TYC 1031 1262 1: an anomalous Cepheid in a double-lined eclipsing binary

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ABSTRACT

The multicolour light curves and radial velocities for TYC 1031 1262 1 have been obtained and analysed. TYC 1031 1262 1 includes a Cepheid with a period of 4.15270 ± 0.00061 d. The orbital period of the system is about 51.2857 ± 0.0174 d. The pulsation period indicates that the secular period is increasing at a rate of of 2.46 ± 0.54 min yr⁻¹. The observed B, V and R magnitudes have been cleaned of the intrinsic variations of the primary star. The remaining light curves that have been obtained consist of eclipses and proximity effects, and these have been analysed to obtain the orbital parameters. The system consists of two evolved stars, F8 II + G6 II, with masses of \( M_1 = 1.640 \pm 0.151 M_\odot \) and \( M_2 = 0.934 \pm 0.109 M_\odot \) and radii of \( R_1 = 26.9 \pm 0.9 R_\odot \) and \( R_2 = 15.0 \pm 0.7 R_\odot \), respectively. The pulsating star almost fills its corresponding Roche lobe, which indicates the possibility that mass loss or transfer has taken place. We find an average distance of \( d = 5070 \pm 250 \) pc, using the BVR and JHK magnitudes, and also the V-band extinction. The kinematic properties and the distance to the Galactic plane (i.e. 970 pc) indicate that it belongs to the thick-disc population. Most of the observed and calculated parameters of TYC 1031 1262 1 lead to its classification as an anomalous Cepheid.

Key words: binaries: eclipsing – binaries: spectroscopic – stars: fundamental parameters – stars: variables: Cepheids.

1 INTRODUCTION

Pulsating variables are located in a restricted region, the so-called Cepheid instability strip (IS) in the Hertzsprung–Russell (HR) diagram. This region includes \( \delta \) Scuti, RR Lyrae and Population I and II Cepheids. These can be used as an important basis for testing theories on stellar structure and evolution, as well as pulsation mechanisms. These variables have very different masses, effective temperatures and chemical abundances. The stars in the IS are found not only in a wide range of masses but also among very young Population I type stars to very old Population II type stars. These stars in the IS reveal many properties of the stellar interiors.

At the beginning of the 20th century, Miss Leavitt made the great discovery that there is a relation between the period and the absolute magnitude of Cepheid variables in the Small Magellanic Cloud. Three decades later, Baade (1953) called attention to the difference in the period–luminosity (hereafter P–L) relations of the Cepheids in globular clusters and the classical Cepheids. Thus, the Cepheids are divided into two groups: Population I (usually called Type I) Cepheids and Population II (or Type II) Cepheids. Population I Cepheids are about 1.5 mag brighter than Population II Cepheids for the same pulsation periods. Taking into account this difference, Blaauw & Morgan (1954) made a revision of the P–L relation for the classical Cepheids. These variables are still used as distance indicators not only for our galaxy but also for nearby spiral and irregular galaxies. While Type I Cepheids are young-disc stars, associated with spiral arm and thin-disc populations evolved from main-sequence stars with masses from 3 to 15 solar masses, Type II Cepheids can be old-disc, thick-disc or halo stars, with masses smaller than the Sun (see Wallerstein 2002, and references therein). Type II Cepheids are divided into three subclasses with regards to their pulsation periods: BL Her stars with a period of \(< 7 \) d, W Vir stars with \( 7 < P < 20 \) d and RV Tau type variables with \( P > 20 \) d. Recently, Soszynski et al. (2008) have suggested divisions at 4 and 20 d. The masses and radii of these stars have been estimated from their pulsation properties. BL Her stars are common in globular clusters and in the disc of our galaxy. Harris (1981) has shown that four of the 12 field BL Her stars have \([\text{Fe/H}]\) values less than \(-1.5\), and have been identified as halo objects with a mean distance from the Galactic plane of \(1.8\) kpc. In contrast, the other eight stars have metallicities near or above solar values. Their mean distance from the Galactic plane is about \(0.25\) kpc, indicating the characteristics of a thick- or thin-disc population. There are some metal-poor variables with periods between \(0.5\) d and three or more days, lying above

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the RR Lyrae type stars, which might have an entirely different origin compared to normal Type II Cepheids in the globular clusters. These variables are called anomalous Cepheids (hereafter ACs). They are found in the general field, globular clusters and nearby dwarf spheroidal galaxies. Anomalous Cepheids are brighter than Type II Cepheids at fixed colour, and hence they follow a different P–L relation (Soszynski et al. 2008). Fiorentino et al. (2006) (see also references therein) have suggested that ACs are an extension of Type I Cepheids to lower metallicities and masses. Moreover, they have predicted a mass range for ACs of 1.9 < M/M⊙ < 3, which might be the product of a mass of about M < 4 M⊙.

Only six Type II Cepheids are known to be spectroscopic binaries. TX Del, IX Cas, AU Peg and ST Pup are single-lined binaries for which spectroscopic observations and the resultant orbits have been published. Because of the low orbital inclination, no eclipses have been detected in these binaries. Recently, Antipin, Sokolovski & Ignatieva (2007) and Khruslov (2008) have discovered two Cepheid variables in eclipsing binaries: TYC 1031 1262 1 and NSV 10993. The pulsation periods are nearly identical (i.e. 4.2 d) but the orbital periods are about 51 and 40 d, respectively. In the second part of the OGLE-III catalogue of variable stars, Soszynski et al. (2008) have presented 197 Type II Cepheids, of which seven are eclipsing variables and 83 are ACs in the Large Magellanic Cloud (LMC). Because the masses and radii of these stars have been measured directly from the eclipse light curves and radial velocities, a detailed study of these Cepheids in eclipsing binaries would be very worthwhile.

