TOWARD UNDERSTANDING THE NATURE OF THE YOUNG DETACHED BINARY SYSTEM HD 350731

F. SOYDUGAN1,3, F. ALİÇAVUŞ1,3, S. BİLİR2, E. SOYDUGAN1,3, Ç. PÜŞÜLLÜ1,3, AND T. ŞENYÜZ1,3

1 Department of Physics, Faculty of Arts and Sciences, Çanakkale Onsekiz Mart University, TR-17100 Çanakkale, Turkey; Fsoydugan@comu.edu.tr
2 Department of Astronomy and Space Science, Faculty of Science, Istanbul University, TR-34119, University-Istanbul, Turkey
3 Astrophysics Research Center and Ulupınar Observatory, Çanakkale Onsekiz Mart University, TR-17100, Çanakkale, Turkey

Received 2014 November 13; accepted 2015 June 15; published 2015 July 23

ABSTRACT

The young binary system HD 350731 is a noteworthy laboratory for studying early-type binaries with similar components. We present here an analysis of differential multi-color photometric and spectroscopic observations of the double-lined detached system. Accurate absolute parameters were determined for the first time from a simultaneous solution of the light and radial velocity curves. HD 350731 consists of two B8V-type components with masses and radii, respectively, of \( M_1 = 2.91 \pm 0.13 \, M_\odot, M_2 = 2.80 \pm 0.14 \, M_\odot, \) \( R_1 = 2.11 \pm 0.05 \, R_\odot, \) and \( R_2 = 2.07 \pm 0.05 \, R_\odot. \) The effective temperatures were determined based on analysis of disentangled spectra of the components and were derived to be 12,000 \( \pm \) 250 and 11,830 \( \pm \) 300 K for the primary and secondary components, respectively. The measured projected rotational velocities, 69.2 \( \pm \) 1.5 km s\(^{-1}\) for the primary and 71.0 \( \pm \) 1.7 km s\(^{-1}\) for the secondary, were found to be closer to the pseudo-synchronous velocities of the components. Comparison with evolutionary models suggests an age of 120 \( \pm \) 35 Myr. Kinematic analysis of the unevolved binary system HD 350731 revealed that it belongs to the young thin-disk population of the Galaxy.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: individual (HD 350731)

1. INTRODUCTION

Precise knowledge of the absolute parameters of stars (masses, radii, etc.) is a means to better understand the structure and evolution of galaxies. Eclipsing binary stars are the most important objects for determining these basic parameters of stars. In order to derive the mass, radius, temperature, and other physical parameters of eclipsing binary stars, spectroscopic, photometric, and interferometric data are required. In particular, the quality of the observational data plays a crucial role in precisely determining the absolute parameters of the component stars. Among the eclipsing binary stars, detached double-lined spectroscopic binaries are the best sources for more accurately acquiring the main physical properties of stars (e.g., Southworth 2013; Lacy et al. 2015). Well-measured detached eclipsing binaries have been recently listed and studied based on distributions of their absolute parameters by Torres et al. (2010) and Eker et al. (2014).

HD 350731 (BD+20 4323, GSC 01624-00493, \( V = 9^{m}60 \)) was identified as an eclipsing binary system with eccentric orbit by Otero et al. (2004). In the AGK3 catalog, the spectral type of the system is given as A0 by Heckmann (1975) based on the Henry Draper (HD) catalog. However, Nesterov et al. (1995) suggested it was B9 using the extension charts of the HD catalog. The first photometric study, based on \( BVR, I, \) light curves, was conducted by Kleidis et al. (2008) in which, in addition to preliminary photometric analysis, it was suggested that HD 350731 indicates apsidal motion.

In this study, the first detailed photometric and spectroscopic analysis was carried out, based on newly obtained data. After descriptions of the spectroscopic and photometric observations, Section 3 presents a spectral analysis, which contains radial velocity measurements of the components, preliminary orbit solution, spectroscopic light ratio, spectral disentangling, and model atmosphere application. An analysis of multi-color light and radial velocity curves is given in Section 4, followed by apsidal motion analysis. The absolute parameters and kinematic properties of the system are detailed in Section 6. Finally, we conclude the study with the results and discussions.

2. OBSERVATIONS

New multi-color photometric observations of HD 350731 were performed at Çanakkale Onsekiz Mart University Ulupınar Observatory, Turkey over 11 nights in 2012 August and September. Observations were carried out with a 60 cm Cassegrain telescope equipped with a SBIG STL1001E CCD camera. One secondary minimum was also observed with a 122 cm Cassegrain–Nasmyth telescope incorporating an Apogee Alta U42 CCD camera. The data were collected using Bessell \( B, \) \( V, \) and \( R, \) filters. HD 350730 (A0) and HD 350727 (F5) were used as comparison and check stars, respectively. CCD frames were reduced in the standard way: bias and dark frames were subtracted from the frames and then corrected for flat-fielding. Such reduced images were used to extract the differential magnitudes of HD 350731. The C-Munipack code was used for these processes. The standard deviation of variations between the observed comparison and check stars was determined to be about 0.01 mag for all passbands.

