THE CONTACT BINARY GSC 04778–00152 WITH
A VISUAL COMPANION

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Abstract. Photometric and spectroscopic observations of the unstudied 12th-magnitude eclipsing binary GSC 04778–00152 are presented. We report the discovery of a visual companion about 1 mag fainter and 2 arcsec away from the binary. By subtracting the light contribution of the visual companion, we obtain the $UBVRI$ light curves of the binary system alone. The shape of the light curve indicates that GSC 04778–00152 is an A-type W UMa contact binary. From light-curve modeling, we derive parameters of the binary system.

Key words: binaries: close – stars: individual (GSC 04778–00152)

1. INTRODUCTION

The variable star GSC 04778–00152 ($\alpha_{\text{J2000}} = 05^h31^m21^s$, $\delta_{\text{J2000}} = -7^\circ23'42''$) was discovered by the All Sky Automated Survey (ASAS) and classified as a contact or semi-detached binary with the period of 0.51746 days (Pojmański 2002). The reported $V$-magnitude at maximum brightness was 11.95 and the amplitude of variation in $V$ was 0.29 mag.

We detected the variability of GSC 04778–00152 from wide-field images of the $\delta$ Sct star V1162 Ori in January of 2006. Later we conducted follow-up observations, collecting photometric data in multiple passbands and a few spectra. All these data will be published in a forthcoming data paper (Tuvikene et al., in prep.).

2. OBSERVATIONS AND DATA REDUCTION

2.1. CCD photometry

CCD photometry was carried out on 31 nights during 5 runs between 2006 January and 2007 October. We used the 0.41-m Meade telescope at Observatorio Cerro Armazones (OCA), Chile, the 2.4-m Hiltner telescope at the MDM Observatory, Arizona, USA, and the 1.0-m telescope at SAAO, Sutherland, South Africa. A Johnson $V$ filter was used at OCA and MDM, while at SAAO the observations were made with $UBVRI$ filters.
The CCD images from the MDM Observatory revealed a slightly fainter visual companion (hereafter star B) about 2 arcsec away from the eclipsing binary (star A). The stars A and B are indicated in Fig. 1.

CCD frames were reduced and aperture photometry was performed as described in Tuvikene & Sterken (2006). Aperture photometry was used to extract the magnitudes of the isolated stars in the field, and to measure the total brightness of the stars A and B together. In order to extract the magnitudes of stars A and B separately, we analysed a subset of CCD frames with PSF photometry, using DAOPHOT routines in ESO-MIDAS.

On the basis of four nights over a 90-day time interval, the visual companion B did not show any variability. This allowed us to subtract the contribution of star B from the composite light curves acquired with aperture photometry.

The Landolt standard star SA 98193 and about 15 surrounding secondary standards were observed in a photometric night. These observations, together with the published data from Galadí-Enríquez et al. (2000), were used to establish the transformation of the magnitudes to the standard UBVRI system. The standard magnitudes and colours of stars in the GSC04778–00152 field are presented in Table 1.

\begin{table}[h]
\begin{center}
\begin{tabular}{lccccc}
Star & $V$ & $B-V$ & $U-B$ & $V-R$ & $V-I$
\hline
A (min II) & 12.524 (0.009) & 0.504 (0.010) & 0.088 (0.012) & 0.298 (0.011) & 0.570 (0.011)
A (min II) + B & 12.078 (0.009) & 0.584 (0.010) & 0.140 (0.010) & 0.326 (0.011) & 0.647 (0.011)
B & 13.264 (0.013) & 0.757 (0.017) & 0.271 (0.036) & 0.387 (0.021) & 0.792 (0.017)
GSC 04778–00131 & 12.501 (0.009) & 0.549 (0.010) & 0.052 (0.008) & 0.334 (0.011) & 0.646 (0.011)
GSC 04778–00064 & 13.322 (0.010) & 0.642 (0.011) & 0.101 (0.007) & 0.385 (0.011) & 0.741 (0.012)
GSC 04778–00105 & 13.657 (0.012) & 0.687 (0.013) & 0.095 (0.015) & 0.422 (0.017) & 0.815 (0.016)
\end{tabular}
\end{center}
\caption{UBVRI photometry for stars in the GSC04778–00152 field.}
\end{table}

