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Detached eclipsing binaries:

Analysis of BD-00 3357 ⋆

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Abstract. We study detached eclipsing binaries as potential distance tracers and test bench for stellar evolution. In BD-00 3357 eclipses are partial and the orbital period is $1\overset{d}{.}4$. We employ both spectroscopic and photometric observations in order to solve for the parameters of this system. The model of the star was obtained using the Wilson-Devinney method. As result we obtained the semimajor axis value of 7.65$R_\odot$ and the mass ratio 0.78. The derived masses and radii are $M_1 = 1.73 M_\odot$, $M_2 = 1.34 M_\odot$ $R_1 = 1.78 R_\odot$, $R_2 = 1.32 R_\odot$, respectively. These values correspond to the slightly evolved F0 and F6.5 components of age less than 1Gyr. The distance of the star was estimated to be 310 pc and the corresponding parallax is 3.24 mas.

Key words. eclipsing binaries – binaries: spectroscopic – stars: individual: BD-003357

1. Introduction

Detached eclipsing binaries constitute accurate distance and age indicators Paczyński(1997). Bright systems within reach of the trigonometric parallax provide an opportunity to establish the zero point of these scales in a fashion relatively free of the systematic errors and using modest telescopes (e.g. Dimitrov et al.(2004)).

The star ASAS 174619-0018.7 from the All Sky Automated Survey (ASAS, Pojmański, 1997) catalogue of light curves reveals two partial eclipses of comparable depth. The period obtained by ASAS is $1\overset{d}{.}399646$ and the amplitude of the light curve is $0\overset{m}{.}173 \pm 0.027$. We selected it for a closer study as potential detached binary. We identify this object as BD-00 3357 and TYC-5082-1517-1. The FK5(J 2000.0) coordinates of the star are $17^h\ 46^m\ 19\overset{s}{.}42$ and -00°18′38.″1. The PPM catalogue quotes the spectral type as A2 but this value is inconsistent with the color index of the star. The visual magnitude measured by Tycho 2 is $9\overset{m}{.}99 \pm 0.04$. The color index given by Tycho 2 catalogue is $B-V = 0.42 \pm 0.06$ and corresponds to the temperature of 6700K. The light curve obtained by ASAS 2 (I band) apart from two eclipses with different depth reveal some elipsoidal distortion in maximum. The ratio of the depths of primary and secondary eclipse reveal a temperature difference between components about 800K. ASAS 3 is still collecting V data for this object. This relatively bright star was not included into Hipparcos main catalogue. Search of Simbad database revealed no radial velocity data for this star, hence we obtained our own spectroscopic observations. Our observations and the updated ephemeris are presented in Sects. 2. The photometric and spectroscopic solution of the binary by the Wilson-Devinney method is obtained in Sect. 3. In section 4 we discuss the model, age and distance of the binary.

2. Data

2.1. Spectroscopy

Our spectra were collected at Bulgarian National Astronomical Observatory Rozhen(NAO) and David Dunlop Observatory near Toronto, Canada(DDO). First set of observations was obtained in August 2001 in NAO with the 2 m RCC telescope equipped with the Coudé spectrograph. We observed the spectral regions near H_α an NaD. The covered ranges of spectra are from 6450 Å to 6650 Å and 5800 Å to 6000 Å respectively with a dispersion of 0.2 Å per pixel. The wavelength calibration was ensured using a thorium-argon lamp. The detector was an liquid nitrogen cooled SITE 1Kx1K, 24 μm CCD-matrix. The H_α and NaD spectra were measured with the IRAF RVIDLINES task.

The following observations, at NAO and DDO were made near Mg triplet (MgTri 5175Å). At DDO we used the 1.9 m

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⋆ Based on spectroscopic observations collected at National Astronomical Observatory Rozhen, Bulgaria and David Dunlop Observatory, Canada. We use photometric observations in I and V band from ASAS (All Sky Automated Survey).

