The early-type near-contact binary system

V337 Aql revisited

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Abstract

The close binary V337 Aql consists of two early B-type components with an orbital period of 2.7339 d. New multi-band photometric observations of the system together with published radial velocities enabled us to derive the absolute parameters of the components. The simultaneous light and radial velocity curves solution yields masses and radii of $M_1=17.44\pm0.31\ M_\odot$ and $R_1=9.86\pm0.06\ R_\odot$ for the primary and $M_2=7.83\pm0.18\ M_\odot$ and $R_2=7.48\pm0.04\ R_\odot$ for the secondary component. Derived fundamental parameters allow us to calculate the photometric distance as 1355\pm160 pc. The present analysis indicates that the system is a near-contact semi-detached binary, in which a primary star is inside its Roche lobe with a filling ratio of 92 percent and the secondary star fills its Roche lobe. From O-C data analysis, an orbital period decrease was determined with a rate of $-7.6 \times 10^{-8}\ yr^{-1}$. Kinematic analysis reveals that V337 Aql has a circular orbit in the Galaxy and belongs to a young thin-disc population.
1 Introduction

V337 Aql (HD 177284, BD -02 4840, SAO 142979, V = 8\textsuperscript{m}.64) is a \(\beta\) Lyr type eclipsing binary system with an orbital period of \(\sim 2.7339\) days. The first estimation of the photometric parameters of the system based on its photographie light curve analysis was given by Wright & Dugan (1936). Using several plate spectra, Feast & Thackeray (1963) measured the radial velocities and classified the system as a double-line spectroscopic binary. In the study of Catalano et al. (1971), the first complete photoelectric light curve of the system was published and reported asymmetries and variations on its light curve. They also announced that the orbital period of the system was decreasing. Alduseva (1977) mentioned the amplitude variations and instabilities on the \(UBV\) light curves of V337 Aql as being connected with mass exchange between the components and also, using radial velocity measurements, estimated the masses of the components to be \(M_1 \sim 16M_\odot\) and \(M_2 \sim 10M_\odot\). \(B\) and \(V\) light curves obtained by Alduseva (1977) were also solved by Giuricin & Mardirossian (1981); however, their results strongly differed from those of Catalano et al. (1971). Mayer (1987) reported the changes in the orbital period related with the light-time effect. A study on the orbital period variation of V337 Aql was published by Šimon (1999), in which, although the data in the \(O-C\) diagram indicated scattering, he suggested a possible decrease in the
orbital period, which corresponded to $\Delta P/P \approx -6.5 \times 10^{-10}$ days$^{-1}$. Lastly, Mayer et al. (2002) measured the radial velocities of the components of V337 Aql based on high resolution echelle spectra and gave the orbital parameters. They also analyzed the light curve published by Catalano et al. (1971) and reported the absolute parameters of the components.

In this study, new photometric analysis of the early-type eclipsing binary system V337 Aql is presented. After presenting information and background studies of the system, new photometric data are described in Section 2, followed by analysis of the orbital period variation. In the next section, the simultaneous solution of $BVR$ light curves together with published radial velocity curves is outlined. In the last section, the results and discussion, which include absolute parameters of the components, comparing the system with the similar eclipsing binaries and also kinematic properties are presented.

2 Observations

New photometric observations of V337 Aql were performed at the Çanakkale Onsekiz Mart University Observatory over 22 nights in the observation season of 2012. During the observations of the system, a 60-cm Cassegrain telescope, equipped with Apogee ALTA U42 CCD camera and Bessell $BVR$ filters, was used. The camera is of $13.5 \times 13.5$ microns pixel size and provides an effective field of view (FOV) of $17.5 \times 17.5$. The total number of the points obtained was 9880 in all filters. TYC 5132-878-1 and TYC 5128-840-1 were used as comparison and check stars, respectively. Reductions of the CCD images and
Aperture photometry were made using the C-Munipack\(^1\) software package in the standard mode. The difference magnitude between the comparison and check stars did not indicate any significant light variation. The errors of individual observational points were estimated as about 0\(^m\).01 in all the filters. Figure 2 represents the \(BVR\) light curves of the system. The orbital phase in the figure was computed according to the following light elements given by Kreiner (2004):

\[
HJD \ (MinI) = 2452500.334 + 2^{1}.733882(1) \times E
\]

(1)

All observational data shown in Fig. 2 was used the light curve synthesis given in Section 4.