Spectroscopic observations of HD 350731 were performed using the Cassegrain spectrograph installed on the 1.85 m Plaskett telescope at Dominion Astrophysical Observatory (DAO), British Columbia, Canada. The spectrograph has a spectral resolving power of about \( R = 9000.\) A back-illuminated SITe CCD of 1752 \( \times \) 532 pixels (size 15 \( \mu \)m) was used to record spectra spanning from about 4370 to 4630\( \AA.\) During the observations, 21 spectra for HD 350731 and several spectra for 21 Peg were taken. The spectra of the reference star 21 Peg were used to measure the RVs of the components. All spectral data were acquired between 2012 August 6 and September 6. The spectroscopic data reduction was handled using the appropriate tasks in the IRAF package.

http://c-munipack.sourceforge.net/

http://iraf.noao.edu/
with the following steps: background subtraction, division by flat-field spectrum, wavelength calibration using an Fe-Ar lamp, and normalization to the continuum.

### 3. SPECTROSCOPIC ANALYSIS

#### 3.1. Radial Velocities (RVs) and the Preliminary Orbital Solution

In order to determine the orbital parameters of HD 350731, the RVs of the components must be measured. Taking into account the spectral type of the system, given as B9 by Nesterov et al. (1995), 21 Peg (B9.5 V, $V_i = -0.2$ km s$^{-1}$) was chosen as the RV standard star for both components. The cross-correlation technique (CCT) was used to determine the RVs of the components. Simkin (1974) gave a useful description of the CCT, which is widespread, especially for RV measurements of binary stars (e.g., Hill 1993; Gunn et al. 1996; Frasca et al. 2002; Soydugan et al. 2007). The CCT was applied with the FXCOR routine in the IRAF package, which was developed based on the standard Tonry & Davis (1979) algorithm. The weights of RVs and their standard errors were calculated according to the usual formulas given by Topping (1972, p. 89) and Tonry & Davis (1979). The measured RVs of both components are given in Table 1 together with their standard errors, which are between 4 and 9 km s$^{-1}$ for the components.

As can be seen in the light curves of the system, the secondary minimum is not located at the 0.5 orbital phase and indicates a displacement compared to the primary minimum. Therefore, HD 350731 likely has an eccentric orbit and this must be taken into account in the orbital solution. Using the RVs listed in Table 1 and adopted ephemeris from Kleidis et al. (2008), we obtained the orbital parameters of the system listed in Table 2 in order to have input data for the KOREL application and for the simultaneous analysis of light and radial velocity curves. The preliminary orbit parameters together with their uncertainties are given in Table 2.

### 3.2. Spectroscopic Light Ratio

Spectroscopic line ratios ensure constraints on the luminosity ratios of the components determined from the light curve solutions at similar wavelengths, as reported in the study of Petrie (1939) and applied in many studies (e.g., Andersen et al. 1983; Southworth & Clausen 2007; Garcia et al. 2014). This also helps us to reduce the degeneracy that occurs in the light curve solutions of eclipsing binaries with similar components for the radii of the components, if the binary is a partially eclipsing system. In this study, we have derived a spectroscopic light ratio for the system using the spectral line of Mg ii at 4481 Å. Equivalent widths (EWs) of Mg ii lines for both components were measured using the SPLIT task in the IRAF package on seven spectra taken at phases out of eclipse. The weighted mean ratio was found to be $EW_2/EW_1 = 0.953 \pm 0.042$, which can be accepted to be the light ratio of the components around 4481 Å. Since the components of HD 350731 are almost equal and have very similar spectral properties, the spectral correction and wavelength dependence for the light ratio are negligible.

### 3.3. Spectral Disentangling

In order to derive the atmospheric parameters of the components of HD 350731, the individual spectrum for each component is required. The method of spectral disentangling of the composite spectra was invented and described by Simon & Sturm (1994). A good discussion and assessment of this approach was given by Pavlovski & Hensberge (2010) and Pavlovski & Southworth (2012). The disentangled method was also preferred in this study to decompose the observed spectra of the system to its components, as applied in some studies (e.g., Groenewegen et al. 2007; Torres et al. et al. 2007; Lehmann et al. 2013; Harmanec et al. 2014). The KOREL code presented by Hadrava (1995) was used for spectral disentangling. The Fortran code KOREL was developed based on the Fourier analysis technique to disentangle component spectra in binary or multiple stellar systems.

