New light curve analysis and period changes of the HW Vir-type binary system V1828 Aql

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ABSTRACT

The new *BVRI* photometric observations of the HW Vir-type eclipsing binary system V1828 Aql (P = 0.11037399 days) were presented. From these measurements, 16 new eclipse times have been obtained. The light curves in *BVRI* colors and the radial curves were simultaneously analyzed by using the Wilson–Devinney method for the system parameters. The system consists of a very hot primary component (T_1 = 42000 K) and a cold secondary component (T_2 = 3077 ± 250 K). The absolute dimensions were found as follows: (M_1 = 0.351 ± 4 0.040 $M_{\odot}$, M_2 = 0.095 ± 0.011 $M_{\odot}$, R_1 = 0.176 ± 0.007 $R_{\odot}$, R_2 = 0.140 ± 0.007 $R_{\odot}$, L_1 =86.91 ± 6.76 $L_{\odot}$ and L_2 = 0.002 ± 0.001 $L_{\odot}$).

The orbital period variation of V1828 Aql was made using all available light minimum times. From the (O - C) diagram, the orbital period shows a variation possibly attributable to the light travel time effect by the presence of the third body. The third body orbital period is $P_3 = 3317.7^{+18.9}_{-17.2}$ days, its minimal mass is $M_3 = 13.24^{+0.11}_{-0.14}$ M_J. The mass value calculated for the third body shows, that this object is right at the border between the planets and the brown dwarfs.

1. Introduction

HW Vir systems are the rare evolved eclipsing binaries consist of a hot subdwarf star (sdOs, sdBs) and a low-mass main-sequence star. The hot compact stars of the systems are core helium-burning stars with very thin hydrogen envelopes that are found on the blue end of horizontal branch of the Hertzsprung–Russell diagram, and they have masses around 0.5 $M_{\odot}$. The low-mass main-sequence stars of the systems are mostly late M-dwarf. HW Vir systems mostly have short periods (around 0.1 days). The short period indicates that they have undergone a common envelope phase followed by a spiral-in phase. Currently, about two dozen HW Vir systems have been known, and some of them have been observed over extended periods. These systems are crucial to study the formation of hot subdwarf stars and low-mass white dwarfs, the common-envelope phase, and the pre-phase of cataclysmic variables.

V1828 Aql (=NSVS 14256825, =2MASS J20200045+0437564) is a HW Vir type eclipsing binary star system with an orbital period as very short 0.11037399 days. The light curve of V1828 Aql is shown typical features of HW Vir-type system. There are quite significant variations in outside of the eclipses that is caused by the reflection effect which results from heating of the atmosphere of the cold component by the hot component.

The light variability of V1828 Aql was found from data of Northern Sky Variability Survey (NSVS) (Wozniak et al., 2004). Wils et al. (2007) derived an orbital period of $2^h.6496$. The first detailed photometric and spectroscopic observations of the system was made by Almeida et al. (2012). They analyzed the light curves and radial velocity curves using Wilson–Devinney method and determined the photometric and absolute parameters of the system. They calculated the mass of the hot component M_1= 0.419 $M_{\odot}$, the mass of the cold component M_2= 0.109 $M_{\odot}$, the radius of the hot component R_1= 0.188 $R_{\odot}$, the radius of the cold component R_2= 0.162 $R_{\odot}$. In the same study, the temperatures of the hot and cold component were given as T_1= 42000K and T_2= 2550K, respectively.

V1828 Aql has attracted the attention of many investigators due to changes in the orbital period. This case was discussed by Wils et al. (2007), Kilkenny and Koen (2012), Beuermann et al. (2012), Almeida et al. (2013), Lohr et al. (2014), Nasiroglu et al. (2017) and Zhu et al. (2019). The variations in the system's orbital period were often attributed to the light-time effect caused by the presence of additional

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Table 1
Data for V1828 Aql, comparison and check stars.