3 Orbital Period Variation

The \(O-C\) diagram of V337 Aql in the database of the \(O-C\) Atlas of Eclipsing Binaries (Kreiner et al. 2001) indicates orbital period change. Although the visual (v) and photovisual (p) minima times contain relatively large errors and also large scatter, the orbital period variation can be studied using photographic (pg), photoelectric (pe) and CCD minima times. We collected the data from the \(O-C\) Atlas of Eclipsing Binaries (Kreiner et al. 2001) and combined them with three minima times (one primary and two secondary) determined from the new data listed in Table 1. New minima times were calculated using the Kwee & van Woerden (1956) method. For the \(O-C\) analysis, 20 photographic, 8 photoelectric and 3 CCD minima times were used, while their weights were selected as per the following: pg = 5, pe and CCD = 10.

\(^{1}\) http://c-munipack.sourceforge.net/
The $O-C$ values were plotted against the epoch number in Fig. 1. As shown in Fig. 1, the general trend of $O-C$ data can be represented by a downward parabola indicating a long-term orbital period decrease. Hence, by applying a weighted least-squares fitting, the following quadratic ephemeris with errors is derived:

$$HJD \left( MinI \right) = 2434896.8712(7) + 2^d.7338836(1) \times E - 7.8(2) \times 10^{-10} \times E^2(2)$$

Using the quadratic term, the rate of orbital period decrease can be derived to be $dP/dt = -7.6 \times 10^{-8} \text{ yr}^{-1}$. As can be seen in Fig. 1, the downward parabolic term represents the general trend of the $O-C$ data well and the last three minima times obtained in this study also support the variation.

4 Light Curve Synthesis

The BVR light curves obtained in this study and the radial velocities given by Mayer et al. (2002) of V337 Aql were solved simultaneously using the Wilson-Devinney (WD) program (Wilson & Devinney, 1973). The difference magnitudes (867 points in $B$, 1152 points in $V$ and 957 points in $R$ filters)
for each filter were converted to intensity units using the mean magnitudes at 0.25 orbital phase. Although a semi-detached configuration was suggested for V337 Aql (Catalano et al. 1971, Alduseva 1977, Giuricin and Mardirossian 1981, Mayer et al. 2002), firstly, the detached mode (Mode 2 in W-D code) was used to check whether the surface potentials of the components reached their Roche limits or not. After trials, it was seen that the secondary component filled its Roche lobe and it was concluded that the semi-detached system configuration should be taken into account. Therefore, Mode 5 in W-D code was selected for the analysis.

In the light curve solutions, some parameters were fixed as the following: The effective temperature of the primary component was adopted as 28000 K (Popper 1980) for the B0.5 spectral class suggested by Roman (1956) and Mayer
et al. (2002). The bolometric albedos $A_{1,2}$ were taken from Rucinski (1969) to be 1.0 for the components with radiative envelope. The bolometric gravity-darkening coefficients $g_{1,2}$ were set to 1.0 for radiative atmospheres from von Zeipel (1924). The corresponding logarithmic bolometric and monochromatic limb-darkening coefficients used were from van Hammes (1993) tables. The secondary minimum is seen at 0.5 phase and the ascent and descent duration of the secondary and primary minimum are the same, therefore, a circular orbit ($e = 0$) was assumed. The third light ($l_3 = 0$) was fixed to zero since no evidence was found during trials. The adjusted parameters are the semi-major axis of orbit ($a$), radial velocity of the system’s mass center ($V_\gamma$), phase shift ($\phi$), orbital inclination ($i$), surface temperature of the secondary component ($T_2$), non-dimensional surface potential of primary component ($\Omega_1$), mass ratio ($q$) and the fractional luminosity of the primary component ($L_1$). The input values of $a$, $V_\gamma$ and $q$ were taken into account from the orbit solution of Mayer et al. (2002).

Results from our simultaneous solution of $BVR$ light curves are given in Table 2. The corresponding theoretical light curves are plotted in Fig. 2 overlaying the observational points. Roche geometry of the system is represented by Binary Maker code (Bradstreet 1990), as illustrated in Fig. 3.

