THE LOW-MASS INTERACTING BINARY SYSTEM OO Aql REVISITED: A NEW QUADRUPLE SYSTEM

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ABSTRACT
In this study we present photometric and spectroscopic variation analysis and an orbital period study of a low-mass interacting system OO Aql. Simultaneous solution of the light and radial velocity curves provides us with a determination of a new set of stellar physical parameters for the primary and the secondary companion, \(M_1 = 1.05(2) \, M_\odot\), \(M_2 = 0.89(2) \, M_\odot\), \(R_1 = 1.38(2) \, R_\odot\), \(R_2 = 1.28(2) \, R_\odot\), \(\log(L_1/L_\odot) = 0.258\), and \(\log(L_2/L_\odot) = 0.117\), and the separation of the components was determined to be \(a = 3.333(16) \, R_\odot\). Newly obtained parameters yield the distance of the system as 136(8) pc. Analyses of the mid-eclipse times indicate a period increase of \(\dot{P}/P = 4 \times 10^7\) yr that can be interpreted in terms of the mass transfer \((dM/dt) = 5 \times 10^{-8} \, M_\odot\) yr\(^{-1}\) from the less massive component to the more massive component. Our new solution confirmed that OO Aql is a multiple system in the form of AB + C + D. We found initial astrophysical parameters for the component of the system and its current age to be 8.6 Gyr using a non-conservative stellar evolution model (EV-TWIN code).

Key words: binaries: close – binaries: general – stars: evolution – stars: fundamental parameters – stars: individual (OO Aql)

Online-only material: color figures

1. INTRODUCTION
One of the fundamental problems of modern astrophysics in stellar structure and evolution is the evolution of interacting binary systems. The evolution of stellar components in close binary systems depends on several physical processes that are different from the evolution of solar-like stars. Mass loss due to stellar activity as a result of escaping plasma from the star, mass transfer between stellar components, and angular momentum loss are the most crucial parameters in the evolution of interacting systems. In addition, a third (or fourth) component orbiting the system also affects the orbital period and therefore the evolution of a binary system. One way to get detailed information on stars is to determine their orbital and physical parameters. We selected the multiple system OO Aql for our project. Its physical parameters are obtained precisely and therefore it is quite a convenient system for examining a multiple interacting system’s evolutionary stages.

The G-type contact binary system OO Aql (HD 187183, \( \alpha_{2000} = 194812.65, \delta_{2000} = +091832.38, V = 9^\circ 49, B - V = 0^\circ 77 \)) was classified as a variable star by Hoffleit (1932). Then it was observed by Binnendijk (1968), Pohl (1969), Pohl & Kizilirmak (1970, 1975), Djurašević & Erkapić (1998), and Lafta & Grainger (1985). Djurašević & Erkapić (1998) studied the system’s light variation in detail and analyzed the light curves obtained in different observing seasons. Analysis of the system yielded the Roche lobe filling factor \(f\) to be 0.08 and the orbital inclination angle to be 86°. In the same study, the authors also provided a detailed model of a stellar spot. OO Aql has an unusually high mass ratio. Spectroscopic studies of OO Aql were provided by Hrivnak (1989), Hrivnak et al. (2001), and Pribyl et al. (2007). Hrivnak (1989), studying the Ca and H lines, derived the semi-amplitude of the radial velocity curve and the mass function of the components. He obtained a mass ratio of 0.843(8). Hrivnak et al. (2001) studied IUE satellite observations of the system and reported variation in the Mg II \(h\) and \(k\) lines. By using photometric and spectroscopic data Hrivnak et al. (2001) derived the mass of the components to be \(M_1 = 1.05 (2) \, M_\odot\) and \(M_2 = 0.88 (2) \, M_\odot\), and the radius of the components to be \(R_1 = 1.38 (2) \, R_\odot\) and \(R_2 = 1.28 (2) \, R_\odot\). Recently, accurate radial velocities were obtained by Pribyl et al. (2007). They derived the semi-amplitude of the radial velocity curve and the mass function of the components to be \(K_1 = 153.03 \, \text{km s}^{-1}\), \(K_2 = 180.81 \, \text{km s}^{-1}\), and \((M_1 + M_2) \sin^3 i = 1.954(19) \, M_\odot\).