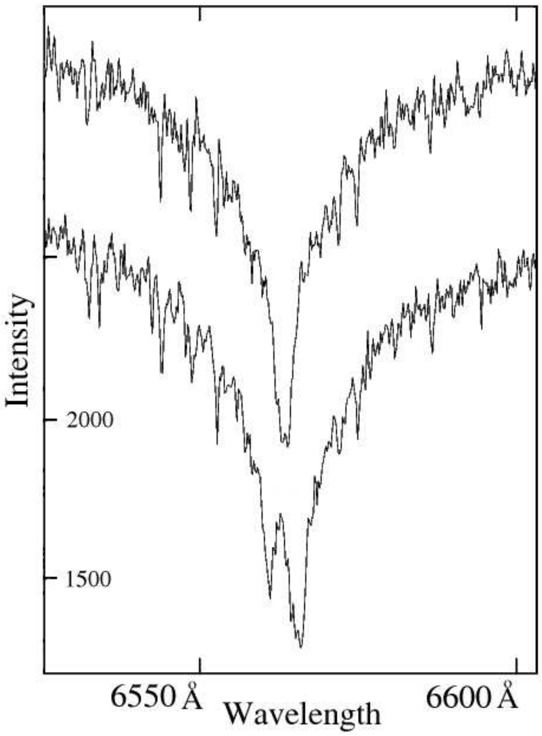

Fig. 1. Examples of spectra in H_α region for phases 0.46 and 0.65.

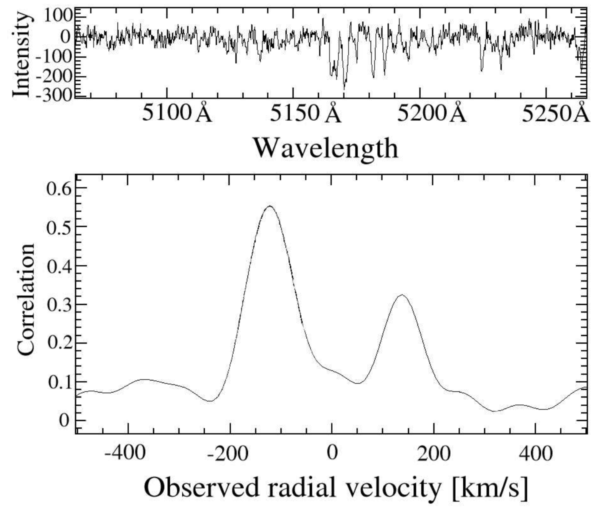

Fig. 2. Object spectrum and crosscorelation function for Calcium triplet 5175 Å spectrogram for phase 0.202. The measured heliocentric radial velocities are $V_1 = -106.7$ and $V_2 = +155.8$ km/s.

telescope with its Cassegrain spectrograph giving a dispersion of 0.16 Å per pixel. The spectral ranges were from 5060 Å to 5265 Å for NAO and from 5025 Å to 5350 Å for DDO. The exposure times of all spectra are 1200 s with the signal-to-noise ratio of about 80. For measuring the MgTri data we used the IRAF cross-correlation task FXCOR.

The mean square error of the results listed in Table 1 for the first component is 5.6 km/s and for the second component 5.2 km/s. For some spectra in the first set blending prevented secure measurement of the lines of weak component. No such problems were encountered in measurement of velocities by cross-correlation in the MgTri range. Prior to any detailed spectral clasification, we could only state they resemble F2/F8 spectral standarts. This and small proper motion of the binary, amounts to 0.022 arcsec/y, are both consintent with an ordinary Population I star.

2.2. Photometry

The light curves available from ASAS are in I and V band. The I band ASAS 2 observations were collected over one year starting at October 1998. The V band ASAS 3 observations are still collected. The infra red observations present two minima with different depths and noticeable curvature of the maxima. The amplitude of variations is $0^{\rm m}.137\pm0.027$ and the period given by ASAS is $1^{\rm d}.399646$. This set contains 828 points with the standard deviation $0^{\rm m}.04$. Although errors of individual observations are large, as expected for a small telescope, large number of observations compensates for that yielding a well defined light curve. The coverage of all phases is good. For modelling we use both I and V band observations

