Periodic Variation Studies of the Two Short Period W UMa-type Eclipsing Binaries: LX Lyn and V0853 Aur (Postprint)

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Abstract

In this paper, new light curves (LCs) of contact eclipsing binary (CEB) systems LX Lyn and V0853 Aur are presented and analyzed by using the 2015 version of the Wilson-Devinney (W-D) code. In order to explain their asymmetric LCs, cool starspots on the components were employed. It is suggested that their fill-out degrees are f = 12.0% (LX Lyn) and f = 26.3% (V0853 Aur). At the same time, we found that LX Lyn is a W-type eclipsing binary (EB) with an orbital inclination of i = 8488 and a mass ratio of q = 2.31. V0853 Aur is also a W-type CEB with a mass ratio of q = 2.77 and an orbital inclination of i = 7926. Based on all available times of light minimum, their orbital period changes are studied by using the O − C method. The O − C diagram of LX Lyn reveals a cyclic oscillation with a period of about 14.84 yr and an amplitude of 0.0019 days, which can be explained by the light-travel time effect (LTTE) due to the presence of a third body with a minimum mass of 0.06M . For V0853 Aur, it is discovered that the O − C diagram of the system also shows a cyclic oscillation with a period of 9.64 yr and an amplitude of 0.03365 days. The cyclic oscillation of V0853 Aur can be attributed to the LTTE by means of a third body with a mass no less than 3.77M . The third body may play an important role in the formation and evolution of these systems.

Full Text

Preamble

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Periodic Variation Studies of the Two Short Period W UMa-type Eclipsing Binaries: LX Lyn and V0853 Aur

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Abstract

In this paper, new light curves (LCs) of contact eclipsing binary (CEB) systems LX Lyn and V0853 Aur are presented and analyzed using the 2015 version of the Wilson-Devinney (W-D) code. To explain their asymmetric LCs, cool starspots on the components were employed. The suggested fill-out degrees are f = 12.0% (LX Lyn) and f = 26.3% (V0853 Aur). We found that LX Lyn is a W-type eclipsing binary (EB) with an orbital inclination of i = 84.88° and a mass ratio of q = 2.31. V0853 Aur is also a W-type CEB with a mass ratio of q = 2.77 and an orbital inclination of i = 79.26°. Based on all available times of light minimum, their orbital period changes were studied using the O − C method. The O − C diagram of LX Lyn reveals a cyclic oscillation with a period of about 14.84 yr and an amplitude of 0.0019 days, which can be explained by the light-travel time effect (LTTE) due to the presence of a third body with a minimum mass of 0.06 M . For V0853 Aur, the O − C diagram also shows a cyclic oscillation with a period of 9.64 yr and an amplitude of 0.03365 days. This cyclic oscillation can be attributed to the LTTE caused by a third body with a mass no less than 3.77 M . The third body may play an important role in the formation and evolution of these systems.

Key words: stars: activity -(stars:) binaries (including multiple): close -(stars:) binaries: eclipsing -(stars:) brown dwarfs -stars: evolution -stars: formation

1. Introduction

The formation and evolution of short-period W UMa-type eclipsing binaries (EBs) remain an open question. It is predicted that they formed from initially short-period detached binaries, experiencing angular momentum loss (AML) (e.g., Vant Veer 1979; Qian 2003; Qian 2017; Li et al. 2007; Qian et al. 2018) controlled by magnetic activity, and evolved into contact configurations with very low mass ratio (e.g., Li et al. 2004). Because these binaries have a common convective envelope (CCE) (Lucy 1968), the surface effective temperatures of the components are very close, and the depths of occultations are almost equal.

Binnendijk (1970) made a more accurate comparison of the temperatures and divided them into A and W types. More importantly, the two components of a contact eclipsing binary (CEB) can exchange matter through the Lagrangian point, which can change the evolutionary track of each star in the system. Moreover, it is found that many CEB systems have an extra companion (Pribulla & Rucinski 2006), such as J0344 (Zhang et al. 2020), WW Dra (Liao & Qian 2010), V752 Cen (Zhou et al. 2019), PZ UMa (Zhou & Soonthornthum 2019), J1155 (Zhang et al. 2019), and NSVS 01286630 (Zhang et al. 2018b). The existence of the third body can cause the O − C values of the binary system to change periodically, which is also called the light-travel time effect (LTTE).