Our $V$-band photometry covers 4 primary minima which were used for period analysis. The times of minimum were determined with the Kwee–van Woerden method (Kwee & van Woerden 1956) and are listed in Table 2.
Table 2. Heliocentric Julian dates of minima.

| HJD          | Error [days] | Minimum | E [days] | O – C [days] |
|--------------|--------------|---------|----------|--------------|
| 2453746.61205| 0.00022      | primary | 0        | 0.00006      |
| 2454080.88796| 0.00014      | primary | 646      | −0.00015     |
| 2454139.36075| 0.00020      | primary | 759      | 0.00020      |
| 2454167.30315| 0.00010      | primary | 813      | 0.00001      |

Using a linear weighted least-squares fit, we obtain the following ephemeris for the primary minima:

$$\text{HJD (Min I) = 2453746.61199 + 0.5174553 E}$$

$$\pm 0.00021 \pm 0.0000003$$ (1)

The constant star GSC 04778–00131 of similar brightness and colours as star A, was used as the comparison star for the binary. The differential $UBVRI$ light curves, phased with the derived period, are plotted in Fig. 2. The shape of the light curve is typical for W UMa type systems. It can be seen that the eclipses have unequal depths and that the secondary minimum displays an interval of constant brightness, indicating total occultation. Star A is therefore an A-type W UMa star where the more massive component has the greater surface brightness.

2.2. CCD astrometry

Astrometric measurements of stars A and B were performed on the basis of CCD frames from the MDM Observatory. The seeing in these frames varied between 1.4 and 1.8 arcsec. The stellar images were fitted with PSF, using DAOPHOT software. The PSF was constructed from the Moffat function on which empirical corrections were applied.

In order to determine the pixel scale and the orientation of the detector, we observed 13 astrometric standard stars in the open cluster NGC 1647. The coordinates and proper motions of the stars were taken from Geffert et al. (1996).

The measurements of star B relative to star A are presented in Table 3. The columns list the epoch of the measurement, the number of CCD frames ($N$), the angular separation with standard error ($\rho$, $\sigma_\rho$), and the position angle, measured from north to east, with standard error ($\theta$, $\sigma_\theta$). The position of star B in 2007 October coincides, within the errors, with the position measured in 2006 December.

Table 3. Astrometric measurements of star B relative to star A.

| Epoch (Julian year) | $N$ | $\rho$ ["] | $\sigma_\rho$ ["] | $\theta$ [°] | $\sigma_\theta$ [°] |
|---------------------|-----|-------------|-------------------|--------------|------------------|
| 2006.9429           | 21  | 2.131       | 0.002             | 311.67       | 0.08             |
| 2007.7947           | 11  | 2.133       | 0.002             | 311.76       | 0.10             |
Fig. 2. Light curves of GSC 04778–00152. Top: differential light curve including the contribution of star B. Dots refer to the OCA data, filled circles to the MDM data and plus signs denote the SAT y magnitudes transformed to the Johnson V scale. Middle: phase diagram of the binary star A, with the light of star B subtracted (SAAO data). The light curve solution is shown as a continuous line. Bottom: B – V colour curve of star A (circles), together with the synthetic curve (solid line).
2.3. Photoelectric photometry

The system was observed with the Strömgren Automatic Telescope (SAT) at ESO, La Silla at three occasions in 2006 November and 2007 January. A diaphragm of 17 arcsec was used. Extinction corrections were derived from standard-star observations, and transformations to the standard $uvby$ system were based on the methods described by Olsen (1994). The averaged indices at phases 0.35 and 0.70 are: $V = 11.93 \pm 0.01$, $b - y = 0.377 \pm 0.009$, $m_1 = 0.055 \pm 0.008$, $c_1 = 0.534 \pm 0.023$. Figure 2 (top) shows the $y$ magnitudes transformed to the Johnson $V$ scale. There is a systematic difference of $0.02 \pm 0.06$ between the photoelectrically determined $V$ and the result from CCD imaging. We attribute this difference to the selection of standard stars, and to different detector and filter characteristics.

