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V355 And: a neglected detached binary in a multiple star system

B. Özkardeş[1,2]

[1] *Department of Space Science and Technologies, Faculty of Arts and Sciences, Çanakkale Onsekiz Mart University, Terzioğlu Kampüsü, TR-17020, Çanakkale, Turkey, (E-mail: burcu@comu.edu.tr)*

[2] *Çanakkale Onsekiz Mart University, Astrophysics Research Center and Ulupınar Observatory, TR-17100, Çanakkale, Turkey*

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Abstract. The analysis of light curves (from TESS, ASAS–SN and KWS databases) of the eclipsing binary V355 And is presented for the first time. The *O-C* diagram was constructed using all available times of minimum light together with the ones determined in this study, and the revised ephemeris was obtained. The final photometric model describes V355 And as an Algol-like type binary star with a detached configuration. Absolute parameters of the components of the system were found to be: masses, M_1=1.56 ± 0.01 $M_\odot$ and M_2=1.38 ± 0.01 $M_\odot$, radii, R_1=1.70 ± 0.03 $R_\odot$ and R_2=1.38 ± 0.03 $R_\odot$, and effective temperatures, T_1=6650 ± 200 K and T_2=6235 ± 201 K. Considering interstellar extinction the distance to V355 And was computed as 117 ± 7 pc. The evolutionary state of V355 And is also discussed using the Geneva stellar models.

Key words: Stars: binaries: eclipsing; Stars: absolute parameters; Stars: Individual V355 And

1. Introduction

Eclipsing binary systems are important celestial objects in astrophysics in determining the astrophysical parameters of stars in our galaxy, the Milky Way, and nearby galaxies and understanding stellar evolutionary status. Since the proximity and ellipsoidal effects are not important in detached binary systems, their absolute parameters can be derived more accurately from the solutions of light and radial velocity curves. This paper focuses on the neglected eclipsing binary V355 And. The primary objectives of the present study are to determine the absolute dimensions of V355 And and to examine the evolutionary state of the system's components. Literature-based studies of this neglected binary star are summarized below.

V355 And is an Algol-type binary star and a component of the visual binary WDS 00442–4614. The eclipsing nature and multiplicity of the system were discovered by the Hipparcos satellite (ESA, 1997). The system has a fainter ($\Delta V_{Hip} \simeq 1^m.17$) component at a separation of 1.41 arcsec and a position angle of 5.5 deg. The target system V355 And is one of the poorly studied eclipsing binary stars. Kazarovets et al. (1999) gave the GCVS name and variability type of the system in their 74th name-list of variable stars. Tikkanen (2002) published the complete visual light curve of V355 And and revealed the light elements to be T_0=2452295.088(8) and P=4.71841(2). Imbert (2006) determined the spectroscopic orbits of 25 binary stars, including the double-lined system V355 And, using 1402 *Coravel* radial velocity measurements. Zasche et al. (2009) presented a new catalog of visual double systems containing eclipsing binaries as one component. For V355 And, they suggested the visual orbit's period to be in the order of 3000 yr according to the orbital coverage. Hubscher (2015) recorded one minimum light time in the I–filter for the system. Some photometric properties of the multiple system V355 And are given in various catalogues (e.g. Malkov et al., 2006; McDonald et al., 2012; Avvakumova et al., 2013; Paunzen, 2015; Soubiran et al., 2016). The fundamental data for V355 And is given in Table 1.

Table 1. Fundamental data based on the ASAS–SN database for V355 And.

Star Name	ASASSN–VJ004411.33+461407.2
LCID	51037
RA, DEC	11.0472, 46.2353
Epoch (HJD)	2457747.80809
V mag	7.97
Amplitude	0.73
Type	VAR

2. O-C analysis

2.1. Data

For V355 And, there are few times of minimum light in the literature: Tikkanen (2002) observed the system visually and obtained 5 minima times. In the *O-C* Gateway archive[1], 4 minima times of the eclipsing binary V355 And are recorded. In this study, 9 minima times of the system were obtained from the photometric light curves of the SuperWASP (Wide Angle Search for Planets; Butters et al., 2010) and TESS (Transiting Exoplanet Survey Satellite; Ricker et al., 2015) surveys. Newly determined minima times were computed with the software Minima Vers.27 published by B. Nelson[2] using the Kwee & van Woer-

[1] http://var2.astro.cz/ocgate/index.php?lang=en

[2] https://www.variablestarssouth.org/software-by-bob-nelson/

den (1956) method. All minima times in HJD were converted to $\mathrm{BJD_{TDB}}$ using the HJD2BJD calculator[3] (Eastman et al., 2010) because the calculated times of minima from TESS observations were in the $\mathrm{BJD_{TDB}}$ time system. Minima times of V355 And are tabulated in Table 2.