The W UMa-type binaries have an obvious period cutoff phenomenon at 0.22 days (Rucinski 1992). According to the latest observations, some CEBs with periods shorter than 0.22 days have been discovered. For example, Davenport et al. (2013) reported a CEB SDSS J001641-000925 with a period of 0.19856 days, and Nefs et al. (2012) also discovered nine EB candidates with periods less than 0.22 days from the Wide Field Camera Transit Survey. Meanwhile, Drake et al. (2014) identified 231 binaries with orbital periods less than 0.22 days using data from the Catalina Sky Survey. After that, Zhang & Qian (2020) proposed a new period cutoff limit at 0.15 days based on many observations and theoretical analysis. The detailed reasons for the period cutoff phenomenon are still unclear. There are several explanations: Rucinski (1992) first proposed the complete convection limit to explain this phenomenon, but it is limited by the contact structure model. Then, some researchers thought that because the timescale of AML is very long, it is difficult to form this kind of binary system (St pień 2006; St pień & Gazeas 2012). In addition, Jiang et al. (2012) believe that it is the result of mass transfer instability during the initial detached phase.

Thanks to the Wide Angle Search for Planets (SuperWASP) survey, LX Lyn (= 1SWASP J080150.03+471433.8) was first discovered and identified as a W UMa-type binary candidate with an orbital period of 0.2175 days (Norton et al. 2011). Then, the first photometric solutions were carried out by Terrell & Gross (2014), who performed a low-resolution spectroscopic analysis and found that it is an over-contact EB. After that, Darwish et al. (2017) explored the relationships between mass-luminosity and mass-radius of the two components, and they ascertained that the less massive component is above the empirical M–R relation (Lucy 1973; Eker et al. 2015). It is found that LX Lyn is an important case to study the formation of a CEB with an orbital period near 0.22 days (Loukaidou et al. 2022).

V0853 Aur (= NSVS 4484038 = 1SWASP J055416.98+442534.0) was first discovered by the Northern Sky Variability Survey (Hoffman et al. 2009). Subsequently, the SuperWASP project determined its orbital period as 0.218495 days (Lohr et al. 2013). Then, its first photometric solutions in the B and V bands were obtained, and it was found that the target is a CEB system (Zhang et al. 2014b). Dimitrov et al. (2015) acquired its low-resolution spectrum and mass ratio of q = 0.792. Thereafter, using the O − C method, Lu et al. (2020) first studied its orbital period variations. They reported a cyclic oscillation, which may be caused by magnetic activity or a third body.

2. Photometric Observation

We obtained new multi-band LCs of LX Lyn and V0853 Aur using the 60 cm reflecting telescope at the Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences. The LCs of LX Lyn in VRcIc bands were acquired on 2020 January 18 and are displayed in Figure 1. Two stars near the target were selected as comparison and check stars (see Table 1). We also adopted the Simple Aperture Photometry (SAP) LCs of LX Lyn from the Transiting Exoplanet Survey Satellite (TESS) from sector 20 with 30 minute cadence and sector 47 with 10 minute cadence. Based on our observations, we obtained 10 light minima times and listed them in Table 2.

For V0853 Aur, we also obtained new photometric LCs in the VRcIc bands on 2021 November 30 and 2020 December 25. The observed images were reduced using the software IRAF, and the corresponding LCs are shown in Figure 2. At the same time, we collected the TESS LCs from sector 19 with 30 minute cadence. In addition, 13 new light minima times were determined and are listed in Table 3.

3. The Analysis of Orbital Period Changes

The O − C method is a useful way to study orbital period changes of binary systems (Qian et al. 2013; Zhang et al. 2018b). For CEBs, orbital period modulations are very common, such as parabolic, cyclic, or both. Exploring the causes of these modulations is very important for detailed study of the dynamical evolution of binary systems and for searching for third bodies. Generally, mass loss through stellar winds and mass transfer between the components can cause secular period variations. In addition, cyclic changes of the orbital period can be explained by the Applegate mechanism or the LTTE (Irwin 1952; Applegate 1992; Borkovits et al. 2016).

