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Photometric study of W UMa type binaries in the old open cluster Berkeley 39

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Abstract The study of W UMa binary systems gives a wealth of information about their nature as well as their parent bodies (if any), like clusters. In this paper, we present the I passband photometric solutions of four W UMa binaries in the open cluster Berkeley 39 using the latest version of the W–D program. The result shows that two binary systems are W-subtype W UMa binary systems and the other two systems are H-subtype W UMa binary systems. No third body has been found in any of the four systems. We found a correlation between the period and mass-ratio as well as temperature and mass-ratio for the respective variables, which is similar to the relationship between mass ratio and total mass of the contact binaries as shown by van't Veer and Li et al.

Key words: binaries: eclipsing — binaries: close

1 INTRODUCTION

The old open cluster Berkeley 39 (Be 39) is located in the direction of the galactic anti-center ($\alpha_{2000} = 7^{\rm h}46^{\rm m}48^{\rm s}$, $\delta_{2000} = -4°40'$, $l = 223.5°$, $b = 10.1°$). A systematic survey of Be 39 revealed 12 short period eclipsing binaries (Kaluzny et al. 1993) and later found 5 more variable stars in which one is a W UMa type binary system (Mazur et al. 1999). The study of the Color Magnitude Diagram (CMD) of Be 39 along with Padova stellar evolutionary models (Girardi & Bertelli 1998) yields an age of around 6 ± 1 Gyr (Carraro et al. 1998). A similar age constraint was proposed by Kassis et al. (1997) using the cluster CMD along with theoretical models by Bertelli et al. (1994). Applying theoretical and recent observational constraints, Percival & Salaris (2003) found an age of around 7.5$\pm$1.0 Gyr. The de-reddened distance modulus for Be 39 was found to be 12.97$\pm$0.09 along with metallicity, [Fe/H]= -0.15 ± 0.09 (Percival & Salaris 2003).

Since no photometric analysis was carried out for the eclipsing binaries present in the Be 39 cluster, we have analyzed the light curves of four eclipsing binary systems, $V1$, $V4$, $V7$ and $V8$, which have relatively high amplitudes. A similar kind of study was carried out on the W UMa type binaries in open clusters NGC 6791 and Be 33 (Rukmini & Vivekananda Rao 2002; Rukmini et al. 2005). From the analysis performed on these systems, it was found that the mass-ratios were close to unity and, in one case, greater than unity (Rukmini & Vivekananda Rao 2002; Rukmini et al. 2005). A detailed spectroscopic observation was suggested to know the true nature of these objects. The aim of the present paper is to derive the photometric elements of the selected four W UMa systems discovered in Be 39 using the latest Wilson-Devinney (W-D) program and compare with binaries studied in other clusters. Further, it is also aimed at exploring any possible correlations between the derived parameters.

2 DATA AND ANALYSIS

The observations were carried out by Kaluzny et al. (1993) at the Las Campanas Observatory using the 1.0 m Swope telescope with a 1k $\times$ 1k CCD in the I passband along with the B and V passbands on the last day of the observation cycle. The data were collected on the following six days: November (1990 Nov 29), December (1990 Dec 1, 2), January (1991 Jan 1, 29) and February (1991 Feb 26). We have used the I passband data published in that paper to obtain the photometric parameters of the respective systems ($V1$, $V4$, $V7$ and $V8$). Further observations of the cluster were carried by the same group during 1992/1993 and they discovered new variable stars along with previous ones. Out of the total 17 variable stars discovered in Be 39, 12 variables belong to EW type, 3 are EA type, 1 is a δ Scuti and 1 is EB type. Kaluzny et al. (1993) have found that four variables are blue stragglers which mimic the light curves of W UMa type binaries ($V1$, $V2$, $V10$, $V12$).

The observed data of selected variables in the cluster Be 39 are plotted to obtain the respective light curves (see Fig. 1). All of them have amplitudes greater than 0.4. The phases of the variables were calculated using the accurate periods published in Mazur et al. (1999).

