

Dynamic Evolution of the Eclipsing Overcontact Binary Star System BI CVn (Postprint)

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Full Text

Preamble

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Dynamic Evolution of the Eclipsing Overcontact Binary Star System BI CVn

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Abstract

We present a comprehensive analysis of BI CVn, an eclipsing overcontact binary system. New BVR photometric observations, combined with available spectroscopic data, were analyzed simultaneously using the Wilson-Devinney method to derive the orbital and physical parameters of the system. The resulting stellar parameters are $M_1 = 0.58 \pm 0.01 M_\odot$, $M_2 = 1.42 \pm 0.02 M_\odot$, $R_1 = 0.88 \pm 0.01 R_\odot$, $R_2 = 1.31 \pm 0.01 R_\odot$, with an orbital separation of $a = 2.80 \pm 0.01 R_\odot$. Based on all available CCD times of minimum light, including both ground-based and TESS observations, the (O – C) diagram of BI CVn was analyzed. The orbital period exhibits a long-term decrease at a rate of $-2.3239 (\pm 0.0001) \times 10^{-8}$ day yr⁻¹, likely due to mass transfer from the more massive to the less massive component. Superimposed on this trend is a cyclic variation with a period of 56.84 ± 0.08 yr, indicative of a light-travel time effect caused by a third body, whose estimated mass is $0.63 \pm 0.02 M_\odot$. Using these derived parameters, we modeled the binary's evolution through non-conservative processes with the Binary Star Evolution code. The evolutionary tracks of the components were examined in multiple parameter planes, leading to an estimated merger timescale of approximately 2.70 Gyr.

Key words: (stars:) binaries: eclipsing –stars: fundamental parameters –stars: individual (BI CVn)

1. Introduction

W UMa-type systems are eclipsing binary stars with orbital periods of less than a day that exhibit continuous variations in their light curves. These systems consist of two solar-type stars that are either nearly or fully in contact with one

another. Both components have filled their own Roche lobes and are surrounded by a common convective envelope. Despite their advanced age, the components of W UMa-type systems exhibit rapid rotation. These systems may be progenitors of fast-rotating single stars known as blue stragglers, observed in star clusters (e.g., Samec et al. 2011). Due to strong tidal interactions between the stars, their spins and orbits are synchronized. Additionally, they have the shortest orbital periods and lowest angular momentum of all main-sequence binary systems. It is predicted that these systems constantly lose angular momentum, causing their orbits to shrink and the stars to move closer together, ultimately leading to the merging of the two stars into a single entity (e.g., van't Veer 1979). The most significant observational evidence of this process is the discovery that Nova Sco, which erupted in 2008, resulted from the collision and merging of the binary components in V1309 Sco (Tylenda et al. 2011). Bulut & Aşkın (2022) found that 21% of W UMa systems brighter than $V = 10$ mag in the General Catalog of Variable Stars are triple systems. These are important systems for studying the formation and evolution of multiple systems, as well as being unique astrophysics laboratories for investigating many physical phenomena such as orbital period change, gravitation, mass loss, mass transfer between components, and orbital angular momentum evolution.

BI Canum Venaticorum (BI CVn, NVS 6077 = BD +372356 = 2MASS J13031641+3637005 = GSC 2534-1628 = HIP 63701) was first identified as a variable star by Filatov (1960), who suggested that it may belong to the W UMa-type of eclipsing binary. The system has been studied by numerous authors (Zhukov 1982; Liu & Tan 1984, 1988; Demircan 1987; Maceroni & van't Veer 1996; Nelson et al. 2014), who classified it as a W-subtype W UMa binary and proposed mass transfer as a reason for the increase in its orbital period. Maceroni & van't Veer (1996) later classified it as an A-subtype and determined its absolute parameters. Lu (1988) reported a mass ratio of 0.41 based on his spectroscopic observations. Finally, Nelson et al. (2014) performed photometric and spectroscopic analysis of the system, determining the photometric and absolute parameters by analyzing the light curves and radial velocity curves of BI CVn.

In this study, we present new CCD observations of BI CVn together with their photometric solutions. We also analyze changes in the orbital period using all available eclipse times, which show a combination of cyclical fluctuations and a continuously decreasing period. With these results, we study the dynamical evolution scenarios of the system and determine its initial orbital parameters.

