Period change investigation of the low mass ratio contact binary BO Ari

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Abstract

A photometric study and period change analysis for the A-type low mass ratio contact binary BO Ari is presented. The *BVR* light curves were fitted by using the Wilson-Devinney method. The photometric solution yields a low mass ratio of $q = 0.1754(\pm 0.0016)$ with a contact degree of $f = 27.72\%(\pm 2.37\%)$. We found a long-term orbital period decrease at a rate of $dP/dt = -3.49 \times 10^{-7} \text{ d yr}^{-1}$. This result indicates that the system is undergoing mass transfer from the primary component to the secondary with a mass transfer rate of $\dot{m}_1/m_1 = -7.77 \times 10^{-8} \text{ yr}^{-1}$. With the period decrease, the inner and outer critical Roche surfaces will tighten and cause the degree of contact to increase. Therefore, BO Ari may evolve into a deeper contact system.

Keywords: stars: binaries: close, stars: binaries: eclipsing, stars: individual (BO Ari)

1. Introduction

A system consisting of two stars close enough to be embedded in a common envelope, is called contact binary. These systems are classified as A-type for a system in which the more massive component is clipped by the other one at primary minimum, or W-type for the opposite case (Binnendijk, 1970). Typically, the A-type systems tend to be hotter (Yakut and Eggleton, 2005)

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and have longer orbital periods (e.g. Rucinski and Duerbeck, 1997; Gazeas and Niarchos, 2006; Terrell, Gross and Cooney, 2012) than the W-type systems. The more massive component of the contact system is generally a main sequence star, while the less massive one is oversized due to its advanced evolutionary stage (Stępień, 2006).

Many researches found orbital period variations, explained by mass exchange between the components (Singh and Chaubey, 1986; Pribulla, 1998). A long-term period decrease is usually interpreted as the system is undergoing a process of mass transfer from more massive component to the less massive one and/or angular momentum loss (AML) by magnetic breaking (e.g. Vilhu, 1981; Rucinski, 1982). The result of an orbital period decrease is a deeper contact degree (e.g. Christopoulou et al., 2011; Yang, 2011). On the other hand, systems with a period increase, are predicted by the thermal relaxation oscillation (TRO) theory (e.g. Lucy, 1976; Robertson and Eggleton, 1977), to evolve into TRO cycle (e.g. Li and Qian, 2013; Liu et al., 2014). The shorter-term cyclic period change can be explained by the light time effect (LTE) due to a third body orbit around the eclipsing pair in the triple system (Irwin, 1952; Pribulla and Rucinski, 2006).

BO Ari (RA(2000) = 02^h12^m08^s.78, Dec.(2000) = 27°08′18″.2), was identified as EW type binary by Nicholson and Varley (2006) with the first measured light minimum of HJD = 2451479.6566 and the orbital period of 0.3182 d. The revised period was obtained to be 0.3181963 d by Acerbi, Barani and Martignoni (2011). BO Ari was classified as an A-type system. Acerbi, Barani and Martignoni (2011) reported a mass ratio of $q = 0.1889$ and fillout of $f = 58.7\%$. Furthermore, $B_{\text{Tycho}} = 10.664$ and $V_{\text{Tycho}} = 10.083$ for BO Ari were reported in the Tycho 2 catalogue (Høg et al., 2000).

This study presents *BVR* observations for BO Ari and investigation on the orbital period change, cyclic variation and an analysis of the photometric light curve. Section 2 presents the photometric observations. An analysis for long-term orbital period changes and cyclic variations is described in Section 3. Section 4 presents a model fit to the light curve and derivation of the system parameters. Finally, Section 5. contains discussion and conclusions.

2. Observations

BO Ari was observed at Sirindhorn Observatory, Chiang Mai University on November 21, 24 and 26, 2011. The 0.5-m telescope, equipped with a SBIG ST10-XME CCD, was used for *BVR* filter bands with an exposure

Figure 1: The observed light curves in B (open dots), V (squares) and R (triangles) filter bands for BO Ari on November 21 (top), 24 (middle) and 26 (bottom), 2011.

time of 30 seconds. A total of 1446 individual observations were obtained for all three filter bands (482 observations per filter band). Data reduction and *BVR* differential magnitude measurements were made with the IRAF package.