	System	R.A.	Dec.	B (mag)
V	V1828 Aql	$20^h\ 20^m\ 00^s.459$	$+04^\circ\ 37'\ 56''.520$	$12^m.90$
C1	TYC 504-933-1	$20^h\ 20^m\ 03^s.259$	$+04^\circ\ 48'\ 17''.252$	$11^m.87$
C2	TYC 504-1033-1	$20^h\ 20^m\ 08^s.845$	$+04^\circ\ 38'\ 12''.705$	$11^m.98$

components. Beuermann et al. (2012) reported the existence of a giant planet with a mass of about 12 $M_j$in V1828 Aql. Almeida et al. (2013) found two cyclic variations with periods of P_3= 3.49 years and P_4 = 6.86 years in the (O-C) curve. They explained this situation by the existence of two planets with masses of M_3= 2.9 $M_j$and M_4 = 8 M_j, respectively. Wittenmyer et al. (2013) showed that the orbit would be unstable at short time scales in the two-planet model for V1828 Aql. Hinse et al. (2014) pointed out that the current (O-C) cycle of the system is not long enough to detect the additional body. Nasiroglu et al. (2017) also made (O-C) analysis of the system. They calculated a third body with a period of P_3=9.95 years and a mass of M_3= 14.75 M_j. Finally, Zhu et al. (2019) published new minima times and they calculated the mass and period of the third body as M_3= 14.15 M_j, P_3= 8.83 years, respectively.

2. Observations

New photometric observations of V1828 Aql were carried out by TÜBİTAK National Observatory's (TUG) 100-cm telescope (T100) with SI 1100 series CCD camera (Fairchild 486 BI, Cryo-tiger cooling, 15 µm pixel size, 4096 × 4037 pixel) using *B-V-R-I* filters during the season July 2018 (single night) and August 2018 (Two nights) and «anakkale Onsekiz Mart University Ulupınar Observatory's (COMUG) 30-cm telescope (T30) with ALTAU47 CCD camera (E2V CCD47-10, Peltier cooling, 13 µm pixel size, 1024 × 1024 pixels) using *R* filter during the season August 2019 lasting 2 nights. Relevant data for the eclipsing system (V), the comparison (C1) and the check (C2) stars is given in Table 1. All data in this table are taken from SIMBAD.

The reduction of the CCD images was carried out using the C-MUNIPACK[1] program. All the CCD images were calibrated using bias, dark and flat images.

During of observations and in *BVRI* bands, a total of 16 new minima times, with 8 primary minima times among them were observed. New minima times and their errors were calculated by Kwee–van Woerden method (Kwee and van Woerden, 1956). The averages value were calculated for the times of minima obtained in the different filters during the same observational night. The minima times which were obtained as Julian Date - Universal Time (JD-UTC) were converted to Barycentric Julian Date - Dynamical Time (BJD-TDB) using a code.[2] published by Eastman et al. (2010) The new minima times obtained in the BJD are given in Table 2.

The phases of the light curves were calculated using the following light elements given by Wils et al. (2007). The reference time (To) and its error were converted to BJD format.

$$BJD(minI) = 2454274.2088(1) + 0.11037410(2) \times E \quad (1)$$

3. Modeling of light curves

The *BVRI* light curves obtained in TUG and the radial velocity curves taken from Almeida et al. (2012) were solved simultaneously by using the Wilson and Devinney (1971) synthesis code. Almeida et al. (2012) performed the spectroscopic observations using the Cassegrain spectrograph attached to the 1.6-m telescope at the Observatòrio do Picodos Dias/Laboratòrio Nacional de Astrofisica (OPD/LNA) facilities in Brazil. They obtained 36 spectra using 1.8 Åresolution.

Table 2
New minima of times of V1828 Aql.

