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Photometric investigation of eight ultra-short period eclipsing binaries from OGLE

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Abstract We performed a detailed photometric analysis of eight ultra-short period eclipsing binaries (USPEBs) using the Wilson-Devinney method. We present the modeled light curves and derived photometric solutions. The USPEBs with period (P)$\leq$0.21 d considered in our study belong to W-subtype having shallow contact factor (f)$<\sim$20%, high mass ratio (q)$>\sim$0.7 and later spectral types. The absolute parameters for these short-period binaries were derived applying empirical relations. We discuss the evolutionary stage of these USPEBs using the mass-radius, color-density and period-color diagrams. The objects showed poor metallicities, and some objects were even found to be existing around fully convective limits. The period distribution of USPEBs exhibited a sharp cut-off at 0.22 d; however, we observed significant deficits for our objects in the literature. We examined the statistics of USPEBs studied to date (in terms of the distribution of period, mass ratio and component temperatures of USPEBs) and observed that a dominant distribution of component temperatures for these USPEBs was towards lower temperatures.

Key words: stars: low-mass — stars: evolution — stars: low-mass — binaries: eclipsing — binaries: close

1 INTRODUCTION

Short period eclipsing binaries are known to be key gauges to investigate and understand fundamental stellar properties. Studies of these binaries (also known as W UMa systems) to date have indicated a well-defined short period limit of about 0.22 d. These binaries whose orbital periods are shorter than 0.22 d are considered scarce systems and termed as ultra-short period eclipsing binaries (USPEBs) (Rucinski 1992, 2007). For many years, OGLE BW3 V38 was known to be the shortest period binary ($P\sim$0.1984 d) with M-dwarf components. It was discovered by Udalski et al. (1994) and studied in detail by Maceroni & Rucinski (1997). Later, many rich samples of ultra-short period binaries were cataloged by Norton et al. (2011), Nefs et al. (2012), Lohr et al. (2013), Drake et al. (2014) and Soszyński et al. (2015). These USPEBs, found in large numbers, influence constraints on the models, corresponding to dynamically stable configurations of binaries; however, no detailed analysis exists for most of these binaries to date. Among these USPEBs, only a handful of M-dwarf binaries have been studied so far. However, we observed an increase in the presence of these M-type binaries with their discovery through Super Wide Angle Search for Planets (SuperWASP), Gran Telescopio CANARIAS (GTC), Sloan Digital Sky Survey (SDSS) and Palomar spectroscopy (Drake et al. 2014). These sources are known to be active, flaring stars and their components are fully convective. Such convective structures below a certain binary orbital period (Rucinski 1992, 1997; Paczyński et al. 2006; Becker et al. 2011) make them unique. Examining these binaries will help in understanding the mechanism involved in the formation of such tight systems, which is different from the formation of early-type main sequence stars. Since they constitute 0.26% of all known contact systems (Drake et al. 2014), their study becomes pivotal in understanding late-type binaries in evolutionary stages, associated with mass transfer, angular momentum loss (AML), binary mergers, etc. Because of the impoverished statistics on USPEBs studied so far, the models explaining their structure and evolution continue to be an unresolved problem in stellar astrophysics (Dimitrov & Kjurkchieva 2015).

Encouraged by the above mentioned interesting concerns, we were motivated to carry out a detailed photometric investigation of such binaries. As part of this project, we shortlisted a set of USPEBs from Soszyński et al. (2015) who presented 242 eclipsing and ellipsoidal binaries in OGLE fields towards the Galactic bulge with $P<0.22$ d. The objects in the study belong to K-M spectral types, close to a short period cut-off limit (P $\leq$ 0.22 d), and other details are listed in Table 1.

2 DATA COLLECTION

For our investigation, we collected data from the OGLE-III survey that conducted long-term observations of fields towards the Galactic bulge during its tenure in 2001–2009. The OGLE-III survey relies on the 1.3 m Warsaw telescope located at Las Campanas Observatory (LCO) in Chile. Most of the observations employed the Cousins I-band and Johnson V-band filters for obtaining color information with magnitudes ranging from about 13 to 20.5 in I-band. The effective temperatures for the primaries were determined using $V - I$ color (Pecaut & Mamajek 2013) whose magnitudes ranged between 16–18 in I-band (Soszyński et al. 2015). We selected eight USPEBs from 242 eclipsing binaries listed in the OGLE Survey (utilizing OGLE-III and -IV) with $P<0.22$ d. Out of the 242 objects from Soszyński et al. (2015) and Soszyński et al. (2016), Soszynski et al. categorized 75 objects to be W UMa type. From these 75 classified objects, we shortlisted 46 objects with amplitudes >0.3. Out of these 46 objects, 20 objects had both V and I light curves. Finally, from these 20 objects, we chose eight binaries for our study based on their minimum scatter $\leq$0.03 in the light curves.