Nineteen spectra of the system obtained at DAO were used for the disentangling process. The wavelength region 4375–4575 Å, which includes Mg ii and He i spectral lines, was used. The orbital properties besides the systemic velocity...
of the system \(V_c\) could be determined with KOREL. However, the RVs of the components derived from KOREL are not independent, as noted by Lehmann et al. (2013). Therefore, we used the orbital properties listed in Table 2 as input data for the KOREL application. Finally, we derived the radial velocity amplitudes \(K_1\) and \(K_2\) from two different methods, which are compatible within better than 2 km s\(^{-1}\). The fractional light contribution of the components determined from the spectroscopic analysis was used. At the end of the process, separate spectra of the primary and secondary components were obtained. Some observed composite spectra of the system at different orbital phases, together with the model spectra and decomposed spectrum of the components calculated by KOREL in the wavelength range 4450–4500 Å, are shown in Figure 1.

### 3.4. Model Atmosphere Application

The physical parameters of the components of HD 350731 can be derived from analysis of the RVs of the components and light curves. On the other hand, if one can obtain decomposed spectra of the components, their atmospheric parameters can be found by line-profile fitting. The advantages of the spectral disentangling method for the spectroscopic analysis of the eclipsing binaries’ components are presented in the studies of Hensberge et al. (2000) and Pavlovski & Hensberge (2005). Therefore, we obtained the individual spectrum of the components of HD 350731 considering these previous studies when making our spectral analysis. The Spectroscopy Made Easy (SME) code, which enabled us to determine the basic atmospheric parameters of the components by matching the computed spectrum to the observed one, was used for the analysis. SME was developed by Valenti & Piskunov (1996) and includes several model atmospheres to compute synthetic spectra. The code uses a Levenberg–Marquardt algorithm to fit an observing spectrum with a synthetic one. The code has been applied in many studies to determine the atmospheric properties of stars (e.g., Torres et al. 2012; Soydugan et al. 2013). For the application, Kurucz (1993) model atmospheres were used and the atomic data for the spectral lines were taken from the Vienna Atomic Line Database (Piskunov et al. 1995; Kupka et al. 1999).

The disentangled spectrum of both components in the wavelength region 4375–4575 Å included Mg II at 4481 Å and He I at 4471 Å spectral lines. These data were used to compute the model atmospheres. The microturbulent velocities we adopted for the components were 3 km s\(^{-1}\), which is an appropriate value for late-type B stars (e.g., Adelman 1996; Usenko et al. 2000). The surface gravities of both components were fixed at the dynamical values determined from the solution of the light and radial velocity curves (see Table 8). After preparing the SME code to fit the spectrum of the components of HD 350731, atmospheric parameters, namely \(T_{\text{eff}}\) and \(\nu\sin i\), adjusted during the analysis were determined assuming solar abundance taken from Asplund et al. (2009). The resulting parameters and their uncertainties estimated using the \(\chi^2_{\text{min}} = 1\) method as described by Lampton et al. (1976) are listed in Table 3. In Figure 2, the decomposed spectra of the components and the synthetic spectra calculated using the best model parameters in Table 3 are compared. The figure also shows the observed composite spectrum of HD 350731 together with the computed spectrum, which was calculated using the model atmosphere parameters in Table 3, taking into account light contributions at the orbital phase of 0.2. The

### Table 3

| Parameter | Primary Value | Secondary Value |
|-----------|---------------|-----------------|
| \(T_{\text{eff}}\) (K) | 12000 ± 250 | 11830 ± 300 |
| \(\log g\) (cgs) | 4.25\(^a\) | 4.25\(^a\) |
| \(\nu\sin i\) (km s\(^{-1}\)) | 69.2 ± 1.5 | 70.1 ± 1.7 |

**Note.**

\(^a\) Dynamical values adopted from analysis of light and radial velocity curves.
synthetic composite binary spectrum in Figure 2 was calculated using the BinMag IDL visualization code (developed by O. Kochukov). As seen in Figure 2, the synthetic spectra agree well with the composite binary spectrum and individual spectra of the components.

4. ANALYSIS OF LIGHT AND RADIAL VELOCITY CURVES

The $BVR_c$ light curves and RVs of the components of HD 350731 have been modeled using version v34 of the JKTEBOP code (Southworth et al. 2004, 2005b; Southworth 2013). The code is based on the EBOP program, which was developed by P. Etzel (Etzel 1981; Popper & Etzel 1981). It was written in FORTRAN77 by J. Southworth and uses the Levenberg–Marquardt algorithm to reach the best model. We preferred the JKTEBOP code since it was stable and very fast and includes various error-estimate algorithms. This code is also very useful for well-detached eclipsing binaries as tested in several studies (e.g., Ratajczak et al. 2010; Debosscher et al. 2013; Lehmann et al. 2013).