2. CCD Photometric Observations

Photometric observations of BI CVn were conducted using an ALTAU47 CCD camera (E2V CCD47-10, Peltier cooling, 13 μ m pixel size, 1024 \times 1024 pixels) mounted on the 30 cm Schmidt-Cassegrain telescope (T30) at Çanakkale Onsekiz Mart University Ulupnar Observatory (COMUG). The observations were carried out over four nights—on 2015 April 12 and 28, and May 8 and 9.

Johnson-Cousins BVR filters were used during the observations. Some catalog information for the eclipsing binary system (V), the comparison star (C1), and the check star (C2) from the SIMBAD database is presented in Table 1.

The CCD image reductions were performed using the C-MUNIPACK software package (Motl 2007). The procedure for bias correction, flat-field correction, and aperture photometry was applied to all the CCD images.

From our new CCD observations with the BVR filters, a total of seven new times of light minima were determined, four of which were primary minima. The new times of minima and their uncertainties were calculated using the well-known method of Kwee & van Woerden (1956). For times of minimum light obtained in BVR filters on the same observation night, average values were calculated. These minimum times were published by Bulut et al. (2017). BVR light curves of the system are displayed in Figure 1. The phases were calculated using the following linear light elements given by Nelson et al. (2014):

$$\text{HJD minI} = 2456385.9771 + 0.38420923 \times E$$

3. Photometric Solutions

The light curves in the BVR bands, along with the radial velocity curves provided by Nelson et al. (2014), were analyzed together using The PHysics Of Eclipsing BinariEs (PHOEBE) code (version 0.31, Prša & Zwitter 2005), which is an implementation of the Wilson-Devinney computational (W-D) program (Wilson & Devinney 1971). Nelson et al. (2014) collected spectroscopic data using the Cassegrain spectrograph attached to the 1.85 m Plaskett telescope at Dominion Astrophysical Observatory in Victoria, British Columbia, Canada. Their dataset includes a total of seven spectra of medium resolution.

The W-D program offers several modes to model different binary system configurations. In this study, Mode 3, representing an “over-contact binary not in thermal equilibrium,” was chosen. The control parameter IPB was set to 1, which allows the decoupling of the secondary star’s luminosity (L_2) and temperature (T_2), enabling independent adjustments of the luminosities of both stars (L_1 and L_2).

Several parameters were fixed during the analysis based on the system’s known properties. The temperature of the primary star (T_1) was set to 6125 K, as determined by Nelson et al. (2014). The gravity-darkening coefficients ($g_1 = g_2$) and bolometric albedos ($A_1 = A_2$) were fixed at their theoretical values of 0.32 and 0.50, respectively, consistent with convective atmospheres (Lucy 1968). The monochromatic limb-darkening coefficients ($x_{1,2}$) were automatically interpolated by the PHOEBE code based on the tables provided by van Hamme (1993). A circular orbit was assumed, with the orbital eccentricity (e) set to 0 and the longitude of periastron (ω) fixed at 90° . Third light (l_3) was excluded from the analysis by setting it to 0.

There is a clear asymmetry between the maxima of the light curve of BI CVn, suggesting the presence of the O'Connell effect (O'Connell 1951). To account for this effect, a cold spot on the secondary star was defined in the light curve solution. Adjustable parameters included the reference epoch (T_0), orbital period (P), semimajor axis (a), systemic radial velocity (V_γ), orbital inclination (i), surface temperature of the secondary star (T_2), the dimensionless surface equipotential (Ω_1 and Ω_2), the mass ratio ($q = M_2/M_1$), and monochromatic luminosity of the primary star (L_1). The W-D program iteratively adjusted these parameters until the corrections for each free parameter fell below their respective standard deviations.

The optimal parameters derived from the analysis are listed in Table 2. Figure 1 compares the observed light curves in BVR bands with the theoretical models, while Figure 2 displays the modeled radial velocity curves. The geometric configuration at phase 0.24 is shown in Figure 3. Nelson et al. (2014) performed light curve analysis for three sets of light curve data taken by different observers at different observatories. The light curve analysis results given in Table 2 are in reasonable agreement with the results of Nelson et al. (2014).

