THE FIRST PHOTOMETRIC ANALYSES OF THE ALGOL BINARY SYSTEMS GSC 04328-02164 AND GSC 03164-01558

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Received 2015 June 15; accepted 2015 October 6; published 2016 January 7

ABSTRACT

The CCD observations for the eclipsing Algol type binary systems GSC 04328-02164 in wideband BVR, I filters and GSC 03164-01558 in B and I filters have been analyzed using the PHOEBE package (v 0.31a) to determine their orbital and physical parameters. The absolute parameters and evolution parameters of the two systems have been determined. The results show that the mass ratio, inclination, distance, and age for the system GSC 04328-02164 are equal to \( q = 0.674 \pm 0.002 \), \( i = 75.997 \pm 0.022 \), \( d = 375.477 \pm 4.299 \) pc, and \( \tau = 26.76 \pm 15.65 \times 10^8 \) years, respectively. For the other system, GSC 03164-01558, \( q = 0.941 \pm 0.006 \), \( i = 88.0484 \pm 0.030 \), \( d = 444.651 \pm 9.444 \) pc, and \( \tau = 53.63 \pm 9.16 \times 10^8 \) years.

Key words: binaries; eclipsing – stars; evolution – stars; fundamental parameters – stars; individual (GSC 04328-02164, GSC 03164-01558)

1. INTRODUCTION

Eclipsing binaries studies often involve a combination of photometric (light curve) and spectroscopic (mainly radial velocity curve) data. Analysis of the light curve yields, in principle, the orbital inclination and eccentricity, relative stellar sizes and shapes, the mass ratio in some cases, the ratio of surface brightnesses, and brightness distributions of the components (due to tidal and non-uniformly rotating Roche limit of the components; see Barman 1991), among other quantities. If radial velocities are available, the masses and semimajor axis may also be determinable. Many other parameters describing the system and component stars may be determined, which are of great importance in studies of stellar structure and evolution (Kallrath & Milone 1999).

The two systems GSC 04328-02164 and GSC 03164-01558 were recently discovered as variable Algol type eclipsing binaries by Juryšek & Hoňková (2012) and Liakos & Niarchos (2010), respectively. The detached binary system GSC 04328-02164 (CzeV336 Cam = TYC 4328-02164-1) was found in the field of the eclipsing binary system V335 Cam during a CCD photometric session at the Observatory and Planetarium of Johann Palisa, Ostrava, Czech Republic, with a period of 1.384868 (Juryšek & Hoňková 2012). They used the 200 mm telescope of the Observatory of Johann Palisa and an SBIG-ST8XE CCD camera with an area of 1350 \times 1020 square pixels, with a field of view (FOV) 39.4 \times 26.3'. The filters BVR, I were used on 13 nights between 2011 December 5th and 2012 July 30th. A total of 5981 CCD frames were obtained. All frames have been reduced using software package C-Munipack (http://c-munipack.sourceforge.net/). The stars GSC 04328-01782 and GSC 04328-02207 were chosen as comparison and check stars. Table 1 shows the catalog ID, coordinates, and \( B \) and \( V \) magnitudes from the UCAC4 catalog for the variable 1, comparison, and check stars. Juryšek & Hoňková (2012) used the following ephemerides:

\[
\text{Min. I (HJD)} = 2455392.4033 + 4.4377 \times E, \tag{1}
\]

where Min. I (HJD) represents the epoch of minima in heliocentric Julian dating and \( E \) is the number of integer cycles needed to calculate the phases for all observed points, drawing the light curves represented in normalized flux in the \( B \), \( V \), \( I \), filters as shown in Figure 2. For the system GSC 4328-2164 we found in the catalog (All-sky spectrally matched Tycho-2 stars, Pickles & Depagne 2010) that the spectral type is F2III (\( T_{\text{eff}} \) and metallicities for Tycho-2 stars, Ammons et al. 2006) and that the effective temperature is equal to 7025 K.