HD 350731 is a partially eclipsing binary with almost identical components. In this case, the degeneracy may occur in the determination of the radii of the components. Therefore, we used the spectroscopic line ratio as given in Section 3.2 to constrain the range of the ratio of the radii ($k$). As the first step, the luminosity ratio was adopted at 0.953 as determined from the spectroscopy during the analysis of the $B$ light curve, since the Mg II line at 4481 Å was used to derive the spectroscopic light ratio. Thus, the $k$ value was found to be 0.993 ± 0.030. In order to check the $k$ value and examine the distributions of $k$ values against the surface brightness ratio of the components ($J_2/J_1$), we scanned for corresponding $\chi^2$ values of these two parameters in each solution. Then, $\chi^2$ values of the solutions were mapped into contours that indicate the uncertainties in Figure 3. As shown in the figure, the $k$ value of 0.993 can be seen around the lowest $\chi^2$ value. After that, the resulting $k = 0.993$ was adopted during the analysis of $V$ and $R_c$ light curves. The third light contribution ($I_3$) was assumed to be 0.0 after several iterations since it did not vary significantly. We used the linear limb darkening coefficients as adopted parameters for the components corresponding to the photometric filters used since the quadratic and logarithmic laws did not give better fits. The adjustable parameters are the central surface brightness ratio of the components ($J_2/J_1$), the sum of the fractional radii ($r_1 + r_2$), the ratio of the fractional radii ($k$) for only the $B$ filter, the orbital inclination ($i$), eccentricity ($e \sin\omega$, $e \cos\omega$), phase shift, radial velocity amplitudes of the components ($K_1$ and $K_2$), and the systemic velocity ($V_r$).

In order to determine uncertainties for the solutions, we used task 9 of the JKTEBOP code and calculated 1σ errors with the Monte Carlo algorithm. The resulting parameters are presented in Table 4 together with their uncertainties for $B$, $V$, and $R_c$ filters. The adopted photometric parameters, which are the weighted mean of the solutions in each filter, are listed in Table 5. In this table, the final orbital parameters and their uncertainties calculated by JKTEBOP are also given. A comparison between observed and computed light curves is presented in Figure 4 together with the residuals of the observational data from the best fits, while the RVs of the components together with the best fits are shown in Figure 5.

![Figure 3. Contour map indicating the distribution of the results from the $B$ light curve analysis for the correlated parameters of surface brightness ratio ($J_2/J_1$) and ratio of the fractional radii ($k$) of the components. The position of the plus symbol in the figure represents the minimum $\chi^2$ value.](image)

5. APSIDAL MOTION ANALYSIS

The apsidal motion of HD 350731 was indicated for the first time by Kleidis et al. (2008). In order to establish a preliminary estimation of the apsidal motion elements based on the commonly used method of $O-C$ data analysis, we collected published minimum times and determined two primary and two secondary minimum times from our observations, as listed in Table 6. In total, 15 minimum times were obtained.

The analysis was made using code written by Zasche et al. (2009), which was developed based on the mathematical methods reported by Giménez & García-Pelayo (1983). For the analysis, the orbital inclination and eccentricity were adopted as $i = 81.70$ from the light curve analysis and $e = 0.079$ from

---

Table 4

| Parameters | $B$ | $V$ | $R_c$ |
|-----------|-----|-----|-------|
| $r_1 + r_2$ | 0.399 ± 0.003 | 0.400 ± 0.003 | 0.404 ± 0.004 |
| $k$ | 0.993 ± 0.030 | 0.993* | 0.993* |
| $r_1$ | 0.2000 ± 0.0031 | 0.2000 ± 0.0014 | 0.2028 ± 0.0018 |
| $r_2$ | 0.1986 ± 0.0031 | 0.1995 ± 0.0014 | 0.2014 ± 0.0018 |
| $i(\text{°})$ | 81.83 ± 0.09 | 81.75 ± 0.10 | 81.40 ± 0.11 |
| $J_2/J_1$ | 0.968 ± 0.010 | 0.977 ± 0.011 | 0.976 ± 0.015 |
| $e \sin\omega$ | 0.0349 ± 0.0060 | 0.0310 ± 0.0020 | 0.0330 ± 0.0078 |
| $e \cos\omega$ | 0.0719 ± 0.0004 | 0.0720 ± 0.0008 | 0.0717 ± 0.0006 |

Note.
* Fixed during the analysis.