We obtained some follow-up photometric V observations to update the ephemeris. For this purpose we employed 0.4 m Newton telescope of Poznan University Observatory, equipped with KAF 400 CCD camera and located at Borowiec (Poland). We used Starlink CCLR package for reduction and extraction of the aperture photometry from our observations. The typical errors of the obtained results are about $0^{\rm m}.01$. The time span between the two sets, ASAS I and our V is six years. Combination of the two data sets enabled derivation of an improved period of BD-00 3357, P=$1^{\rm d}.399660\pm5\cdot10^{-7}$. The improved ephemeris is

$$\text{Min I} = \text{HJD } 2,452,530.4516 + 1^{\rm d}.399660 \cdot E \qquad (1)$$

where the uncertainty of the time of the primary transit is $0^{\rm d}.0005$. As the phase shift between primary and secondary minimum listed in Table 2 is less than 0.0004, we assumed the circular orbit. Phase zero corresponds to the time of the deeper minimum, the eclipse of the more massive star (1) by the lighter component (2).

3. Willson-Devinney Model

3.1. Joint spectroscopic and photometric solution

To determine the stellar parameters we use the updated Wilson-Devinney (1971) method for the synthesis of the light and radial velocity curves wrapped up in the optimization package of Plewa (1992 and references there).

The fit of our radial velocity curve with the model yields results listed in (Table 4). The ratio of radial velocity amplitudes suggest that masses of components are quite different and that their separation is about 7,6 solar radii.

There are inconsintent clues in the literature about the temperature of components. The spectral type from Simbad, based

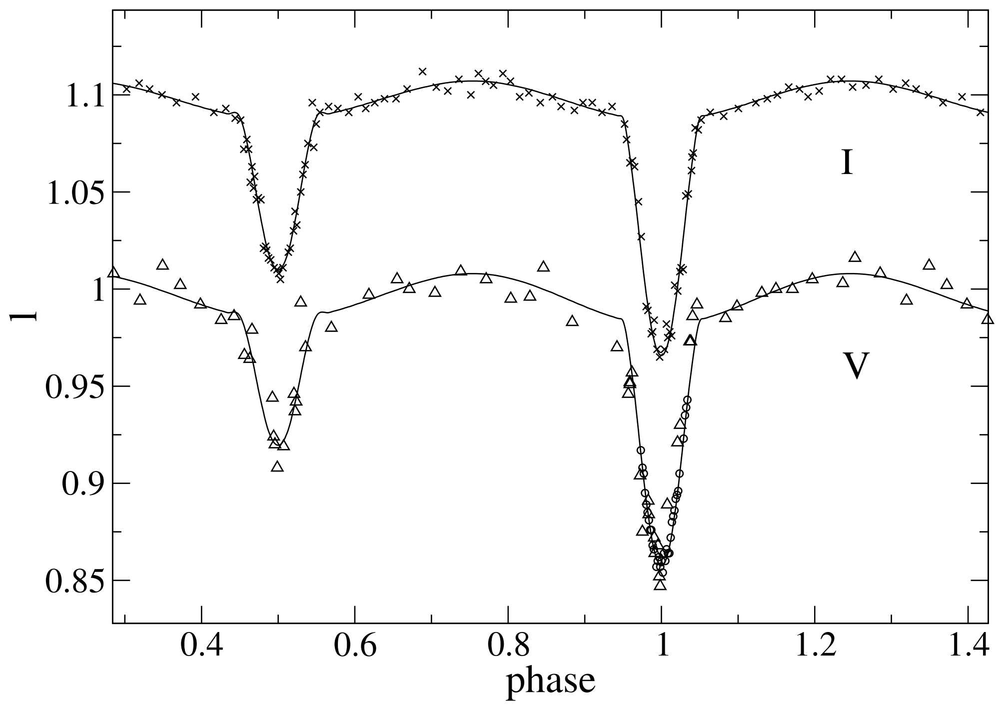

Fig. 3. Synthetic and observed light curves of BD-00 3357. The observation sets are indicated with symbols: × - for *I* band ASAS2, △ for *V* band ○ for our *V* band Borowiec observations of the primary minimum. The ASAS observations are binned into normal points. For better coverage of the curve we use denser normal points during eclipses. The *I* curve is shifte vertically for clarity. At phase zero the primary component (1) is being eclipsed by the secondary (2).

on the PPM catalogue, is A2. It is inconsistent with but the Tycho 2 color index suggesting Sp=F5 (Sect. 1). Comparison of our CaTri spectra with the standard stars confirms the Tycho 2 value. Other database, NOMAD, quotes the same $B-V$ color index as as Tycho 2 (0.42) and inconsistent with it $V-R$ value of 0.28.