BJD	Error (d)	Epoch	Type	Filter	Obs.
2458308.327108	0.000298	36549.5	II	*BVRI*	TUG
2458308.382288	0.000087	36550.0	I	*BVRI*	TUG
2458308.437514	0.000226	36550.5	II	*BVRI*	TUG
2458308.492759	0.000084	36551.0	I	*BVRI*	TUG
2458337.410692	0.000062	36813.0	I	*BVRI*	TUG
2458337.465831	0.000263	36813.5	II	*BVRI*	TUG
2458338.459286	0.000224	36822.5	II	*BVRI*	TUG
2458338.514435	0.000076	36823.0	I	*BVRI*	TUG
2458338.569672	0.000244	36823.5	II	*BVRI*	TUG
2458702.418080	0.000036	40120.0	I	*R*	COMUG
2458702.473299	0.000111	40120.5	II	*R*	COMUG
2458702.528449	0.000052	40121.0	I	*R*	COMUG
2458705.342937	0.000128	40146.5	II	*R*	COMUG
2458705.398126	0.000054	40147.0	I	*R*	COMUG
2458705.453285	0.000133	40147.5	II	*R*	COMUG
2458705.508474	0.000033	40148.0	I	*R*	COMUG

Wilson–Devinney code has several modes for the different types of light curves. These modes are 2, 3, 4, and 5 correspond to the scenarios in which the binary components are detached, overcontact, semi-detached with star 1 accurately filling its limiting lobe, and semi-detached with star 2 precisely filling its limiting lobe, respectively. In the application of this procedure, we chose mode 2, and set the control parameter IPB = 1. In this case, the coupling between (L_2) and (T_2) is severed and the luminosity of both stars (L_1, L_2) can be adjusted.

During the analyses, we fixed several parameters. These parameters may be estimated from the known characteristics of the stars. The temperature (T_1) of the primary star was taken to be 42000K from Almeida et al. (2012). The logarithmic limb darkening coefficients were calculated by van Hamme (1993). For the primary hot component, the bolometric albedo and the gravity-darkening exponent were fixed at A_1= 1.0 and g_1= 1.0 by taking into consideration of the temperature of the component (Ruciński, 1969; Lucy, 1967). Because of the reflection effect, the temperature of the surface of the cold component facing the hot component is higher than the rest of the surface of cold component, so the coefficient of bolometric albedo and gravity-darkening exponent for the cold component were set to A_2= 1.0 and g_2= 0.32. It is assumed that this system has a circular orbit and the orbital eccentricity (e = 0) and the longitude of periastron (ω = 90°) were fixed. We set the third light l_3 = 0 in our analysis.

On the other hand, the adjustable parameters were the reference epoch time of the light elements T_0, the orbital period of the system P, the semi-major axis a, the radial velocity of the center of the mass V_γ, the orbital inclination i, the temperature of secondary component T_2, the dimensionless surface potentials of components Ω_1 and Ω_2, the mass ratio of components q, and the monochromatic luminosity of the primary component L_1. To attain models, calculations with Wilson–Devinney code were repeated until the correction of each free parameter becomes smaller than its standard deviation. The result parameter values obtained from the analyses are given in Table 3. Fig. 1 shows the light curves obtained from the observations in the *BVRI* filters and the model curves obtained from the analyses. The theoretical velocity curves shows in Fig. 2.

4. Absolute dimensions

Absolute dimensions for the components of V1828 Aql are calculated from the photometric elements given in Table 3. The absolute parameters of the system are listed in Table 4. As seen in this table, the relative uncertainties are smaller than 1% for the absolute masses and radii of both components.