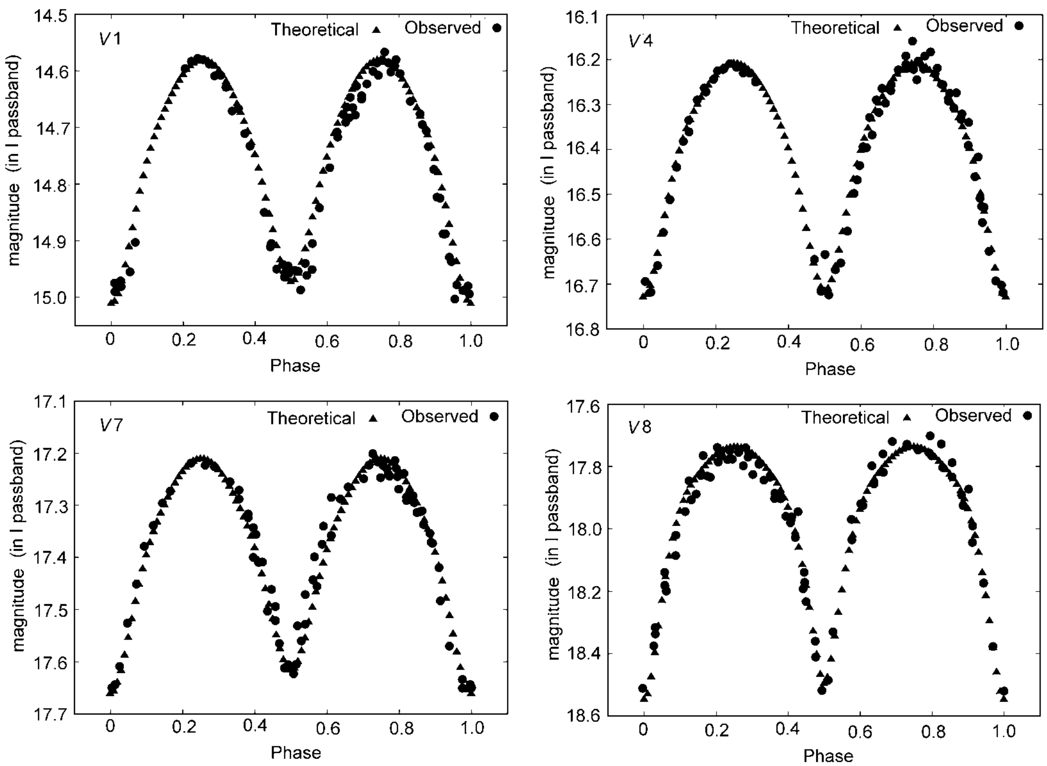

Fig. 1 Best fit to the I passband light curve of the four variables present in Berkeley 39. The filled circles represent the observed data and the filled triangles represent the theoretical points.

3 PHOTOMETRIC SOLUTIONS

The photometric solutions were obtained by using the latest W-D program with an option of non-linear limb darkening via a square root law along with many other features (Wilson & Devinney 1971; Van

Table 1 Values of Σ for Various Combinations of q and i for the $V1$, $V4$, $V7$ and $V8$ Variables

	$V1^a$		$V4$		$V7$		$V8$	
q	i	Σ	i	Σ	i	Σ	i	Σ
0.5	01.22	0.084	05.35	0.099	10.76	0.043	10.25	0.107
0.6	03.22	0.074	14.76	0.063	22.023	0.035	27.49	0.094
0.7	07.88	0.065	30.71	0.051	33.54	0.027	37.87	0.081
0.8	11.32	0.055	41.84	0.039	42.66	0.021	47.30	0.069
0.9	21.61	0.046	51.98	0.028	50.64	0.014	56.62	0.055
1.0	31.38	0.038	59.68	0.018	56.862	0.008	63.10	0.041
1.1	38.90	0.031	65.04	0.009	61.891	0.004	68.31	0.028
1.2	45.83	0.024	69.20	0.003	65.77	0.0017	72.10	0.018
1.3	51.70	0.018	72.66	0.001	69.08	0.002	75.30	0.010
1.4	57.62	0.010	75.67	0.003	71.98	0.005	78.22	0.0052
1.5	60.14	0.007	78.48	0.009	74.16	0.011	80.98	0.0035
1.6	63.25	0.004	81.19	0.018	-	-	84.125	0.005
1.7	65.83	0.0018	83.11	0.028	-	-	87.90	0.010
1.8	68.194	0.0017	84.26	0.120	-	-	92.12	0.017
1.9	70.23	0.0032	-	-	-	-	-	-
2.0	72.42	0.0065	-	-	-	-	-	-