---

http://www.astro.keele.ac.uk/~jjk/codes.html.
the orbital analysis. The resulting preliminary apsidal motion parameters are given in Table 7, while the $O-C$ diagram with theoretical fits is shown in Figure 6. The changing rate in longitude of the periastron is $\dot{\omega} = 0.0170 \pm 0.0082$ degree cycle$^{-1}$, which corresponds to an apsidal motion period of $U = 92$ years. As seen in Table 7, the errors of the parameters are high and the parameters are not sensitive since 15 minimum times, which cover only 9 years, were used for the analysis. However, the results can be accepted for a preliminary estimation of the apsidal motion properties and improved by adding new times of minima.

6. ABSOLUTE PROPERTIES AND KINEMATIC BEHAVIOR

Analysis of the light curve of HD 350731 and the RVs of its components led to the acquisition of accurate absolute dimensions and physical properties for the first time. In order to calculate the absolute parameters and their uncertainties, except for the effective temperatures, which were determined from spectral analysis, we used the JKTABSDIM code, which was developed by Southworth et al. (2005a). In this code, the uncertainties are calculated very robustly and a complete error budget is found for every output parameter. Derived

![Figure 4](image-url) Figure 4. Observed and theoretical light curves of HD 350731 in BVR filters (a) and the residuals from the best fits (b).

![Figure 5](image-url) Figure 5. RV curves of the components of HD 350731 plotted vs. orbital phase. Filled and open circles represent RVs of the primary and secondary components, respectively. The solid line represents orbital solution for the primary component and the dashed line for the secondary component. The residuals are indicated below.
fundamental parameters are listed in Table 8. The physical constants used for the calculations are given by Southworth (2011).

The accuracy of the masses is better than 5%, while the radius values of the components are good to about 2.5%. We calculated the E(B−V) color excess for HD 350731 from the dust maps of Schlafly & Finkbeiner (2011). Because the system is relatively close to the Sun, the color excess value from Schlafly & Finkbeiner (2011) needed to be reduced according to the distance. The J band absolute magnitude of the system was calculated using the color–luminosity relation of Bilir et al. (2008). Then, the calculated color excess E(B−V) = 0.157 mag was reduced using the equation of Bahcall & Soneira (1980). The color excess value is consistent with the position of HD 350731 in the Milky Way. The interstellar absorption value (A_v) has been calculated to be 0.49 mag from the commonly accepted formula A_v = 3.1 × E(B−V). The distance of the system was found to be 703 ± 34 pc based on the apparent system magnitude, the light ratio of the system’s components, and interstellar extinction values. The temperatures of the components determined from spectroscopic analysis are consistent with the spectral types of B8V+B8V, according to calibrations given by Sung et al. (2013).

The components of the system have similar properties since the temperature difference between the components was found to be ΔT = 170 K, which is smaller than the 1σ uncertainties for the effective temperatures of both components (see Table 3). Furthermore, the masses and radii values were very close, as seen in Table 8. From the photometric analysis, the system was found to be detached and the Roche lobe filling ratios were calculated to be 63% and 64% for the primary and secondary components, respectively.

In order to analyze the kinematical properties of HD 350731, we used the system’s center of mass velocity, distance, and proper motion values. The proper motion data (μ₀, cosδ, μ₀) = (1.0 ± 0.7, −8.7 ± 0.8) mas yr⁻¹ were taken from the Fourth US Naval Observatory CCD Astrograph Catalog (UCAC4; Zacharias et al. 2013), whereas the center of mass velocity V_c = −10.1 ± 0.4 km s⁻¹ and distance d = 703 ± 34 pc were obtained in this study. The system’s space velocity was calculated using Johnson & Soderblom’s (1987) algorithm. To obtain the precise space velocity, a first-order galactic differential rotation correction was taken into account (Mihalas & Binney 1981). The differential rotation corrections were calculated as 16.23 and 0.89 km s⁻¹ and applied to U and V space velocity components, respectively. The W velocity is not affected in this first-order approximation. As for the local standard of rest correction (LSR), Coşkunoğlu et al. (2011) values (U, V, W) = (8.50, 13.38, 6.49) km s⁻¹ were used and the total space velocity of HD 350731 was obtained as $\mathbf{V}_\text{tot} = 10.1\pm 0.4$ km s⁻¹. The corrected space velocity components are (U, V, W) = (6.10± 2.39, −9.26± 1.56, −10.54± 2.57) km s⁻¹. The total space velocity and space velocity component values are in agreement with young-disk stars (Leggett 1992).