5 Results and Discussion

The new $BVR$ photometric observations of the early-type eclipsing binary V337 Aql combined with radial velocities from the literature (Mayer et al. 2002) were analyzed to determine its fundamental properties. The system configuration was found to be semi-detached; the primary component being
Table 2

Parameters of V337 Aql derived from simultaneous analysis of BVR light curves and RVs of components. Probable errors in last digits are given in parenthesis.

| Parameter                      | W-D solution | Parameter                     | W-D solution |
|--------------------------------|--------------|-------------------------------|--------------|
| \(a(R_\odot)\)                | 24.12(11)    | \(L_1/(L_1 + L_2) - B\)      | 0.708(15)    |
| \(i(\text{deg})\)             | 83.66(8)     | \(L_1/(L_1 + L_2) - V\)      | 0.701(14)    |
| \(V_γ(\text{km s}^{-1})\)     | 38.6(9)      | \(L_1/(L_1 + L_2) - R\)      | 0.696(14)    |
| \(T_1(\text{K})\)             | 28000\(^a\) | \(L_2/(L_1 + L_2) - B\)      | 0.292        |
| \(T_2(\text{K})\)             | 23640(40)    | \(L_2/(L_1 + L_2) - V\)      | 0.299        |
| \(Ω_1\)                       | 2.9803(54)   | \(L_2/(L_1 + L_2) - R\)      | 0.304        |
| \(Ω_2\)                       | 2.7772       | \(r_1\) (mean)               | 0.409(5)     |
| Phase shift                    | 0.0007(3)    | \(r_2\) (mean)               | 0.310(4)     |
| \(q (=M_2/M_1)\)              | 0.449(5)     |                               |              |

\(^a\): Adopted from Popper (1980)

in its Roche lobe, while the secondary component filling its Roche lobe. V337 Aql can be classified as a near-contact binary since the Roche lobe filling ratio of the hotter component is about 92 percent. Based on the photometric and spectroscopic elements in Table 2, the basic astrophysical properties of the components and the orbital parameters of the system were derived and given Table 3. For the calculations, solar values and bolometric corrections (\(BC\)) for the components were adopted from Drilling & Landolt (2000). The masses of the components were calculated as 17.44 M\(_{\odot}\) and 7.83 M\(_{\odot}\) for the primary
and secondary, respectively, which are consistent with the masses of B0 and B3 main sequence stars according to the tables of Drilling & Landolt (2000). As mentioned by Mayer et al. (2002), the radii of the components have higher values compared with main-sequence stars. This is probably related the effects of mass and angular momentum transfer and also mass loss from the system. This scenario may be expected since the system is semi-detached and has very hot components.

Using the $U$-$B$ and $B$-$V$ colours of the system given by Popper & Dumont (1977), we applied the $Q$-method given by Johnson & Morgan (1953) to determine colour excess $E(B-V)$, which was found to be 0.80 mag. The high value of colour excess is consistent with the location of the system in the Milky Way
(Galactic coordinates: $l=32.57$ deg and $b=-0.76$ deg). Interstellar absorption in the $V$ filter was calculated to be 2.48 mag based on the common formula $A_v = 3.1 \times E(B-V)$. Using apparent system magnitude, interstellar extinction and light ratio of components, the photometric distance of the system was estimated as $1355\pm160$ pc.

The locations of the components of V337 Aql and also some early-type eclipsing binaries showing $\beta$ Lyr type light curves (Table 4) in the Hertzsprung-Russell (HR) diagram are presented in Fig. 4. Zero Age Main Sequence (ZAMS), Terminal Age Main Sequence (TAMS) and all evolutionary tracks and isochrones for solar chemical composition are taken from Ekström et al. (2012). The surface gravity values of the components of V337 Aql in Table 3 and the locations of the components in the HR diagram indicate that the component stars are within the main-sequence band and close to TAMS. The location of the primary component of V337 Aql in the diagram is very close to the evolutionary track of $17\,M_\odot$ calculated for a single star with solar abundance, which is consistent with its mass value and an isochrone of about 8 Myr. On the other hand, the less massive component seems to have higher luminosity and temperature with respect to its mass. The secondary component appears close to an isochrone of about 15 Myr.