2.4. Spectroscopy

Spectroscopic observations were carried out at the Tartu Observatory, Estonia, using the 1.5-in telescope with the Cassegrain spectrograph ASP-32 and Andor Newton CCD camera. The spectrograph was used in low and moderate resolution modes with 600 and 1200 lines/mm gratings. Three regions of the spectrum were observed: blue (3635–5785 Å), yellow-red (5150–7250 Å) and near-infrared (7340–9240 Å). The spectral resolution varied between 2025 and 4340 and the mean dispersion was between 0.53 and 1.35 Å/px.

Three spectra in the yellow-red and one in the near-infrared region were obtained in 2007 January and February. The integration time was 50 min for all spectra. The blue region was covered in 2007 October and November, with integration times of 60 and 90 min. The resulting signal-to-noise ratio was between 50 and 80, depending on the wavelength.

Due to the average seeing of 4 arcsec and the 2 arcsec wide slit, which was oriented in the north-south direction, we also recorded a contribution of star B in the spectra. Being redder than star A (Table 1), star B affects the spectrum in the red region, while in the blue region the contamination is not noticeable.

The low-resolution spectrum of the blue region, obtained on 2007 October 31 / November 1, was used to derive the $\beta$ index of GSC 04778–00152. The normalised spectrum was convolved with the response curves of the H$\beta$ wide and narrow filters of the SAT photometer. The instrumental $\beta$ index was then transformed to the standard system, using observations of 7 standard stars from Olsen (1983), yielding $\beta = 2.658 \pm 0.025$.

3. ANALYSIS

3.1. Spectral type

From the photoelectric photometry of GSC 04778–00152 (including star B) we derived the reddening-free colour indices $[c_1]$ and $[m_1]$ (Strömgren 1966), which point to a spectral type of F3–F5 for the binary.

Using the Digital Spectral Classification Atlas\footnote{http://nedwww.ipac.caltech.edu/level5/Gray/Gray_contents.html}, we analysed the spectrum obtained on 2007 October 31 / November 1 (Fig. 3). The strength of the G-band relative to H$\gamma$ and the strengths of Ca II K and H lines lead to a spectral type
around F5. The widths of the hydrogen lines and their strengths compared to metallic lines also refer to F5. Comparing the G-band strength of GSC04778–00152 with the observed Hβ standards of spectral classes F4V and F6V, places our target in between them. There is no evidence that luminosity class is above IV, the luminosity-sensitive lines are more similar to those in dwarfs.

We conclude that the spectral class of star A at phase 0.25 is F5V. The uncertainty of our estimation does not exceed one subclass. As can be seen from the $B - V$ curve (Fig. 2, bottom), the system colour does not change between phase 0.25 and the secondary minimum, where we see only the hotter binary component. Therefore the estimated spectral class corresponds mainly to the primary star of the binary.

3.2. Stellar parameters

The $uvby$ indices from Section 2.3, together with the $\beta$ index from Section 2.4 enable us to determine approximate stellar parameters. Applying the Vienna TempLogG v2 web interface\(^2\), we obtain $E_{b-y} = 0.112 \pm 0.060$, $M_V = 2.7 \pm 0.5$, $T_{\text{eff}} = 6500 \pm 300 \text{K}$, and $\log g = 4.0 \pm 0.4$. The system is at a distance $d = 560 \pm 180 \text{pc}$. Note that these parameters apply to the composite system A + B.

The absolute magnitude and distance may also be derived from the luminosity calibration of contact binaries (Rucinski & Duerbeck 1997). By using the intrinsic colour index, which corresponds to the F5V spectral type, $(B - V)_0 = 0.44$ (Straižys 1977), and the period value (Section 2.1), we get $M_V = 2.7 \pm 0.4$ and $d = 740^{+170}_{-110} \text{pc}$.