4. Changes in the Orbital Period

Investigation of orbital period variations plays a vital role in understanding the dynamical evolution of binary star systems, the existence of additional bodies, and mass exchange between stellar components. Accordingly, studies on orbital period changes are of considerable significance in binary system research. The first detailed analysis of the orbital period variation of BI CVn was conducted by Qian et al. (2008), who reported a secular decrease in the orbital period at a rate of $dP/dt = -1.51(\pm 0.12) \times 10^{-7} \text{ day yr}^{-1}$. Furthermore, they identified a periodic oscillation with an amplitude of 0.151 days and a period of approximately 27.0 yr. This cyclic modulation was interpreted as the result of the light-travel time effect (LITE) due to a gravitationally bound third body, with the minimum mass of this third component estimated to be $0.58 M_\odot$.

In the present study, we constructed an updated (O – C) diagram for BI CVn by compiling all available times of minimum light from the literature. During our photometric observations, we recorded seven eclipses, including four primary eclipses. Additionally, 491 minima times were obtained from TESS data. New minimum times and their associated errors were calculated using the technique described by Kwee & van Woerden (1956). The TESS-based minimum times are listed in Table 3, while the others are presented in Table 4. Since TESS observation times are provided in Barycentric Julian Date (BJD), other observed minima were converted from Heliocentric Julian Date (HJD) to BJD using an online conversion tool (<https://astrutils.astronomy.osu.edu/time/>). As a result, a total of 719 minimum times were collected. The (O – C) values were calculated using the linear ephemeris given in Equation (1). The resulting (O – C) diagram, displayed in the upper panel of Figure 4, reveals cyclical variations superimposed on a parabolic trend, exhibiting a long-term orbital period

decrease.

The (O – C) analysis was conducted using the computer program developed by Zasche et al. (2009). A total of 707 observed minima times were included in the analysis, with observational weights assigned based on the observation method: visual data were weighted as 1, photographic data as 5, while photometric and CCD data as 10. The parabolic variation observed in the (O – C) diagram is typically attributed to mass transfer between the stellar components or mass loss from the binary system. This variation can be modeled using the following ephemeris:

$$\text{BJD minI} = T_0 + P \times E + Q \times E^2$$

where the quadratic term indicates a steady decrease in the orbital period. The derived rate of period change is $dP/dt = 2Q/P = -2.3239 (\pm \$0.0001) \times 10^{-8}$ day yr^{-1} , consistent with ongoing mass transfer from the more massive to the less massive component.

Residuals from the parabolic fit reveal additional cyclic variations in the (O – C) data. Such periodic modulations are generally attributed to one of two mechanisms: (1) magnetic activity cycles in one or both stars, or (2) LITE induced by an unseen tertiary component gravitationally bound to the system. The periodic component of the (O – C) diagram was modeled using the classical LITE formulation proposed by Irwin (1959) for triple systems:

$$(O - C) = \frac{a_{12} \sin i_3}{c} \left[\frac{1 - e_3^2}{1 + e_3 \cos \nu} \sin(\nu + \omega_3) + e_3 \sin \omega_3 \right]$$

where a_{12} is the semimajor axis of the eclipsing binary's orbit around the center of mass of the triple system, i_3 is the inclination, e_3 the eccentricity, ν the true anomaly, and ω_3 the longitude of periastron. The parameters derived from the combined parabolic and LITE fit are presented in Table 5.

The top panel of Figure 4 illustrates the best-fitting model superimposed on the (O – C) data, while the residuals are shown in the bottom panel. The analysis reveals a cyclic variation with a semi-amplitude of 0.0256 ± 0.0007 day and a modulation period of 56.84 ± 0.08 yr. From this model, the minimum mass of the third body is estimated to be $0.63 \pm 0.02 M$.

An alternative explanation for cyclic (O – C) variations involves magnetic activity in one or both components, as proposed by Applegate (1992). In this scenario, orbital period changes arise due to cyclic variations in the stellar quadrupole moment ΔQ , expressed as (Lanza & Rodonò 2002):

$$\Delta Q = \frac{Ma^2}{9}$$

where M is the mass of the magnetically active star, and a is the orbital separation. The computed values of ΔQ for the two components are $5.2 \times 10^{49} \text{ g cm}^2$ and $1.3 \times 10^{50} \text{ g cm}^2$, respectively. These values are significantly lower than the typical range of 10^{51} - 10^{52} g cm^2 expected for the Applegate mechanism to be viable (Lanza & Rodonò 1999), indicating that magnetic activity is unlikely to account for the observed cyclic behavior in BI CVn.