To determine the population type of HD 350731, we used Dinescu, Dinescu et al.’s (1999) N-body code, and obtained the galactic orbit of the system. In this code, the timescale for generating the orbits was assumed to be 3 Gyr, and the calculation steps were 2 Myr. The 3 Gyr timescale was assumed so that precise orbits would be created, even though this is longer than the nuclear timescale of early-type stars. The orbits of HD 350731 on the X−Y and Z planes around the galactic center are shown in Figure 7. The system’s apogalactic ($R_{\text{max}}$) and perigalactic ($R_{\text{min}}$) distances obtained were 7.72 and 7.09 kpc, respectively. According to the N-body code, the maximum vertical separation from the galactic plane of the system is |z_{\text{max}}| = 100 pc. The following formulae were used to derive the planar ($e_p$) and vertical ($e_v$) eccentricities:

\[
e_p = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{max}} + R_{\text{min}}},
\]

\[
e_v = \left(\frac{|z_{\text{max}}| + |z_{\text{min}}|}{R_m}\right)
\]

where $R_m$ is the mean of $R_{\text{min}}$ and $R_{\text{max}}$. The planar and vertical eccentricities were calculated as $e_p = 0.04$ and $e_v = 0.01$, respectively. These eccentricities show that HD 350731 is in a circular orbit around the mass center of the Galaxy and that it belongs to the young thin-disk population.

Table 8
Astrophysical Properties of HD 350731

| Parameter                        | Primary     | Secondary    |
|---------------------------------|-------------|--------------|
| Mass ($M_\odot$)                | 2.91 ± 0.13 | 2.80 ± 0.14  |
| Radius ($R_\odot$)              | 2.11 ± 0.05 | 2.07 ± 0.05  |
| Temperature (K)                 | 12000 ± 250 | 11830 ± 300  |
| log L ($L_\odot$)               | 1.92 ± 0.04 | 1.88 ± 0.05  |
| log g (cgs)                     | 4.25 ± 0.02 | 4.25 ± 0.02  |
| Orbital period (days)           | 1.63511 ± 1 × 10⁻⁵ |
| Orbital separation ($R_\odot$)  | 10.43 ± 0.02|
| Mass ratio                      | 0.965 ± 0.004 |
| Systemic velocity (km s⁻¹)      | −10.1 ± 0.4  |
| Distance (pc)                   | 703 ± 34     |
| V (mag)                         | 9.60^a       |
| $M_\text{bol}$(mag)             | −0.05 ± 0.11 | 0.05 ± 0.12  |
| BC (mag)                        | −0.66^b      |
| $M_r$(mag)                      | 0.61 ± 0.11  | 0.67 ± 0.12  |
| Measured $v$ sin i (km s⁻¹)     | 69.2 ± 1.5   | 70.1 ± 1.7   |
| Pseudo-synchronous $v$ sin i (km s⁻¹) | 67.5 ± 0.3 | 67.0 ± 0.3 |
| Synchronous $v$ sin i (km s⁻¹)  | 65.4 ± 0.3   | 64.1 ± 0.3   |
| Age (Myr)                       | 120 ± 35     |

Note.
^a SIMBAD Database.
^b Sung et al. (2013).

Figure 6. O−C diagram for HD 350731 obtained with the parameters given in Table 7. Primary and secondary minimum times are indicated by filled and open circles, respectively.
7. DISCUSSION AND CONCLUSION

Double-lined detached eclipsing binaries (DBs) are valuable sources for determining the precise fundamental properties (mainly masses and radii) of stars. A recent catalog of this type of binary was published by Eker et al. (2014). It consists of 257 DBs; their 388 component stars have better than 5% accuracy in their masses and radii. When one examines the basic properties of the DBs in the catalog (especially the mass ratio, mass, radius, and temperature of the components), it can be seen that there is no detached eclipsing binary system that has absolute properties similar to HD 350731. The spectral type of the system was determined to be B8V+B8V, while the masses were derived to be $M_1 = 2.91 \pm 0.13 M_\odot$ and $M_2 = 2.80 \pm 0.14 M_\odot$ for the primary and secondary components, respectively. Therefore, DBs with a mass ratio in the range of 0.95–1.0 and spectral type O and/or B need to be studied further in order to fill the gap in this parameter range. This is necessary to understand the evolution and structure of early-type stars.

The mass–luminosity relation (MLR) was updated recently by Eker et al. (2015) using DB data. In this study, they identified four mass domains and derived MLRs for these mass ranges. For comparison, using the MLR given in the mass ranges $2.4 M_\odot$ and $7 M_\odot$, we calculated luminosity values on a logarithmic scale to be $1.96 L_\odot$ and $1.89 L_\odot$ for the primary and secondary components, respectively. The predicted values from the updated classical MLR agree with the values derived from the Stefan-Boltzmann law (see Table 8).

