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Abstract

We presented the first photometric light curve solutions of four W Ursae Majoris-type contact binary systems. This investigation utilized photometric data from the Transiting Exoplanet Survey Satellite and Gaia Data Release 3 (DR3). We used the PHysics Of Eclipsing BinariEs Python code and the Markov Chain Monte Carlo method for these light curve solutions. Only TIC 249064185 among the target systems needed a cold starspot to be included in the analysis. Based on the estimated mass ratios for these total eclipse systems, three of them are categorized as low mass ratio contact binary stars. The absolute parameters of the systems were estimated using the Gaia DR3 parallax method and the orbital period and semimajor axis (P–a) empirical relationship. We ascertained that the TIC 318015356 and TIC 55522736 systems are A-subtypes, while TIC 249064185 and TIC 397984843 are W-subtypes, depending on each component's effective temperature and mass. We estimated the initial masses of the stars, the mass lost by the binary system, and the systems' ages. We displayed star positions in the mass–radius, mass–luminosity, and total mass–orbital angular momentum diagrams. In addition, our findings indicate a good agreement with the mass-temperature empirical parameter relationship for the primary stars.

Full Text

Four Total Eclipsing Contact Binary Systems: The First Photometric Light Curve Solutions Employing TESS and Gaia Surveys

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Abstract

We present the first photometric light curve solutions for four W Ursae Majoris-type contact binary systems. This investigation utilizes photometric data from the Transiting Exoplanet Survey Satellite (TESS) and Gaia Data Release 3 (DR3). We employed the PHysics Of Eclipsing BinariEs (PHOEBE) Python code and the Markov Chain Monte Carlo (MCMC) method for these light curve solutions. Only TIC 249064185 among the target systems required inclusion of a cool starspot in the analysis. Based on the estimated mass ratios for these total eclipse systems, three of them are categorized as low mass ratio contact binary stars. The absolute parameters of the systems were estimated using the Gaia DR3 parallax method and the orbital period–semimajor axis (P–a) empirical relationship. We determined that TIC 318015356 and TIC 55522736 are A-subtypes, while TIC 249064185 and TIC 397984843 are W-subtypes, according to each component's effective temperature and mass. We estimated the initial masses of the stars, the mass lost by the binary system, and the systems' ages. We display the star positions in the mass–radius, mass–luminosity, and total mass–orbital angular momentum diagrams. Additionally, our findings indicate good agreement with the mass–temperature empirical parameter relationship for the primary stars.

Key words: (stars:) binaries (including multiple): close — stars: fundamental parameters — methods: data analysis

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1. Introduction

W Ursae Majoris (W UMa)-type eclipsing contact binary systems consist of two late-type stars with short orbital periods. The two components in these systems overfill their respective critical Roche lobes and share a common envelope (Kopal 1959). Contact binaries are generally classified into two subtypes, A and W (Binnendijk 1970), which can be determined by estimating the temperatures and masses of the stars.

The stars in contact systems transfer mass and energy to each other (Lucy & Wilson 1979), and their orbital periods change during this process. The orbital period of contact systems plays a crucial role in studying empirical fundamental parameters and understanding the evolutionary processes of these systems (Lazarević et al. 2021; Loukaidou et al. 2022). Studies have investigated the upper and lower cut-offs of these systems' orbital periods (Zhang & Qian 2020), showing that contact systems' orbital periods typically lie between about 0.2 and 0.6 days (Poro et al. 2024e). Asymmetric light curves in contact and near-contact binaries are commonly observed at phases 0.25 and 0.75. This phenomenon is generally referred to as the O'Connell effect (O'Connell 1951), which is crucial for studying stellar magnetic activity. This asymmetry in light curves is typically resolved by including one or more starspots.

In recent decades, surveys such as Kepler (Borucki et al. 2010), the Catalina Sky Survey (Marsh et al. 2017), the All-Sky Automated Survey for Supernovae (ASAS-SN; Jayasinghe et al. 2018), the Asteroid Terrestrial-impact Last Alert System (Heinze et al. 2018), and the Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2015) have contributed to a dramatic increase in the number of known eclipsing contact binaries. However, our knowledge of W UMa stars remains incomplete despite these improvements. Light curve modeling, mass ratio estimation, and component temperature determination enable the calculation of absolute stellar parameters: the masses, radii, and luminosities of the components in solar units (Kallrath & Milone 1999). Additionally, increasing the number of well-studied W UMa binaries with absolute parameters enables astronomers to derive empirical parameter relationships.