3.1. LX Lyn

A total of 91 light minima times were used to analyze the orbital period changes of LX Lyn. Among them, six are from Terrell et al. (2014), eight are from Dimitrov et al. (2015), and six are from Darwish et al. (2017). In addition, the TESS space mission, SuperWASP, and All-Sky Automated Survey for SuperNovae (ASAS-SN) provided another 61 eclipse times.

The O − C values were calculated with the following linear ephemeris:

$$\text{Min.I} = \text{BJD}$$

The calculated O − C values of LX Lyn are listed in Table 2. After fitting, we corrected the ephemeris to the following equation:

$$\text{Min. I} = \text{BJD} + 0.01446 \sin(\theta + \phi)$$

The final O − C diagram is plotted in Figure 3. It is apparent that the O − C diagram of LX Lyn exhibits a periodic oscillation. It should be noted that a circular orbit was assumed during our analysis. Moreover, weights of $1/\sigma^2$ were assigned to these data, where σ is the error. The corresponding O − C curve is depicted in Figure 3.

3.2. V0853 Aur

We collected 61 light minima times of V0853 Aur from published literature (Christian et al. 2006; Zhang et al. 2014b; Dimitrov & Kjurkchieva 2015; Hong-Peng Lu et al. 2020). At the same time, based on several sky surveys, we also obtained some light minima times from SuperWASP (23), ASAS-SN (5), and TESS (8). During our calculation, the following linear ephemeris was adopted:

$$\mathrm{Min.I} = \mathrm{BJD}$$

All the O − C values we used are listed in Table 3. Applying the least squares method, the new formula obtained is as follows:

$$\mathrm{Min.I} = \mathrm{BJD} + 0.02235\sin(\theta - \phi)$$

The final O − C diagram is plotted in Figure 4. It is apparent that the O − C diagram of V0853 Aur exhibits a periodic oscillation.

4. Photometric Solutions Obtained with the Wilson-Devinney Method

In order to study the targets thoroughly, it is necessary to obtain the photometric solutions of these two systems. During our analysis, the 2015 version of the Wilson-Devinney (W-D) program was used (Wilson & Devinney 1971; Wilson 1979, 1990, 1993; Van Hamme & Wilson 2003, 2007; Wilson 2008; Wilson et al. 2010; Wilson 2012; Wilson & Van Hamme 2014). The adjustable parameters are: the orbital inclination, i; effective temperature of the secondary component, T_2; luminosity contributions of the primary component, L_1; the dimensionless potentials, Ω_1 and Ω_2; and the mass ratio, q. Moreover, two parameters in our fit are fixed: the bolometric albedo $A_1 = A_2 = 0.5$ (Ruciński 1969), and the gravity-darkening exponents were chosen as $g_1 = g_2 = 0.32$ (Lucy 1967). The bolometric limb-darkening coefficients and limb-darkening coefficients were computed via the linear darkening law from Van Hamme (1993).

4.1. LX Lyn

Based on the LAMOST data, we set the temperature of the primary to 4780 K (Green et al. 2019). LX Lyn has been classified as a W UMa type EB (Terrell et al. 2014), so we used mode 3 (contact mode) to analyze its LCs. The q-search method was utilized to ascertain the appropriate mass ratio. It was found that the lowest point of the q-search curve is about 2.31. It should be noted that the LCs of LX Lyn have a negative O' Connell effect (O' Connell 1951). In order to fit the LCs of the system better, we adopted a cool starspot model. After many iterations of fitting, we obtained the best photometric solutions with one spot on the primary component. Our best photometric elements together with published results are listed in Table 4. The q-search curve of LX Lyn is plotted in Figure 5.

The theoretical LCs calculated with the cool spots are shown in Figure 6, and the geometrical structure of the system is illustrated in Figure 7. Additionally, we analyzed the LCs from TESS (LCTESS2019 and LCTESS2021), which also exhibit obvious asymmetry. During our fitting, we also fixed the temperature T_1 at 4780 K and added a cool starspot. It should be noted that LCTESS2019 and LCTESS2021 show different O' Connell effects. The final photometric solutions are listed in Table 4, and the theoretical LCs are shown in Figure 6(a) and (b), respectively.