We had to resort to iterations in order to obtain a self-consistent values of temperatures. Retrospectively, after dereddening our color index becomes 0.35(Sect. 4). The temperature and luminosity difference of the two components, are both well restricted by our model fit. From the dereddened color index and taking into account the luminosity and temperature difference from the preliminary solution we obtain the temperature of the first component to be 7250K. We used stellar atmospheres model in our light curve fits. Our preliminary solution yielded the temperature difference between the two stars of about 800K. The solution was consistent with the radiative envelope of the first component. Accordingly in the final solution we apply for the gravity darkening coefficient and albedo g=1.0 and A=1.0, respectively. For the second component we found temperature of 6425K hence we adopt g=0.32 and A=0.5. The limb darkenning coefficients were taken from Van Hamme 1993.

For the final model fit the temperature of the primary component, darkenning and albedo coefficients were all fixed at the values given above. The final Wilson-Devinney solution fits our radial velocity data from Table 1 and *I*, *V* photometry from ASAS 2,3 and from Borowiec Observatory. The solution is presented in Table 4. The stellar parameters derived from it are listed in Table 5. The observed and synthetic and radial velocity- and light-curves are compared in figures 4 and 3.

3.2. Photometric only solution

Ellipsoidal distortions in the light curve do carry save information on radii and consequently also on inclination. To check the involved systematic errors we performed separate solution with no radial velocity use. The result were two solutions with similar quality, one yeilding $q = 0.77 \pm 0.04$, close to the spectroscopis value and onather 0.62 ± 0.02 with slightly better χ^2.

4. Age and Distance

From the values of the parameters of BD-00 3357 listed in tables 4 and 5 follows estimate of its the distance. Given other sources of errors it suffices to assume that both stars are spherical and that their bolometric surface brightness is $\sigma T_{\rm e}^4$. The

Table 1. Radial velocity measurements grouped by site and spectral range.

HJD sp. region	RV1 km s^{-1}	$(O-C)_1$ km s^{-1}	RV2 km s^{-1}	$(O-C)_2$ km s^{-1}	phase
H_α					
2452100+ NAO					
30.2883	+91.9	−6.3	−105.3	+3.6	0.642
30.3032	+95.0	−7.9	−112.5	+2.4	0.652
30.4180	+122.0	−1.5	−138.2	+3.3	0.734
30.4322	+123.6	−0.4	−133.8	+8.4	0.744
30.2746	−98.0	−9.8	+130.7	+0.1	0.346
30.2891	−88.7	−5.0	–	–	0.362
NaD					
2452100+ NAO					
26.4516	+71.3	−4.6	–	–	0.901
26.4664	+74.4	+5.0	–	–	0.911
Mg triplet (5175 Å)					
2452800+ DDO					
85.5512	−112.4	−3.7	155.7	−1.4	0.239
85.5566	−108.5	+0.4	162.2	+4.7	0.250
85.5724	−107.3	+1.2	154.6	−2.5	0.261
88.5685	−67.1	−7.4	88.5	−5.6	0.402
88.5944	−52.0	−3.8	81.2	+1.9	0.421
2453100+ NAO					
37.4274	−106.7	−3.1	155.8	+5.0	0.202
37.4420	−102.4	+3.2	158.4	+7.0	0.212
37.4563	−107.0	+0.1	162.3	+5.8	0.222
93.4802	−113.6	−4.7	163.3	+6.7	0.249
93.4947	−108.6	+0.0	164.0	+0.1	0.259
2453200+ NAO					
21.3082	−77.4	+0.6	117.8	+0.1	0.131
21.3225	−68.4	+14.5	114.7	−9.3	0.141

