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Detached eclipsing binaries: Analysis of BD-00 3357 ⋆

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Abstract. We study the detached eclipsing binaries as potential distance tracers and useful test bench of the 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 of 7.65$R_\odot$ and the mass ratio of 0.78. The derived masses and radii are $M_1 = 1.73M_\odot$, $M_2 = 1.34M_\odot$ $R_1 = 1.78R_\odot$, $R_2 = 1.32R_\odot$, 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: binaries: eclipsing – binaries: spectroscopic – stars: individual BD-00 3357

1. Introduction

Detached eclipsing binaries (DEBs) constitute accurate distance and age indicators (Paczyński 1997). The disadvantage of use of the DEBs rests with the complexity of the photometric *and* spectroscopic observations, required for solution for the binary parameters and distance. Still, modern telescopes of 5+ m diameter enable use of DEBs as distance tracers within the Local System of galaxies. The advantage of use of the DEBs is in small systematic errors and in attainable accuracies as high as 1-3%. The physics and geometry of orbital effects in DEBs is well understood hence little scope for any systematic errors from their modelling (e.g. Torres & Ribas 2002 and Poper 1998 and references therein).

The chief remaining uncertainty of the zero point calibration of the distances derived from the DEB's solution concerns of the temperature-surface luminosity relation (Kruszewski & Semeniuk 1999). The ultimate accuracy in this respect is attainable by modern quality observations of the bright DEBs within reach of the trigonommetric parallax, obtainable with telescopes of modest size. Additionally, bright DEB yield important tests of the stellar structure and evolution (e.g. Torres & Ribas 2002; Lastennet et al.2003).

Renewed interest resulted in surveys of the DEBs, *either* photometric or spectroscopic (e.g. Devor 2005; Carquillat et al. 2004; Marrese and references therein). Despite these efforts the number of bright unevolved DEB with available good observations *both* photometric and spectroscopic remains surprasingly small (Torres & Ribas 2002). Hipparcos observations tend to be sparse and use bands difficult to model. However, extensive photometric coverage of the bright DEBs in standard filters is provided by the ASAS survey (Pojmański 2004). This situation motivated our present series reporting spectroscopic study of the selected bright DEBs (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 $-00^\circ 18' 38\overset{''}{.}1$. The PPM catalogue quotes the spectral type as A2 but this value is inconsistent with the colour index of the star. The visual magnitude measured by Tycho 2 is $9\overset{m}{.}99 \pm 0.04$. The colour index given by Tycho 2 catalogue is $B-V = 0.42 \pm 0.06$ and corre-

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⋆ Based on spectroscopic observation 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).

sponds 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.

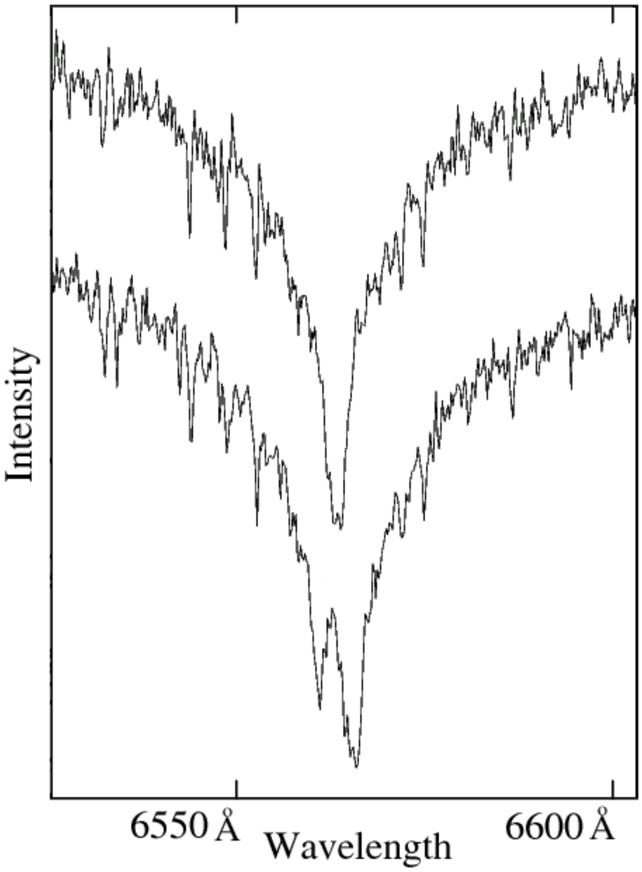

Fig. 1. Examples of spectra in H_α region for phases 0.46 and 0.65.