3 PHOTOMETRIC ANALYSIS

Soszyński et al. (2015) created model light curves using a script developed by Pilecki & Stepien (2012) to classify binary systems that were observed in OGLE. However, the details of photometric parameters were neither reported nor discussed previously in the literature. Therefore, we performed a detailed photometric analysis of the eight USPEBs chosen and obtained the photometric elements. We also discuss their state of evolution in this study. We carried out a detailed photometric analysis of the variables using the Wilson-Devinney (WD) method (version 2003). Nonlinear limb darkening option via square root law, along with many other features, was applied to derive photometric elements and constrain the mass-ratio (q) parameter (Wilson & Devinney 1971; Van Hamme & Wilson 2003). We initially selected mode-2 (detached-configuration) for the analysis using the WD code, which was later modified to mode-3 (contact-configuration), as the solution was diverging. The method adopted for modeling light curves is discussed in Priya et al. (2013) and Joshi et al. (2016). The effective temperatures of the primary components (T_1) were fixed assuming stellar components to be main sequence stars, based on $V - I$ color indices (Pecaut & Mamajek 2013) and the method adopted by Soszyński et al. (2015).

Assuming a convective nature of the envelopes, the gravity darkening coefficients were fixed as $g_1 = g_2 = 0.32$ (Lucy 1967), bolometric albedos $A_1 = A_2$ were set at 0.5 (Rucinski 1969) and limb darkening coefficient values were fixed at $x_1 = x_2 = 0.8$ (Al-Naimiy 1978) for the I passband. Parameters such as orbital inclination (i), effective temperature of the secondary component (T_2), dimensionless potentials of stars ($\Omega_1 = \Omega_2$) and relative luminosity of primary component (L_1) were adjusted. For all systems in this study, these parameters were fitted until a minimum weighted square deviation of $\sum W(O-C)^2$ spanned over a selected range of 'q'. We applied the q-search method to determine the value of 'q' (Priya et al. 2011, 2013; Rukmini et al. 2001). After that, we executed differential correction (DC) until we obtained a minimum $\sum$, and checked the fitted parameters for the presence of third light by freeing the L_3 parameter for all the systems in this study. We used the best-fit parameters derived after DC in the LC program and plotted the resulting light curves. We observed a good agreement between observed and synthetic light curves, as displayed in Figure 1. The solutions obtained are listed in Table 2.

4 DISCUSSION AND CONCLUSIONS

We obtained the photometric solutions for the selected eight USPEBs using the WD method, v.2003. We found that all eight systems were high mass ratio, late-type binaries and categorized as W-subtype systems (Binnendijk 1970; Rucinski 1974). However, none of them showed any spot activity or evidence of third light. The components have almost equal surface temperatures, and the temperature difference between them (ΔT) is $<\sim 106$ K. Such temperature difference indicates that system components are in thermal contact, and large amounts of energy transfer from the more massive to the less massive component take place. All of them show shallow fill-out factors ($f<20\%$), suggesting that these system components are in a broken contact phase, which is a typical property observed in USPEBs (Hilditch 1989).

Liu et al. (2018) predicted that USPEBs have a better-constrained empirical global parameter relation than that of F, G and early K type contact binaries because most of them are above the zero-age main sequence (ZAMS) and un-evolved. This feature is good for estimating the pa-