In this investigation, we present a photometric analysis of four contact binary systems. The paper is organized as follows: Section 2 provides specifications of the target systems and the data set. Section 3 contains the light curve solutions. Section 4 presents the estimation of absolute parameters. Finally, Section 5 includes the discussion and conclusion.

2. Target Systems and Data Set

For this investigation, we selected four contact binary stars: TIC 249064185, TIC 318015356, TIC 397984843, and TIC 55522736. Based on the appearance of their light curves, these systems exhibit total eclipses, but detailed photometric analysis has not yet been performed on them. The target systems are all categorized as contact binary stars in several catalogs, including ASAS-SN (Jayasinghe et al. 2018), ZTF (Chen et al. 2020), GCVS (Samus' et al. 2017), APASS DR9 (Henden et al. 2015), and VSX catalogs. The general characteristics of the targets are presented in Table 1, including the names of the systems in various catalogs, coordinates and distances from the Gaia DR3 database, and reference ephemerides including orbital period P_0 and minimum time t_0 from the literature. We utilized an online tool to convert the Heliocentric Julian Date

(HJD) to the Barycentric Julian Date (BJDTDB) since t_0 was reported in HJD.

We used TESS data to analyze these systems. TESS provides high-quality time-series data for each target system, obtained from the Mikulski Archive for Space Telescopes (MAST). TESS-style light curves were extracted from MAST using the LightKurve code. The data were detrended using the TESS Science Processing Operations Center pipeline (Jenkins et al. 2016). We selected each system's light curves based on the most recent or highest-quality observed TESS sector available. The characteristics of the observations and sectors used in this study are listed in Table 2. The apparent magnitude (V) of the systems in Table 2 is from the TESS Input Catalog (TIC) v8.2 database.

We also used data from the Gaia space-based telescope. Time-series photometric data were accessed through the online service provided by the Gaia team at the Astronomisches Rechen-Institut. The data were downloaded in VOTable format, a standard file format used in the Virtual Observatory, and analyzed using TOPCAT (Taylor 2005). We extracted Gaia's G photometric filter data.

3. Light Curve Solutions

We analyzed the light curves of the contact systems using the PHysics Of Eclipsing BinariEs (PHOEBE) Python code version 2.4.9 (Prša et al. 2016; Conroy et al. 2020). We also utilized the BSN application. The four target binary systems' light curves were investigated for the first time. The short orbital period and classification in the catalogs led us to choose a contact mode, and the light curves of each system exhibited eclipsing contact binary features. We assumed a bolometric albedo of $A_1 = A_2 = 0.5$ and gravity-darkening coefficients of $g_1 = g_2 = 0.32$ (Lucy 1967; Ruciński 1969). The PHOEBE code provided the limb darkening coefficients as a free parameter, and the stellar atmosphere was modeled using the Castelli & Kurucz (2004) study.

We set the effective temperature of the hotter stars using the temperature reported by Gaia DR3. The effective temperature set for the hotter star is close to the value obtained from the orbital period–effective temperature (P–T_1) relationship presented by Lazarević et al. (2021). Comparing the final effective temperatures of the hotter stars to the Gaia DR3 values, they fall within an acceptable range (Poro et al. 2025).

We obtained the mass ratio (q) of the systems through q-search in the photometric data, searching a range of mass ratios between $q = 0.1$ and $q = 10$. We then narrowed the interval and searched again according to the minimum sum of squared residuals. Figure 1 displays the q-search results for the four systems. The q-search curves show a sharp minimum, which allows determination of an acceptable mass ratio for these total eclipsing contact systems (Li et al. 2021; Poro et al. 2024d).

The well-known O'Connell effect is indicated by the asymmetry in the brightness maxima in the light curves of eclipsing binary stars (O'Connell 1951; Sriram et al. 2017). One explanation for this phenomenon is the existence of starspots due to magnetic activity on the stellar surface. Only TIC 249064185 required a cool starspot in our analysis.