Table 2. Minima times of V355 And.

$\mathrm{BJD_{TDB}}$(+2400000)	Type	Method	Reference
52271.5000±0.0210	p	visual	
52276.2170±0.0160	p	visual	
52283.2910±0.0070	p	visual	Tikkanen (2002)
52295.0900±0.0080	p	visual	
52309.2420±0.0110	s	visual	
56928.5218±0.0033	p	CCD	
57256.4517±0.0064	s	CCD	$O-C$ Gateway
57992.5188±0.0015	s	CCD	
58379.4208±0.0015	s	CCD	
54418.3577±0.0004	p	CCD	SuperWASP
54373.5245±0.0004	s	CCD	
58768.6916±0.0001	p	CCD	
58778.1289±0.0002	p	CCD	
58782.8474±0.0001	p	CCD	
58766.3361±0.0002	s	CCD	TESS
58771.0540±0.0001	s	CCD	
58780.4909±0.0001	s	CCD	
58785.2092±0.0001	s	CCD	

2.2. New light elements

We can examine whether the orbital period of a binary system has changed using the *O-C* diagram. In the case of V355 And, the *O-C* values of the minima times listed in Table 2 were calculated using T_0=2458768.6916 (from TESS observations) and P=4.71841 (from Tikkanen, 2002), and thus the *O-C* diagram of the system was created. A linear regression of all *O-C* values was performed to obtain the revised ephemeris, given in equation (1). The residuals are plotted in Fig. 1. In this figure, it is clearly seen that the period of the system has been constant throughout the time interval of 18 years.

$$Min\ I\ (BJD_{\mathrm{TDB}}) = 2458768.6924(\pm 0.0011) + 4^{d}.7183707(\pm 0.0000013) \times E, \quad (1)$$

where the values in brackets are the uncertainties.

[3]http://astroutils.astronomy.ohio-state.edu/time/hjd2bjd.html

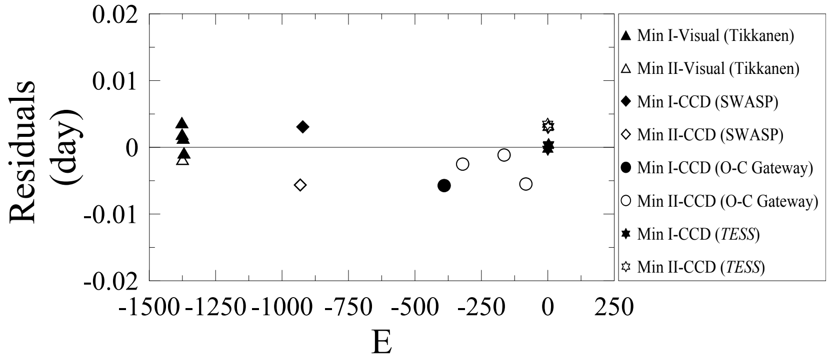

Figure 1. A plot of *O–C* residuals versus the ephemeris used in equation (1).

3. Light curve modeling

3.1. Data

The neglected binary V355 And was observed by five different photometric surveys: The All-Sky Automated Survey for Supernovae (ASAS–SN; Shappee et al., 2014; Kochanek et al., 2017; Jayasinghe et al., 2018), Kamogata/Kiso/Kyoto Wide-field Survey (KWS; Maehara, 2014), Hipparcos, SuperWASP and TESS. The photometric light curves observed by the TESS[4], ASAS–SN[5] and KWS[6] were analyzed, while the Hipparcos and SuperWASP light curves were not solved because of the inadequate phase covering and more scattered data.