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 the 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 spectral ranges extend from 6450 Å to 6650 Å and from 5800 Å to 6000 Å, respectively, with the 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 both at NAO and DDO were made near Mg triplet (MgTri 5175Å). At DDO we used the 1.9 m 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 the weak component. No such problems were encountered in the measurement of velocities by cross-correlation in the MgTri range. Prior to any deailed clasification of the spectra, we could only state they resemble F2/F8 spectral standarts. This and the small proper motion of the binary amounting to 0.022 arcsec/y, are both consintent with an ordinary Population I star.

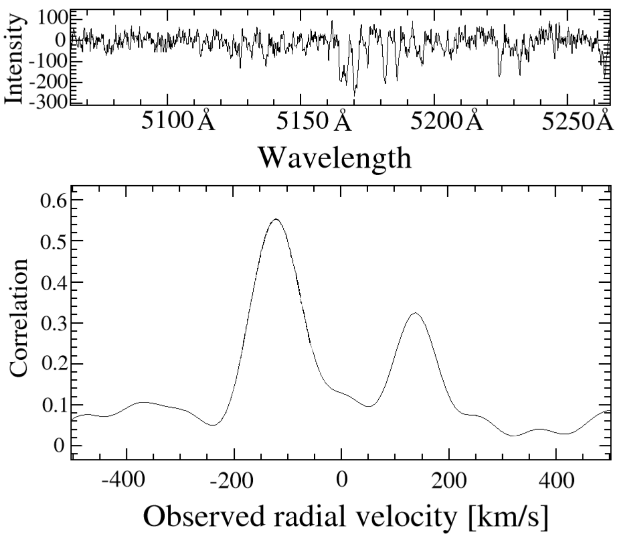

Fig. 2. Object spectrum and crosscorelation function for Calcium triplet 5175 Å spectrogram for phase 0.202. The measured heliocentric radial velocities are $V_1 = -106.7$ and $V_2 = +155.8$ km/s.

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 still are beeing collected. The infra red observations present two minima with different depths and noticeable curvature of the maxima. The amplitude of the light curve is

Table 1. Radial velocity measurements grouped by site and spectral range. Last column present phases of orbital motion.

HJD	RV1 km s^{-1}	$(O-C)_1$ km s^{-1}	RV2 km s^{-1}	$(O-C)_2$ km s^{-1}	ph.
H_α					
2452100+	NAO				
30.2883	+91.9	−6.3	−105.3	+3.6	.642
30.3032	+95.0	−7.9	−112.5	+2.4	.652
30.4180	+122.0	−1.5	−138.2	+3.3	.734
30.4322	+123.6	−0.4	−133.8	+8.4	.744
30.2746	−98.0	−9.8	+130.7	+0.1	.346
30.2891	−88.7	−5.0	–	–	.362
NaD					
2452100+	NAO				
26.4516	+71.3	−4.6	–	–	.901
26.4664	+74.4	+5.0	–	–	.911
Mg triplet (5175 Å)					
2452800+	DDO				
85.5512	−112.4	−3.7	+155.7	−1.4	.239
85.5566	−108.5	+0.4	+162.2	+4.7	.250
85.5724	−107.3	+1.2	+154.6	−2.5	.261
88.5685	−67.1	−7.4	+88.5	−5.6	.402
88.5944	−52.0	−3.8	+81.2	+1.9	.421
2453100+	NAO				
37.4274	−106.7	−3.1	+155.8	+5.0	.202
37.4420	−102.4	+3.2	+158.4	+7.0	.212
37.4563	−107.0	+0.1	+162.3	+5.8	.222
93.4802	−113.6	−4.7	+163.3	+6.7	.249
93.4947	−108.6	+0.0	+164.0	+0.1	.259
2453200+	NAO				
21.3082	−77.4	+0.6	+117.8	+0.1	.131
21.3225	−68.4	+14.5	+114.7	−9.3	.141

$0\overset{m}{.}137\pm0.027$ and the period given by ASAS is $1\overset{d}{.}399646$. This set contains 828 measurements with the standard deviation $0\overset{m}{.}04$. Large errors of individual observations, consistent with the small size of the telescope, are compensated by the large number of observations yielding a well defined light curve. The coverage of all phases is good. For modelling we use both the I and V band observations.

We obtained some V band follow-up photometric observations to update the ephemeris. For this purpose we employed the 0.4 m Newton telescope of Poznan University Observatory at Borowiec station (Poland), equipped with KAF 400 CCD camera. For reduction and extraction of the aperture photometry from our observations we used Starlink CCLR package. The typical errors of the obtained results are about $0\overset{m}{.}01$. 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=$1\overset{d}{.}399660\pm5\cdot10^{-7}$. The improved ephemeris is

$$\text{Min I} = \text{HJD}\ 2,452,530.4516 + 1\overset{d}{.}399660\cdot E \tag{1}$$

where the uncertainty of the time of the primary transit is $0\overset{d}{.}0005$. As the phase shift between primary and secondary minimum listed in Table 3 is less than $0\overset{d}{.}0004$, 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).

