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Discovery of star systems at the merger limit by large astronomical surveys

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Abstract. This study presents the identification and the best photometric solution of 92 low mass ratio (LMR) totally eclipsing contact binaries in Catalina Sky Survey data, among which 37 are new discoveries, six are candidates for mergers, and a unique ultra-short period LMR.

Key words: contact binaries- eclipsing binaries – fundamental parameters– data analysis

1. Introduction

A low mass ratio contact binary (LMRCB) is a type of binary star system where the two stars have a significant difference in mass. They are believed to exhibit a low mass ratio cut-off and will merge into fast-rotating single stars due to Darwin's instability (Darwin & Glaisher, 1879). The research on LMRCBs is essential to our understanding of the merging process and the theoretical low mass ratio limit that is still debated around 0.070.1 (Rasio, 1995; Arbutina, 2009). Recently Pešta & Pejcha (2023) found a dependence of the minimum mass ratio on the structure of the components. The confirmation by Tylenda et al. (2011) that Nova 2008 Sco (V1390 Sco) is a red nova formed by the merger of eclipsing cool contact binary components has also increased interest in the different ways leading to stellar mergers. Although the observed period of the premerger of V1309 Sco was long for the observed population of contact binaries (1.4 days), and the primary was more evolved in the suggested model of Stępień (2011), the low mass ratio (0.1-0.15) of the progenitor triggered the investigation of the orbital stability of LMRCBs in search of pre-mergers.

To study LMRCBs at the merger limit, large astronomical surveys such as ASAS-SN (in the V filter; Shappee et al., 2014; Jayasinghe et al., 2018), Catalina Sky Surveys (CSS; Drake et al., 2014b), Zwicky Transient Facility (ZTF[1], in g and r; Masci et al., 2019), and the Asteroid Terrestrial-impact Last Alert System (ATLAS[2], o and c bands; Heinze et al., 2018) play a crucial role as they discover a large number of contact binaries. Although without spectroscopy the automated methods of classification can result in erroneous samples, we can take advantage of the totality in eclipses to search for the most reliable mass ratio (Terrell & Wilson, 2005; Hambálek & Pribulla, 2013)

1.1. Methodology

The sample used focuses on the initial sample of 30 743 eclipsing binaries (Drake et al., 2014a), classified as eclipsing contact binaries from the Catalina Real-Time Survey Data Release 2 (CRTS DR2), and includes observations from 2004-2013. The data was obtained unfiltered to maximize throughput and transformed to an approximate V magnitude. After excluding systems with less than 150 observations and periods longer than 0.8 days, we removed outliers and poor measurements, cleaned the light curves (LCs), and determined the initial epoch values. LMRCBs with total eclipses have LCs with flat bottoms of long duration, unlike common contact systems. We compiled LCs from 42 well-studied LMRCBs based on mass ratios, eclipse totality, and V-band LC availability and performed a high order (20 terms) Fourier decomposition (FD) of the phase-folded, normalized flux LCs of both samples. The performance of FD of the phase-folded, normalized flux LCs of both samples revealed that higher order coefficients can separate LMRCBs from the common contact systems. After visually examining 2100 discoveries, we recognized 92 LMRCBs, including 37 that are newly identified (the remaining 55 systems are common to Sun et al. (2020)).

In addition, new multicolor photometric observations for three of them (CSS J210228.3-031048, CSS J231513.3+34533, and CRTS J163819.6+03485) were carried out using the Ritchey_Chrétien 2.3 m Aristarchos telescope at Helmos Observatory, Greece in 2018-2021.

[1] https://irsa.ipac.caltech.edu/
[2] https://atlas.fallingstar.com/

2. Light-curve modeling and results

The photometric properties of the binaries were analyzed by light curve modeling with PHOEBE-0.31a scripter (Prsa & Zwitter, 2005; Papageorgiou et al., 2019), to explore the parameter space through a detailed scan in the mass ratio–inclination plane, using also in some cases the PIKAIA [3] genetic algorithm optimizer. The uncertainties in the derived physical parameters were estimated by performing Monte Carlo simulations (Papageorgiou & Christopoulou, 2015; Papageorgiou et al., 2023). In the absence of spectroscopic data, given the photometric mass ratio of contact binaries with total eclipses, we use our semi-empirical mass-luminosity relation for the primary component (Christopoulou et al., 2022) to estimate the absolute parameters

$$\log L_1 = \log(0.63 \pm 0.04) + (4.8 \pm 0.2) \log M_1. \quad (1)$$

using the systems temperature by Stassun et al. (2019), the distance by *Gaia* Early Data Release 3 (EDR3; Bailer-Jones et al., 2021) or *Gaia* Data release 3 (DR3; Gaia Collaboration, 2022), and the total line-of-sight Galactic extinction from the 3D dust reddening map of Green et al. (2019). The physical parameters of the 37 new LMRCBs are presented in Christopoulou et al. (2022) and Lalounta et al. (in prep) and of the 92 systems in Lalounta (PhD 2023)[4]. The main results from our study shown in Fig. 1 are as follows:

- The distribution of the mass ratio of the 92 CSS LMRCBs systems has a peak of 0.12 although a significant number has q=0.17. 10% systems have $q < 0.10$ whereas the lower value is 0.07± 0.02 (CSS_J075839+131355).
- Primary masses M_1 are $1.0 - 1.4 M_\odot$ whereas there are a lot of systems with $M_1 > 1.4 M_\odot$ which is unusual for contact binaries (e.g 22% of systems have $M_1 > 1.5 M_\odot$).
- The distribution of T_1 shows that the majority has $T_1 > 6000K$ and 13% has $T_1 > 7000K$ larger than the mean primary temperature 5758±928 K of contact binaries (Latković & Čeki, 2021).
- The 92 CSS LMRCBs present deep, medium, and shallow degrees of contact although 50% of them have $f > 45\%$. By including all previously known LMRCBs from literature (updated Table A1; Christopoulou et al., 2022) together with contact binaries with spectroscopic mass ratio (EW_{sp}), we confirm their conclusion that the smaller the q value, the larger the fill-out factor distribution range.

We compared our parameters of the 55 common systems to those of Sun et al. (2020) using CRTS DR1 data, different analysis, and relations for the absolute parameters and found that the mass ratios are similar within the reported

[3] http://n2t.net/ark:/85065/d70r9ntr
[4] https://hdl.handle.net/10889/26132

errors. We observe the largest deviation in the ratio of the temperatures of the components when their difference is increasing.

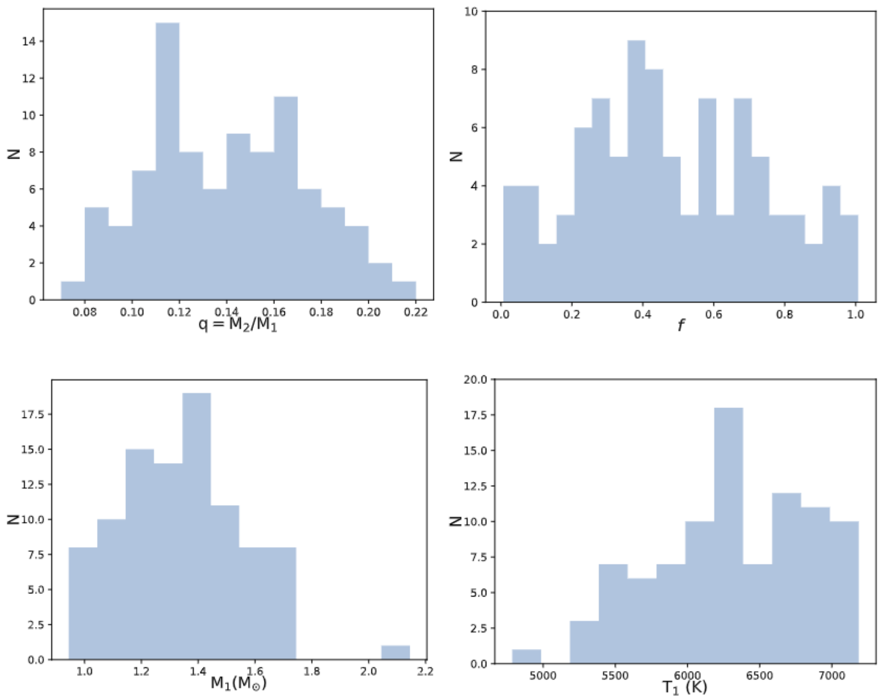

Figure 1. The distributions of q, f, M_1 and T_1 of the 92 CSS LMRCBs

2.1. Orbital stability

To investigate the dynamical stability we apply

– Darwins criterion by adopting the gyration radius k_2^2=0.205 for convective secondary because of its very low mass and k_1 from the derived linear relationships (Christopoulou et al., 2022) as $k_1 = -0.250\,M + 0.539$ for stars with $M = 0.5-1.4\,M_\odot$ and $k_1 = 0.014\,M+0.152$ for stars with $M > 1.4M_\odot$.