5. Absolute Dimensions

The absolute parameters of eclipsing binary star systems can be determined through simultaneous analysis of their radial velocity and light curves. For BI CVn, the photometric mass ratio of the components ($q = M_2/M_1$) was determined to be 2.436 ± 0.003 . The separation between the centers of mass of the component stars was derived as $a = 2.80 \pm 0.01 R$, as presented in Table 2. Using Kepler's third law, expressed as $M_1 + M_2 = a^3/P^2$, the masses of the components were calculated to be $M_1 = 0.58 \pm 0.01 M$ and $M_2 = 1.42 \pm 0.02 M$.

Applying the definition of fractional radii, $r_{1,2} = R_{1,2}/a$, from Table 2 together with the mean fractional radii ($r_1 = 0.3066 \pm 0.0005$ and $r_2 = 0.4698 \pm 0.0005$), the radii of the primary and secondary components were calculated as $R_1 = 0.88 \pm 0.01 R$ and $R_2 = 1.31 \pm 0.01 R$, respectively. These absolute parameters are summarized in Table 6. The bolometric corrections (BC) are taken from Flower (1996) based on the effective temperatures of the component stars, and the bolometric absolute magnitude of the Sun is assumed to be $M_{\text{bol}} = 4.75$.

The interstellar reddening was estimated using the infrared dust emission maps from Schlafly & Finkbeiner (2011), yielding a color excess of $E(B-V) = 0.0113 \pm 0.0003$. Using this color excess and the apparent magnitude ($V = 10.31$) at maximum light, the distance to the system was calculated to be $219 \pm 10 \text{ pc}$. This value aligns well with the distance of 221 pc derived from the trigonometric parallax (4.52 mas) reported in Gaia Data Release 3 (DR3; Gaia Collaboration et al. 2021).

6. Evolution Models and Discussion

The evolution models of BI CVn were developed using the Binary Star Evolution (BSE) code created by Hurley et al. (2002). This fast and efficient code is designed for simulating the evolution of binary star systems, providing detailed modeling of tidal interactions including the circularization of eccentric orbits and synchronization of orbital and spin motion. The code also accounts for angular momentum loss mechanisms such as gravitational radiation and magnetic braking. In the modeling process, contact binaries are assumed to consist of initially detached components. The models were constructed using the absolute parameters given in Table 6.

Estimating the initial parameters of the components in BSE models is challeng-

ing. However, it can be assumed that the initial masses of the components were larger than their current masses. After experimentation, we chose the initial masses of the components as $1.64 M$ and $0.69 M$, the initial period as $P_0 = 1.87$ day, and the mass fraction of heavy elements as $Z = 0.02$. The mass transfer pattern proposed by St pień & Kiraga (2015) is considered during the semi-detached and contact phases. The simplified dynamo model of Eggleton (2006) was used to account for mass loss due to magnetic braking and stellar winds. Parameters related to dynamo-origin mass and angular momentum loss were taken as $cml = 0.2$ and $chl = 1.0$, respectively. Calculations began at the zero-age main sequence (ZAMS), with the eccentricity assumed to be zero. To evaluate the compatibility of the modeling with the system, the mass, radius, period, relative radii, and positions of the model and the system on the Hertzsprung-Russell (HR) diagram were analyzed, with special attention given to the agreement between the system and the model during the contact phase.

In panel (a) of Figure 5, the positions of the components on the log R-M plane are plotted along with their evolution tracks. The filled and open symbols represent the primary and secondary stars, respectively. The black solid line represents the evolutionary track of the primary component, while the black dashed line shows the change in the Roche lobe radius of the primary component. Similarly, the solid turquoise line represents the evolutionary track of the secondary component, and the dashed turquoise line shows the Roche lobe radius of the secondary component. The ZAMS is displayed as a blue dashed line, and the terminal-age main sequence is represented as a purple dashed line. The evolutionary tracks of the components start from the points marked with plus signs. The point labeled (SD) indicates where the initially massive component fills its Roche lobe, initiating the semi-detached phase. After this point, the massive component transfers mass to the smaller component, causing the smaller component to move up along the ZAMS. During mass exchange, the component gaining mass becomes younger, while the one losing mass ages. At point (C), both components simultaneously fill their Roche lobes and enter the contact phase.