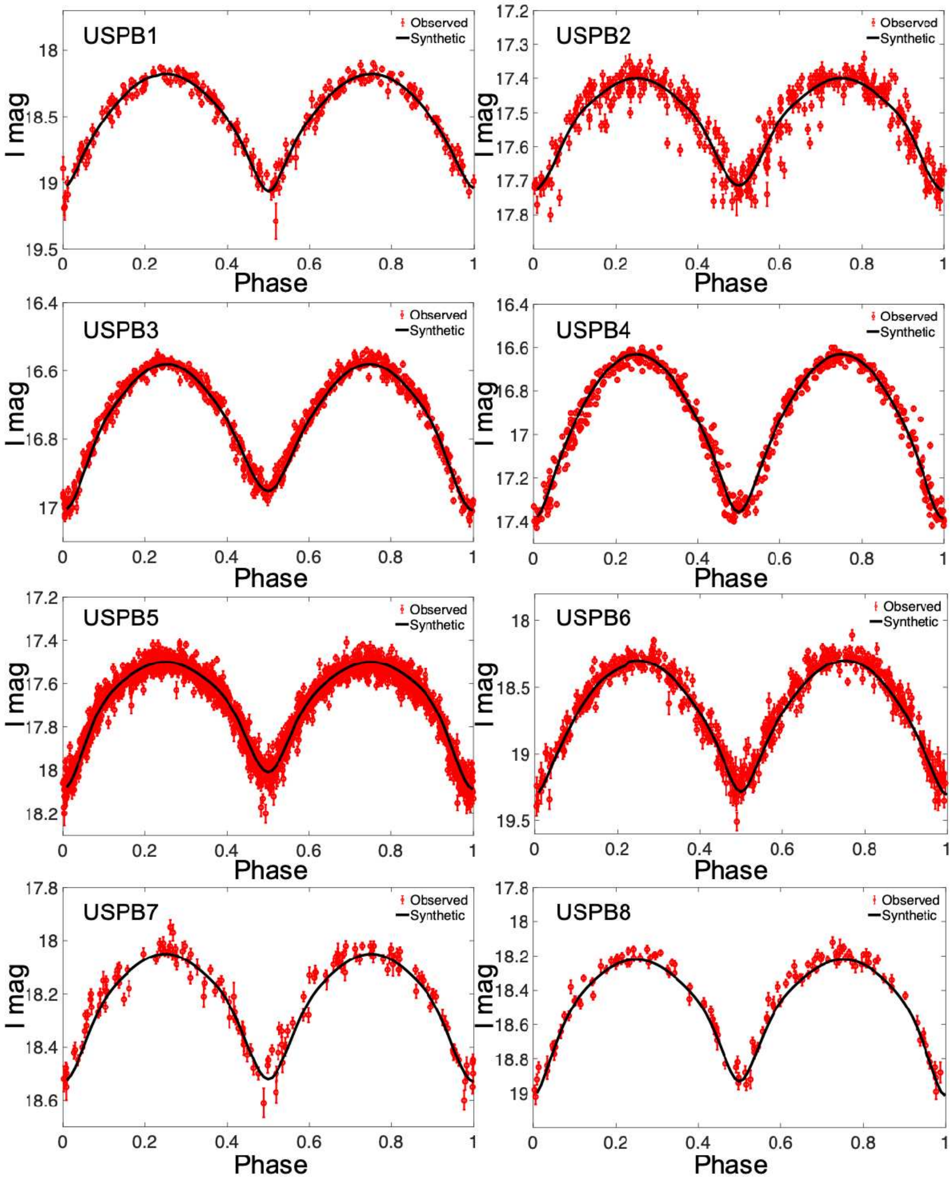

Fig. 1 Theoretical light curves (*solid lines*) computed applying the WD method compared to the observed light curves of the eight USPEBs.

rameters of USPEBs when spectroscopic data are lacking. By adopting the empirical relations (Eqs. (1) and (2)) of 'a' and 'M' given by Dimitrov & Kjurkchieva (2015) for short and ultra-short period W UMa type stellar systems with periods <0.27 d, the target orbital axis 'a' (in $R_\odot$) was calculated along with the absolute parameters $M_{1,2}$, $R_{1,2}$ and $L_{1,2}$ (in solar units) tabulated in Table 3.

$$a = (-1.154 + 14.633 \times P - 10.319 \times P^2)\, R_\odot \,. \quad (1)$$

$$M = (\frac{0.0134}{P^2}[-1.154+14.633\times P-10.319\times P^2]^3)\, M_\odot \,. \quad (2)$$

A detailed explanation supplementing the period cut-off limit of USPEBs has been addressed previously in the literature (Rucinski 1992; Rucinski et al. 2007; Stepien 2006b, 2011; Jiang et al. 2012; Qian et al. 2015b). Theories given by Stepien (2006b) and Jiang et al. (2012) contrasted with each other based on different assumptions concerning AML. According to Stepien (2006b) and Stepien (2011), the timescale of AML for short period binaries with low mass components may increase beyond the age of the universe. Jiang et al. (2012) suggested that the cause for contact binaries with masses less than 0.63 $M_\odot$ and periods less than 0.2 d was due to unstable mass transfer. Nefs et al. (2012) proposed that these systems were mostly predicted to be triple systems. The third body plays a significant role in the origin of such systems by removing angular momentum (AM) from the central pair.