3.3. Light-curve solution

The $BVRI$ light curves of star A were solved simultaneously with the binary star modeling package PHIOEBE, version 0.29d (Prša & Zwitter 2005), which uses the Wilson-Devinney code as back-end. Curve-dependent weights were applied,
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according to the photometric errors in separate passbands. The program was run in the mode “overcontact binary not in thermal contact”.

Assuming a spectral type of F5V and using the effective temperature calibration from Gray et al. (2003), we fixed $T_{\text{eff},1} = 6530$ K for the primary component. We also adopted the gravity darkening coefficients, $g_1 = g_2 = 0.32$, and the albedo values, $A_1 = A_2 = 0.5$, for the modeling. Subscripts refer to the binary components. A logarithmic limb-darkening law was chosen, as suggested by Van Hamme (1993). The fitted parameters were the mass ratio, $q = m_2/m_1$, the orbital inclination, $i$, the effective temperature of the secondary, $T_{\text{eff},2}$, the surface potential, $\Omega_1 = \Omega_2$, and the luminosities of the primary star. The luminosity in $U$ was fitted separately, using the $U$-band light curve alone and fixing all the parameters from the $BVRI$ solution.

For error evaluation we carried out a bootstrap-resampling experiment, analogous to the one described in Maceroni & Rucinski (1997). Half of the $BVRI$ data points were randomly selected and the resampled light curves were simultaneously solved with the program PHOEBE, using the complete light-curve solution as a starting point. The procedure was repeated 100 times.

The derived binary system parameters are listed in Table 4. We give both sets of estimates, the complete light-curve solution with standard errors from PHOEBE, and the median values of the parameters with uncertainties at 68 percent confidence level from the bootstrap experiment. The synthetic light and colour curves are plotted in Fig. 2.

Table 4. System parameters from the light-curve solution of star A. Subscripts refer to the binary components.

| Parameter | Solution | Bootstrap | Parameter | Solution | Bootstrap |
|-----------|----------|-----------|-----------|----------|-----------|
| $q = m_2/m_1$ | 0.1822(7) | 0.1819(13) | $\Omega_{\text{in}}$ | 2.1878 | |
| $i$ [°] | 78.07(17) | 78.13(27) | $\Omega_{\text{out}}$ | 2.0711 | |
| $T_{\text{eff},1}$ (fixed) [K] | 6530 | Fill-out | $r_1/a$ (pole) | 0.5026 | 0.5028(10) |
| $T_{\text{eff},2}$ [K] | 6039(7) | 6041(10) | $r_1/a$ (side) | 0.5516 | 0.5519(14) |
| $\Omega_1 = \Omega_2$ | 2.1524(28) | 2.1516(50) | $r_1/a$ (back) | 0.5762 | 0.5764(16) |
| $[L_1/(L_1 + L_2)]_U$ | 0.8725(17) | 0.8711(16) | $r_2/a$ (pole) | 0.2365 | 0.2365(6) |
| $[L_1/(L_1 + L_2)]_V$ | 0.8623(11) | 0.8623(11) | $r_2/a$ (side) | 0.2473 | 0.2474(7) |
| $[L_1/(L_1 + L_2)]_R$ | 0.8567(10) | 0.8567(13) | $r_2/a$ (back) | 0.2897 | 0.2900(15) |
| $[L_1/(L_1 + L_2)]_I$ | 0.8511(9) | 0.8511(14) | |

4. CONCLUSIONS

GSC 04778–00152 is a slightly-reddened eclipsing contact binary with a visual companion. Companion B is redder and about 1 mag fainter than binary A. The stars have an angular separation of 2.132±0.002 arcsec which, at the derived distance of 600–800 pc, would mean a physical separation of more than 1000 AU. It is, therefore, not very likely that stars A and B belong to a bound system.

Our spectra indicate that the spectral type of star A at phase 0.25 is F5V which is mainly attributed to the primary component. The corresponding effective temperature is 6530 K. From the light-curve solution we get that the secondary component has 18 percent of the mass of the primary and is about 500 K cooler.
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