Spectral data enable us to find the temperatures and projected rotational velocities of the components. The disentangled spectra of the components obtained from the KOREL analysis were used for the application to the model atmosphere. As a result, the temperature of the primary and secondary components was found to be 12,000 and 11,830 K, respectively. The surface gravity values ($\log g_{1,2}$) calculated from the masses and radii of the components were adopted during the spectral analysis. The projected rotational velocities ($v \sin i$) of the components were measured to be 69.2 and 70.1 km s$^{-1}$ for the primary and secondary components, respectively. Within the errors, the measured $v \sin i$ values agree with the pseudosynchronous velocities of the components in Table 8, which were calculated on the basis of the formulations by Hut (1981).

The orbit of the system is slightly eccentric, determined from the orbital solution and also an analysis of the multi-color light curves and RVs of the components. The secondary minimum can be seen to have shifted from an orbital phase of 0.5. This is an indication of apsidal motion in the system. We collected 15 minimum times together with newly measured eclipse times to study the apsidal motion by means of an $O-C$ analysis. The apsidal motion parameters could not be determined accurately since the observed eclipse times were not well covered. The apsidal motion was found to have a rate of $\dot{\omega} = 0.0170 \pm 0.0082$ degree cycle$^{-1}$, which corresponds to an apsidal motion period of about 92 years.

The locations of the components of HD 350731 are seen in Figure 8. The zero-age main sequence (ZAMS) and the evolutionary tracks for the exact masses of the components,
and the isochrones for solar chemical composition, are taken from the Yonsei–Yale (Y$^2$) series of Yi et al. (2001). As seen in Figure 8, the components are a bit away from the ZAMS line and the age of the system was estimated to be $120 \pm 35$ Myr from the Y$^2$ isochrones. A kinematic analysis indicated that the system leaves the galactic plane around $100$ pc during its movement on the galactic orbit. This is evidence for HD 350731’s membership in the thin-disk population. The positions of the components in the HR diagrams are in agreement with the evolutionary tracks for masses of $2.91 M_\odot$ and $2.80 M_\odot$.

As a general conclusion, we mention that the photometric and spectroscopic analysis of HD 350731 leads us to extend the database of DBs with intermediate mass components with similar properties. This is important since in the catalog of DBs by Eker et al. (2014) there are only a few systems with a mass ratio close to $q = 1.0$ and components with masses greater than $2.8 M_\odot$ (e.g., $\eta$ Mus, V799 Cas, V906 Sco). The unevolved binary system HD 350731 belongs to the young thin-disk population of the Galaxy with an estimated age of $120 \pm 35$ Myr. In order to make a detailed abundance analysis and verify the population type of the system, more high resolution spectroscopic data are needed. New eclipse times are also required to enlarge the time interval for better analysis and to confirm the apsidal motion parameters.

This research was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK, grant No. 111IT224). The authors thank the anonymous referee for valuable suggestions and comments that helped us to improve the study. We thank Čanakkale Onsekiz Mart University Astronomy Projects Coordination Unit and Ulupınar Observatory together with Istanbul University Observatory Research and Application Center for their support and allowing the use of the T122 and IST60 telescopes. The project was supported partly by National Planning Agency (DPT) of Turkey (project DPT-2007K120660 carried out at Čanakkale Onsekiz Mart University) and the Scientific Research Projects Coordination Unit of Istanbul University (project no. 3685). We gratefully acknowledge the support of the NRC (Canada) Herzberg Institute of Astrophysics. The authors especially thank Dr. D. Bohleider and Dr. D. Monin for their hospitality and allowing telescope time for observations at the Dominion Astrophysical Observatory, Canada. This research has made use of the SIMBAD and NASA Astrophysics Data System Bibliographic Services.