Table 2. Times of minima of BD-003357 from photometric observations

Date	HJD	minimum	source
11 Aug. 1999	2,451,401.56674	I	ASAS I
9 July 1999	2,451,368.67506	II	ASAS I
4 Sept. 2004	2,453,253.31699	I	Borowiec V

bolometric magnitude follows from the Stephan-Boltzman law (Lang 1978):

$$M_{bol} = 42.37 - 5\ log\left(\frac{R}{R_\odot}\right) - 10\ log\ T_e \qquad (2)$$

yielding $M_{V1} = 2.61$ and $M_{V2} = 3.84$. We adopt V magnitude of $9^{m}_{.}98$ from Tycho 2 and the bolometric corrections corresponding to a temperatures of 7250K and 6425K as $BC_{V1} = -0.09$ and $BC_{V2} = -0.15$ (Astrophysical Quantities 1999). These values need correction for reddening at the galactic coordinates, longitude $25^{\circ}_{.}06$ and latitude $+14^{\circ}_{.}30$. From Burnstein and Heils (1982) maps of the color excess we obtain $E(B-V) =$ 0.24 per Kpc and iteratively find the values of Av and distance. Finally, we obtain parallax $\pi = 3.24 \pm 0.74$ mas corresponding to distance of 310 ± 60 pc. Thus BD-00 3357 lies less than 100ps from the Galactic Disc plane. Main source of systematic errors in distance is color ambiguity and possible clumping of

Table 3. Orbital parameters of BD-003357

Parameter	Component 1	Component 2
fitted:		
K (km s^{-1})	116.6 ± 1.0	150.1 ± 1.4
V_γ (km s^{-1})	7.6 ± 1.4	
calculated:		
$A \sin i$ ($R_\odot$)	7.37 ± 0.05	
$A_{1,2} \sin i$ (10^6 km)	2.44 ± 0.02	2.89 ± 0.03
$M_{1,2} \sin^3 i$ ($M_\odot$)	1.55 ± 0.03	1.20 ± 0.02
other quantities:		
N_{obs}	20	17
σ (km s^{-1})	5.7	5.2

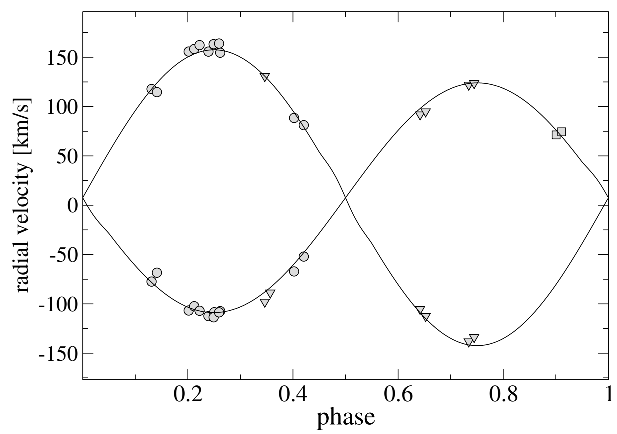

Fig. 4. The synthetic and observed radial velocity curve of BD-00 3357. The synthetic curve is computed with the Wilson-Deviney code. Symbols indicate velocities different spectral range: ○ near 5175Å, △ - H_α line only and □ - two NaD measurements. The curve for the more a maximum at phase 0.75.

Table 4. The best fit model of BD-00 3357

Parameter	component 1	component 2
i	$74^{\circ}_{.}75 \pm 0^{\circ}_{.}72$	
q	0.776 ± 0.018	
$A(R_\odot)$	7.649 ± 0.079	
T	7250 K	6425 ± 30 K
Ω_{12}	5.11 ± 0.49	5.64 ± 0.37
l_I	0.750 ± 0.012	0.250 ± 0.011
l_V	0.793 ± 0.022	0.207 ± 0.020
$x_{12}(I)$	0.303	0.352
$x_{12}(V)$	0.501	0.551
g_{12}	1.0	0.32
a_{12}	1.0	0.5

Table 5. Absolute dimensions of the components, calculated from Wilson-Devinney model (Table 4). The masses and the radii are given in solar units and log(g) in *cgs*.