4.2. V0853 Aur

Based on published results, the temperature of the primary star was adopted as 5560 K. Using the same method, we fitted the LCs of V0853 Aur with mode 3 and the same adjustable parameters. We noted that the LCs of V0853 Aur still have obvious asymmetry, and the differential magnitude at phase 0.25 is approximately 0.1 mag less than at phase 0.75. Therefore, we added the cool starspot during our analysis. At the beginning, we carried out a q-search ranging from 0.1 to 5 for the mass ratio. The q-search result shows that the possible value of the mass ratio is near q = 2.7727. Subsequently, we input the value of mass ratio as q = 2.7727 and set it as an adjustable parameter. In order to obtain the best photometric results, a third light (l_3) was also added. The final photometric solutions are listed in Table 5. The q-search curve of V0853 Aur is plotted in Figure 8. The theoretical LCs of TESS and ours are shown in Figure 9(a) and (b), respectively. The geometric structure of the system is illustrated in Figure 10.

5. Discussion and Conclusion

In Section 3, we analyzed the orbital period variations of LX Lyn and V0853 Aur. In Section 4, after fitting the LCs of the targets, we obtained their photometric solutions. In this section, we will discuss the results of the above two sections in detail.

5.1. Photometric Solution

Based on the photometric results, we calculate the contact degree as f = 12%, indicating that LX Lyn is a shallow-contact EB. We found that LX Lyn is a W-subtype EB with a mass ratio of q = 2.31 and an orbital inclination of i = 84.88°. The temperature difference between the two components is about ΔT

= 72 K. At the same time, the photometric solutions of TESS LCs from sectors 20 and 47 are similar, although they have different exposure times. In addition, we also calculated the fundamental parameters of the target using the empirical formula provided by Gazeas (2009):

$$M = 0.434 \log P + 1.4,$$

$$R = 0.434 \log P + 1.6,$$

$$L = 1.102 \log P + 4.3,$$

where P is orbital period, q is mass ratio, M is mass, R is radius, and L is luminosity. The fundamental parameters we calculated for LX Lyn are M_1 = 0.311 M , M_2 = 0.719 M , R_1 = 0.584 R , R_2 = 0.836 R , L_1 = 0.173 L , and L_2 = 0.358 L (Table 6), respectively. The LCs of LX Lyn show a negative O' Connell effect, which could be caused by magnetic activity from the components. In Table 4, we noted that the parameters of cool starspots are somewhat different, which could be the result of the evolution of the starspots themselves (Zhang et al. 2014a). We also noted that the mass ratio of Loukaidou et al. (2022) is q = 0.451, which is exactly the reciprocal of q = 2.31. The photometric solutions reveal that LX Lyn is a totally eclipsing EB with a high orbital inclination (>85°), so our photometric physical parameters are reliable (Li et al. 2022).

Using the same method, we also obtained the photometric solutions of V0853 Aur. It is suggested that V0853 Aur is a W-subtype CEB with a mass ratio of q = 2.77. The contact degree (f = 26.3%) reveals that it is a medium-contact system with similar surface temperatures of the components (ΔT = 276 K). According to Kepler' s third law, we calculated the semimajor axis of the orbit to be a = 1.510 R . Based on the photometric results, using the empirical formula provided by Gazeas (2009), the mass, radius, and luminosity of the target were calculated as M_1 = 0.257 M , M_2 = 0.712 M , R_1 = 0.572 R , R_2 = 0.885 R , L_1 = 0.160 L , and L_2 = 0.386 L , respectively. Due to the LCs of the system being asymmetric, we adopted a cool starspot model. A cool starspot on the surface of a star can destroy the symmetry of the LCs (Zhou et al. 2016; Zhang et al. 2018a). It should be noted that our photometric solutions have significant differences with previously published results, such as the orbital inclination (i) and effective temperature of the secondary component (T_2). One main reason for this is the migration of cool starspots. With the evolution of cool starspots, the photometric solutions of the target will be affected, as seen in V410 Aur (Liao et al. 2022) and EE Cet (Yang & Wang 2023). Moreover, we also found third light during our analysis, and the existence of the third light is another important reason. It should be noted that the parameters of the starspot are somewhat different, which could be the result of the evolution of starspots (Zhang et al. 2014b; Zhang et al. 2019).