[a] Variable name

Hamme & Wilson 2003). The visual inspection of these variables resembles a W UMa type nature of variability and hence mode 3 was used in the program. The parameters adopted in the solutions are as follows: the effective temperature for star 1 is taken on the basis of un-reddened $B-V$ values published by Mazur et al. (1999) and using Allen's table (2000). The secondary component's effective temperature ($T_{\mathrm{e},c}$) was assumed to be equal to the primary component's temperature. The values of limb darkening coefficients, x_h and x_c = 0.80 for the I band, were taken from Al-Naimy (1978). The gravity-darkening coefficients G_h and G_c for the I passband were set to 0.32 and the values of albedo A_h and A_c were fixed at 0.5, which is appropriate for the convective nature of the component stars.

Since no spectroscopic observations are available for the variables, we had to constrain the most important parameter, mass-ratio, to be $q = m2/m1$. In order to find the best value of mass-ratio, we executed the code for various assumed values of mass-ratio while keeping in the mind that the surface potential (Ω_h=Ω_c) also changes with respect to mass-ratio. Initially, all the parameters were fixed as mentioned above, except q and i, which are adjustable parameters. Further, both of these parameters are not adjusted simultaneously. Several runs of the DC program were executed to obtain the minimum ΣW(O-C)^2. After performing several computational runs, we found the best mass-ratio value for the respective light curves. Table 1 shows the values of Σ for different combinations of q and i.

After obtaining the best set of q and i, the DC program was executed to obtain the values of the following parameters: inclination (i), secondary component temperature ($T_{\mathrm{e},c}$), surface potential (Ω) and monochromatic luminosity of the primary component (L_h), third light parameter (L_3) and limb darkening coefficients (x_h and x_c) . The program was executed until the sum of residuals ΣW(O-C)^2 attained a minimum. The results of the final analysis are shown in Table 2. Using the final parameters given in Table 2, theoretical light curves were computed using the LC program of Wilson-Devinney and the fits are shown in Figure 1. The quality of the fits was checked by performing a chi square (χ^2) test on the $\Sigma W(O-C)^2$ values obtained and the confidence level was found to be about 95% for all the four variables.

4 DISCUSSION AND RESULTS

The study of W UMa variable systems present in clusters is important in order to understand the underlying physics of their formation and it also provides some information about the parent cluster. In this paper, we have analyzed four eclipsing variables present in the old open cluster Berkeley 39. We used the latest W-D program to derive the photometric solutions. The result of each system is discussed below.

Table 2 Photometric Elements Obtained for Four Variables by Using the W-D Method

Element		$V1$	$V4$	$V7$	$V8$
Period (d)		0.4052	0.3813	0.2780	0.2288
$T^{a}_{\mathrm{e},h}$ (K)		5560	5560	5150	4700
$T_{\mathrm{e},c}$ (K)		5291±84	5507±77	4900±84	4652±50
q^{a}		1.80	1.31	1.38	1.47
$q*^{b}$		0.55	0.76	0.72	0.68
$i(^{\circ})$		68.24±0.50	72.97±0.46	66.68±0.48	83.07±0.92
Ω		4.7426±0.0038	4.2055±0.0024	4.2043±0.0037	4.5868±0.0043
f^{c}		0.1338	0.0315	0.2997	0.1050
r_h	pole	0.3187±0.0032	0.3332±0.0031	0.3387±0.0021	0.3147±0.0020
	point	0.4152±0.0041	0.4568±0.0043	0.4528±0.0041	0.3930±0.0052
	side	0.3328±0.0022	0.3489±0.0022	0.3547±0.0025	0.3279±0.0032
	back	0.3627±0.0023	0.3803±0.0030	0.3854±0.0030	0.3550±0.0035
r_c	pole	0.3862±0.0022	0.3782±0.0021	0.3705±0.0021	0.3789±0.0038
	point	0.4980±0.0041	0.5123±0.0042	0.4919±0.0033	0.4710±0.0062
	side	0.4073±0.0042	0.3986±0.0030	0.3898±0.0028	0.3984±0.0042
	back	0.4351±0.0050	0.4284±0.0032	0.4193±0.0031	0.4241±0.0041
L^{d}_{h}		0.4565±0.0123	0.4448±0.0098	0.4991±0.0153	0.4179±0.0098
L^{d}_{c}		0.5435	0.5551	0.5008	0.5821
L_3		0.0	0.0	0.0	0.0
x_h		0.80±0.05	0.80±0.05	0.80±0.05	0.80±0.05
x_c		0.80±0.05	0.80±0.05	0.80±0.05	0.80±0.05
Σ		0.00132	0.00121	0.00146	0.00285
Spectral type		G5	G5	K0	K2-K3
A^{a}_{h}		0.5	0.5	0.5	0.5
A^{a}_{c}		0.5	0.5	0.5	0.5