When we look at the positions of the less massive components of early-type binaries in the HR diagram, which were determined using the parameters listed in Table 4, all components have higher luminosity and temperature values with respect to their masses, similar to the cooler component of V337 Aql. This phenomenon is very common for the cooler components of classical Algols (İbanoglu et al. 2006). The primaries of the massive binaries XZ Cep, V606 Cen and IU Aur seem to be close to the evolutionary tracks calculated
Table 3
Fundamental parameters of close binary V337 Aql parameters of V337 Aql. Uncertainties are given in brackets.

| Parameter                              | Symbol | Primary   | Secondary  |
|----------------------------------------|--------|-----------|------------|
| Spectral type                          | Sp     | B0 V      | B3 V       |
| Mass (M$_\odot$)                       | $M$    | 17.44(0.31) | 7.83 (0.18) |
| Radius (R$_\odot$)                     | $R$    | 9.86(0.06) | 7.48 (0.04) |
| Separation (R$_\odot$)                 | $a$    | 24.12 (0.11) |
| Orbital period (days)                  | $P$    | 2.7338794 |
| Orbital inclination (°)                | $i$    | 83.66(0.08) |
| Mass ratio                             | $q$    | 0.449(0.005) |
| Eccentricity                           | $e$    | 0.0       |
| Surface gravity (cgs)                  | log $g$ | 3.69(0.01) | 3.58(0.01) |
| Integrated visual magnitude (mag)      | $V$    | 8.64*     |
| Integrated colour indices (mag)        | $U-B$, $B-V$ | -0.52*, 0.49* |
| Colour excess (mag)                    | $E(B-V)$ | 0.80       |
| Visual absorption (mag)                | $A_V$  | 2.48      |
| Intrinsic colour index (mag)           | $(B-V)_0$ | -0.31     |
| Temperature (K)                        | $T_{\text{eff}}$ | 28000 (500) | 23640(500) |
| Luminosity (L$_\odot$)                 | log $L$ | 4.73 (0.04) | 4.20(0.04) |
| Bolometric magnitude (mag)             | $M_{\text{bol}}$ | -7.08 (0.09) | -5.75(0.10) |
| Abs. visual magnitude (mag)            | $M_V$  | -4.11(0.04) | -3.20(0.04) |
| Bolometric correction (mag)            | $BC$   | -2.97     | -2.55      |
| Systemic velocity (km s$^{-1}$)        | $V_\gamma$ | 38.6(0.9) |
| Distance (pc)                          | $d$    | 1355(160) |
| Proper motion (mas yr$^{-1}$)           | $\mu_{\alpha}\cos\delta$, $\mu_\delta$ | -0.70(0.80), -4.30(0.80)** |
| Space velocities (km s$^{-1}$)         | $U,V,W$ | 35.02 (3.33), 8.60 (5.16), -4.60 (5.23) |

*Popper & Dumont (1977), ** Zacharias et al. (2013).
Table 4

Basic physical parameters of some early-type eclipsing binaries indicating \( \beta \) Lyr type light curves.

| System  | Spectral Type | System Type | P (day) | \( M_1 \) (\( M_\odot \)) | \( R_1 \) (\( R_\odot \)) | \( T_1 \) (K) | References |
|---------|---------------|-------------|---------|-----------------|-----------------|------------|------------|
| CC Cas  | O8.5III       | D           | 3.366344| 18.3            | 10.08           | 34500      | 1          |
|         | B0.5          |             |         | 7.6             | 4.02            | 28300      |            |
| TU Mus  | O7V           | C           | 1.387283| 16.7            | 7.2             | 38700      | 2          |
|         | O8V           |             |         | 10.4            | 5.7             | 33200      |            |
| XZ Cep  | O9.5V         | D           | 5.097253| 15.8            | 7.0             | 30000      | 3          |
|         | B1III         |             |         | 6.4             | 10.5            | 23120      |            |
| V606 Cen| B0-0.5V       | C           | 1.495096| 14.7            | 6.8             | 29200      | 4          |
|         | B2-3V         |             |         | 8.0             | 5.2             | 21870      |            |
| IU Aur  | B0.5          | SD          | 1.811474| 14.5            | 6.2             | 29825      | 5          |
|         | B0.5          |             |         | 7.3             | 5.7             | 26830      |            |

\( ^{a} \) D: detached, SD: semi-detached, C: contact systems; References: (1) Hill et al. (1994), (2) Penny et al. (2008), (3) Harries et al. (1997), (4) Lorenz et al. (1999), (5) Harries et al. (1998)

for their masses. However, the more massive components of TU Mus and CC Cas are far from their expected positions in the HR diagram, estimated using the single-star evolutionary models. These discrepancies in V337 Aql and the other examples given may be related the effects of mass-transfer and/or loss during evolution of the systems.