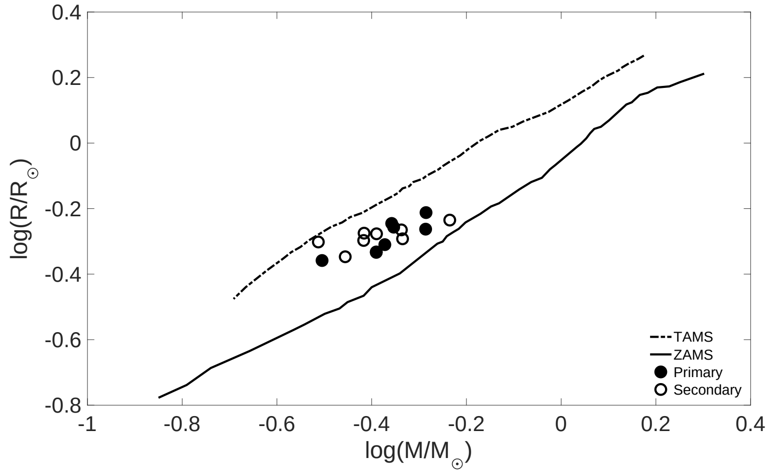

Fig. 2 Mass-radius distribution for eight USPEBs where the mass-radius relation for ZAMS and TAMS lines was adopted from Stepien (2006a).

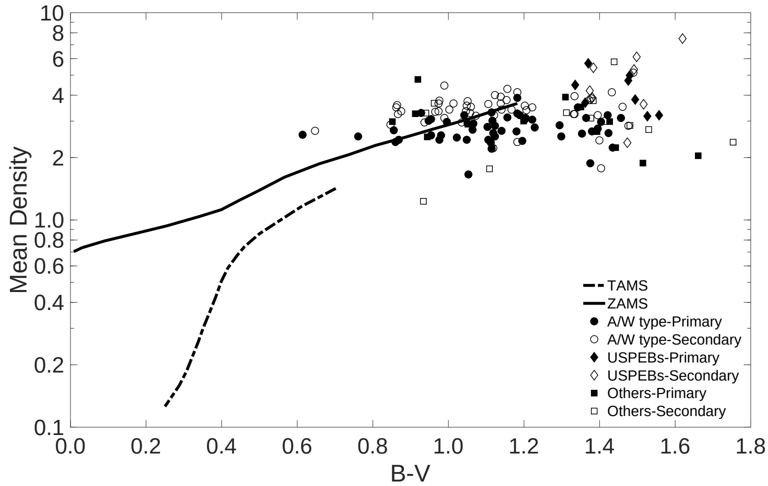

Fig. 3 The color-density diagram was adopted from Li et al. (2019) and the variable in our study was overplotted. The ZAMS and TAMS lines were extracted from fig. 3 of Mochnacki (1981) and marked with *solid* and *dashed lines*, respectively.

Table 1 Details of the Eight USPEBs Considered in This Study

Star (OGLE-BLG-ECL-)	HJD_0 (2450000+)	R.A. (h m s)	Dec (° ′ ″)	I_{mag} (mag)	Amplitude (mag)	Orbital Period (d)
000015 (USPEB1)	5000.18653	17 35 09.37	–30 12 44.8	18.173	0.877	0.205390
000038 (USPEB2)	5000.07887	17 41 46.29	–34 17 52.5	17.404	0.320	0.202223
000039 (USPEB3)	5000.11863	17 43 05.13	–24 32 42.7	16.575	0.411	0.204719
000104 (USPEB4)	5000.07012	17 59 31.86	–33 59 15.9	16.628	0.782	0.200749
000133 (USPEB5)	5000.07375	18 03 54.84	–30 27 10.0	17.505	0.556	0.204019
000184 (USPEB6)	5000.05443	18 13 54.61	–29 24 42.7	18.275	1.067	0.191307
000215 (USPEB7)	5000.16816	18 47 45.32	–29 30 18.0	18.025	0.500	0.192322
000222 (USPEB8)	5000.08073	19 00 43.67	–31 21 55.0	18.188	0.796	0.205228