The main purpose of TESS is to explore planetary transits by scanning the chosen sky over a period of two years. TESS observational data comes from sectors that cover a 24°x90° region in the sky. The observations of 32 sectors in total have been completed so far. TESS observations of V355 And (T_{mag}=7.42, TIC 601366244) were made in 120 s cadence during Sector 17 starting in October 2019. In this study, Simple Aperture Photometry (SAP) Flux data with QUALITY=0 of V355 And, which consists of 12,613 photometric points for the system, was converted into magnitude values. The average values per each three data points were used to generate the normalized data, thus nearly 4200 normal points in total. The photometric phases of the TESS light curve were computed using equation (1).

The ASAS–SN project aims to survey the whole sky up to 18th magnitude and focuses on the discovery of bright nearby supernovae. In the ASAS–SN Variable Stars database 666,502 light curves are available, including the *V*–band light curve of the target binary V355 And obtained between October

[4]https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html
[5]https://asas-sn.osu.edu/
[6]http://kws.cetus-net.org/ maehara/VSdata.py

2013 and January 2018. The ASAS–SN light curve of V355 And is composed of about 1800 data points in V mag. The outliers with $\sigma \geq 0.0004$, where $\sigma = \frac{error\,of\,observation\,point}{observation\,point}$, were removed from the ASAS–SN data. The remaining data points, ∼1480, were processed in the analysis. Using equation (1), the phases of the ASAS–SN light curve were calculated.

KWS is designed for the automated wide-field optical survey of bright transits and variable stars via a small CCD camera and lens to achieve a photometric precision of < 5% for stars with V–band magnitude between 5 and 11. KWS observations of V355 And were made between December 2010 and January 2020, and nearly 1200 data points were obtained in total in the V and I_c filters. The scattered data points with $\sigma \geq 0.00095$ for V and $\sigma \geq 0.00013$ for I_c were removed from the KWS data, thus a total of ∼800 data points remained for the analysis. Equation (1) was used for phasing the KWS–VI_c light curves.

The spectroscopic orbital parameters of the system given by Imbert (2006) are tabulated in Table 3. The spectroscopic mass ratio ($q = \frac{K_1}{K_2}$) of V355 And is calculated to be 0.88 based on this table. Public data of the radial velocity curves of the eclipsing pair can be extracted from the webpage[7] of SB9 (Pourbaix et al., 2004).

Table 3. Spectroscopic orbital parameters of V355 And from Imbert (2006).

Parameters	Unit	Primary	Secondary
T0	HJD	48929.67±0.007	
Period	day	4.71835±0.00002	
e	–	0 (fixed)	
ω	deg	0 (fixed)	
K	km/s	85.01±0.28	96.59±0.30
V_γ	km/s	6.93±0.17	
asin(i)	km	$5.52 \times 10^6 \pm 0.02 \times 10^6$	$6.27 \times 10^6 \pm 0.02 \times 10^6$
$m\sin^3(i)$	$M_\odot$	1.56±0.01	1.38±0.01

3.2. Analysis

If both a light curve and radial velocity curves of an eclipsing binary system are obtained, the absolute parameters of that system can be determined more precisely. The Wilson-Devinney (WD) code (Wilson & Devinney, 1971), appended with the Monte Carlo (MC) algorithm (Zola et al., 2010), was used for the light curve modeling. In the first step, due to its high inherent accuracy (each datum on the order of 0.0001 mag), the TESS light curve of V355 And was solved. The MC procedure outlined by Zola et al. (2010) was followed, and the spectroscopic mass ratio value was kept fixed. In the second step, ASAS–SN and

[7]https://sb9.astro.ulb.ac.be/

KWS light curves were solved. The ASAS–SN and KWS light curves both have lower photometric accuracy and show more scattering at their maximum levels (see Fig. 2). On the other hand, there are not enough observation points in the depths of the minima of KWS light curves. As it is well known, the depths of minima of a given light curve are important factors in determining the surface potential parameters (then the fractional radii) of component stars. Therefore, in the solution of ASAS–SN and KWS light curves, these surface potential parameters (Ω_1, Ω_2) were fixed at the values obtained from the solution of the TESS light curve, and the other parameters were adjusted.