The other detached binary system, GSC 03164-01558, was found in the field of UW Cyg during a CCD photometric session at the University of Athens observatory, Athens, Hellas —Greece (Liakos & Niarchos 2010). They classified the system as an Algol eclipsing binary with a period of 4.5377, and they used the 400 mm telescope of the University of Athens Observatory, Athens, Hellas (Greece) and an SBIG ST-10XME CCD camera with a FOV 25' \times 17'. The filters \( B \) (Bessel) and \( I \) (Bessel) have been used through the following dates: 2010 June 20–22 and 30; 2010 July 1, 3–7, 15–21, 23, and 25; and 2010 August 2. A total of 541 CCD frames were obtained. All frames were reduced using the software package C-Munipack. The stars GSC 03164-01593 and GSC 03164-00269 were chosen as comparison and check stars as shown in Table 1. Liakos & Niarchos (2010) used the following ephemerides:

\[
\text{Min. I (HJD)} = 2455392.4033 + 4.4377 \times E, \tag{2}
\]

where Min. I (HJD) represents the epoch of minima in heliocentric Julian dating and \( E \) is the number of integer cycles needed to calculate the phases for all observed points, drawing the light curves represented in normalized flux in \( B \) and \( I \) as shown in Figure 4.

We did not find any spectroscopic information for the detached binary system GSC 03164-01558.

2. LIGHT CURVE ANALYSIS

For the system GSC 04328-02164, Juryšek & Hoňková (2012) used the corrected \( B(10.101) \) and \( V(9.857) \) magnitudes of the comparison star from the AAVSO Photometric All-sky...
Survey (APASS; Henden et al. 2009) and they used the corrected $J$ and $K$ magnitudes from the 2MASS catalog to calculate the $R_e$ (9.679) and $I_e$ (9.571) magnitudes. From the previous corrected values of the magnitude of the comparison star they transformed the instrumental magnitudes of the variable star into standard Johnson–Cousins $B$, $V$, $R_e$, and $I_e$ photometric systems and they derived the corrected observed color index at the maximum and at the both minima as follows: $(B - V)_{\text{Max}} = 0.354 \pm 0.011$, $(B - V)_{\text{II}} = 0.363 \pm 0.018$, and $(B - V)_{\text{III}} = 0.340 \pm 0.012$. Due to the primary component (hotter) being in the front at the secondary minimum, we can use the observed $(B - V)_{\text{III}}$, which is equal to 0.340 $\pm$ 0.012, to estimate the effective temperature of the primary component. Further examinations are made for the color–temperature relation obtained from the model atmosphere calculations, which are frequently used in the theoretical work of stellar evolution. This leads us to use the effective temperatures calculated by different authors for the system GSC 04328-02164 as follows: Johnson (1966) gave $T_{\text{eff}} = 6832$ K; Gray (2005) gave $T_{\text{eff}} = 6866$ K; Flower (1996) gave $T_{\text{eff}} = 7014$ K; Reed (1998) gave $T_{\text{eff}} = 7200$ K; Drilling & Landolt (2002) gave $T_{\text{eff}} = 7060$ K; and Ammons et al. (2006) gave $T_{\text{eff}} = 7059$ K. Since the physical parameters, especially the effective temperature, are much less sensitive to the metallicity in $(V - K)$ and $(J - H)$ than in $(B - V)$, we do not depend on $(B - V)$ alone. From the UCAC4 Catalog (Zacharias et al. 2012), we found the color index $(J - H)$ of the system GSC 04328-02164 to be equal to 0.130, which corresponds to $T_{\text{eff}} = 7020$ K (Tokunaga 2002, p. 143). The mean $T_{\text{eff}}$ of all of the above values is 7007 $\pm$ 125 K, which is used as the effective temperature of the primary component (hotter) of the system GSC 04328-02164 in the light curve analysis.