Qian et al. (2007) and Qian et al. (2013a) purported that these systems evolve into short-period systems via AML, through the magnetic stellar wind. The systems in our study belong to either K or M spectral type that is very close to the cut-off limit (i.e., $P<0.22$ d). The orbital AM (J_{rel}) of these binaries, obtained utilizing the equation proposed by Popper & Ulrich (1977), is listed in Table 3. The computed orbital AM of these binaries was smaller than the AM values defined for the contact systems. An orbital AM with a low fill-out factor implies past episodes of AML

Table 2 Photometric Parameters of the Eight USPEBs Obtained Using the WD Method

USPEB	1	2	3	4	5	6	7	8
period (d)	0.2054	0.2022	0.2047	2007	0.20402	0.1913	0.1923	0.2052
$T_{e,h}$ (K)	3460	3597	3377	4005	3706	3694	3991	4051
$T_{e,h}$ (K)	3494±32	3565±31	3271±8	3972±10	3622±6	3714±20	3966±30	3984±19
q	0.74±0.05	1.13±0.06	1.86±0.02	0.92±0.05	1.09±0.02	0.70±0.01	0.86±0.06	0.74±0.09
i (°)	81.61±1.00	65.32±0.70	67.61±0.22	77.48±0.38	74.40±0.17	81.90±0.83	71.46±0.70	80.96±0.71
Ω	3.0230±0.092	4.0324±0.093	4.9879±0.027	3.3354±0.074	3.8949±0.025	2.8751±0.022	3.5023±0.113	3.2067±0.159
fillout factor (f)	0.0106	0.0644	0.2048	0.0296	0.0288	0.0025	0.0342	0.003
r_h pole	0.4332±0.0187	0.3354±0.0118	0.3109±0.0028	0.4049±0.0133	0.3494±0.0035	0.4484±0.0049	0.3639±0.0164	0.3861±0.0261
side	0.4695±0.0268	0.3505±0.0143	0.3254±0.0035	0.4349±0.0184	0.3666±0.0044	0.4916±0.0074	0.3828±0.0204	0.4095±0.0338
back	0.5311±0.0516	0.3785±0.0207	0.3611±0.0057	0.4928±0.0352	0.3981±0.0066	0.5765±0.0184	0.4144±0.0300	0.4477±0.0529
r_c pole	0.3749±0.0220	0.3928±0.0113	0.4130±0.0025	0.3865±0.0140	0.3640±0.0034	0.3936±0.0059	0.3518±0.0167	0.3566±0.0278
side	0.4029±0.0303	0.4278±0.0139	0.4390±0.0032	0.4140±0.0190	0.3828±0.0043	0.4282±0.0086	0.3694±0.0207	0.3766±0.0354
back	0.4846±0.0830	0.5849±0.0194	0.4695±0.0044	0.4762±0.0396	0.4137±0.0063	0.5653±0.0535	0.4014±0.0310	0.4172±0.0591
L_h	5.9975	5.7482	5.9063	5.873	5.8879	5.74003	6.0079	6.3247
L_c	6.5689	6.8182	6.6601	6.6934	6.6785	6.82637	6.5585	6.2417
$\sum$	0.0168	0.0209	0.0075	0.0272	0.0723	0.0603	0.007	0.0054
spectral type	M_3	M_2	M_3	K_8	M_1	M_1	K_8	K_7

h – hot component; c – cool component.

Table 3 The absolute parameters, AM (H_{orb}), AML rate ($\frac{dH}{dt}$) and orbital AM ($\log J_{rel}$) obtained for the eight USPEBs.

