THE INTERACTING EARLY-TYPE BINARY V382 Cyg

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Received 2012 July 26; accepted 2012 October 24; published 2012 December 6

1 INTRODUCTION

Massive interacting binary systems are the progenitor candidates of some high-energy phenomena in astrophysics (e.g., supernovae). Solar-type close binary systems with convective envelopes can evolve in different ways compared to close massive stars. Yakut & Eggleton (2005) modeled late-type close binary systems assuming conservative and non-conservative cases. Those authors proposed that a detached configuration can evolve into a semi-detached configuration followed by a contact configuration. Except for late-type systems, we have less information on the evolution of the interactive massive binary systems since there are a few binary systems with well-determined parameters. Therefore, systems like V382 Cyg, RY Sct (Djurašević et al. 2008), and V729 Cyg (B. Yaşarsoy et al. 2013, submitted), etc., are crucial for observational studies of close massive binaries.

Photometric studies of V382 Cyg have been published by different researchers. The binary system V382 Cyg was discovered to be a variable star by Morgenroth (1935) and Petrov (1946) and they classified the system as an eclipsing binary. The photometric UBV light variations of the system were obtained by Landolt (1964) by using the 16 inch KPNO telescope. Modeling the light and radial velocity curves of the system, Bloomer et al. (1979) derived an orbital inclination of 87° and $M_1 = 26.7 (5) \, M_\odot$ and $M_2 = 18.9 (4) \, M_\odot$. Later photometric studies were performed by Cester et al. (1978), Mayer et al. (1986), Harries et al. (1997), Değirmenci et al. (1999), and Qian et al. (2007).

Spectroscopic studies of the system were provided by Pearce (1952), Popper (1978), Koch et al. (1979), Harries et al. (1997), Burkholder et al. (1997), and Mayer et al. (2002). Popper (1978), studying the He i and He ii lines, derived the semi-amplitude of the radial velocity curve and the mass function for the components to be $K_1 = 255 \, \text{km s}^{-1}$, $K_2 = 360 \, \text{km s}^{-1}$, $M_1 \sin^3 i = 26.7 \, M_\odot$, and $M_2 \sin^3 i = 18.9 \, M_\odot$. Later on, Popper & Hill (1991) recalculated the parameters to be $K_1 = 276 \, \text{km s}^{-1}$ and $K_2 = 400 \, \text{km s}^{-1}$ and the masses to be $M_1 = 32.6 (1.8) \, M_\odot$ and $M_2 = 22.9 (1.3) \, M_\odot$. By using photometric and spectroscopic data, Harries et al. (1997) derived the mass of the components to be $M_1 = 26.0 (7) \, M_\odot$ and $M_2 = 19.3 (4) \, M_\odot$. Recently, Mayer et al. (2002) derived the masses for the stars to be $M_1 = 29.2 \, M_\odot$ and $M_2 = 21.2 \, M_\odot$. Spectral types of the components were defined by Pearce (1952) as O6.5+O7.5, by Popper (1980) as O7.3+O7.7, by Harries et al. (1997) as O7.3+O7.7, and by Burkholder et al. (1997) as O6.5V(f) + O6V(f). They provided the distance modulus of 11.5(5) mag for the system. Garmany & Stencel (1992) classified V382 Cyg as a member of Cyg OB1 association.

2 NEW OBSERVATIONS

The observations were carried out on 25 nights in 2007–2011 with the 40 cm telescope that is equipped with the 2048 × 2048 Alta CCD camera at Ege University Observatory (EUO). The exposure times were 15 s for $B$, 5 s for $V$, 4 s for $R$, and 4 s for $I$ filter. The reduction and analysis of the frames have been managed using the IRAF packages to subtract the bias and dark then divide flat field, followed by aperture photometry (DIGIPHOT/APPHOT). Comparison and check stars were selected: HD 193204 ($V = 8^m 32$, $B - V = 0^m 46$), GSC 2684 1450 ($V = 9^m 60$, $B - V = 1^m 12$), HD 228802 ($V = 9^m 63$, $B - V = 0^m 44$), and HD 193344 ($V = 7^m 60$, $B - V = -0^m 06$). The magnitudes and colors were obtained from the TYCHO-2 catalog (Høg et al. 2000). We studied all of the nights and each frame separately during the data reduction and standard deviations were estimated for the $B$, $V$, $R$, and $I$ bands to be 0.018, 0.013, 0.016, and 0.015, respectively. 3095, 2861, 2871, and 2772 points were obtained in the $B$, $V$, $R$, and $I$ bands, respectively. We list all the observed data in Table 1. The light curves of the system obtained in this study are shown in Figure 1(a).