	component 1	component 2
Mass	1.73 ± 0.04	1.34 ± 0.03
Radii	1.78 ± 0.20	1.32 ± 0.07
$log(g)$	4.18 ± 0.12	4.33 ± 0.07
M_{bol}	2.52 ± 0.53	3.69 ± 0.37
R_{point}	1.81 ± 0.29	1.33 ± 0.10
R_{side}	1.78 ± 0.20	1.31 ± 0.07
R_{back}	1.80 ± 0.20	1.33 ± 0.07
R_{pole}	1.76 ± 0.19	1.31 ± 0.07

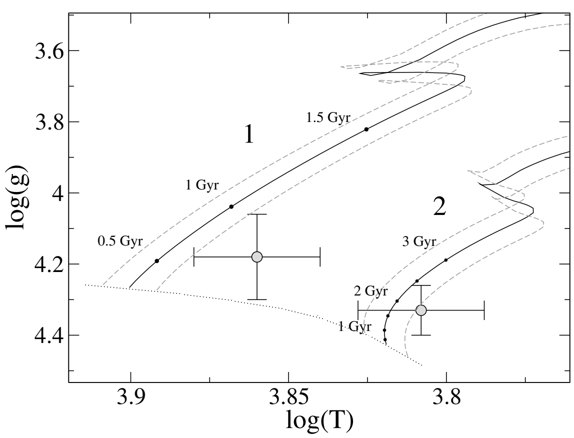

Fig. 5. Evolutionary tracks for components of BD-00 3357. Solid lines represent the evolutionary tracks($Z = 0.02$); dotted line - zero age main sequence (ZAMS); dashed lines corresponds to the masses errors. Note that any systematic errors would likely shift both components by the same amount, without change of their mutual arrangement.

extinction. The latter error should not exceed half of A_V, i.e. 0.12 mag in M_V.

Figure 5 displays $log(g) - log(T)$ plot with the evolutionary tracks corresponding to masses of components and for standard population I metallicity $Z = 0.02$. Over-plotted are positions of both components derived from their fitted parameters. The most possible reason of a shift between these positions and the evolutionary tracks is an error in $B - V$ corresponding to a shift of temperatures by 300K. Alternatively non-standard metallicity (about 0.03) yields better consistency with our model. Note that for as young system enhaced mettalicity is possible. Solutions with lower $log(g)$ are unacceptable as they produce excess ellipsoidal variations. Note that no systematic error would likely change the mutual arrangement of components on the plot. Thus BD-00 3357 is less than 1.0 Gyr old.

5. Conclusions

New photometric and spectroscopic observations of the eclipsing binary BD-00 3357, combined with ASAS photometry, have allowed us to to determine the orbital and physical parameters of the star. The solution led us to conclude that BD-00 3357 is a young, detached eclipsing binary. Because of its distance of 310 pc and magnitude V=9.99 and uncomplicated physics BD-00 3357 constitutes a suitable target for modern trigonometric parallax surveys (e.g. GAIA) and for callibration of the zero point of the eclipsing binary distance scale (Paczynski, 1997).

The principal source of systematic error in the present study is ambiguity of the color of the system. In order to tighten any systematic error we request follow up precise multicolor photometry out of eclipses, particularly in the infrared band (IR), in order to derive exact temperature of the primary with little interference from the interstellar extinction. Given accurate values of other parameters, the IR photometry would yield distance and stellar surface luminosity relatively free of dependence on any models.

However, the temperature difference between components is already tightly constrained by the observations. Hence differential comparision of properties of the components with their evolutionary tracks is relatively free of any systematic errors of either distance or temperature. In this way we find the age of BD-00 3357 in the range 0.5–1.0 Gyr. The metallicity is probably higher than solar see Section 4.

In general photometric solutions for partially eclipsing binaries are deemed to suffer from the degeneracy/indeterminacy of inclination and mass ratio, i and q. Let us observe that in our particular case the degeneracy is largely mitigated by the need to reproduce marked ellipsoidal distortion in the detached system. In this way radii and consequently i and q become restricted and facilitate reliable solution even for eclipses as shallow as in BD-00 3357.

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