For the other system, GSC 03164-01558, we have derived the color indexes out of the eclipse and in both minima as follows: $(B - V)_{\text{Max}} = 1.478 \pm 0.002$, $(B - I)_{\text{II}} = 1.513 \pm 0.042$, and $(B - I)_{\text{III}} = 1.507 \pm 0.020$. We have used the $(B - I)$ color index and applications of the $(B - I)$ versus $(B - V)$ relationship $(B - I) = 2.36 \times (B - V)$ (Natali et al. 2004) to determine the following values: $(B - V)_{\text{Max}} = 0.626 \pm 0.040$, $(B - V)_{\text{II}} = 0.641 \pm 0.042$, and $(B - V)_{\text{III}} = 0.639 \pm 0.020$. Similar to the system GSC 04328-02164, we can use the observed $(B - V)_{\text{III}}$, which is equal to 0.639 $\pm$ 0.020, to estimate the effective temperature of the primary component (hotter). We found the effective temperatures calculated by different authors for the system GSC 03164-01558 as follows: Johnson (1966) gave $T_{\text{eff}} = 5720$ K; Gray (2005) gave $T_{\text{eff}} = 5776$ K; Flower (1996) gave $T_{\text{eff}} = 5751$ K; Reed (1998) gave $T_{\text{eff}} = 5974$ K; and Drilling & Landolt (2002) gave $T_{\text{eff}} = 5714$ K. From the UCAC4 Catalog (Zacharias 2012), we found the color index $(J - H)$ of the system GSC 03164-01558 to be equal to 0.342,
which corresponds to $T_{\text{eff}} = 5710$ K (Tokunaga 2002, p. 143). The mean value of the above $T_{\text{eff}}$ values equals $5774 \pm 101$ K, which is used as the effective temperature of the primary component (hotter) of the system GSC 03164-01558 in the light curve analysis.

For all observed light curves of both systems, GSC 04328-02164 and GSC 03164-01558, in each band we adopted bolometric albedo and gravity-darkening exponents in accordance with the stellar convective envelope with $T_{\text{eff}} < 7500$ K, where $A_1 = A_2 = 0.5$ (Rucinski 1969) and $g_1 = g_2 = 0.32$ (Lucy 1967). For the treatment of limb-darkening, we used logarithmic functions for both bolometric and bandpass limb-darkening laws. The corresponding coefficients were taken from Van Hamme’s (1993) table.

Since no spectroscopic radial velocity measurements were available for the selected binaries used in this study, $q$ was determined using the extensive $q$-search method from the light curve modeling, as discussed in Deb et al. (2010), in order to determine the most probable mass ratio for both systems. In this technique, test solutions were computed at a series of assumed mass ratios ($q$), with the values ranging from 0.10 to 1.0 in steps of 0.01. Each of the test solutions was computed in the model of the detached binary. For each assumed $q$, a fit solution was obtained and the resulting sum of the squared deviations for each value of $q$ was plotted. The values of $q$ corresponding to the minima of the sum of the squared deviations obtained for each system were taken as the initial mass ratios in the modeling. The diagram in Figure 1 shows that for the system GSC 04328-02164, a minimum occurs at a value around $q = 0.68$, and for the system GSC 03164-01558, a minimum occurs at a value around $q = 0.95$.

Through the light curve solution of both systems, the commonly adjustable parameters employed are; the orbital inclination ($i$), the temperature of the secondary components ($T_2$), surface potentials ($\Omega_1$, $\Omega_2$), mass ratio ($q$), and the monochromatic luminosity $L_1$ and $L_2$.

2.1. GSC 04328-02164

The light curves of the system GSC 04328-02164 in the $BVR_I$ bands have been analyzed using the PHOEBE package, version 0.31a (Prša & Zwitter 2005). To download the PHOEBE package visit the website (http://phoebe.fiz.uni-ij-si/). With the PHOEBE software we have used the model of the detached binary to estimate a set of parameters that represent the observed light curves. The best photometric fitting has been reached after several runs, which shows that the primary component is more massive and hotter than the secondary one, with a temperature difference of about 1619 K. The accepted parameters are listed in Table 2, while Figure 2 displays the observed light curves together with the synthetic curves in the $BVR_I$ bands. According to the effective temperature of both the primary and secondary components of the system GSC 04328-02164 and from the calibration of Morgan–Keenan (MK) spectral types for the main sequence class (see Drilling & Landolt 2002, Table 15.7) the spectral types are nearest to F2 and G0, respectively. Using the geometrical and physical parameters listed in Table 2 with the Binary Maker 3 (BM3) program (Bradstreet 2005), in Figure 3 we present the Roche geometry of the system for the $B$ filter.