The orbital period variation analysis of OO Aql has been performed by Binnendijk (1968), Essam et al. (1992), and Borkovits et al. (2005). Essam et al.’s and Binnendijk’s studies revealed a parabolic variation, in other words the existence of a mass transfer. The subsequent study by Demircan & Gürol (1996) discussed the parabolic and sinusoidal variation. The authors detected the presence of a third body orbiting the binary system with a period of 89 yr. Borkovits et al.’s (2005) analyses reveal a sinusoidal variation as a result of the third body orbiting the system with about 75 yr orbital period in an eccentric orbit of 0.06. The calculated minimum mass of the tertiary component is 0.7 \(M_\odot\). Finally, the results obtained by Zasche (2005) show parabolic and sinusoidal variations due to the presence of a third body with a 72 yr period and discuss the existence of a fourth body.

In this study, newly obtained VRI light curves and published radial velocity curves are analyzed simultaneously. The orbital and physical parameters of the system as well as the distance of the system are precisely derived. Following the observational information given in Section 2, a period variation study is presented in Section 3. Light and radial velocity models are presented in Section 4, and in Section 5 physical parameters of the binary system are presented. Finally, the evolution of the binary system is discussed and the results are summarized.

2. NEW OBSERVATIONS
New light variations of the system OO Aql were obtained using the 40 cm diameter telescope at the Ege University
Observatory (EUO) on 10 nights. VRI filters were used. Observations were performed on 2012 July 20, 21, 22, 27, 28, 29; August 4, 5; and September 8, 9. On September 8, 9 only minimum times were obtained. Apogee CCD 2048X2048 was used during the observations. TYC 1058-689-1 and TYC 1058-409-1 were selected as comparison stars as they have been used in previous studies presented in the literature. Observations of each night were reduced separately with IRAF APPHOT packaging. During the reduction processes, each nightly bias correction and darkness are removed from all the images and divided by flat images to obtain scientific frames. Differential photometry of these calibrated images was used to obtain the difference in magnitudes \((V - C)\).

Observation errors for \(V\), \(R\), and \(I\) filters were 0.011, 0.007, and 0.007, respectively. In Figure 1 we show the light variations \((V - C)\) in VRI colors. As shown in Figure 1, there is a difference in maxima that is not as prominent that as obtained by Djurašević & Erkapić (1998). This issue will be re-addressed in Section 4. We obtained three new minimum times throughout these new observations. They are collated with those published and listed in Table 1 with their errors.

3. PERIOD VARIATION ANALYSES

There are many factors that may change the orbital period of a close/interacting binary system. The most important of these factors are mass transfer between the stellar component stars, mass loss due to stellar activity, and third (or fourth) body dynamic effects. Especially in close interacting binary systems, these effects can be identified remarkably by observations. We can estimate this variation by measuring accurate times of minimum light. Minimum time observations that spread over many years allow us to determine the nature of the variation better. Systems such as OO Aql are good candidates to find these types of variations. The difference between the observed \((O)\) and calculated \((C)\) minimum times in an eclipsing system can provide us with information about any orbital period variation(s).

A stellar component of a contact binary system transfers mass to its companion from point L1. This causes an increase/a decrease in orbital period. This change depends on the mass of the mass-transferring and -accreting stars. In addition, in the presence of a third body, periodic orbital period variation occurs. In the case of mass transfer as well as in the existence of a third body, the \(O - C\) variations show a sinusoidal variation superimposed on a parabolic variation. OO Aql is a contact system where one of the components loses mass to its companion with a third/fourth component orbiting the binary system. Hence, both parabolic and double-sine-like variation are expected in its \(O - C\) variation:

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

These kinds of changes are usually expressed in the form given in Equation (1). \(T_o\) and \(E\) are the starting epoch for the primary minimum and eclipse cycle number; \(P_o\) is the orbital period of the binary; \(a_{12}\), \(i'\), \(e'\), and \(\omega'\) are the semimajor axis, inclination, eccentricity, and the longitude of the periastron of the eclipsing pair about the third body; and \(\nu'\) denotes the true anomaly of the position of the center of mass (see Kalomeni et al. 2007 for details). The first two terms of the equation are linear while the third term represents a parabolic variation due to the mass transfer and the fourth term represents the effect of a third body.

A total of 189 both primary and secondary times of minimum light, obtained with photoelectric and CCD techniques with three new minimum times presented in this study, were used in the analysis. All collected minimum times are listed in Table 1. Those times with Equation (1) were analyzed by the least-squares method using the ephemeris HJD Min\(I = 2438239.720+0.5067883 \times E\) given in Demircan & Gürol (1996) as the initial ephemeris. During the analysis, the visual and photographic times showed so much scattering that they have been ignored. Instead, reliable photoelectric and CCD observations were used in times of minimum light analyses. All the times of minimum light were given the same weights during the \(O - C\) analysis.