Variable	M_1 ($M_\odot$)	M_2 ($M_\odot$)	R_1 ($R_\odot$)	R_2 ($R_\odot$)	L_1 ($L_\odot$)	L_2 ($L_\odot$)	H_{orb} ($\times 10^{51}$)	$\frac{dH}{dt}$ ($\times 10^{41}$)	$\log J_{rel}$
USPEB1	0.5185	0.3837	0.6135	0.5309	0.2316	0.1877	1.5062	–4.65	–0.915
USPEB2	0.4071	0.4600	0.4639	0.5433	0.1008	0.1125	1.4292	–2.12	–0.938
USPEB3	0.3128	0.5819	0.4381	0.582	0.0692	0.0967	1.3806	–1.44	–0.953
USPEB4	0.4431	0.4076	0.5538	0.5286	0.1901	0.1639	1.3839	–3.32	–0.952
USPEB5	0.4244	0.4626	0.4898	0.5103	0.1369	0.1221	1.4915	–2.44	–0.919
USPEB6	0.4388	0.3072	0.5685	0.499	0.2433	0.2011	1.0619	–3.63	–1.067
USPEB7	0.4071	0.3501	0.4653	0.4498	0.1524	0.1324	1.1193	–2.24	–1.044
USPEB8	0.5175	0.3829	0.5461	0.5044	0.2095	0.1491	1.5008	–3.68	–0.917

Table 4 List of Well Studied USPEBs along with Objects in the Study

Variable	Period (d)	r_p	r_s	$(B-V)_p$	$(B-V)_s$	ρ_1 (g cm^{-3})	ρ_2 (g cm^{-3})
USPEB1[a]	0.2054	0.433	0.375	1.53	1.52	3.17	3.62
USPEB2[a]	0.2022	0.393	0.335	1.49	1.50	3.81	6.12
USPEB3[a]	0.2047	0.413	0.311	1.56	1.62	3.20	7.50
USPEB4[a]	0.2007	0.405	0.387	1.36	1.38	3.68	3.89
USPEB5[a]	0.2040	0.364	0.349	1.48	1.49	4.71	5.32
USPEB6[a]	0.1913	0.394	0.448	1.18	1.47	4.98	2.36
USPEB7[a]	0.1923	0.364	0.352	1.37	1.38	5.70	5.43
USPEB8[a]	0.2052	0.386	0.357	1.34	1.37	4.48	4.21
NSVS 4484038[b]	0.2185	0.407	0.364	0.912	0.962	3.26	3.66
NSVS 7179685[b]	0.2097	0.326	0.456	1.309	1.377	3.92	3.10
NSVS 4761821[b]	0.2175	0.479	0.464	0.944	0.934	2.52	1.23
NSVS 2700153 [b]	0.2285	0.409	0.364	0.852	0.940	2.98	3.28
NSVS 925605[b]	0.2176	0.474	0.408	1.442	1.753	2.23	2.37
NSVS 8626028[b]	0.2174	0.418	0.380	1.198	1.31	3.00	3.29
GSC 2314-0530[b]	0.1926	0.550	0.290	1.661	1.803	2.04	7.10
OGLE BW3 V38[c]	0.1984	0.510	0.440	1.514	1.529	1.88	2.73
NSVS 4876238 [d]	0.2218	0.453	0.264	1.427	1.438	2.98	5.80
ASAS 0718-03[d]	0.2113	0.404	0.371	1.350	1.383	3.51	3.76
SWASP 0746+22[d]	0.2208	0.327	0.505	1.051	1.115	2.90	2.22
NSVS 2729229[d]	0.2288	0.421	0.384	1.393	1.480	2.67	2.86
NSVS 10632802[d]	0.2207	0.344	0.479	0.919	1.109	4.77	1.76

[a] This study; [b] Dimitrov & Kjurkchieva (2015); [c] Maceroni & Montalbán (2004), Jiang et al. (2012); [d] Kjurkchieva et al. (2018).