The following parameters were adopted and fixed during all iterations. The temperature of the primary component was fixed at 6650 K corresponding to the F5 spectral type given by the Hipparcos catalogue using Drilling & Landolt (2000)'s calibration for MK spectral types. The bolometric gravity-darkening exponents (g_1=g_2=0.32) and albedos (A_1=A_2=0.5) of the components were set at their theoretical values as suitable for the spectral type of component stars, following Lucy (1967) and Ruciński (1969), respectively. The square-root limb-darkening law was adopted with limb-darkening coefficients from the calibration tables of Claret & Bloemen (2011) and Claret et al. (2013), depending on the filter wavelengths and temperatures of the primary and secondary components. Besides synchronous rotation of the components, a circular orbit for the systems was also assumed.

The free parameters in the light curve fitting were the orbital inclination (i), phase-shift (ϕ), temperature of the secondary component (T_2), non-dimensional surface potential parameters of components (Ω_1 and Ω_2), luminosity of the primary (L_1) and third light contribution ($\frac{L_3}{L_{total}}$). In the MC process, an assumed range within realistic bounds for each free parameter should be defined. In the analysis, the search ranges of the adjusted parameters are given in Table 4.

The parameters of the WD+MC solution are listed in Table 4 with the errors corresponding to a 90% confidence level. The best theoretical fits of the WD+MC modeling program are compared with the observed light curves in Fig. 2. The 2D plot of the parameter space for degeneracies between the chosen five parameters (i, T_2, Ω_1, Ω_2 and L_3) are shown in Fig. 3 using MC confidence levels. There are considerable degeneracies between Ω_1 and Ω_2 and between i and L_3, while no degeneracies are seen between i and T_2, i and Ω_1 and i and Ω_2. Such degeneracies between the geometric and physical parameters were found in some detached binaries (see Garcia et al., 2014; Sürgit et al., 2017).

Table 4. Selected search ranges of adjusted parameters in the WD+MC method.

System	i (deg)	ϕ	T_2 (K)	Ω_1 and Ω_1	L_1	$\frac{L_3}{L_{total}}$
V355 And	70–90	-0.01–0.01	5500–6600	9.0–14.0	2.0–12.0	0.1–0.50

Table 5. Results of the analysis of light curves of V355 And.

Parameters	TESS	ASAS-SN	KWS
$i\,(^\circ)$	88.1±0.2	87.5±0.2	88.1±0.2
ϕ	-0.0006±0.0001	-0.0007±0.0001	-0.0007±0.0001
$T_1\,(K)$	6650 (fixed)	6650	6650
$T_2\,(K)$	6414±12	6237±14	6297±23
$q = M_2/M_1$	0.88 (fixed)	0.88	0.88
Ω_1	10.867±0.109	10.867	10.867
Ω_2	11.838±0.191	11.838	11.838
$r_1\,(mean)$	0.100±0.001	0.100	0.100
$r_2\,(mean)$	0.082±0.001	0.082	0.082
L_1/L_{total} -$TESS$	0.45±0.02	–	–
L_1/L_{total} -V	–	0.46±0.01	0.45±0.02
L_1/L_{total} -I_c	–	–	0.46±0.01
L_3/L_{total} -$TESS$	0.29±0.02	–	–
L_3/L_{total} -V	–	0.30±0.01	0.28±0.01
L_3/L_{total} -I_c	–	–	0.28±0.01
$\sum W(O-C)^2$ -$RV1$	0.0003	0.0003	0.0003
$\sum W(O-C)^2$ -$RV2$	0.0003	0.0003	0.0003
$\sum W(O-C)^2$ -$LC-TESS$	0.0194	–	–
$\sum W(O-C)^2$ -$LC-V$	–	0.2548	0.2843
$\sum W(O-C)^2$ -$LC-I_c$	–	–	0.1731

4. Results and discussion

A detailed photometric data analysis of V355 And was performed in this study for the first time. The best-fitting model reveals that V355 And has a detached configuration, and the primary and secondary components fill 34% and 31% of their Roche limiting lobes, respectively. In the following subsections, the obtained absolute parameters and evolutionary status of the system are given.

4.1. Absolute dimensions

The absolute dimensions of V355 And were calculated from the combination of the TESS light curve solution and the RV curve solution, and are given in Table 6 with their uncertainties. The solar values, T_{eff}=5771.8±0.7 K, M_{bol}=4.7554±0.0004 mag and g=27423.2±7.9 cm/s^2, taken from Pecaut & Mamajek (2013), were used in the computations.