[1] Available in http://c-munipack.sourceforge.net/

[2] Available in http://astroutils.astronomy.ohio-state.edu/time/index.html

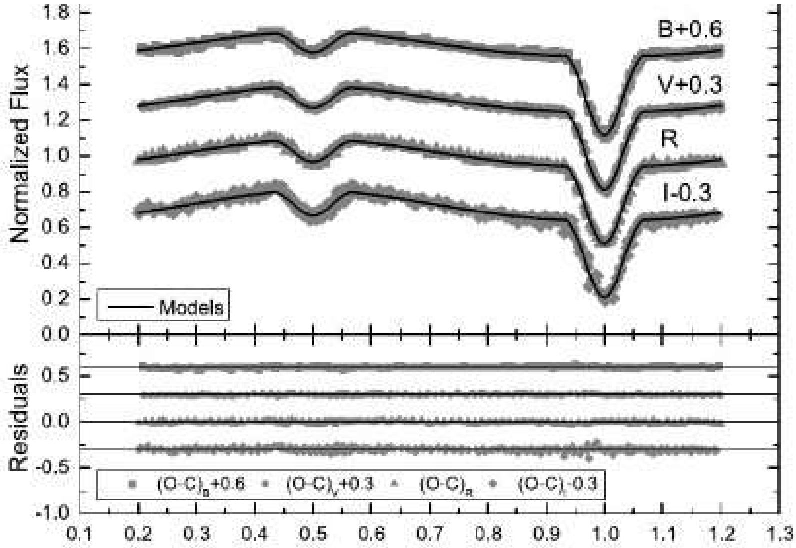

Fig. 1. *B*, *V*, *R* and *I* light curves for V1828 Aql. The points are the individual observations. The solid lines are the theoretical light curves based on the parameters in Table 3. The residuals from theoretical light curves subtracted are shown in bottom panel.

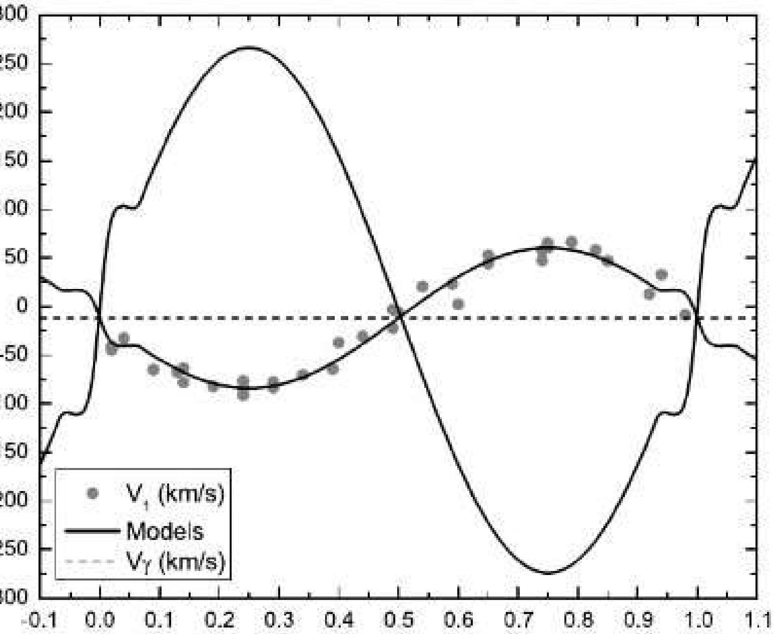

Fig. 2. Radial velocity (dots) and model (solid line) curves of V1828 Aql. The dashed line represents the average velocity of the system ($V_\gamma = -12.24$ km/s).

Additional quantities listed in Table 3 include the luminosities, absolute magnitudes, and the distance. Interstellar reddening toward V1828 Aql was taken from Stassun et al. (2019) and is E(B-V) = $0^m.823$. Along with the apparent visual magnitude of the system out of eclipse ($V = 13^m.331$; Henden et al.) and the bolometric corrections from Eker et al. (2018), we deduce a distance of 730 ±97 pc. The calculated distance is not far from the distance of 753 ±20 pc deduced from the trigonometric parallax listed in the Gaia/EDR3 catalog (Gaia Collaboration, 2016b, 2020a).