2.2. GSC 03164-01558

To determine the orbital and physical parameters of the system GSC 03164-01558 we have used the same program (PHOEBE). The light curve analyses have been made for the available $B$ and $I$ light curves. After many trials the orbital and physical parameters of the system were derived and are listed in Table 2, while Figure 4 displays the observed light curves in $B$ and $I$ together with the synthetic curves. Results show that star 1 is the more massive and hotter component, while star 2 is the less massive and cooler one. Using the orbital and physical parameters listed in Table 2 with the BM3 program, in Figure 5 we present the Roche geometry of the system in the $B$ filter. According to the effective temperature of both the primary and secondary components of the system GSC 03164-01558 and from the calibration of MK spectral types for the main sequence class (see Drilling & Landolt 2002, Table 15.7), the spectral types are nearest to G2 and K2, respectively.

3. ABSOLUTE PARAMETERS OF THE SYSTEMS

Spectroscopic observations are one of the most important sources for physical parameters estimation. The two studied systems were recently discovered and there is no available radial velocity for either system. We have used the simple approximation formulae (Harmanec 1988), which relate the effective temperature with other basic physical parameters (mass, radius, luminosity, and bolometric magnitude) to determine the absolute parameters for the components of the two systems GSC 04328-02164 and GSC 03164-01558, as shown in Table 3.

The estimated physical parameters show that the primary components in both systems are more massive than the secondary components. We have used the absolute properties of the

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**Table 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GSC 04328-02164</th>
<th>Parameter</th>
<th>GSC 03164-01558</th>
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</thead>
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<tr>
<td>epoch</td>
<td>2455906.561</td>
<td>epoch</td>
<td>245592.4033</td>
</tr>
<tr>
<td>Period</td>
<td>1.784686 day</td>
<td>Period</td>
<td>4.4377 day</td>
</tr>
<tr>
<td>$i_1$</td>
<td>75997 ± 0.022</td>
<td>$i_2$</td>
<td>880984 ± 0.030</td>
</tr>
<tr>
<td>$T_1$</td>
<td>7000 K (fixed)</td>
<td>$T_1$</td>
<td>5774 K (fixed)</td>
</tr>
<tr>
<td>$T_2$</td>
<td>6069 K ± 37</td>
<td>$T_2$</td>
<td>4930 K ± 219</td>
</tr>
<tr>
<td>$q$</td>
<td>0.674 ± 0.002</td>
<td>$q$</td>
<td>0.94110 ± 0.00627</td>
</tr>
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<td>$L_1/(L_1+L_2)h$</td>
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<td>$L_1/(L_1+L_2)h$</td>
<td>0.5110</td>
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<tr>
<td>$L_2/(L_1+L_2)h$</td>
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<td>0.4890</td>
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<td>$L_1/(L_1+L_2)v$</td>
<td>0.5029</td>
</tr>
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<td>$L_2/(L_1+L_2)v$</td>
<td>0.4971</td>
</tr>
<tr>
<td>$L_1/(L_1+L_2)B$</td>
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<td>$L_1/(L_1+L_2)B$</td>
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<tr>
<td>$L_2/(L_1+L_2)B$</td>
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<td>$L_2/(L_1+L_2)B$</td>
<td>0.5028</td>
</tr>
<tr>
<td>$T_1(X_B)$</td>
<td>0.5727</td>
<td>$T_1(X_B)$</td>
<td>0.5727</td>
</tr>
<tr>
<td>$T_2(X_B)$</td>
<td>0.4273</td>
<td>$T_2(X_B)$</td>
<td>0.4273</td>
</tr>
<tr>
<td>$g_1 = g_2$</td>
<td>0.032 (fixed)</td>
<td>$g_1 = g_2$</td>
<td>0.032 (fixed)</td>
</tr>
<tr>
<td>$A_1 = A_2$</td>
<td>0.50 (fixed)</td>
<td>$A_1 = A_2$</td>
<td>0.50 (fixed)</td>
</tr>
<tr>
<td>$X_{IB}$</td>
<td>0.597</td>
<td>$\Sigma(\alpha-c)^2$</td>
<td>±0.03</td>
</tr>
<tr>
<td>$X_{IB}$</td>
<td>0.605</td>
<td>$\Sigma(\alpha-c)^2$</td>
<td>±0.03</td>
</tr>
<tr>
<td>$X_{IV}$</td>
<td>0.494</td>
<td>$\Sigma(\alpha-c)^2$</td>
<td>±0.03</td>
</tr>
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<td>$X_{CV}$</td>
<td>0.497</td>
<td>$\Sigma(\alpha-c)^2$</td>
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</tr>
<tr>
<td>$X_{Rc}$</td>
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<td>$\Sigma(\alpha-c)^2$</td>
<td>±0.03</td>
</tr>
<tr>
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</tr>
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<td>$X_{Ic}$</td>
<td>0.314</td>
<td>$\Sigma(\alpha-c)^2$</td>
<td>±0.03</td>
</tr>
</tbody>
</table>