5.2. Orbital Period Variation

Using the O − C method, we found that the O − C curves of LX Lyn and V0853 Aur show periodic variations. At present, cyclic period changes can be explained as resulting either from magnetic activity of one or both components (Applegate 1992). If magnetic activity is the main reason, variations in the gravitational quadrupole moment (ΔQ) may produce observed oscillations (Zhang et al. 2018b). The changes of gravitational quadrupole moment ΔQ can be calculated according to the following two formulas (Lanza & Rodonò 2002):

$$\Delta Q = \frac{Ma^2 \Delta P}{P},$$

$$\Delta Q = \frac{Ma^2 \Delta e}{e},$$

where a is the separation between both components and M is the mass of the active component (Yang et al. 2012). For LX Lyn, we computed the values of ΔQ as follows: $\Delta Q_1 = 2.47 \times 10^{48}$ g cm^2 and $\Delta Q_2 = 5.70 \times 10^{48}$ g cm^2. For V0853 Aur, we obtained the values of $\Delta Q_1 = 5.33 \times 10^{49}$ g cm^2 and $\Delta Q_2 = 1.48 \times 10^{50}$ g cm^2. These results are evidently smaller than the typical values of 10^{51}-10^{52} g cm^2 for close binaries (Lanza & Rodonò 1999; Yang et al. 2014). Therefore, we can rule out the Applegate mechanism as the main reason for interpreting the cyclic variations of LX Lyn and V0853 Aur at present.

In the situation of LTTE working in a circular orbit, we calculated the parameters of the third body and listed them in Tables 7 and 8. According to our analysis, the orbital period of the tertiary component of LX Lyn is $P_3 = 14.84$ yr, and the amplitude is A = 0.00191 days. For V0853 Aur, its period is $P_3 = 9.64$ yr and the amplitude is A = 0.0337 days. According to the O − C fitting parameters, the distance of the binary system to the barycenter of the triple system can be calculated with the equation:

$$a_{12} \sin i_3 = \frac{cA_3}{2\pi},$$

where c is the speed of light and A_3 is the amplitude of the O − C oscillation. We obtained a_{12} sin i_3 = 0.53 au (LX Lyn) and 8.83 au (V0853 Aur). The mass function and the mass of the tertiary companion are computed with:

$$f(m) = \frac{(a_{12} \sin i_3)^3}{P_3^2},$$

and we could obtain the minimum mass of the third body with the orbital inclination of i_3 = 90°. The M_3,min of LX Lyn is 0.06 M . For LX Lyn, it should be noted that we did not find third light during our analysis, so we guess that the companion might be a low-mass M-type star or brown dwarf.

For V0853 Aur, the M_3,min we calculated is about 3.77 M . A third light was found during our fitting, so we think that the third body of V0853 Aur could be a massive star.

Usually, for low-mass EBs, the timescale of AML is very long, and it is difficult to become a CEB with a period shorter than 0.22 days (Zhou et al. 2016; Zhang et al. 2019). As discussed by Qian et al. (2015), the magnetic torques from stellar winds could speed up the AML, which is favorable for the formation of a CEB. Meanwhile, Lu et al. (2020) and Dimitrov & Kjurkchieva (2015) reported that the components of both targets show strong magnetic activities, e.g., chromospheric emission lines and stellar spots on the photospheres. We also thought the third body might extract angular momentum from the central binary system during early dynamical interaction or late evolution, which could also shorten the time of orbital evolution for these EBs (Liao & Qian 2010; Zhou et al. 2016; Li et al. 2021). Therefore, orbital shrinkage due to rapid AML may result in the formation of contact systems similar to LX Lyn and V0853 Aur.

In addition, we also collected the fundamental parameters of some short-period contact binaries with a third body and listed them in Table 9. From Table 9, it is discovered that many components of these systems are late-type stars with masses less than 1 M . Most of these systems are shallow CEBs, and their third bodies are usually low-mass stars, except for V0853 Aur. Another special case is WW Dra, and a study suggested that the mass of its third body is no less than 6.43 M (Liao & Qian 2010). More observations (photometric and spectroscopic) are still necessary to verify these results in the future.

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