– the instability mass ratio criterion of (Wadhwa et al., 2021) that involves the mass of the primary and the degree of contact.

Systems that fulfill both criteria $(J_s/J_o)_k \sim 0.3$ and $q/q_{inst} \sim 1$ are considered candidates for merging. These are

– CSS_J075839.9+131355

– CSS_J090748.9+375447
– CSS_J093010.1-021624
– CSS_J095733.5+151606
– CSS_J224450.0+071816
– CSS_J231513.3+345335.

2.2. The unique low mass ratio and ultra short period contact binary

We have discovered the first LMRCB binary system CRTS_J163819.6+034852 ($q = 0.16 \pm 0.02$) with a period (P=0.2053321 d) under the contact binary period limit (Fig 2 left). It appears to be an A subtype, in deep contact ($72 \pm 15\%$), in which a primary of $F5/F4$ spectral type is eclipsed during the deeper minimum. Based on the analysis of the dedicated BVRI LCs and LCs from CSS, ASAS-SN, ZTF, ATLAS and the distance of Gaia DR3, the physical parameters are estimated as $M_1 = 1.19 \pm 0.02 M_\odot$, $M_2 = 0.19 \pm 0.02 M_\odot$, $R_1 = 0.93 \pm 0.02 R_\odot$, $R_2 = 0.44 \pm 0.01 R_\odot$, $L_1 = 1.45 \pm 0.07 L_\odot$ and $L_2 = 0.31 \pm 0.05 R_\odot$ (Papageorgiou et al., 2023).

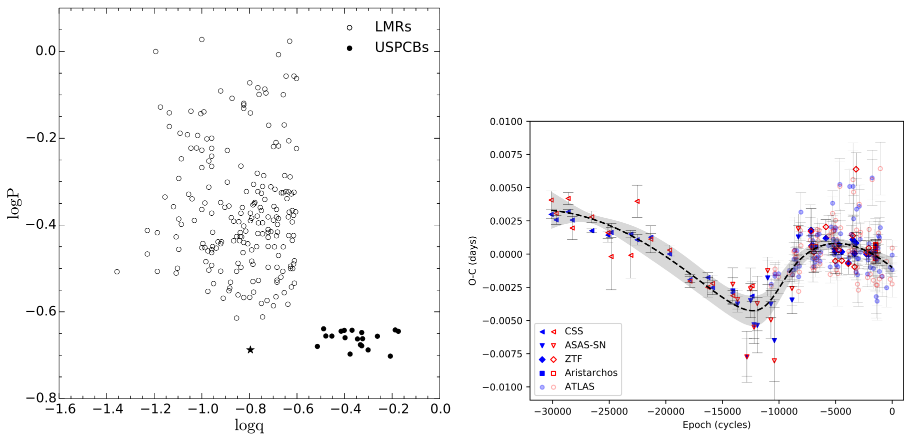

Figure 2. (left) Distribution of LMRCBs (open circles, from Christopoulou et al., 2022) and Ultra Short Period Contact Binaries (USPCBs) (filled circles, from Papageorgiou et al., 2023) in the $\log q - \log P$ plane. The star symbol represents CRTS_J163819. (right) $O - C$ diagram of CRTS_J163819. The dashed line represents the full contribution of the quadratic plus LTTE ephemeris.

In the time span of 15 yr (2004–2021), the orbital period of this unique object decreases at a rate of -7.11×10^{-8} days yr^{-1} implying mass transfer at the rate of $dM_1/dt = -2.61 \times 10^{-8} M_\odot$ yr^{-1} in addition to a periodic variation, interpreted by the light travel time effect (Figure 2 right). The latter may be due to the presence of a circumbinary companion of minimum mass $M_3 = 0.18 M_\odot$ at a separation from the binary $\sim 11.0 AU$. Through the analysis of stability criteria, CRTS_J163819.6+03485 is currently in a stable contact stage. According to Stepien (2006) and Stępień & Kiraga (2015, and references therein) the formation and evolution investigation of the progenitors of CRTS J163819.6+03485 indicate that it may have evolved from a detached binary with masses $0.89 + 0.46 M_\odot$ and an initial period of 2.2 days or from a detached binary with masses $1.01 + 0.35 M_\odot$ and 2.5 days that required around 10.7 and 7.2 Gyr, respectively, to match the current properties of the system.

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