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two systems, with the fundamental relation $d = 10^{(m-Mv+5)/5}$, to calculate the distance $d$ (in parsecs) of both systems as shown in Table 3, where $m$ and $Mv$ are the apparent and absolute magnitudes, respectively.

4. EVOLUTIONARY STATE OF THE SYSTEMS

In order to study the evolutionary status of the two systems GSC 04328-02164 and GSC 03164-01558 we have plotted the physical parameters (listed in Table 3) of the components of the two systems on the H–R, M–R, and M–L diagrams in Figures 6–8 using the evolutionary tracks for the non-rotating model, which have been computed by Mowlavi et al. (2012) for both zero-age main sequence stars (ZAMS) and terminal-age main sequence stars (TAMS) with metallicity $Z = 0.014$ (Solar metallicity). As is clear from Figures 6–8, the components of the two systems are located on/near the ZAMS for all relations; therefore the components of the two systems appear to be main sequence stars and the primary components appear to be more massive and hotter than the secondary components.

In order to determine the age of the two systems, we have plotted the theoretically calculated models of temperature with luminosity ($T–L$) isochrone diagram in Figure 9, by Mowlavi et al. (2012), and we have specified the position of the components. From this diagram the age ($\tau$) of the system GSC 04328-02164 is equal to $26.76 \pm 15.65 \times 10^8$ years and the age of the system GSC 03164-01558 is equal to $53.63 \pm 9.16 \times 10^8$ years.

5. SUMMARY AND CONCLUSIONS

The main contribution of the present paper is the first determination of the orbital and physical parameters of the recently discovered Algol type eclipsing binary systems GSC 04328-02164 and GSC 03164-01558. In the absence of spectroscopic observations, we can consider the eclipsing binary system as a point source, where the effective
temperature varies in time. Both components contribute to this effective temperature according to their sizes, individual temperatures, and the inclination. The effective temperature of the binary is directly revealed by the color index, the observational behavior of which is well known. We can estimate the effective temperatures of the brighter components from the color indices during the eclipse. The estimated effective temperature of the system GSC 04328-02164 of the hotter component, which is equal to 7007 K, is reliable with the $T_{\text{eff}}$ (7059 K), which was found in the catalog of $T_{\text{eff}}$ and metallicities for Tycho-2 stars (Ammons et al. 2006).

The photometric mass ratios of the systems are determined with the $q$-search method. We have solved the light curves using the PHOEBE package (v 0.31a). The results show that the mass ratio, inclination, distance, and age for the system GSC 04328-02164 are equal to $q = 0.674 \pm 0.002$, $i = 75.997 \pm 0.022$, $d = 375.477 \pm 4.299$ pc, and $\tau = 26.76 \pm 15.65 \times 10^8$ years, respectively. For the other system, GSC 03164-01558, $q = 0.941 \pm 0.006$, $i = 88.0484 \pm 0.030$, $d = 444.651 \pm 9.444$ pc, and $\tau = 53.63 \pm 9.16 \times 10^8$ years.

We have found that the spectral types of the primary and secondary components of the system GSC 04328-02164 are nearest to F2 and G0, respectively, and the spectral types of the primary and secondary components of the system GSC 03164-01558 are nearest to G2 and K2, respectively. The derived absolute elements were used to study the evolutionary status of the two components. It was found that both systems belong to the main sequence.

Note that without radial velocity studies, which are needed for a completely reliable determination of the mass ratio and the orbital separation in an eclipsing binary, the orbital and physical parameters of the targets found by this study are to be...
considered preliminary. A combined spectroscopic and photometric study of these stars would be an important next step for a more accurate determination of the orbital and physical parameters.

This work was performed as a part of the M.Sc. thesis of Miss Amal Said Hamed. This work was also supported by the STDF (Science and Technological Development Fund, Ministry for Scientific Research, Egypt), project ID 1335.

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