Using Equation (1) we analyzed all the available times of minimum light taking into account the mass transfer and a third body. Residuals of the analysis show a sine-like variation (Figure 2(b)). The last term in Equation (1), therefore, is rewritten for a fourth body and the analysis is redone. Figure 2 shows the number of cycles versus \(O - C\) variation. Figure 2(a) represents the effects of mass transfer and both third and fourth body effects. Figure 2(b) shows only the fourth body effect and Figure 2(c) shows the residuals after removing each effect.

![Figure 1](image-url)

Figure 1. (a) V, R, and I observations of OO Aql obtained at EUO. TYC 1058-689-1 was used as a comparison star. The solid line shows the theoretical fit obtained using the parameters given in Table 3. (b) The radial velocity variation of the OO Aql system. The observational points were obtained from Pribulla et al.'s (2007) study.

(A color version of this figure is available in the online journal.)
The parameters obtained from the orbital period analysis of OO Aql are listed in Table 2. In this table the orbital elements for the third body (Star D) and fourth body (Star C) are given separately. The fourth body that is closer to the binary star is named Star C and the farthest one is named Star D. Our analysis was based on the Wilson–Devinney code (Wilson & Devinney 1971). The adjustable photometric parameters and the limb-darkening coefficients were also set as free parameters as well as the time of minimum light T0 and the orbital period, P. The results obtained are shown in Table 3.

The solution results are shown graphically with the solid line in Figure 1(a). Open circles show observation points and the solid line presents the theoretically obtained solution. The radial velocity results obtained in the same solution are shown in Figure 1(b). The light curve analysis result is in agreement with observations. However, a slight discrepancy near the phase in Figure 1(b). This discrepancy may be the stellar activity manifesting as stellar spots. The O’Connell effect, the difference observed in maximum light, was not observed distinctly in this study. For this reason, the light curve solution was performed assuming no stellar spots.

4. SIMULTANEOUS SOLUTIONS OF LIGHT AND RADIAL VELOCITY CURVES

V, R, and I passband magnitudes are normalized and converted into normalized flux for light curve analyses. During the normalization, the mean magnitudes of V, R, I bands were taken to be −0.976, −1.182, and −1.333, respectively. Our new light variations with Pribulla et al.’s (2007) radial velocity data were solved simultaneously. Albedos (A1, A2) were obtained from Rucinski (1969) and gravity-darkening coefficients (g1, g2) were taken from Lucy (1967). The logarithmic limb-darkening law was used with the coefficients adopted from van Hamme (1993) for a solar composition star. During solutions due to the uncertainties in observations different weights were given for each color. Solutions were obtained with Phoebe (Prša & Zwitter 2005), which is based on the Wilson–Devinney code (Wilson & Devinney 1971). The adjustable photometric parameters were orbital inclination i, surface potential \( \Omega_1 = \Omega_2 = \Omega \), temperature of the secondary component \( T_2 \), luminosity \( L_1 \), and the mass ratio q. The center of mass velocity \( V_0 \) and semimajor axis a were also set as free parameters as well as the time of minimum light T0 and the orbital period, P. The results obtained are shown in Table 3.

The solution results are shown graphically with the solid line in Figure 1(a). Open circles show observation points and the solid line presents the theoretically obtained solution. The radial velocity results obtained in the same solution are shown in Figure 1(b). The light curve analysis result is in agreement with observations. However, a slight discrepancy near the phase in Figure 1(b). This discrepancy may be the stellar activity manifesting as stellar spots. The O’Connell effect, the difference observed in maximum light, was not observed distinctly in this study. For this reason, the light curve solution was performed assuming no stellar spots.
5. PHYSICAL PARAMETERS

The physical parameters of an eclipsing double-lined spectroscopic binary system OO Aql can be obtained accurately. A sufficient number of the radial velocity data of the system with the newly obtained accurate multi-color CCD observations allow us to determine the system parameters precisely. The effective temperature of the Sun is taken to be 5777 K and its absolute magnitude was taken to be 4.732 mag while calculating the physical parameters of the component stars. The mass of the primary star is obtained as 1.05 $M_\odot$ and the mass of its companion is obtained as 0.89 $M_\odot$. The results obtained are slightly different from those existing in the literature.