Table 2. Times of minima of BD-00 3357 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

3. Wilson-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).

The fit of our radial velocity curve with the model yields results listed in Table 3. 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 the components. The spectral type from Simbad, based on the PPM catalogue, is A2. It is inconsistent with the Tycho 2 colour 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 $B-V$ colour 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 the temperatures. Retrospectively, after dereddening our $B-V$ colour 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 colour index and taking into account the luminosity and temperature difference from the preliminary solution we obtain the temperature of the first component of 7250K. In our light curve fits we used the stellar atmospheres models.

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

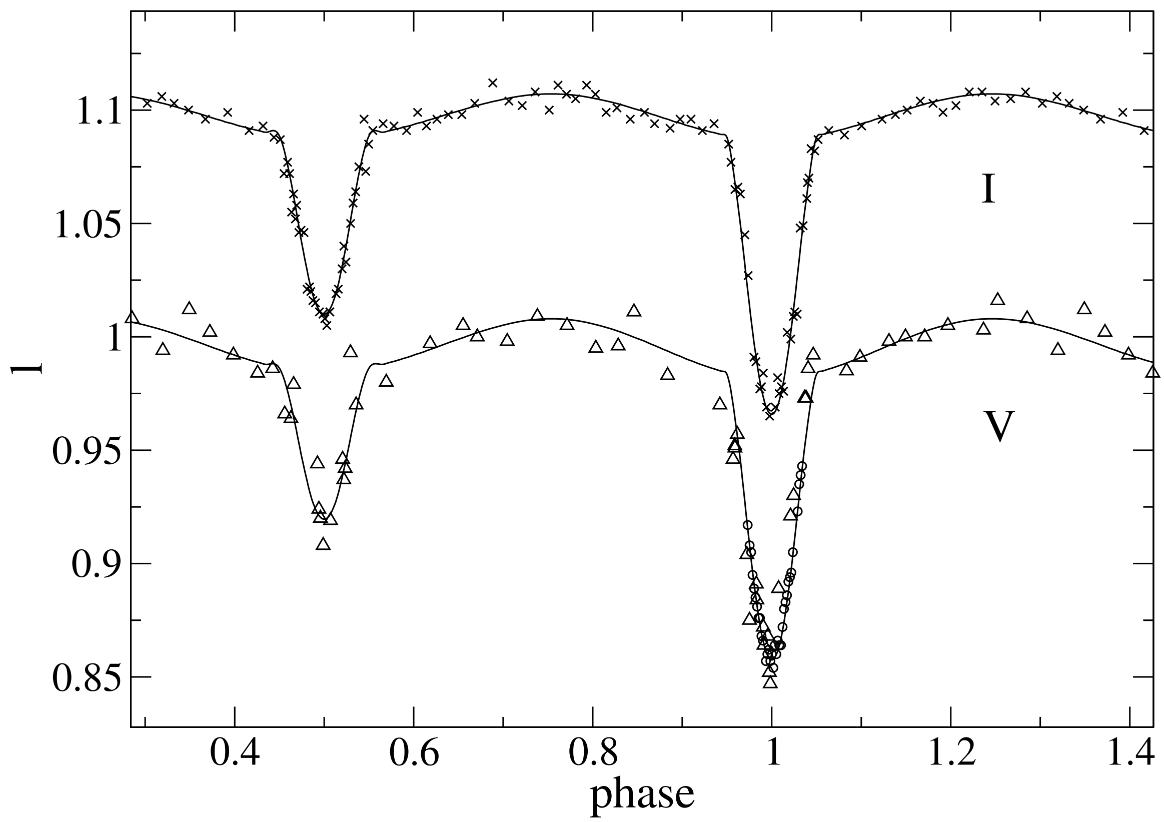

Fig. 3. Synthetic and observed light curves of BD-00 3357. The observation sets are indicated with symbols: $\times$ - for I band ASAS2, $\triangle$ for V band $\bigcirc$ for our V band Borowiec observations of the primary minimum. The ASAS observations are binned into normal points. For better coverage 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).

Table 3. Orbital parameters of BD-00 3357

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

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

Parameter	component 1	component 2
i	$74.^\circ75 \pm 0.^\circ72$	
q	0.776 $\pm$ 0.018	
A(R$_\odot$)	7.649 $\pm$ 0.079	
T	7250 K	6425 $\pm$ 30 K
Ω_{12}	5.11 $\pm$ 0.49	5.64 $\pm$ 0.37
$l_{\rm I}$	0.750 $\pm$ 0.012	0.250 $\pm$ 0.011
$l_{\rm V}$	0.793 $\pm$ 0.022	0.207 $\pm$ 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

light curves and the radial velocity curves are demonstrated in Figures 4 and 3.