5. Orbital period changes

In the presence of a third body gravitationally bounded to binary star systems, the difference between the observed (O) and calculated (C) minimum times of the system may produce a regular cyclical variation over time. This effect, which we call the light travel time effect (LTTE), shows itself as a sinusoidal variation in (O-C) diagrams. This sinusoidal variation can be modeled as follows (Borkovits et al., 2015).

$$\Delta_{LTTE} = -\frac{a_{12}\sin i_2}{c}\frac{(1-e_2^2)\sin(\nu_2+\omega_2)}{1+e_2\cos\nu_2} \tag{2}$$

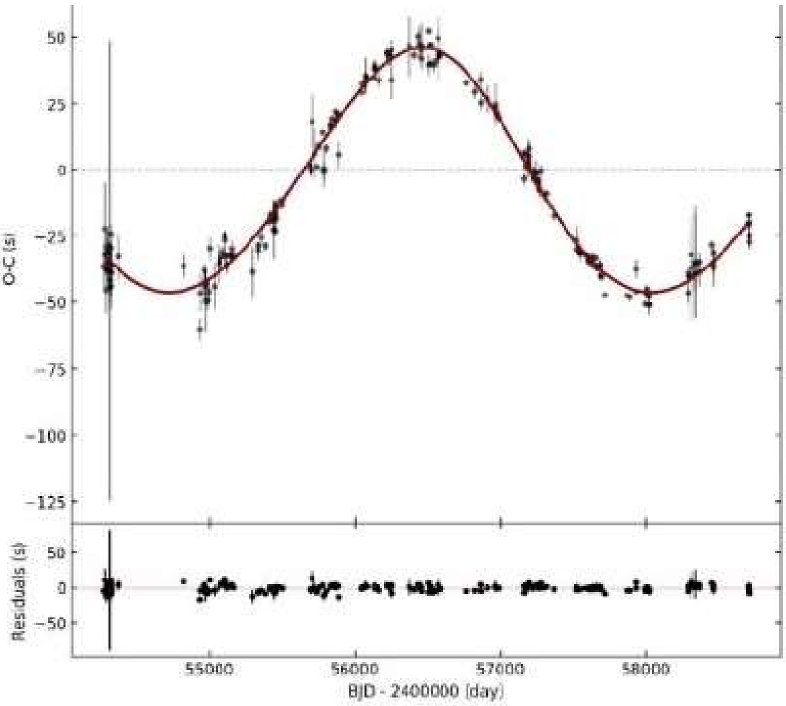

Fig. 3. (O-C) diagram of V1828 Aql (top panel) and residuals from model (bottom panel).

Table 3
The results of the light curve analysis of V1828 Aql.

Parameter	Almeida et al. (2012) (*V*)	This work (*BVRI*)
T_0 (BJD)	–	2458308.38238 ± 0.00002
P (day)	–	0.1103742 ± 0.0000001
a ($R_\odot$)	0.80 ± 0.04	0.74 ± 0.03
V_γ (km/s)	–	−12.24 ± 0.69
i (°)	82.5 ± 0.3	82.18 ± 0.14
T_1 (K)	42000 ± 500	42000
T_2 (K)	2400 ± 550	3077 ± 250
Ω_1	4.55 ± 0.11	4.496 ± 0.023
Ω_2	2.69 ± 0.12	2.823 ± 0.056
q	0.260 ± 0.012	0.27 ± 0.12
A_1- A_2	1.00 - (1.20 ± 0.12)	1.00 – 1.00
g_1- g_2	0.3 - 0.3	1.00 – 0.32
$L_1/(L_1+L_2)_B$	–	0.999 ± 0.001
$L_1/(L_1+L_2)_V$	–	0.999 ± 0.001
$L_1/(L_1+L_2)_R$	–	0.999 ± 0.001
$L_1/(L_1+L_2)_I$	–	0.998 ± 0.002
$L_2/(L_1+L_2)_B$	–	0.001
$L_2/(L_1+L_2)_V$	–	0.001
$L_2/(L_1+L_2)_R$	–	0.001
$L_2/(L_1+L_2)_I$	–	0.002
r_1 (pole)	0.233 ± 0.005	0.2362 ± 0.0011
r_1 (point)	0.236 ± 0.006	0.2399 ± 0.0011
r_1 (side)	0.235 ± 0.005	0.2383 ± 0.0011
r_1 (back)	0.236 ± 0.006	0.2393 ± 0.0011
r_2 (pole)	0.194 ± 0.014	0.1834 ± 0.0120
r_2 (point)	0.210 ± 0.019	0.1950 ± 0.0160
r_2 (side)	0.198 ± 0.016	0.1861 ± 0.0127
r_2 (back)	0.207 ± 0.018	0.1927 ± 0.0149