The mass-time diagram in panel (b) shows the changes in the theoretical masses of the components and the total mass. The turquoise solid line represents the initially massive component, and the black solid line represents the initially smaller component. The red solid line shows the change in total mass. The dashed horizontal lines labeled (1) and (2) indicate the observed masses of the components. The vertical blue line labeled (SD) marks when the initially massive component fills its Roche lobe, while the vertical black dashed line labeled (C) indicates when both components fill their Roche lobes and the system enters the contact phase. The dashed red line labeled (A) represents the predicted age of the system in the model. After the contact phase, the dashed horizontal lines (1) and (2) intersect the theoretical masses simultaneously at vertical line (A).

In panel (c), the changes in the theoretical radii of the components over time are shown. The solid turquoise line indicates the radius of the initially massive

component, and the dashed turquoise line represents its Roche lobe radius. The black solid line shows the radius of the initially smaller component, and the dashed black line indicates its Roche lobe radius. The vertical blue line marks when the initially massive component fills its Roche lobe, while the vertical black dashed line marks when both components fill their Roche lobes. The dashed red line labeled (A) represents the predicted age of the system in the model.

Panel (d) shows the change of the theoretical orbital period of the system versus time. The black dashed horizontal line represents the observed orbital period. The vertical blue dashed line marks when the initially massive component fills its Roche lobe, and the vertical black dashed line marks when both components fill their Roche lobes and the system enters the contact phase. The dashed red line represents the predicted age of the system in the model. After the contact phase, the theoretical and observational curves intersect at approximately 2.65 Gyr.

Panel (e) shows the system's status on the HR diagram. The black dot indicates the initially massive component, and the open dot represents the initially smaller component. The black and turquoise solid lines show the evolutionary paths produced by the model for the initially massive and smaller components, respectively. When the system reaches the contact phase, energy transfer between the components causes the temperatures to equalize and the luminosities to converge, resulting in sharp turns in the diagram.

Acknowledgments

In this study, the radial velocity and BVR light curves of BI CVn were analyzed together using the WD method, and the orbital parameters of the system and the fundamental astrophysical parameters of the components were calculated (Tables 2 and 6). The masses of the components in BI CVn were determined to be $0.58 \pm 0.01 M$ and $1.42 \pm 0.02 M$ for the primary and secondary components, respectively, and their radii were calculated as $0.88 \pm 0.01 R$ and $1.31 \pm 0.01 R$, respectively. According to these results, the hotter component of the system is less massive and has the smaller radius, showing that the more massive and cooler component of the system is more evolved than the less massive and hotter component. Additionally, the temperature difference between the components is very small ($\Delta T = 32$ K), indicating that the system is in thermal contact. The degree of contact of the system was determined to be $f = 17.1\%$. The calculated distance of 219 pc is in good agreement with the Gaia DR3 value.

The change in the orbital period of the system was investigated by (O – C) analysis, accomplished by combining new minimum times with all previously published minimum times from the literature. According to the (O – C) analysis results, the quadratic term representing the parabolic change was calculated as $Q = -0.1217 (\pm 0.0001) \times 10^{-10}$ day. This result corresponds to a decrease in the orbital period of $dP/dt = -2.3239 (\pm 0.0001) \times 10^{-8}$ day yr⁻¹, indicating that the orbital period of BI CVn decreases by 0.2 s per century. The mass

transfer rate from the more massive component to the less massive component was determined as $1.97 \times 10^{-8} \text{ M yr}^{-1}$. The shortening in the orbital period may be a sign of an impending merger in a contact binary.

To describe the asymmetric sinusoidal-shaped periodic variation in the O – C diagram, LITE was applied assuming the existence of a tertiary component around BI CVn. Accordingly, it was found that the orbital semimajor axis length of the possible third component was approximately $4.89 \pm 0.13 \text{ au}$, and its period was approximately $56.84 \pm 0.08 \text{ yr}$. The orbital period of the third component is longer than the value of about 27 yr reported by Qian et al. (2008). The minimum mass of the possible third unseen component in the system was calculated as $0.63 \pm 0.02 \text{ M}$, most likely a cool dwarf star.

Possible evolution scenarios of the system were modeled with BSE code. The variation in parameters such as mass, radius, and period throughout the system's evolution was determined in a manner consistent with their current values. According to the modeling results, the initially more massive component filled its Roche lobe at about 2.1 Gyr and the system reached the semi-detached phase. The system evolved to approximately the observed masses and radii at 2.65 Gyr. The probable merger age was estimated to be about 2.70 Gyr.

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