouw (1971). All the values of bolometric magnitudes are in fair agreement within the limits of error in both the methods.

6. Mass

The Wesselink-radius mass of the stars has been determined using the relationship given by Cox, King & Stellingwerf (1972) as described in an earlier paper (Joshi & Rautela 1980). The masses thus obtained are $\mathfrak{M}_{\mathrm{Wess}}$ = 4.6, 5.3 and 6.1 $\mathfrak{M}_\odot$ for RT Aur, T Vul and ζ Gem respectively.

Table 3. The derived parameters of the Cepheids RT Aur and T Vul and ζ Gem.

Star	Phase	T_e K	$(r-\bar{R})$ 10^{10} cm	$R/R_\odot$	M_{bol} mag
RT Aur	0.030	6685	− 6.40	34.28	−3.57
	0.227	6290	0.70	35.30	−3.37
	0.350	6160	9.10	36.51	−3.35
	0.424	6035	9.30	36.54	−3.26
	0.457	5995	8.90	36.48	−3.23
	0.497	5990	8.20	36.38	−3.22
	0.691	5925	− 0.90	35.07	−3.09
	0.850	6290	−13.45	33.27	−3.24
	0.897	6585	−15.05	33.04	−3.42
	0.921	6605	−13.70	33.23	−3.45
	0.990	6690	− 9.20	33.88	−3.54
T Vul	0.038	6550	1.20	41.24	−3.88
	0.109	6475	8.00	42.22	−3.88
	0.262	6270	15.40	43.28	−3.79
	0.304	6220	16.70	43.47	−3.77
	0.469	6035	16.40	43.43	−3.64
	0.574	5920	12.00	42.79	−3.52
	0.629	5920	8.20	42.25	−3.49
	0.750	6035	− 1.50	40.85	−3.50
	0.815	6340	− 6.10	40.19	−3.68
	0.921	6565	− 7.45	40.00	−3.82
ζ Gem	0.000	6200	− 7.70	69.59	−4.78
	0.159	5915	12.80	72.54	−4.66
	0.252	5755	14.80	72.83	−4.55
	0.311	5730	11.70	72.38	−4.52
	0.360	5680	6.70	71.66	−4.46
	0.450	5625	− 6.50	69.77	−4.36
	0.598	5755	−31.20	66.22	−4.35
	0.626	5850	−32.50	66.03	−4.41
	0.700	6000	−32.20	66.07	−4.52
	0.775	6170	−28.50	66.61	−4.66

Evolutionary masses for the stars have been obtained using Becker, Iben & Tuggle (1977) evolutionary tracks and their mass-luminosity relation as described in an earlier paper (Joshi & Rautela 1980).

Using the standard Population I composition, $Y = 0.30$, $Z = 0.02$ (Iben & Tuggle 1975), the masses are derived to be $\mathfrak{M}_{evo} = 5.4$, 5.9 and 7.6 for RT Aur, T Vul and ζ Gem respectively.

7. Discussion

7.1 *The Temperature Scale*

The $\theta_e - (B-V)_0$ relation obtained by us gives higher temperatures for Cepheids by about 320 K, 200 K and 440 K as compared to the temperatures given by Kraft (1961), Schmidt (1971) and Pel (1978) respectively. This difference in temperatures might be due to the revised calibration of the primary standard α Lyr, revision in colour excesses, the choice of model stellar atmospheres and line-blanketing corrections.

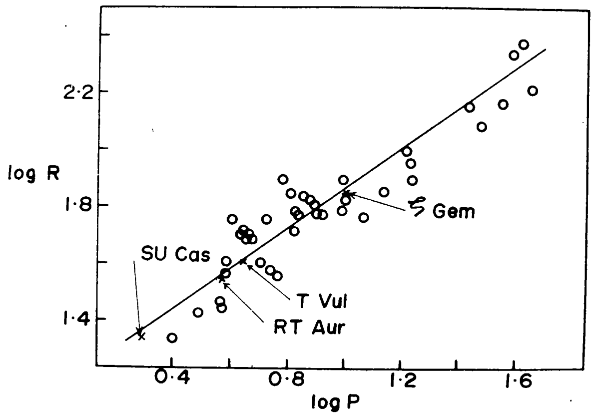

Figure 3. Fit of the stars in the period-radius relationship. Thick line represents the theoretical period-radius relationship given by Cogan (1978), crosses represent the radii determined by us and open circles the radii determined by others for several Cepheids.

7.2 *Fit of the Stars in Period-Radius Relationship*

Our estimated Wesselink radii fit sufficiently well in the theoretical period-radius relationship (Fig. 3) given by Cogan (1978) for Cepheid models occupying the central region of the instability strip. In this figure, we have also plotted the radius of SU Cas determined earlier (Joshi & Rautela 1980). We may infer that the Wesselink method can be used successfully for the determination of the radii for these stars.

7.3 *Ratio of Evolutionary to Pulsation (Wesselink-Radius) Masses*

The evolutionary to Wesselink-radius mass ratio for each star comes out to be greater than unity and ranging from 1.12 for T Vul to 1.25 for ζ Gem. This indicates that Wesselink-radius masses are 11 to 20 per cent lower than those given by evolutionary calculations without mass loss. Cogan (1970) and Rodgers (1970) have found a discrepancy of 20 to 40 per cent. Cox, King & Stellingwerf (1972) have found that pulsation masses are on an average 15 per cent lower than the evolutionary masses, but they remark that their calculations do not strongly support any significant inconsistency between the pulsation masses and evolutionary masses for Cepheids (without mass loss) owing to large uncertainties in the computation of masses. However, they suggested the possibility of a real discrepancy in the pulsation and evolutionary masses. Iben & Tuggle (1972) have also found that pulsation and evolutionary masses are not consistent with each other and have ascribed this inconsistency to (a) the absolute magnitudes assigned to Cepheids in open clusters and associations (making stars fainter by ~ 0.3 mag) and (b) the conversion from raw mean colour into surface temperature (over-estimates of log T_e by ~ 0.025). We have found that a decrement in absolute magnitude by 0.3 mag or a decrease in log T_e by 0.025 does not remove the discrepancy. Also, our temperature estimates indicate that the temperatures of these Cepheids are higher than those determined earlier.

Cox (1979) has estimated the evolutionary and pulsation masses for a large number of Cepheids using the distance scale given by Hanson (1978) and effective temperatures given by Pel (1978). He found that the ratio of pulsation to evolutionary masses is

0.97 ± 0.25. Our estimate for the same is 0.85 ± 0.03. The average mass ratio obtained by us is in fair agreement with those obtained by Cox (1979) within the range of error. Our sample of Cepheids is quite small in comparison to that of Cox (1979). Further, the error in the determination of the Wesselink-radius mass is nearly equal to the mass discrepancy obtained by us. Hence we feel inclined to infer that the difference in the evolutionary to Wesselink-radius masses of these stars may not be due to a real mass discrepancy but due to the systematic errors in the mass determinations.

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