We obtained three new minima times throughout these new observations. They are collated with those published and listed in Table 2 with their errors. Using Table 2 we derived a new linear ephemeris, Equation (1), that we believe to be useful for
Figure 1. (a) The observed and the computed light and (b) radial velocity curves of V382 Cyg. The light curves in $B, V,$ and $R$ bands are altered by values of 0.75, 0.50, and 0.25, respectively, for a good visibility. See the text for details. (A color version of this figure is available in the online journal.)

Table 1

| HJD  | Phase | $\Delta m$ | Filter |
|------|-------|------------|--------|
| 2454292.33107 | 0.3334 | 0.331 | $B$ |
| 2454292.33444 | 0.3352 | 0.330 | $B$ |
| 2454292.33540 | 0.3357 | 0.324 | $B$ |
| 2454292.33636 | 0.3362 | 0.326 | $B$ |
| 2454292.33731 | 0.3367 | 0.325 | $B$ |
| 2454292.33826 | 0.3372 | 0.328 | $B$ |
| 2454292.33922 | 0.3377 | 0.315 | $B$ |
| 2454292.34018 | 0.3382 | 0.326 | $B$ |
| 2454292.34113 | 0.3387 | 0.332 | $B$ |
| 2454292.34209 | 0.3392 | 0.337 | $B$ |
| 2454292.34304 | 0.3397 | 0.330 | $B$ |
| 2454292.34400 | 0.3403 | 0.331 | $B$ |
| 2454292.34495 | 0.3408 | 0.338 | $B$ |
| 2454292.34592 | 0.3413 | 0.329 | $B$ |
| 2454292.34688 | 0.3418 | 0.327 | $B$ |

Notes. Heliocentric Julian Date, phase, ($\Delta m$), and corresponding filters are listed. $\Delta m$ is the magnitude difference between the variable V382 Cyg and the comparison star HD 193204. The phases were calculated using Equation (1).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 2

| HJD* Min | Reference | HJD Min | Reference | HJD Min | Reference |
|----------|-----------|---------|-----------|---------|-----------|
| 2436814.7725 | 1 | 2448167.4765 | 7 | 2449913.4766 | 17 |
| 2439897.8298 | 1 | 2448186.3306 | 7 | 2449913.4785 | 10 |
| 2440385.9310 | 1 | 2448186.3316 | 7 | 2449915.3654 | 17 |
| 2440386.8761 | 1 | 2448447.4743 | 8 | 2449929.5074 | 17 |
| 2440387.8173 | 1 | 2448447.4764 | 8 | 2449930.4476 | 17 |
| 2441129.7698 | 1 | 2448498.3835 | 8 | 2449931.3909 | 17 |
| 2442651.3844 | 2 | 2448498.3844 | 8 | 2449945.3542 | 17 |
| 2442659.8678 | 3 | 2448564.3749 | 9 | 2449946.4757 | 17 |
| 2442940.8071 | 4 | 2448839.6629 | 10 | 2449947.4157 | 18 |
| 2442961.5424 | 3 | 2448843.4381 | 11 | 2449947.4171 | 17 |
| 2443366.9333 | 5 | 2448843.4395 | 12 | 2450671.4673 | 19 |
| 2444445.4450 | 6 | 2448843.4397 | 12 | 2451413.4316 | 20 |
| 2444757.4930 | 6 | 2448589.4664 | 11 | 2451429.4568 | 20 |
| 244482.3538 | 6 | 2448878.3252 | 10 | 2452817.2130 | 21 |
| 2445598.4426 | 5 | 2449221.4843 | 14 | 2453837.2977 | 22 |
| 2446274.3971 | 5 | 2449221.4857 | 13 | 2455340.5686 | 23 |
| 2446325.3087 | 5 | 2449518.4529 | 14 | 2455483.3614 | 24 |
| 2446668.4782 | 5 | 2449534.4780 | 15 | 2455811.4399 | 25 |
| 2447030.4922 | 3 | 2449550.5029 | 14 | 2454344.4913(4) | 26 |
| 2447099.3141 | 3 | 2449567.4771 | 16 | 2455003.4936(5) | 26 |
| 2447444.3744 | 3 | 2449568.4222 | 16 | 2455807.2295(3) | 26 |
| 2448167.4747 | 7 | 2449880.4846 | 17 |