GSC 1761-1578 (RA(2000) = 02^h12^m11^s.18, Dec.(2000) = 27°10′19″.8) and TYC 1761-2130-1 (RA(2000) = 02^h11^m53^s.48, Dec.(2000) = 27°15′34″.5) were used as comparison and check stars, respectively. The observed *BVR* light curves for the three nights covered five times of minimum light, as shown in Fig. 1. All minimum light times were found by phase shifting by about half an orbital period with respect to previous minimum light times. The amplitudes were about 0.47, 0.45 and 0.44 mag, for the *B*-, *V*- and *R*-bands, respectively.

3. Orbital period analysis

This study obtained three primary and two secondary minima. In order to analyze the orbital period change of BO Ari, orbital phases of all available minimum light times were shifted with 0.5 periods from the original sources to correspond with the data in this study as listed in column 4 of Table 1. Early minimum light times were found with nearly equal depths of primary and secondary eclipses such the primary minima could not always be distinguished from secondary minima. This is why we applied a 0.5 phase shift on previous data. This study found that the primary minima had become clearly deeper than the secondary ones but this did not always agree with the previous series of minimum light. After phase shifting, all minimum light times at present were fitted with a linear least-squares as shown in Eq. (1). The result gave a revised orbital period of 0.3181945(±0.0000002) d.

$$\text{Min.I} = \text{HJD}2455887.1405(\pm 0.0006) + 0.3181945(\pm 0.0000002) \times E \quad (1)$$

The orbital period of BO Ari in this study was shorter than the value obtained by Acerbi, Barani and Martignoni (2011). The (*O* − *C*) residuals were calculated by using the Eq. (1), and listed in the Table 1. Quadratic least-squares fitting was applied to the (*O* − *C*) as shown in Eq. (2) with the *rms* of the (*O* − *C*) curve residuals of about 0.00134 d. The (*O* − *C*) curve and corresponding residuals are plotted in Fig. 2. The fitting solution indicated that a long-term orbital period decrease of BO Ari at a rate of $dP/dt = -3.49 \times 10^{-7} \text{ d yr}^{-1}$.

Figure 2: The $(O - C)$ curve (upper panel) and the residuals (lower panel) for BO Ari, corresponding to the Eq. (2).

$$(O - C) = 0.0000(\pm 0.0003) - 1.17(\pm 0.12) \times 10^{-6}E - 1.52(\pm 0.12) \times 10^{-10}E^2 \quad (2)$$

As shown by the residuals in Fig. 2, it seems that there may be a cyclic variation, which can be produced by a LTE due to the presence of a third body in the system (Irwin, 1952; Pribulla and Rucinski, 2006). This cyclic period change can be analyzed with the following formula:

$$\text{Min.I} = T_0 + PE + AE^2 + \tau_3 \quad (3)$$

where $T_0 + PE + AE^2$ includes the quadratic long-term period change. T_0 and P are revised initial epoch and period, and A is a half of the period change per cycle. τ_3 is added for the LTE due to the third companion (e.g. Lee et al., 2011; Zhu, Qian and Li, 2011), as follows:

$$\begin{aligned} \tau_3 &= K \left[\frac{1 - e^2}{1 + e \cos \nu} \sin(\nu + \omega) + e \sin \omega \right] \\ &= K \left[\sqrt{1 - e^2} \sin E^* \cos \omega + \cos E^* \sin \omega \right] \end{aligned} \quad (4)$$

Table 1: All available times of light minimum for BO Ari.