3.2. Photometric only solution

The ellipsoidal distortions in the light curve do carry information on the radii and consequently also on the inclination. To check the involved systematic errors we performed separate solution ignoring the radial velocities. As result we obtained two solutions of comparable quality, one yielding $q = 0.77 \pm 0.04$, close to the spectroscopic one, and another with $q = 0.62 \pm 0.02$ with a slightly better χ^2.

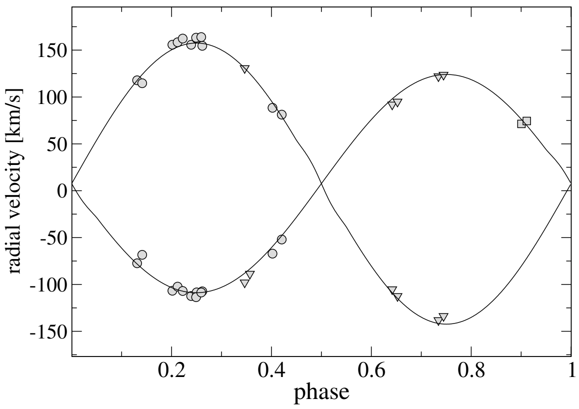

Fig. 4. The synthetic and observed radial velocity curve of BD-00 3357. The synthetic curve is computed with the Wilson-Deviney code. Symbols indicate velocities different spectral range: ◯ near 5175Å, △ - H_α line only and □ - two NaD measurements. The curve for the more massive component one has a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

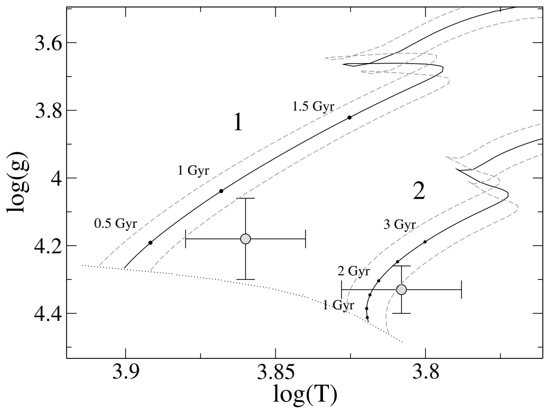

Fig. 5. Evolutionary tracks for components of BD-00 3357. Solid lines represent the evolutionary tracks($Z = 0.02$) of Kim at al.(2002); dotted line - zero age main sequence (ZAMS); dashed lines corresponds to the masses errors. Note that any systematic errors would likely shift both components by the same amount, without change of their mutual arrangement.

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
$M_{\rm bol}$	2.52 ± 0.53	3.69 ± 0.37
$R_{\rm point}$	1.81 ± 0.29	1.33 ± 0.10
$R_{\rm side}$	1.78 ± 0.20	1.31 ± 0.07
$R_{\rm back}$	1.80 ± 0.20	1.33 ± 0.07
$R_{\rm pole}$	1.76 ± 0.19	1.31 ± 0.07

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

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

yielding $M_{\rm V1} = 2.61$ and $M_{\rm V2} = 3.84$. We adopt V magnitude of $9\overset{\rm m}{.}98$ from Tycho 2 and the bolometric corrections corresponding to a temperatures of 7250K and 6425K as $BC_{\rm V1} = -0.09$ and $BC_{\rm V2} = -0.15$ (Astrophysical Quantities, Cox 1999). These values need correction for reddening at the galactic coordinates, longitude $25\overset{\circ}{.}06$ and latitude $+14\overset{\circ}{.}30$. From Burnstein and Heiles (1982) maps of the colour excess we obtain $E(B-V) = 0.24$ per Kpc and iteratively find the values of the A_V and distance. Finally, we obtain the parallax of $\pi = 3.24 \pm 0.74$ mas corresponding to the distance of 310±60 pc. Thus BD-00 3357 lies less than 100pc from the Galactic Disc plane. Main source of systematic errors in distance is colour ambiguity and possible clumping of extinction. The latter error should not exceed half of A_V, i.e. 0.12 mag in M_V and its effect onto average zero point is diminishing with wavelength and the number of systems analused. The former error is critical for the DEBs distance and needs to be callibrated with the trigonometric parallaxes.

Figure 5 displays $log(g) - log(T)$ plot with the evolutionary tracks corresponding to masses of components and for standard population I metallicity $Z = 0.02$ (Kim et al. 2002). 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, enabled us to determine the orbital and physical parameters of the star. The solution led us to conclude that BD-00 3357 is a young Population I 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 the systematic error in the present study is ambiguity of the colour of the system. In order to tighten any systematic error we request follow up multicolour photometry out of the 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 the components is already tightly constrained by the observations. Hence differential comparision of the 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 the 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 a solution even for eclipses as shallow as in BD-00 3357.

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