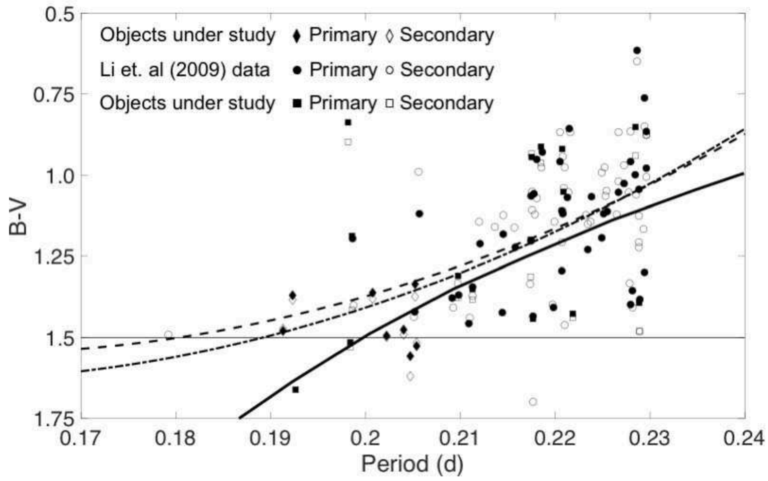

Fig. 4 The period-color diagram of USPEBs is adopted from Li et al. (2019). The *solid black line* represents the SPBE line taken from Rucinski (1998). The *dashed* and *dot-dashed lines* are the quadratic fits to the primary and secondary components, respectively. The *horizontal solid line* at 1.5 (on the $B-V$ axis) signifies the full-convection limit as suggested by Rucinski (1992).

during binary evolution. It also indicates that the systems are not pre-main sequence objects. From the derived primary masses for USPEBs $<0.63\,M_\odot$ (Table 3), we can recall the claim of Jiang et al. (2012) indicating instability in mass transfer leading to the probable coalescence of both the components. However, a discrepancy in the period limit of such short period contact binaries still exists. Our study is an attempt to highlight an unresolved problem in stellar astrophysics, i.e., uncertainty in the period domain of the period-color relation.

Figure 2 depicts the mass-radius distribution for eight USPEBs plotted using Table 3. Both components of the USPEBs manifest identical characteristics, as all data points are above the ZAMS. This indicates evolved or moderately evolved systems. The color-mean density diagram (Fig. 3) was adopted from Li et al. (2019). The objects in our study, along with 55 objects listed by Li et al. (2019), and 13 other well studied objects (Dimitrov & Kjurkchieva 2015; Maceroni & Montalbán 2004; Jiang et al. 2012; Kjurkchieva et al. 2018) were plotted. The mean densities were calculated applying Equations (3) and (4) and are listed in Table 4. We extracted the ZAMS and terminal-age main sequence (TAMS) lines from Mochnacki (1981). We noticed that the eight USPEBs in our study were close to the ZAMS line, satisfying the criteria for W-type stars.

$$\bar{\rho}_1 = \frac{0.0189q}{r_1^3(1+q)P^2} \quad \mathrm{g\,cm^{-3}}. \tag{3}$$

$$\bar{\rho}_2 = \frac{0.0189q}{r_2^3(1+q)P^2} \quad \mathrm{g\,cm^{-3}}. \tag{4}$$

Rucinski (1992) suggested that the fully convective limit causes the short period cut-off of contact binaries, corresponding to a temperature of 3550 K (Pecaut & Mamajek 2013). Thus, considering color index $B-V$ for both components of 76 systems, including the USPEBs in our study, the period-color diagram was plotted (Fig. 4). The dashed black line represents the full-convection limit suggested by Rucinski (1992), and the solid black line signifies the short-period blue envelope (SPBE) adopted from Rucinski (1998). A quadratic term was derived from fitting the data employing the least-squares method. The best-fit equations for the primary and secondary components are expressed below

$$(B-V)_p = 1.002(\pm 2.00) + 32.192(\pm 64.30) \times P + 101.574(\pm 203.20) \times P^2\,, \tag{5}$$

$$(B-V)_s = -0.7870(\pm 1.58) + 31.586(\pm 63.19) \times P + 103.058(\pm 206.20) \times P^2\,. \tag{6}$$

The five systems (USPEB 1, 2, 3, 5 and 6) in our study were mostly seen around the fully convective limit $B-V$ ($\approx$1.5). The remaining three systems (USPEB 4, 7 and 8) were ascertained to be bluer than the SPBE line, which could be related to the claim of Rucinski (1998) that most of the USPEBs are metal-poor stars. However, such speculations can be verified by accurate spectroscopic observations. The existence of USPEBs defined by Rucinski (1992), either below or at the fully convective limit, strongly suggests the need for revision in the existing models that explain the stable configurations of contact binaries (especially USPEBs). Figure 5 illustrates a statistical study of the parameters for 76 USPEBs, considering the upper limit of the period of objects in the study, which may yield