HJD	Type 1	Ref.	Type 2	Epoch	$(O - C)$
1	2	3	4	5	6
2451479.6566	II	[1]	I	-13851.5	-0.0134
2454049.4078	II	[2]	I	-5775.5	-0.0006
2454062.4580	II	[3]	I	-5734.5	0.0036
2454080.4333	I	[3]	II	-5678.0	0.0009
2454081.3877	I	[3]	II	-5675.0	0.0007
2454083.2978	I	[3]	II	-5669.0	0.0016
2454083.4583	II	[3]	I	-5668.5	0.0030
2454084.4127	II	[2]	I	-5665.5	0.0029
2454095.3893	I	[3]	II	-5631.0	0.0018
2454507.2980	II	[4]	I	-4336.5	0.0077
2454808.3040	II	[4]	I	-3390.5	0.0018
2455080.3625	II	[5]	I	-2535.5	0.0040
2455080.5182	I	[6]	II	-2535.0	0.0006
2455103.4279	I	[6]	II	-2463.0	0.0003
2455103.5887	II	[6]	I	-2462.5	0.0020
2455144.3189	II	[6]	I	-2334.5	0.0033
2455392.5071	II	[5]	I	-1554.5	-0.0001
2455487.3294	II	[7]	I	-1256.5	0.0002
2455487.4889	I	[7]	II	-1256.0	0.0006
2455509.4440	I	[7]	II	-1187.0	0.0003
2455528.3768	II	[7]	I	-1127.5	0.0005
2455551.2872	II	[7]	I	-1055.5	0.0009
2455553.1962	II	[7]	I	-1049.5	0.0008
2455887.1396	I	[8]	I	0.0	-0.0009
2455890.1622	II	[8]	II	9.5	-0.0011
2455890.3220	I	[8]	I	10.0	-0.0004
2455892.0716	II	[8]	II	15.5	-0.0010
2455892.2317	I	[8]	I	16.0	0.0001
2456167.9460	II	[9]	I	882.5	-0.0011
2456279.6322	II	[10]	I	1233.5	-0.0012
2456514.9358	I	[11]	II	1973.0	-0.0024
2456516.5260	I	[12]	II	1978.0	-0.0031
2456526.8681	II	[11]	I	2010.5	-0.0024
2456535.9364	I	[11]	II	2039.0	-0.0026
2456560.9145	II	[11]	I	2117.5	-0.0028
2456579.6885	II	[11]	I	2176.5	-0.0022
2456579.8475	I	[11]	II	2177.0	-0.0023

Notes: Column 1: HJD at light minimum. Column 2: types of minimum from original sources. Column 3: references for the sources are as follow: [1] Nicholson and Varley (2006); [2] Martignoni (2011); [3] Acerbi, Barani and Martignoni (2011); [4] Paschke (2009); [5] Demircan et al. (2011); [6] Gökay et al. (2010); [7] Gökay et al. (2012); [8] This study; [9] Nelson (2013); [10] Diethelm (2013); [11] Nelson (2014); [12] Paschke (2014). Column 4: types of minimum with phase shifted of 0.5 periods to correspond with the data in this study. Column 5: epoch. Column 6: $(O - C)$, corresponding to the Eq. (2).

where $K = a_{12} \sin i_3 / c$ is the amplitude of the cyclic variation. The parameters a_{12} , i_3 , e and ω are the semi-major axis, inclination, eccentricity and longitude of the periastron of the binary's orbit around the mass center of the triple system, respectively, and ν is the true anomaly of the position of the binary's mass center in the orbit. E^* is the eccentric anomaly, computed together with Eq. (5) (e.g. Irwin, 1952; Zhu, Qian and Li, 2011; Kriwattana-wong and Poojon, 2015):

$$2\pi \frac{t - T}{P_3} = M = E^* - e \sin E^* \quad (5)$$

where M is the mean anomaly, t is the time of minimum light, T is the time of periastron passage for the third body and P_3 is the orbital period of the third companion in the system. If a cyclic period change is included in the model due to the LTE with an orbital period of 5.54 yrs, the *rms* of the residuals is 0.00116 d, which is not much less than for the solution without LTE in Eq. (2) which is 0.00134 d. These *rms* values of the residuals are of the same order as the amplitude of 0.0011 d of this cyclic variability. Therefore this cyclic variability is not detected at a significant level (in that case the amplitude should have been > 3 times the *rms* values). We therefore conclude that there is no evidence for the presence of a third component.

4. Photometric Solutions

In this study, the secondary minima were slightly higher than the primary ones about 0.06 mag. for all *BVR* bands as shown in Fig. 1. The primary massive star was eclipsed by the less massive star at the primary minimum, indicating that this contact binary is an A-type system, same as identified by Acerbi, Barani and Martignoni (2011). For the A-type contact binary, the more massive component is assigned to be star 1 and the other component is assigned as star 2. The color $(B - V)_{\text{Tycho}} = 0.581$ for BO Ari was collected from the Tycho 2 catalogue (Høg et al., 2000). Since, the relation $(B - V)_{\text{Johnson}} = 0.85 (B - V)_{\text{Tycho}}$ (e.g. Gürol et al., 2011; Kriwattana-wong and Poojon, 2014), the $(B - V)$ color of BO Ari was obtained to be 0.494. This indicates that the primary should be a late F-type main sequence star, with an effective temperature of about 6250 K (Cox, 2000). Coincidentally, the effective temperature of BO Ari was calibrated by using spline method, and reported to be 6252 K (Ammons et. al., 2006). Thus, the effective temperature of the star 1, T_1 , was assumed as 6250 K. This is about 1000 K hotter

Table 2: Parameters for the period change with and without the LTE.