We used PHOEBE's optimization tool to improve the light curve solutions and yield initial results. The final parameter values and their uncertainties were obtained using the Markov Chain Monte Carlo (MCMC) approach based on the emcee package (Foreman-Mackey et al. 2013). Five main parameters—including inclination (i), mass ratio (q), fill-out factor (f), and effective temperatures T_1 and T_2—were considered for the MCMC modeling process. We selected a Gaussian distribution that adequately encompasses the entire observational light curve and employed 36 walkers and 1500 iterations for each target system. According to the light curve solutions, no target system showed evidence of a third body (l_3).

Table 3 presents the results of the light curve solutions. Figure 2 shows corner plots from the MCMC modeling, and Figure 3 displays the observed and final synthetic light curves for the binary systems. Three-dimensional views of the binary systems and starspots are shown in Figure 4, which represents the effective temperature variations on the stellar surfaces (Paki et al. 2023).

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4. Absolute Parameters

One of the main objectives of studies on contact binary systems is to estimate their absolute parameters. Studying the evolution of stellar binary systems requires an appropriate standard of accuracy for estimating absolute parameters such as mass, radius, and luminosity. Using Gaia DR3 parallax yields more accurate results for estimating absolute parameters (Li et al. 2021; Poro et al. 2024b, 2024c). In this estimation method, we used observational parameters such as orbital period P and apparent magnitude V, light curve solution results (q, $l_{1,2}/l$, r(mean)$_{1,2}$, T_1, T_2), and Gaia DR3 parallax. We used $l_{1,2}/l$ from the G filter in the light curve solutions. The V magnitude of each system comes from the TIC database for calculations.

The calculation process and equations used are as follows:

The apparent magnitude is corrected for extinction using:

$$m_V - M_V = 5\log_{10}(d) - 5 + A_V$$

The bolometric correction is applied using:

$$M_{\text{bol}} = M_V + BC$$

The luminosity is calculated from:

$$\log(L/L_\odot) = -0.4(M_{\text{bol}} - M_{\text{bol},\odot})$$

The mass is determined through the mass–luminosity relation:

$$\log(M/M_\odot) = a \cdot \log(L/L_\odot) + b$$

The semimajor axis is derived from:

$$a = \left(\frac{GM_{\rm tot}P^2}{4\pi^2}\right)^{1/3}$$

The individual stellar radii are estimated using:

$$R_{1,2} = r(\mathrm{mean})_{1,2} \cdot a$$

The surface gravity is calculated as:

$$\log g_{1,2} = \log\left(\frac{GM_{1,2}}{R_{1,2}^2}\right)$$

We calculated the extinction coefficient (A_V) using the 3D dust-map Python package considering the Gaia DR3 reported distance (Green et al. 2019). The Flower (1996) study was utilized to compute the bolometric correction (BC) throughout the estimation process.

Reasonable absolute parameter estimation using Gaia DR3 parallax requires a low A_V value (Poro et al. 2024f). Since the A_V values for TIC 249064185, TIC 318015356, and TIC 397984843 are large (Table 4), we also used the orbital period–semimajor axis empirical relationship updated by Poro et al. (2024f) to ensure the validity of our estimations:

$$\log a = 0.73 \log P + 0.45$$

We then used the mass ratio and Kepler's third law to estimate the mass and uncertainty of each star:

$$M_{\rm tot} = \frac{a^3}{P^2}$$

$$M_{1,2} = \frac{M_{\rm tot}}{1+q}$$

The radius of the stars was estimated using r(mean)$_{1}$,$_{2}$. Then L, M_{bol}, and log(g) were calculated using standard astrophysical equations.

The orbital angular momentum (J$_0$) of the systems was calculated for both estimation methods using:

$$J_0 = \frac{q}{(1+q)^2} M_{\rm tot}^{5/3} P^{1/3} G^{2/3}$$

where q is the mass ratio, M_{tot} is the total mass of the system, P is the orbital period, and G is the gravitational constant (Eker et al. 2006).

The results of estimating the absolute parameters for the four systems using both Gaia DR3 parallax and P–a methods are listed in Table 4.

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5. Discussion and Conclusion

We presented the first in-depth light curve solutions and absolute parameter estimations for four contact binary stars, employing TESS and Gaia survey observations. The light curve solutions show that the smallest effective temperature difference between the two stars is 33 K for TIC 318015356, while the largest is 152 K for TIC 397984843 (Table 5). The spectral types of the systems' stars are also presented in Table 5, based on the Cox (2000) and Eker et al. (2018) studies.