[a] Fixed parameters
[b] Inverse mass-ratio
[c] Fill-out factor
[d] In units of total system at phase 0.25

4.1 Variable $V1$

The proper sinusoidal variation of the light curve indicates aspects of the type W UMa's binary nature. The period of the system is around ~0.4052$^{\mathrm{d}}$ and $B-V = 0.66$, which corresponds to G5 spectral type (Kaluzny et al. 1993; Mazur et al. 1999). The maxima and minima are not the same in the I passband and the difference is more clear in the V passband. The best combination of q and i came out to be 1.8 and $\sim 68^{\circ}$, respectively. The computed values of the effective temperatures of the primary and secondary show a difference of 200 K.

4.2 Variable $V4$

The observed and theoretical light curves suggest that the variable is a W type W UMa binary system. The period of the system is around ~0.3813$^{\mathrm{d}}$ and the $B-V = 0.66$ value corresponds to G5 spectral type. The light curve's maxima and minima are equal in the I and V passbands and the effective temperatures of the primary and secondary components are nearly same. The best combination of q and i is 1.31 and ~73°, respectively.

4.3 Variable $V7$

The period of the W UMa binary system is around ~0.2780$^{\mathrm{d}}$ and the value of $B-V = 0.82$ suggests a K0 spectral type. The maxima and minima of the light curve are not the same in the I and V passbands and its difference is comparatively more in the V passband. The best combination of q and i came out to be 1.38 and $\sim 67^{\circ}$ respectively.