Parameters	Values	
	Quadratic	Quadratic plus LTE
T_0 (d)	2455877.1405(± 0.0006)	2455877.1405(± 0.0006)
P (d)	0.3181933(± 0.0000002)	0.3181932(± 0.0000002)
A (d)	$-1.52(\pm 0.12) \times 10^{-10}$	$-1.59(\pm 0.12) \times 10^{-10}$
dP/dt (d yr $^{-1}$)	$3.49(\pm 0.28) \times 10^{-7}$	$3.65(\pm 0.28) \times 10^{-7}$
K (d)	-	0.0011(± 0.0002)
$a_{12} \sin i_3$ (AU)	-	0.19(± 0.03)
e	-	0.24(± 0.06)
ω ($^\circ$)	-	43.0(± 3.7)
P_3 (yr)	-	5.54(± 0.27)
T (d)	-	2456373.2(± 78.6)
rms of residuals (d)	0.00134	0.00116

Notes: Column 1: fitted parameters. Column 2: values of the parameters, corresponding to the quadratic least-squares without the LTE, Eq. (2). Column 3: values of the parameters, corresponding to the quadratic least-squares with the LTE, Eqs. (3) – (5).

that the value assumed in previous study by Acerbi, Barani and Martignoni (2011). The Wilson-Devinney (W-D) method (Wilson and Devinney, 1971; Wilson, 1979, 1990; Wilson and van Hamme, 2003) was used to derive the photometric solution for BO Ari. The W-D code was used in mode 3, with more fixed parameters as follow: the gravity darkening exponents of $g_1 = g_2 = 0.32$ (Lucy, 1967), the bolometric albedo coefficients of $A_1 = A_2 = 0.50$ (Rucinski, 1973), and the limb darkening coefficients of $x_{1B} = x_{2B} = 0.877$, $x_{1V} = x_{2V} = 0.671$ and $x_{1R} = x_{2R} = 0.514$ for the BVR filter bands, corresponding to the temperature T_1 (van Hamme, 1993).

In order to complete the W-D fitting, we adjusted the following parameters: the orbital inclination, i , the mass ratio, q , the surface potential of the components, $\Omega_1 = \Omega_2$, the temperature of the star 2, T_2 , and the monochromatic luminosities for the BVR filter bands of the star 1, L_1 . The relative luminosities of the star 2, L_2 , for all bands were automatically estimated by the W-D code, following the stellar atmosphere model of Kurucz (1993).

The photometric parameters were obtained for the minimum sum of the squared residuals, $\Sigma(O - C)^2 = 0.0124$, resulting in a mass ratio of $q = 0.1754$

Table 3: Photometric parameters for BO Ari.

Parameters	Values	
	Previous study [†]	This study
q	0.1889(± 0.0022)	0.1754(± 0.0016)
T_1 (K)	5307	6250
T_2 (K)	5254(± 12)	6409(± 17)
i ($^\circ$)	80.96(± 0.03)	81.12(± 0.24)
$\Omega_1 = \Omega_2$	2.1340(± 0.0033)	2.1391(± 0.0020)
$g_1 = g_2$	0.30	0.32
$A_1 = A_2$	0.50	0.50
$x_{1B} = x_{2B}$	0.411	0.877
$x_{1V} = x_{2V}$	0.736	0.671
$x_{1R} = x_{2R}$	-	0.514
$L_{1B}/(L_{1B} + L_{2B})$	0.785(± 0.001)	0.8017(± 0.0172)
$L_{1V}/(L_{1V} + L_{2V})$	0.787(± 0.001)	0.8075(± 0.0124)
$L_{1R}/(L_{1R} + L_{2R})$	-	0.8109(± 0.0087)
r_1 (pole)	0.5084(± 0.0008)	0.5044(± 0.0007)
r_1 (side)	0.5606(± 0.0012)	0.5539(± 0.0013)
r_1 (back)	0.5884(± 0.0016)	0.5780(± 0.0017)
r_2 (pole)	0.2488(± 0.0010)	0.2330(± 0.0017)
r_2 (side)	0.2618(± 0.0012)	0.2435(± 0.0022)
r_2 (back)	0.3190(± 0.0032)	0.2848(± 0.0038)
Spot Colatitude ($^\circ$)	** 90	* 74.48(± 3.04)
Spot Longitude ($^\circ$)	** 260.77(± 5.2)	* 315.13(± 3.24)
Spot Radius ($^\circ$)	** 29.96(± 1.6)	* 10.31(± 1.69)
Temperature Factor	** 0.9021(± 0.008)	* 0.95(± 0.02)
$\Sigma(O - C)^2$	0.0132	0.0124
f (%)	58.7(± 0.2)	27.72(± 2.37)