References. (1) Landolt 1975; (2) Mayer 1980; (3) Mayer et al. 1991; (4) Bloomer et al. 1979; (5) Mayer et al. 1986; (6) Andrakakou et al. 1980; (7) Hubscher et al. 1991; (8) Hubscher et al. 1992; (9) Blätter 1992; (10) Mayer et al. 1998; (11) Peter 1992; (12) Hubscher et al. 1993; (13) Hubscher et al. 1994; (14) Peter 1994; (15) Agerer & Hubscher 1995; (16) Blaettler 1994; (17) De˘girmenci et al. 1999; (18) Agerer & Hubscher 1996; (19) Agerer & Hubscher 1998; (20) Agerer & Hubscher 2001; (21) Nagai 2004; (22) Qian et al. 2007; (23) Hubscher 2011; (24) Paschke 2010; (25) Zasche et al. 2011; (26) present study.

The difference between the observed (O) and calculated (C) minima times in an eclipsing binary system can provide us with information about any variation in orbital period. Orbital period studies of V382 Cyg were provided by Mayer et al. (1986), Mayer et al. (1998), De˘girmenci et al. (1999), and Qian et al. (2007). Using minima times, Mayer et al. (1986) deduced the linear elements of the system. De˘girmenci et al. (1999), taking into account only the mass transfer between the components, derived the mass transfer rate from the less massive component to the more massive one, $5 \times 10^{-6} M_\odot$ yr$^{-1}$.

Unlike previous studies of V382 Cyg, in this study we used only the most accurate (photometric and CCD data) minima times. We solve the O–C curve to find a parabolic solution (Figure 2(a)). In order to estimate the light variation that can be ascribed to mass transfer from the less massive companion to the more massive one, a total of 65 data points obtained with photometric/CCD observations are used to study the period variation of the system. Table 2 shows the data used during the analysis. The weighted least-squares method was used in order to determine the parameters of the upward parabolic variation. The residuals (O–C$_1$) indicate a quadratic solution (Figure 2(a)). In order to estimate the light elements (Table 3), the differential correction method is used.
The residuals \((O–C)^2\) show a sinusoidal variation (Figure 2(b)). Therefore, we assumed a sinusoidal variation superposed on an upward parabola during O–C analysis. A sine-like variation in the O–C curve, where both the primary and the secondary minima follow the same trend, suggests a light time effect via the presence of a tertiary component. We used Equation (2) during the O–C analysis:

\[
\text{Min} I = T_0 + P_o E + \frac{1}{2} \frac{dP}{dE} E^2 + \frac{a_{12} \sin i'}{c} \left[ 1 - e'^2 \frac{\sin (v' + \omega') + e' \sin \omega'}{1 + e' \cos v'} \right],
\]

where \(T_0\) is the starting epoch for the primary minimum, \(E\) is the integer eclipse cycle number, \(P_o\) is the orbital period of the eclipsing binary, and \(a_{12}, i', e', \) and \(\omega'\) are the semi-major axis, inclination, eccentricity, and the longitude of the periastron of the eclipsing pair around the third body, and \(v'\) denotes the true anomaly of the position of the center of the mass. The time of periastron passage \(T'\) and orbital period \(P'\) are the unknown parameters in Equation (2) (see Kalomeni et al. 2007 for details).

### 4. SIMULTANEOUS SOLUTIIONS OF LIGHT AND RADIAL VELOCITY CURVES

The BVRI light curves obtained in this study are solved simultaneously with the radial velocity curve of Harries et al. (1997) and Mayer et al. (2002) using PHOEBE (Prša & Zwitter 2005), which is based on the WD code (Wilson & Devinney 1971; Wilson 1979, 1990). During the solution we used weighted light curves that are constructed according to the standard deviation of each filter. The effective temperature of the hot star is chosen according to spectroscopic studies. The albedo values \(A_1\) and \(A_2\) for the hot and cooler components were adopted from Rucinski (1969), while the values of the gravity darkening coefficients \(g_1\) and \(g_2\) were taken from von Zeipel (1924). The logarithmic limb-darkening law was used with the coefficients adopted from van Hamme (1993) for a solar composition star. The adjustable photometric parameters are orbital inclination \(i\), surface potential \(\Omega_{1,2}\), temperature of the secondary component \(T_2\), luminosity \(L_1\), and the mass ratio \(q\). The center of mass velocity \(V_0\), and semi-major axis \(a\), are also set as free parameters as well as the time of minimum light \(T_0\), and the orbital period \(P\). Table 4 summarizes the result of the analysis. \(B, V, R,\) and \(I\) light curves and the velocity curve computed using the determined parameters are shown as solid lines in Figure 1(a).