Table 4
The absolute parameters of V1828 Aql.

Parameter	Almeida et al. (2012)	This work
M_1 ($M_\odot$)	0.419 ± 0.070	0.351 ± 0.040
M_2 ($M_\odot$)	0.109 ± 0.023	0.095 ± 0.011
R_1 ($R_\odot$)	0.188 ± 0.010	0.176 ± 0.007
R_2 ($R_\odot$)	0.162 ± 0.008	0.140 ± 0.007
T_1 (K)	42000 ± 400	42000
T_2 (K)	2550 ± 550	3077 ± 250
a ($R_\odot$)	0.80 ± 0.04	0.74 ± 0.03
$log g_1$ (cgs)	5.51 ± 0.11	5.49 ± 0.02
$log g_2$ (cgs)	5.05 ± 0.13	5.12 ± 0.04
$M_{bol,1}$ (mag)	–	−0.09 ± 0.08
$M_{bol,2}$ (mag)	–	11.76 ± 0.37
L_1 ($L_\odot$)	–	86.91 ± 6.76
L_2 ($L_\odot$)	–	0.002 ± 0.001
V (^{m})	–	13.331 ± 0.171
$E(B-V)$ (^{m})	–	0.0823
d (pc)	–	730 ± 98
d_{Gaia} (pc)	–	753 ± 20

Here, a_{12}, e_2, ν_2, $\omega_2$are the semi-major axis, the eccentricity, the true anomaly and the argument of periastron of the third body orbit, respectively. i_2 is the inclination of binary's orbit relative to the center of mass of triple system and c is the speed of light.

We wrote a computer program in Python using the equations of Borkovits et al. (2015) to model the changes in the (O-C) diagram. The code uses the Python-based version 'PyMultiNest' (Buchner et al., 2014) of the 'MultiNest' (Feroz et al., 2009) code that works with the Nested-sampling algorithm. The code implementation is based on the Bayesian framework method in Masuda (2017).

During our observations, we determined a total of 16 minima times, with 8 primary eclipses among them. New times of the minima and their errors, which were determined by using Kwee & van Woerden (1956)'s method, are presented in Table 2. In addition, we collected the published minima times of the system from the literature. A total of 217 observational minima times were used in the (O-C) analysis. The (O-C) values were computed using the linear light elements given by Eq (1). The observed minima times cover between 2007 and 2019.

The results obtained from the (O-C) analyses are given in Table 5 in comparison with the previous results. The minimum mass of the third body is obtained $13.24^{+0.13}_{-0.14}$ M_J. According to this value, the mass of the third body was calculated about 1.5 $M_J$smaller than that found

Table 5
Orbital parameters of V1828 Aql and its circumbinary substellar component.