The uncertainty of 20 K in the temperature of the secondary component, seen in Table 5, corresponds to the 1-σ formal error resulting from the WD+MC analysis. The standard error of the secondary component's temperature has been corrected to 201 K by adopting the standard error of 200 K in the temperature of the primary component given in Table 6. The Bolometric corrections (BC)

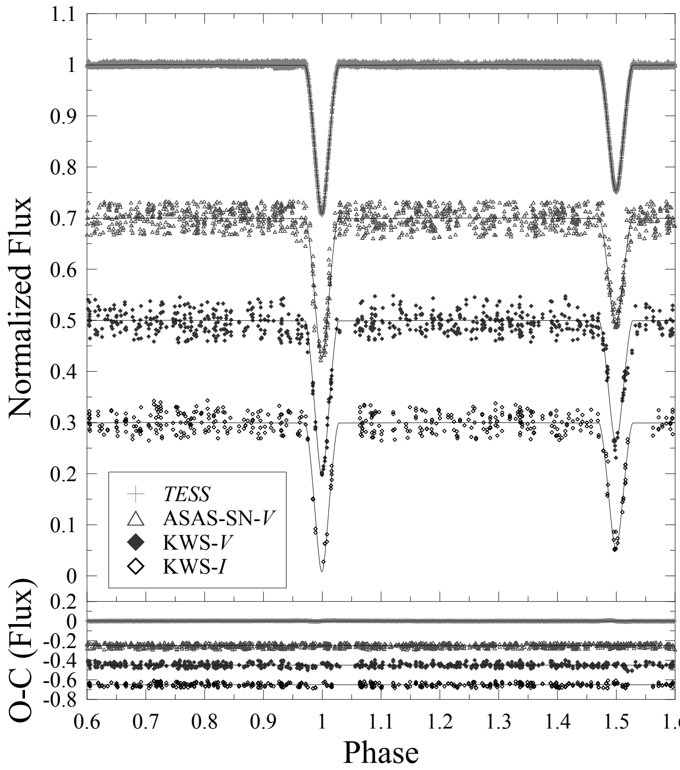

Figure 2. Comparison between the theoretical (solid lines) and TESS (top), ASAS-SN–V (middle) and KWS–VI_c light curves (bottom) of V355 And. The residuals of the WD+MC model fitting are shown in the bottom panel.

of the primary and secondary components were chosen from the tabulation of Flower (1996) to be BC_1=0.016 and BC_2=-0.017, respectively, according to the computed effective temperatures of the components. The absolute magnitudes of both components were then obtained.

Through the well-known equation $E(B-V)$= $(B-V)$–$(B-V)_0$, the color excess of the system was determined as 0.017, where the de-reddened color index $(B-V)_0$ was computed using the absolute magnitude calibrations for detached binaries given by Bilir et al. (2008), while the $(B-V)$ value of the system was taken from the APASS catalogue[8]. The interstellar extinction value A_ν in the V passband was computed as 0.052 mag by means of the well-known formula $A_V = 3.1 \times E(B-V)$. Finally, the distance to V355 And of 117±7 pc was derived from the distance modulus formula. Additionally, the distance of the

[8]APASS Catalogue: The AAVSO Photometric All-Sky Survey, http://www.aavso.org/apass.