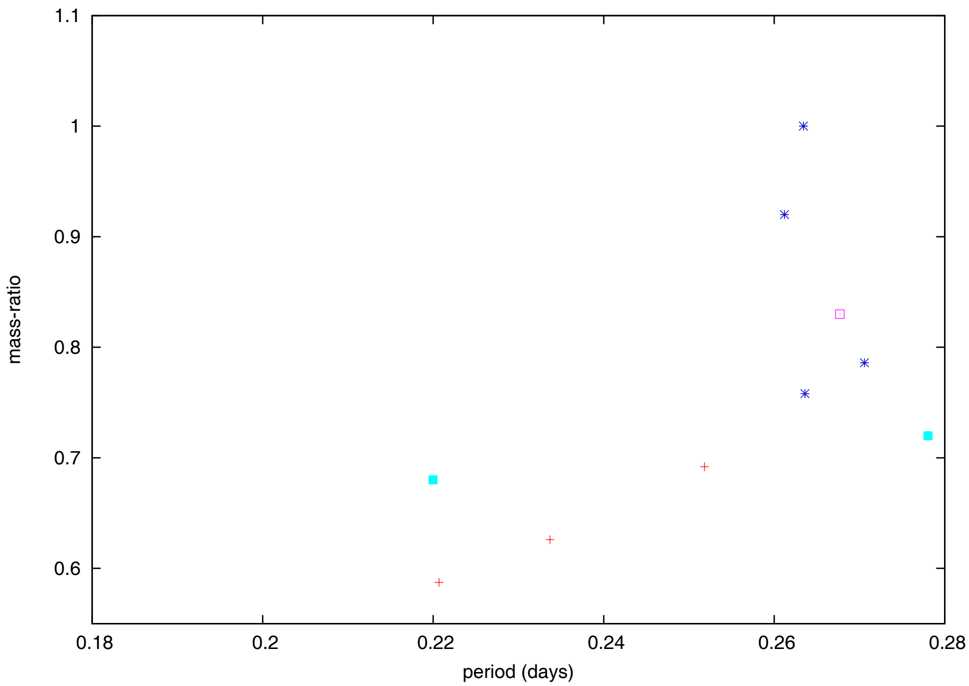

Fig. 2 Increasing trend of period vs. mass-ratio. The plus symbol represents the W-subtype, the star symbol represents the H-subtype, the dot box represents the $V1$ variable in NGC 6791 and the filled box symbol represents the variables $V7$ and $V8$ in Be 39.

4.4 Variable $V8$

The period of the variable was found to be $\sim$0.2288$^{\mathrm{d}}$ and the value of $B - V = 1.02$ indicates a $K2 - K3$ spectral type. The maxima and minima of the light curve are equal in both I and V passbands. No temperature difference is found between the primary and secondary components. This variable has a high inclination angle $\sim 83^\circ$ compared to other variables mentioned above. The mass-ratio is found to be $\sim$1.47.

Here, we have taken the inverse mass-ratio values for further discussion. The inverse mass-ratio ($q*$) values for the studied variables are $q* = 0.55$ for $V1$, $q* = 0.76$ for $V4$, $q* = 0.72$ for $V7$, and $q* = 0.68$ for $V8$. The variables $V4$ and $V7$ belong to H type W UMa binary systems, as their mass-ratio values are greater than 0.72 according to Csizmadia & Klagyivik (2004). The H-subtype classification of contact binaries is the result of the luminosity ratio vs energy transfer parameter study and it was found that the energy transfer rate is less efficient when compared to other contact binary stars (Csizmadia & Klagyivik 2004). Qian (2001) has studied 30 W type W UMa binary systems and found that if the mass-ratio $q > 0.4$, the period increases and if $q < 0.4$, the period decreases with respect to mass-ratio. This result, which is explained by the contact configuration of the systems, is due to a variable angular momentum loss (AML) mechanism and thermal relaxation oscillation (TRO) cycle (Qian 2001). Since the result is based on a small sample, it cannot be extended to other W UMa contact binary systems and if it is a real effect, then theoretical interpretation is needed.

In our study of variables in the open cluster Be 39, four W UMa systems (two W-subtypes and two H-subtypes) have mass–ratios greater than 0.4, suggesting that they are in a period-increasing phase according to Qian (2001). It was found that for all the W-subtype W UMa systems, the period increases along with temperature (Rucinski 1998). Our results indicate that mass-ratio is increasing along with the period of the respective binary systems. We have looked for the light curve solutions of W UMa type contact binaries (Csizmadia & Klagyivik 2004) whose periods are small ($<0.28^{\mathrm{d}}$) and posses relatively high mass-ratio values ($q > 0.55$) and we found that there are a total of seven W UMa type systems out of which four are H-subtype and the remaining are W-subtype. The V1 variable in NGC 6791 (Rukmini et al. 2005) also falls into this category (period 0.2677^{d} and mass-ratio, $q* = 0.83$). For all these W UMa systems, the mass-ratio increases along with the respective period (Fig. 2). The derived photometric mass-ratios of the three variables, i.e $V4$, $V7$ and $V8$ ($V1$ is not a member of the cluster) and CMDs published by Mazur et al. (1999), show a correlation between temperature and mass-ratio; viz. the temperature increases along with the mass ratio for the respective variables. The fractional change in the mass-ratio is about ~ 11 percent for a fractional change of ~ 16 percent in the temperature of the primary component of the respective variable. The mass ratio q changes from 0.68 to 0.76 for a temperature change of 4652 – 5507 K, which is consistent with the study carried out by Rucinski (1998) (see figs. 4, 5 and 6 in Rucinski 1998). The relationship between mass ratio and orbital period and a relationship between the effective temperature and mass ratio for variables in cluster Be 39 are similar to the relationship between mass ratio and total mass of the contact binaries as shown by van't Veer (1996) and Li et al. (2008). To confirm the photometric mass ratio of the variables in Be 39, spectroscopic studies are needed.

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