Notes: [†] Acerbi, Barani and Martignoni (2011).

* Parameters of a starspot on the primary star.

** Parameters of a starspot on the secondary star.

(± 0.0018). This mass ratio was slightly less than the value obtained by Acerbi, Barani and Martignoni (2011). The inclination of the orbit was

Figure 3: The observed light curves in B (open dots), V (squares) and R (triangles) filter bands and the theoretical light curves (solid lines) versus orbital phase for BO Ari.

$i = 81.21^\circ$, confirming total eclipse on the eclipsing pair, strengthening the reliability of the mass ratio. A starspot was added on the primary component, with temperature factor of 0.95, which can explain a small asymmetry of the light curves due to the O’Connell effect. The overcontact degree was found to be $27.72\%(\pm 2.37\%)$, which is about half the degree derived by Acerbi, Barani and Martignoni (2011). This difference could be due to the fixed effective temperature, T_1 , and the corresponding limb darkening coefficients x_1 and x_2 which were assumed to have different values. The theoretical light curves are plotted overlying on the observed ones in Fig. 3, and all photometric elements are listed in Table 3.

5. Discussion and Conclusions

The BVR observations in this study were obtained during three nights in 2011, covering five minimum light times. The light curves confirmed that BO Ari is an A-type, same as firstly reported by Acerbi, Barani and Martignoni (2011). The revised orbital period is obtained to be 0.3181933 (± 0.0000002). The $(O - C)$ residuals were first examined by using the quadratic least-squares fit, showing a downward parabolic trend line, that

indicates the long-term orbital period decrease. The orbital period of BO Ari decreases at a rate of $dP/dt = -3.49 \times 10^{-7} \text{ d yr}^{-1}$.

The $(B - V)$ color of BO Ari was estimated to be 0.494, corresponding to an effective temperature of $T_1 = 6250 \text{ K}$ for the primary star (Cox, 2000). With this result, the effective temperature T_1 and the corresponding limb darkening coefficients of x_1 and x_2 for BVR filter bands (van Hamme, 1993) are quite far from the values in the previous study (Acerbi, Barani and Martignoni, 2011). The photometric elements were derived for mass ratio $q = 0.1754$ with the *rms* of the residuals, $\Sigma(O - C)^2 = 0.0124$, while the contact degree was found to be $f = 27.72\%$. The mass ratio confirms that BO Ari is a low mass ratio contact system. Our results indicate that contact configuration of BO Ari is not very deep. More observations are required to confirm these parameters.

The system shows a long-term period decrease, implying mass transfer from the more massive primary component to the less massive one. The rate of mass transfer $\dot{m}_1/m_1$ can be estimated, under the conservative assumption (Singh and Chaubey, 1986; Pribulla, 1998) by:

$$\frac{\dot{P}}{P} = 3\left(\frac{m_1}{m_2} - 1\right)\frac{\dot{m}_1}{m_1} \quad (6)$$

The resulting rate of mass transfer is $\dot{m}_1/m_1 = -7.77 \times 10^{-8} \text{ yr}^{-1}$. With the mass transfer, the inner and outer critical Roche lobes will shrink and cause the contact degree to increase, similar to the case of WZ Cep (Zhu and Qian, 2009), AH Tau (Yang et al., 2010), and GV Leo (Kriwattanawong and Poojon, 2013). Therefore, the low mass ratio contact binary, BO Ari could evolve into a system with deeper contact.

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