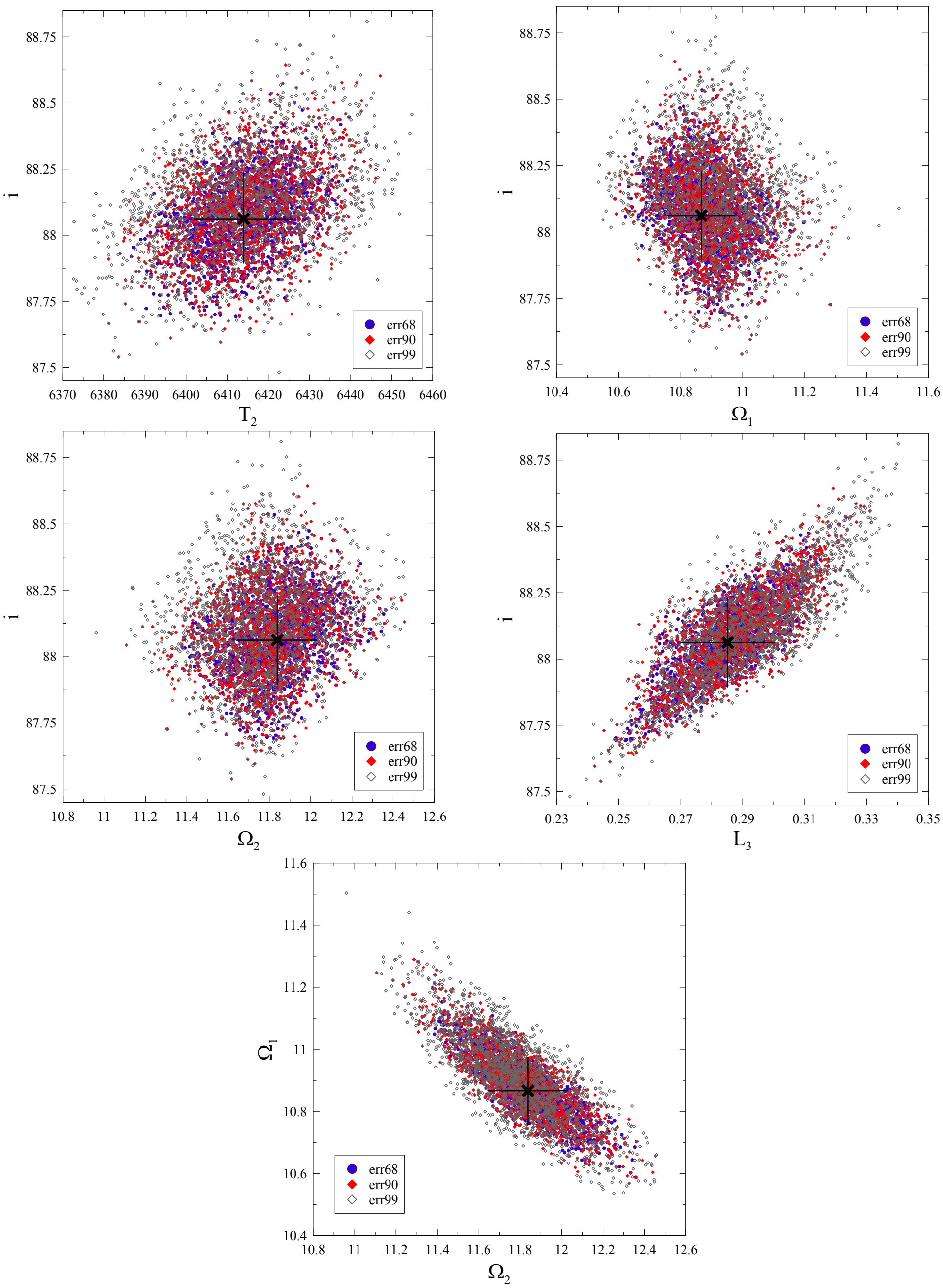

Figure 3. Degeneracies of the selected parameters, (i, T_2, Ω_1, Ω_2 and L_3), for the WD+MC search best fit solution using three confidence levels (68%, 90%, and 99%). Confidence levels are represented by blue-filled circles, red diamonds and grey diamonds. The best-fit solution is represented by the cross symbol with error bars selected from a 90% confidence level.

system was calculated to be 117.9±2.0 pc according to the *Gaia* DR2 parallax (Gaia Collaboration et al., 2018). It is clearly seen that the determined distance is in good agreement when compared with the *Gaia* distance.

Table 6. Absolute parameters of the components of V355 And.