We used the q-search method for photometric space-based data for target systems with total eclipses. TIC 249064185, TIC 318015356, and TIC 55522736, with mass ratios of 1/q = 0.115, q = 0.144, and q = 0.135 respectively, are on the border of systems with extremely low mass ratios (Li et al. 2024). Low-mass ratio contact binary systems ($q \leq 0.25$) have been the subject of numerous investigations, yet many questions remain (Li et al. 2022, 2024). Knowledge of the merging process and low-mass ratio limit depends on studies of contact binaries with low mass ratios.

We employed two methods for estimating absolute parameters. First, we used Gaia DR3 parallax (Poro et al. 2024b, Table 4). This method is accurate when certain restrictions are observed, particularly requiring a low A_V value (Poro et al. 2024f). While TIC 249064185, TIC 318015356, and TIC 397984843 have large A_V values, we carefully calculated the extinction. The difference in calculating the semimajor axis in the Gaia DR3 parallax method is denoted as Δa (Poro et al. 2024d), representing the separation value from the primary star to the secondary star (a_1) and from the secondary star to the primary star (a_2). Calculations following the Gaia DR3 parallax method were done separately for each star, and the $a_{1,2}$ values can differ. If Δa is less than 0.1, the results are acceptable and indicate the accuracy of the light curve solutions (Poro et al. 2024b). As shown in Table 5, Δa values for all target systems are less than 0.1. However, we also considered the P–a empirical relationship to calculate the absolute parameters.

According to the light curve solutions, all four systems exhibit total eclipses. The estimation of absolute parameters confirms that these are W UMa-type contact binaries. Contact systems can be divided into two subtypes, A and

W (Binnendijk 1970). In A-subtype systems, the more massive component is the hotter star, while in W-subtype systems, the less massive component has a higher effective temperature. Therefore, TIC 318015356 and TIC 55522736 belong to the A-subtype, while TIC 249064185 and TIC 397984843 are W-subtype systems (Table 5).

There are three categories for fill-out factors of contact binary systems: deep (f $\geq$ 50%), medium (25% $\leq$ f < 50%), and shallow (f < 25%) eclipsing contact binary stars (Li et al. 2022). According to the fill-out factor results from our light curve solutions, three target systems are of the deep type and one is of medium type. We display the fill-out factor category for each target system in Table 5.

In W UMa-type contact binary systems, understanding the initial masses of the two components provides critical insights into their evolutionary processes. We calculated the initial masses of the primary (M_1) and secondary (M_2) components for the four contact binary systems using the method described by Yildiz & Doğan (2013). The reciprocal mass ratio (1/q) serves as a physical constraint to determine the initial masses of the components. The initial mass of the secondary star was estimated using:

$$M_{2i} = M_2 + \Delta M$$

where ΔM represents the mass transferred from the more massive to the less massive component. The mass lost in the system is represented by M_{lost}, and γ is the ratio of M_{lost} to ΔM:

$$\gamma = \frac{M_{\text{lost}}}{\Delta M}$$

We set $\gamma = 0.664$ based on the Yildiz & Doğan (2013) results. We then used the following equation from Yıldız (2014) to determine the ages of the four targets:

$$t = 10^{(0.042 \cdot M_2 - 0.42)}$$

where M_2 is the current mass of the secondary, and M_L is derived from the mass–luminosity relation. The outcomes, including the initial masses of both stars, the mass loss, and the systems' ages, are presented in Table 5. We found these results to be consistent with those reported by Yildiz & Doğan (2013) and Yıldız (2014).

Based on our estimation of absolute parameters, we display the evolutionary state of the systems on the mass–radius and mass–luminosity diagrams (Figures 5(a) and 5(b), respectively). These figures show the star positions relative to the Terminal-Age Main Sequence (TAMS) and Zero-Age Main Sequence (ZAMS) lines from Girardi et al. (2000). The Th–M_m relationship was presented by

Poro et al. (2024a) using a sample of 428 contact binary systems, where M_m represents the more massive star and T_h the hotter component. According to our results, we placed the stars' positions on the Th–M_m diagram (Figure 5(c)), finding good agreement between the empirical parameter relationship and its uncertainty. We also show the location of each system in the M_{tot}–J_0 diagram (Figure 5(d)) based on the results in Table 4. The area below the quadratic line in Figure 5(d) is associated with contact binary stars, whereas the area above represents detached systems. Consequently, all four target systems lie below the quadratic fit and in the contact binary region.

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