The changing character of the orbital period of V337 Aql is monotonic, similar to several early-type eclipsing binaries (e.g. RY Sct, Z Vul, BF Aur; Šimon 1999). The orbital period of V337 Aql has been decreasing at a rate of 1.8
Fig. 4. Locations of primary and secondary components of some early-type eclipsing binaries (in Table 4) together with components of V337 Aql in log \( L \) - log \( T_{\text{eff}} \) plane. The evolutionary tracks for different masses in solar unit (solid lines), isochrones for different ages in Myr (dashed lines), ZAMS and TAMS for solar chemical composition are adopted from Ekström et al. (2012).

Although the system is semi-detached and an orbital period increase may be expected from the less massive star to the more massive one as in classical Algols, the orbital period of V337 Aql is decreasing. This may be interpreted as mass and angular momentum loss from the system resulting from radiative forces, which may be produced by the hot components. One of the rare examples indicating orbital period decrease among early-type eclipsing binaries is RY Sct. Mass loss from the system at a rate of \( 6 \times 10^{-5} \, M_{\odot} \) yr\(^{-1} \), which may be used to explain the decrease in the orbital period, was determined using radio observations by Milano et al. (1981).

In order to obtain the kinematical properties of V337 Aql, we used the sys-
tem’s center of mass’ velocity, distance and proper motion values, as given in Table 3. The proper motion data were taken from the Fourth US Naval Observatory CCD Astrograph Catalog (UCAC4; Zacharias et al. 2013), whereas the center of mass’ velocity and distance were obtained from this study. The system’s space velocity was calculated using the algorithm given by Johnson & Soderblom (1987). The $U$, $V$ and $W$ space velocity components and their errors were obtained and are given in Table 3. To obtain the precise space velocity the first-order galactic differential rotation correction was taken into account (Mihalas & Binney 1981), and 19.80 and 2.73 kms$^{-1}$ differential corrections were applied to the $U$ and $V$ space velocity components, respectively. The $W$ velocity is not affected in this first-order approximation. As for the Local Standard Rest (LSR) correction, Coşkunoğlu et al. (2011)’s values (8.5, 13.38, 6.49)$\odot$ kms$^{-1}$ for thin disc stars were used and the final space velocity of V337 Aql was obtained as $S = 36.35 \pm 8.07$ kms$^{-1}$. This value is in agreement with the space velocities of other young stars.

To determine the population type of V337 Aql the Galactic orbit of the system was examined. Using Dinescu et al. (1999) N-body code, the system’s apogalactic ($R_{max}$) and perigalactic ($R_{min}$) distances were calculated to be 8.41 and 6.58 kpc, respectively. In addition, the maximum possible vertical separation from the Galactic plane is $|z_{max}|=0.11$ kpc for the system. The following formulae were used to derive the planar ($\epsilon_p$) and vertical ($\epsilon_v$) ellipticities:

$$\epsilon_p = \frac{R_{max} - R_{min}}{R_{max} + R_{min}},$$

(3)

$$\epsilon_v = \frac{(|z_{max}| + |z_{min}|)}{R_{m}},$$

(4)
where \( R_m = (R_{max} + R_{min})/2 \) (Pauli 2005). Due to z-excursions \( R_p \) and \( R_a \) may vary, however this variation is not more than 5 per cent. The planar and vertical ellipticities were calculated as \( e_p = 0.12 \) and \( e_v = 0.03 \). These values show that V337 Aql is orbiting the Galaxy in a circular orbit, and that the system belongs to an extremely young thin-disc population.

In conclusion, we might mention that in order to obtain evidence of mass loss from the system and also membership of young-disc population, further high resolution spectroscopic observation in different wavelength regions for V337 Aql should be made. Moreover, comparing early-type binaries with similar properties shows that more detailed evolutionary models for early-type systems with mass transfer and loss are needed in order to obtain more information about evolutionary differences between these systems.

6 Acknowledgments

This research was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK, Grant no. 111T224) and Scientific Research Projects Coordination Unit of Istanbul University. Project number 3685. We thank Çanakkale Onsekiz Mart University Astrophysics Research Center and Ulupinar Observatory together with İstanbul University Observatory Research and Application Center for their support and allowing use of IST60 telescope. This research has made use of the SIMBAD, and NASA Astrophysics Data System Bibliographic Services.
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