Parameters	Unit	Primary	Secondary
A	$R_\odot$	16.94±0.03	
P_{orb}	days	4.7183808±0.0000001)	
M	$M_\odot$	1.56±0.01	1.38±0.01
R	$R_\odot$	1.70±0.03	1.38±0.03
log g	cgs	4.17±0.02	4.29±0.01
T	K	6650±200	6235±201
M_{bol}	mag	2.99±0.16	3.59±0.14
M_V	mag	2.97±0.16	3.61±0.14
L	$L_\odot$	5.10±0.77	2.92±0.37
M_V	mag	2.10±0.13	
BC	mag	0.016	-0.017
d	pc	117±7	

4.2. Evolutionary status

A comparison of the measured physical parameters of a star with predictions from theoretical models can be made by means of the Hertzsprung–Russell (HR) diagram. According to the iron number abundance, [Fe/H]=0.17, given by Nordström et al. (2004) and Holmberg et al. (2009), the metallicity value was computed to be 0.021 using the relation between Z and [Fe/H] in the logarithmic scale[9]. Therefore, the locations of the components of V355 And were plotted on the log T_{eff}–log $(L/L_\odot)$ diagram (see Fig. 4), namely the HR diagram, using the Geneva stellar evolution models[10] (Mowlavi et al., 2012) for the metallicity Z=0.02. Trials were made for other Z values (Z=0.14 and Z=0.03); however, as it can be seen in Fig. 4, the theoretical evolution model at Z=0.02 is the most suitable for the masses of both components of the system. In addition, we also tried to predict the age of V355 And using the evolutionary isochrones for Z=0.02 adopted from Mowlavi et al. (2012). Consequently, with respect to the HR diagram, it can be said that the components of V355 And are main-sequence stars at the age of $\sim$ 1.26 Gyr.

[9]https://people.umass.edu/wqd/astro640/ToO.pdf
[10]https://www.unige.ch/sciences/astro/evolution/en/database/syclist/

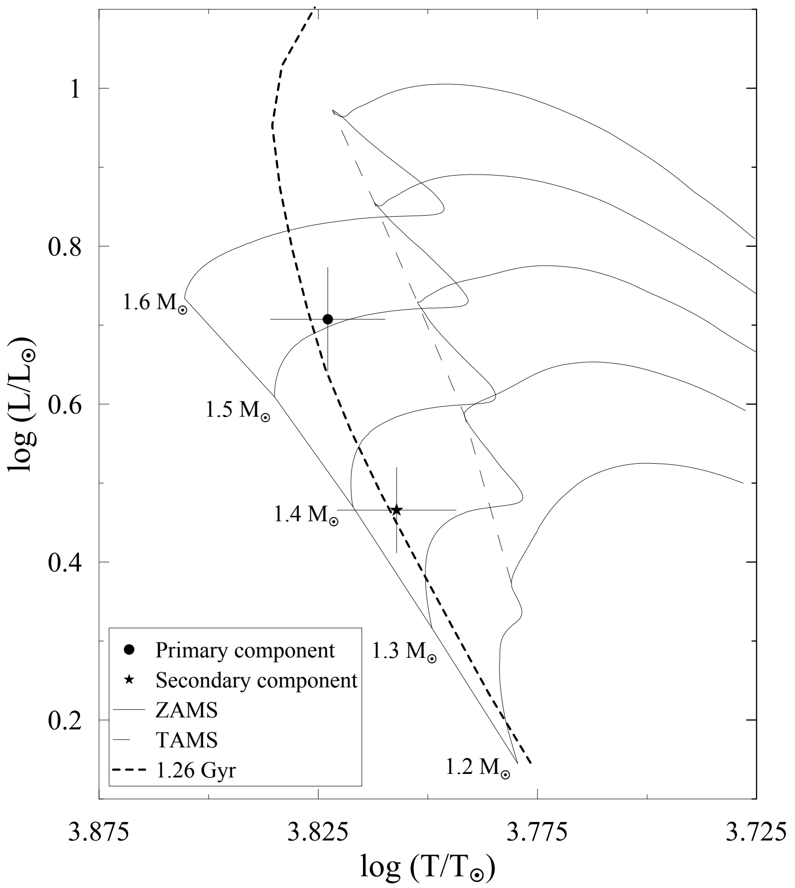

Figure 4. Locations of primary and secondary components of V355 And in the logarithmic temperature-luminosity plane according to Geneva stellar evolutionary models. ZAMS, TAMS and evolutionary tracks were taken from Mowlavi et al. (2012) for the metallicity of Z=0.02. Lines drawn vertically and horizontally denote error bars of the measured parameters. The isochrone for the estimated age of the system at 1.26 Gyr is represented by a dashed line. In the HR diagram the numbers added to the left of ZAMS indicate initial masses.

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