During solution we assumed both contact (C) and semi-detached (SD) configurations. We emphasize that both solutions have similar results (see Table 4). In Figure 1, the light curve fits for a contact and a semi-detached configuration are shown with a dotted line and a solid line, respectively. For the contact model, the filling factor, which is expressed by \((\Omega_{in} - \Omega)/\Omega_{out}\) and varies from zero to unity from the inner \(\Omega_{in}\) to the outer critical surface \(\Omega_{out}\), is calculated to be \(f = 0.09\). New solutions indicate that the system has a weak contact degree or that it is a semi-detached binary with a near-contact configuration.

### Table 3

| Parameter | Unit | Value |
|-----------|------|-------|
| \(T_0\)   | (HJD) | 2436814.7599(59) |
| \(P_o\)   | (day) | 1.885515(2) |
| \(P'\)    | (year) | 43.9(1.7) |
| \(T'\)    | (HJD) | 2419843(1611) |
| \(e'\)    |      | 0.41(8) |
| \(\omega'\) |      | 34(15) |
| \(a_{12} \sin i'\) | (AU) | 2.49(14) |
| \(f(m)\)  | (M_⊙) | 0.0080(2) |
| \(m_{0,3.1=30\circ}\) | (M_⊙) | 5.7 |
| \(m_{0,3.1=90\circ}\) | (M_⊙) | 2.8 |
| \((1/2)(dP/dE)\) | (c/d) | 1.08(1) × 10^{-9} |

Note. The standard errors 1σ in the last digit are given in parentheses.
### Table 4
Simultaneous Analysis Results of the Light and Radial Velocity Curves and Their Formal 1σ Errors for V382 Cyg

| Parameter                      | C         | SD        |
|-------------------------------|-----------|-----------|
| $i (°)$                       | 84.5(1)   | 85.3(2)   |
| $q = M_b / M_t$               | 0.7439(14) | 0.7452(2) |
| $a (R_\odot)$                 | 23.45(13) | 23.47(12) |
| $V_0$ (km s$^{-1}$)           | 7.1(1.6)  | 6.3(1.6)  |
| $\Omega_1$                   | 3.275(3)  | 3.390(9)  |
| $\Omega_2$                   | 3.275(3)  | 3.320     |
| $T_1$ (K)                     | 36000     | 36000     |
| $T_2$ (K)                     | 34415(270) | 34578(240) |
| Fractional radius of primary component | 0.4139(5)   | 0.4087(2) |
| Fractional radius of secondary component | 0.3604(6)   | 0.3526(2) |
| $A_1 = A_2$                   | 1.0       | 1.0       |
| $g_1 = g_2$                   | 1.0       | 1.0       |
| Luminosity ratio: $(L_1 / L_2 + L_2)$ (%) | 57.9    | 56.2      |
| $B$                           | 58.0      | 56.3      |
| $V$                           | 57.7      | 56.1      |
| $R$                           | 57.5      | 55.8      |

Note. The column headers C and SD refer to the contact model and the semidetached model, respectively. See the text for details.

### Table 5
Astrophysical Parameters of the System

| Parameter                      | Unit | Primary | Secondary |
|-------------------------------|------|---------|-----------|
| Mass $(M_t)$                   | $M_\odot$ | 27.9(5) | 20.8(4)   |
| Radius $(R_t)$                 | $R_\odot$ | 9.7(2)  | 8.5(2)    |
| Temperature $(T_{\text{eff}})$ | K    | 36000   | 34415(270) |
| Luminosity $(L)$               | log$(L/L_\odot)$ | 5.152(20) | 4.954(19) |
| Surface gravity $(g)$          | cm s$^{-2}$ | 3.91    | 3.90      |
| Bolometric magnitude $(M_b)$   | mag  | -9.15   | -7.65     |
| Absolute magnitude $(M_V)$     | mag  | -4.75   | -4.38     |
| Period change rate $(P)$       | d yr$^{-1}$ | 4.2(3) $\times$ 10$^{-7}$ |
| Mass transfer ratio $(M)$      | $M_\odot$ yr$^{-1}$ | 6.1(4) $\times$ 10$^{-6}$ |
| Distance $(d)$                 | pc   | 1466(76) |

Note. The standard errors 1σ in the last value are given in parentheses.