REFERENCES

Adelman, S. J. 1996, MNRAS, 280, 130
Andersen, J., Clausen, J. V., Nordström, B., & Reipurth, B. 1983, A&A, 121, 271
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009,ARA&A, 47, 481
Bahcall, J. N., & Soneira, R. M. 1980, ApJS, 44, 73
Bilir, S., Ak, T., Soydugan, E., et al. 2008, AN, 329, 835
Brat, L., Zejda, M., & Svoboda, P. 2007, OEJV, 74, 1
Cox, J., S. K. 1997, in AGK 3. Star Catalogue of Positions and Proper Motions North of $-2.5$ deg. Declination, ed. W. Dieckvoss (Hamburg-Bergedorf: Hamburger Sternwarte)
Hensberge, H., Pavlovski, K., & Verschueren, W. 2000, A&A, 358, 553
Hill, J. M. 1993, in ASP Conf. Ser. 38, New Frontiers in Binary Star Research, ed. K.-C. Leung & J.-S. Nha (San Francisco, CA: ASP), 127
Hut, P. 1981, A&A, 99, 126
Johnson, D. R. H., & Soderblom, D. R. 1987, AJ, 93, 864
Kleidis, S., Robertson, C. W., & Wils, P. 2008, IBVS, 5860
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Kurucz, R. L. 1993, ASP Conf. Ser. 44, A New Opacity-sampling Model Atmosphere Program for Arbitrary Abundances, Peculiar Versus Normal Phenomena in A-type and Related Stars, ed. M. M. Dworetsks, F. Castelli & R. Faraggiana (San Francisco, CA: ASP), 87
Lacy, M., Ridgway, S. E., Sajina, A., et al. 2015, AJ, 802, 102
Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177
Leggett, S. K. 1992, ApJS, 82, 351
Lehmann, H., Southworth, J., Tkachenko, A., & Pavlovski, K. 2013, A&A, 557, 79
Mihalas, D., & Binney, J. 1981, Galactic Astronomy: Structure and Kinematics (2nd ed.; San Francisco, CA: Freeman)
Nesterov, V. V., Kuzmin, A. V., Ashimbaueva, N. T., et al. 1995, A&AS, 110, 367
Otero, S. A., Wils, P., & Dubovsky, P. A. 2004, IBVS, 5570
Pavlovski, K., & Hensberge, H. 2005, A&A, 439, 309
Pavlovski, K., & Hensberge, H. 2010, in ASP Conf. Proc. 435, Binaries—Key to Comprehension of the Universe, ed. A. Pra & M. Zejda (San Francisco, CA: ASP), 207
Pavlovski, K., & Southworth, J. 2012, in IAU Symp. 282, From Interacting Binaries to Exoplanets: Essential Modeling Tools, ed. M. T. Richards & I. Hubeny (Cambridge: Cambridge Univ. Press), 359
Petrie, R. M. 1939, PDAO, 7, 205
Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W., & Jeffery, C. S. 1995, A&AS, 112, 525
Popper, D. M., & Etzel, P. B. 1981, AJ, 86, 102
Ratajczak, M., Kwiatkowsk, T., Schwarzenberg-Czerny, A., et al. 2010, MNRAS, 402, 2424
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Simkin, S. M. 1974, A&A, 31, 129
Simon, K. P., & Sturm, E. 1994, A&A, 281, 286
Southworth, J. 2011, MNRAS, 417, 2166
Southworth, J. 2013, MNRAS, 435, 117
Southworth, J., & Clausen, J. V. 2007, A&A, 461, 1077
Southworth, J., Maxted, P. F. L., & Smalley, B. 2004, MNRAS, 351, 1277
Southworth, J., Maxted, P. F. L., & Smalley, B. 2005a, A&A, 429, 645
Southworth, J., Smalley, B., Maxted, P. F. L., Claret, A., & Etzel, P. B. 2005b, MNRAS, 363, 529
Soydugan, F., Frasca, A., Soydugan, E., et al. 2007, MNRAS, 379, 1533
Soydugan, F., , Soydugan, E., V., & Liakos, A. C., & Liakos, A. 2013, MNRAS, 432, 3278
Sung, H., Lim, B., Bessell, M. S., et al. 2013, JKAS, 46, 103
Tonry, J., & Davis, M. 1979, AJ, 84, 1511
Topping, J. 1972, Errors of Observation and Their Treatment (London: Chapman and Hall)
Torres, G., Andersen, J., & Giménez, A. 2010, ARA&A, 16, 67
Torres, G., Clausen, J. V., Bruntt, H., et al. 2012, A&A, 537, 117
Torres, K. B. V., Lampens, P., Frémat, Y., et al. 2011, A&A, 525, 50
Usenko, I. A., Kovtjukh, V. V., Andrievsky, S. M., et al. 2000, in ASP Conf. Proc. 214, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith & M. Garcia-de la Font (San Francisco, CA: ASP), 71
Valentini, A., & Piskunov, N. 1996, A&AS, 118, 595
Yi, S., Demarque, P., Kim, Y.-C., et al. 2001, ApJS, 136, 417
Zacharias, N., Finch, C. T., Girard, T. M., et al. 2013, AJ, 145, 44
Zejda, M., Mikułasek, Z., & Wolf, M. 2006, IBVS, 5741
Zasche, P., Liakos, A., Niarhos, P., et al. 2009, NewA, 14, 121