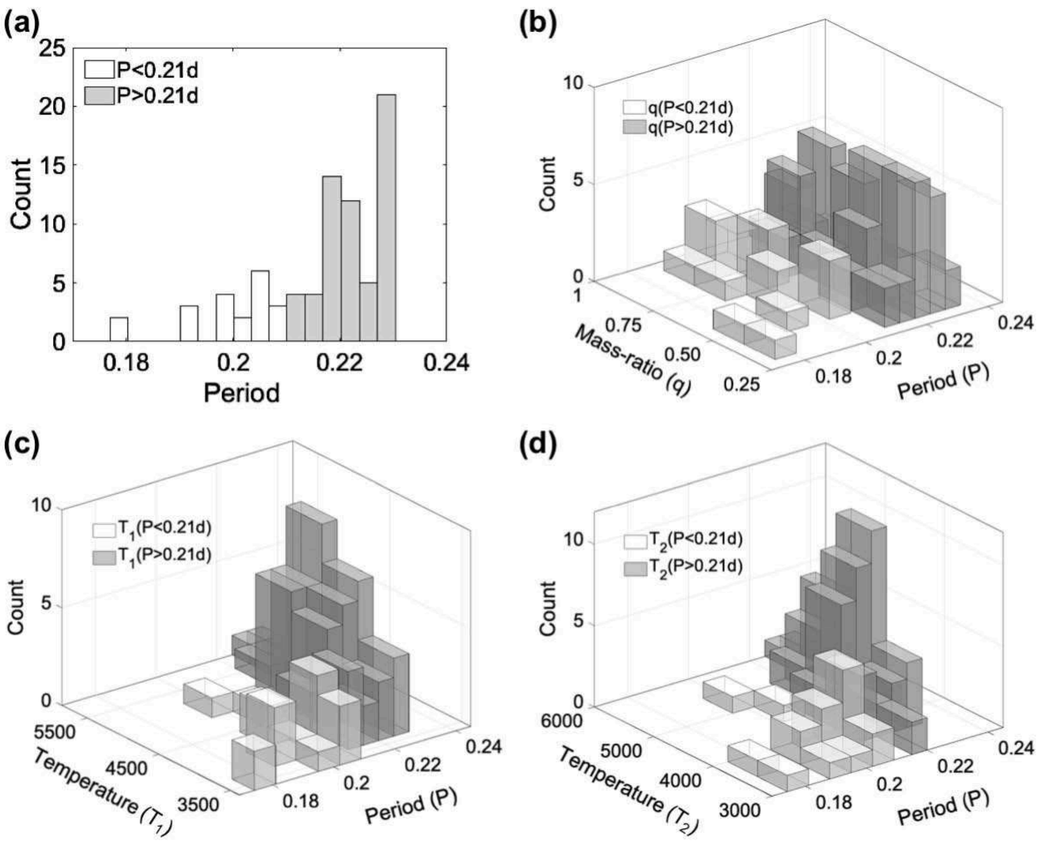

Fig. 5 Number density plots of (a) period distribution, (b) mass-ratio distribution, (c) primary temperature (T_1) distribution and (d) secondary temperature (T_2) distribution.

valuable information on their formation and evolution processes. From Figure 5(a)–(d), the discrepancy in the distribution of objects for periods $<$0.21 d, in contrast to those above 0.21 d, indicates the need for substantial observational studies of USPEBs. However, the dominant distribution of component temperatures was observed to be towards lower values for the short period objects ($P<0.21$ d) and towards higher values for all the others (P $>$ 0.21 d).

To summarize the outcomes of our study, all USPEBs displayed common properties such as later spectral types, shallow contact configuration and poor metallicities. Our study also highlights specific results on their existence with $P<0.22$ d and below the fully convective limit. To accommodate the eight objects in our study (especially the M-dwarf binaries which are considered rare and short-lived by Jiang et al. 2012), we emphasize the need for further refinement of existing theories that explain the formation and evolution of such a rare class of binaries. We did not observe the presence of any third body in our study, which is in contrast to the findings of most USPEBs (Pribulla & Rucinski 2006; D'Angelo et al. 2006; Rucinski et al. 2007; Qian et al. 2013b, 2015a). Further, such findings can be verified only through long-term photometric and spectroscopic observations.

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