The distance of the system is obtained as 136(8) pc. This value is 13% smaller than the value given by SIMBAD. The absorption effect of the interstellar matter was ignored because the system is very close to us. Taking into account the distance of the system and the distance of the third body and the fourth body to the binary system, their angular distances were obtained as 0.138 and 0.074 arcseconds, respectively. The Hubble Space Telescope’s (HST) resolving power is about 0.05 arcseconds. This shows us that the

| Parameter                        | Unit            | Value    |
|----------------------------------|-----------------|----------|
| $T_0$ (d)                        |                 | 24 49193.4990(12) |
| Period, $P$ (d)                  |                 | 0.5067852(1) |
| Inclination, $i$ (°)             |                 | 85.6(1) |
| Mass ratio, $q = M_b/M_c$        |                 | 0.844(8) |
| Mass ratio, $a (R_\odot)$        |                 | 3.337(16) |
| $V_0$ (km s$^{-1}$)              |                 | -53.3(7) |
| $\Omega_1 = \Omega_2$           |                 | 3.391(3) |
| $T_1$ (K)                       |                 | 5700     |
| $T_2$ (K)                       |                 | 5472(55) |
| Fractional radius of primary comp.|                 | 0.4112(6) |
| Fractional radius of secondary comp.|             | 0.3815(6) |
| $A_1 = A_2$                      |                 | 0.6      |
| $g_1 = g_2$                      |                 | 0.32     |
| Luminosity ratio: $L_1/L_1 + L_2$ (%)|             | 58       |
| $V$                              |                 | 58       |
| $R$                              |                 | 58       |
| $l$                              |                 | 57       |

Notes. Indices 1 and 2 refer to the hot and cooler components, respectively. See the text for details.
third and fourth body can be seen as discrete sources in HST’s images.

6. RESULTS AND CONCLUSION

In this study, OO Aql’s VRI band observations obtained at EUO combined with Pribulla et al.’s (2007) radial velocity observations were solved simultaneously and its physical and orbital parameters were precisely obtained. The light and radial velocity observation results are given in Tables 3 and 4. The minimum times light spread over 61 yr combined with those obtained in this study were analyzed. Analysis yields a mass transfer from the massive component to the less massive component at a rate of $5 \times 10^{-8} M_\odot$ yr$^{-1}$, and an M star orbiting the system with an orbital period of 20 yr with a solar-like star with a 52 yr orbital period. Our solutions revealed that the system is a quadruple system AB + C + D. In addition, estimations show that HST can image this system directly.

Observations of quadruple systems spread over many years are important to study the evolution of quadruple systems as a laboratory. In this context, OO Aql is an ideal laboratory to study mass transfer and the angular momentum problem in the presence of a third and fourth body. The majority of contact systems are generally thought to be multiple systems. These systems are usually in the form of binary + star. On the other hand, some of the binary systems (e.g., XY Leo; Yakut et al. 2003) are in the form of binary + binary. Multiple systems like OO Aql, binary+star+star, are known to be fewer in number.

The evolution of close and interacting binary stars depends on the nuclear evolution, mass transfer, mass loss, and angular momentum loss. The effects of these processes are different on each stage of binary evolution. A detached and close binary system during the early stages of main sequence evolves first with nuclear evolution and dynamo-based angular momentum loss. The evolution is then driven by mass transfer of a Roche-lobe-filling primary star. Finally, the system evolves as a contact binary and mass and energy transfer continues between the components. The evolution of close binary stars was discussed in detail by Yakut & Eggleton (2005). The authors in that study discussed how contact binary systems evolve and also defined a new energy transfer process.

Using our newly obtained physical parameters, we provide an evolutionary model of the interacting binary OO Aql. We used the TWIN version of the EV code (Eggleton 1971; Pols et al. 1995; Eggleton & Kiseleva-Eggleton 2002; Yakut & Eggleton 2005) that has been developed by Peter P. Eggleton. We run dozens of models using different initial parameters. The best agreement with the observations was obtained for a model binary system with an initial period of 0.63 days, with primary and secondary masses of 1.18 $M_\odot$ and 1.12 $M_\odot$. Figure 3 shows the mass–radius diagram. The primary star’s evolutionary track is shown in red while its component is shown in green. A system with an orbital period of 0.63 days with 1.18 $M_\odot$ + 1.12 $M_\odot$ components that began to evolve at the main-sequence system evolves 8.5 billion yr later as a semi-detached binary, and a short time later it evolves as a contact system. This system reaches present-day mass and radius values at 8.7 billion yr.

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