Parameter	Nasiroglu et al. (2017)	Zhu et al. (2019)	This work
T_0 (BJD)	$2455793.84006^{+2\times10^{-5}}_{-2\times10^{-5}}$	$2454274.20921 \pm 0.00001$	$2454274.209220^{+1.8\times10^{-5}}_{-1.8\times10^{-5}}$
P_{bin} (day)	$0.1103741099^{+2\times10^{-9}}_{-1\times10^{-9}}$	$0.1103741030 \pm 0.0000000005$	$0.1103741049^{+1.6\times10^{-10}}_{-1.7\times10^{-10}}$
K (s)	$48.9^{+1.6}_{-1.2}$	46.31 ± 0.43	$45.94^{+0.44}_{-0.44}$
$a_{12}sini$ (AU)	–	0.0928 ± 0.0009	$0.0925^{+0.0009}_{-0.0009}$
e	$0.175^{+0.022}_{-0.001}$	0.12 ± 0.02	$0.13^{+0.02}_{-0.02}$
ω (°)	$90.11^{+15.77}_{-12.80}$	133.3 ± 10.3	$128.4^{+6.77}_{-6.49}$
T_3(BJD)	–	2456816.0 ± 93.7	2453459^{+86}_{-81}
P_3(day)	$3632.8^{+309.6}_{-131.7}$	3225.16 ± 21.92	$3313.7^{+18.9}_{-17.2}$
$f\,(m_3)\,(M_\odot)\,(\times10^{-6})$	–	9.63 ± 0.32	$9.63^{+0.29}_{-0.30}$
$M_3(M_J)$ (i=90°)	$14.75^{+0.13}_{-0.13}$	14.15 ± 0.16	$13.24^{+0.13}_{-0.14}$
a (AU)	$3.74^{+0.12}_{-0.08}$	3.12 ± 0.07	$3.35^{+0.01}_{-0.01}$

by Nasiroglu et al. (2017) and Zhu et al. (2019). The (O-C) diagram is shown in Fig. 3, along with the residuals from the observed minima. In Fig. 3, the upper panel shows the linearly corrected periodic change of the new minimum times of the system obtained from the literature and in this study, and the residuals formed by subtracting the model from the data in the lower panel.

6. Results

In this study, the radial velocity and light curves analysis of V1828 Aql was made with the Wilson–Devinney program , and the geometric and physical elements of the system were derived. In addition, the period analysis of the system was performed using all available minima times in the literature and combining our new minima times. The following results were obtained with these analyses.

1. V1828 Aql which is a system of type HW Vir, consists of a very hot primary component (T_1= 42000 K) and a cold secondary component (T_2= 3077 K). Due to the high temperature difference between the components, the light curve of the system shows a marked reflection effect. Because of this influential reflection effect, in the light curve analysis the bolometric albedo was taken as A_2= 1.0 for the secondary component.

2. The masses and radii of the primary and secondary components were obtained as 0.351 ±0.040 $M_\odot$, 0.095 ±0.011 $M_\odot$and 0.176 ±0.007 $R_\odot$, 0.140 ±0.007 $R_\odot$respectively. In addition, distance of the system is 730 ±97 pc.

3. A periodic variation is seen in the (O-C) diagram of V1828 Aql. We assumed that this variation was caused by a third body gravitationally bounded to the system. The period of the cyclic variation was calculated $3313.7^{+18.9}_{-17.2}$ days, . From this variation, the mass function of the third body ($f(m_3)$) was found as 9.989 × 10-6 $M_\odot$. This additional body has a period of $3313.7^{+18.9}_{-17.2}$ days, and an eccentricity of e = $0.13^{+0.02}_{-0.02}$. It is located approximately $3.35^{+0.01}_{-0.01}$ AU from the binary system's center of the mass. If the orbital inclination of the third body is assumed to be i=90°, the minimum mass of the circumbinary companion was calculated as $13.24^{+0.13}_{-0.14}$ M_J. This mass value indicates that it is a substellar object. This result is confirmed findings by Nasiroglu et al. (2017) and Zhu et al. (2019).

Future high-precision observations will help to reveal more detailed features of the system. There is also a need for a large number of new minima times to identify the presence of substellar body that are thought to be gravitationally bounded to the system.

CRediT authorship contribution statement

Ç. Nehir: Methodology, Investigation, Resources, Software, Formal analysis, Writing – original draft. **İ. Bulut:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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