### 5. RESULTS AND CONCLUSION

Newly obtained $B$, $V$, $R$, and $I$ light curves of the early-type interacting system V382 Cyg have been solved with earlier published spectroscopic studies. We derived the orbital and physical parameter of the components with a simultaneous solution and listed the physical parameters in Table 5. We calculated the masses to be 27.9 $M_\odot$ and 20.8 $M_\odot$, which are ~7% higher than those given by Harries et al. (1997) and ~7% lower than Mayer et al.’s (2002) results. The distance of the system to the Sun is estimated to be 1455 ± 76 pc using the observed parameters. During the calculations, bolometric corrections were taken from Lanz & Hubeny (2003), and the effective temperature and absolute magnitude of the Sun were taken to be 5777 K and 4.732 mag, respectively. Garmany & Stencel (1992) proposed that V382 Cyg may be a member of the Cyg OB1 association. The distance to Cyg OB1 reported by Uyaniker et al. (2001) is in the range from 1.25 kpc to 1.83 kpc. In this study, the distance of V382 Cyg was found to be within this range, so it is likely to be a member of Cyg OB1. We have collected 65 mid-eclipse times, including our three new ones, to search for any periodic variation. Analysis of the O–C residuals can give us the reason for periodic and/or non-periodic variation. We applied the least-squares method to Equation (2) to find the rate of change in the period. Then the mass transfer rate is calculated and the possible third-body parameters are estimated (Table 3). According to our analysis, there is a mass transfer from the less massive (initially massive one) to the more massive component $(dM/dt = 6.1 \times 10^{-6} ~M_\odot$ yr$^{-1}$) and the period change rate $P/\dot{P} = 4.5 \times 10^9$. In this study, the mass transfer ratio obtained is nearly 10 times higher than that of Qian et al. (2007). This difference is probably due to their formalism. Additionally, we found new parameters for the tertiary component with a 43.9 yr outer period.

Isolated massive stars and massive stars in binary systems (e.g., V382 Cyg) evolve in different ways. The evolutionary path toward the final supernovae will become significantly different. The nature of the final stellar remnant may also be altered so that while a neutron star might be expected, mass transfer may lead to the formation of a black hole. Observations of systems similar to V382 Cyg can allow us to reveal the nature of the binary evolution and may help us to understand the possible variation of stellar lifecycles (see Eggleton 2010; Eldridge 2009; K. Yakut et al. 2013, in preparation). Using our newly obtained physical parameters, we provide an evolutionary model of the massive interacting binary system V382 Cyg. We used the TWIN version of the EV code (Yakut & Eggleton 2005; Eggleton 2008, 2010) that has been developed by Peter P. Eggleton.

We run a few models using different initial parameters. Among these models the best agreement with the observations is obtained for the model binary system whose initial period is 1.72 days, with primary and secondary masses of 28 $M_\odot$ and 23.5 $M_\odot$, respectively. The first 28 models shrink slightly since the zero-age main sequence is somewhat artificial. The massive component fills its Roche lobe and RLOF begins at model 123. At model 201, the parameters are very consistent with the current observed parameters (Table 6). After two more models it reaches a contact phase. This configuration is consistent with the O–C analysis (see Section 3). Therefore, our models show that the system looks similar to a semi-detached system but is very close to a contact phase. We plotted our result in the H-R diagram and the mass–radius planes (Figure 3). We found the age of the system to be 3.85 Myr, which is in the range of the age of Cygnus OB1 (e.g., Massey et al. 1995).

The authors thank Peter P. Eggleton for his valuable comments and suggestions to improve the quality of the paper and for providing the current version of the EV(TWIN) code, and B. Kalomeni for helpful comments. We are very grateful to an anonymous referee for comments and helpful constructive suggestions which helped us to improve the paper. This study was supported by the Turkish Scientific and Research Council (TÜBİTAK 111T270) and the Ege University Research Fund. K.Y. acknowledges support by the Turkish Academy of
Figure 3. Non-conservative evolution of V382 Cyg in an H-R diagram (top panel) and the \( \log R \) vs. \( M \) plane (bottom panel). More massive and less massive stars are shown respectively in red and green; their respective Roche lobe radii are dark blue and light blue. Initial parameters are \( 28.0 \, M_\odot, 23.5 \, M_\odot \), and 1.72 days with an assumed solar composition. The original primary is now the secondary.

(A color version of this figure is available in the online journal.)

Sciences (TÜBA). The current study is a part of PhD thesis by B. Yaşarsoy.

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