The light variability of TYC 1031 1262 1 (ASAS J182611+1212.6, 2MASS J18261100+1212349, GSC 01031–01262, V = 11.64 mag, B − V = 0.77 mag) was discovered by Pojmanski, Pilecki & Szczepniewski (2005) during the All-Sky Automated Survey (ASAS-3). The variability of this star was also detected independently by Antipin et al. (2007) on Moscow archive plates in Crimea. Using the observations obtained by ASAS-3, the photometric magnitudes obtained from the plates taken with the 40-cm astrophograph in the Crimea and the observations obtained by the Northern Sky Variability Survey (NSVS; Wozniak et al. 2004), they plotted these against time and noticed that a new variable was a Cepheid with some peculiarities. They began to observe TYC 1031 1262 1 with the 50-cm telescope of the Crimean Observatory. These CCD observations clearly revealed the eclipsing nature of the star with a Type II Cepheid component in our Galaxy. The pulsation and orbital periods are estimated to be 4.1523 and 51.38 d, respectively. In 2005 and 2006, Schmidt et al. (2009) carried out V′IHY photometry of Cepheid variable star candidates, including TYC 1031 1262 1. They proposed a pulsation period of about 4.1508 d and classified it as a Type I Cepheid.

In this paper, we present our multicolour photometric and spectroscopic observations of TYC 1031 1262 1. Our main aim is to derive the masses and radii of the components. Thus, the mass and radius of a Type II Cepheid will be revealed, for the first time, directly from spectroscopic and photometric observations. We also discuss the pulsation characteristics of TYC 1031 1262 1 and its place in our Galaxy.

2 OBSERVATIONS

2.1 Photometric observations

The photometric observations in the wide-band Johnson UBVR system were carried out with the 48-cm Cassegrain reflecting telescope and the 35-cm Meade LX200 GPS telescope at the Ege University Observatory. In the observations with the 48-cm telescope, a high-speed three-channel photometer and standard UBVR passbands were used. A thermoelectrically cooled ALTA U+42 2048 × 2048 pixel CCD camera, including BVR passbands, was attached to the Schmidt–Cassegrain type Meade telescope. The BVR observations in 2008 were obtained on 63 nights between March 2 and November 5. The observations in 2009 were obtained on 17 nights between August 3 and October 8. GSC 1031 193 and GSC 1031 1445 are taken as the comparison and check stars, respectively. Some basic parameters of the comparison stars have been taken from the SIMBAD data base, and these are listed in Table 1. Although the programme and comparison stars are very close in the sky, differential atmospheric extinction corrections have been applied, especially for the observations obtained with the 48-cm telescope. While all the programme stars were observed simultaneously with the 35-cm telescope, each star was observed successively with the 48-cm telescope (i.e. at different times). The atmospheric extinction coefficients were obtained from observations of the comparison stars on each night. Moreover, the comparison stars were observed with the standard stars in their vicinity, and the reduced differential magnitudes, in the sense of variable minus comparison, were transformed to the standard system. The standard stars have been chosen from the lists of Landolt (1983, 1992). Heliocentric corrections have also been applied to the times of the observations.

In Fig. 1, we plot the U-, B-, V- and R-passband observations versus the pulsation period of the Cepheid variable. As can be seen, the dominant light variations originate from the pulsation. In the following, the shifted observations correspond to the eclipses. The standard deviations of each data point are about 0.05, 0.03, 0.01 and 0.01 mag in the U, B, V and R passbands, respectively. The observational data can be obtained from the authors.

2.2 Spectroscopic observations

The optical spectroscopic observations of TYC 1031 1262 1 were obtained with the Turkish Faint Object Spectrograph Camera (TFOSC) attached to the 1.5-m telescope on six nights (2011 July–October) under good seeing conditions. Further details about the telescope and the spectrograph can be found at http://www.tug.tubitak.gov.tr. The wavelength coverage of each spectrum was 4000–9000 Å in 12 orders, with a resolving power of λ/Δλ 7000 at 6563 Å and an average signal-to-noise (S/N) ratio of ~120. We have also obtained a high S/N spectrum of α Lyr (A0 V) and HD 50692 (G0 V) to use as templates when deriving the radial velocities (Nidever et al. 2002).

The electronic bias was removed from each image and we used the crreject option for cosmic ray removal. Thus, the resulting spectra were largely cleaned from the cosmic rays. The echelle spectra were extracted and wavelengths were calibrated using an

Table 1. The coordinates, apparent visual magnitudes and the colours of the stars observed.

| Star       | α            | δ            | V (mag) | B − V (mag) |
|------------|--------------|--------------|---------|-------------|
| TYC 1031 1262 1 | 18h26m11.5s | 12°12'34.8" | 11.64   | 0.77        |
| GSC 1031 193 | 18 26 23.7   | 12 15 47.2   | 10.99   | 0.66        |
| GSC 1031 1445 | 18 26 04.9   | 12 07 11.6   | 10.44   | 0.63        |
Fe–Ar lamp source with help of the IRAF1 ECHELLE package (Tonry & Davis 1979).

The stability of the instrument was checked by cross-correlating the spectra of the standard star against each other using the FXCOR task in IRAF. The standard deviation of the differences between the velocities measured using FXCOR and the velocities in Nidever et al. (2002) is about 1.1 km s\(^{-1}\).

3 PULSATION AND ORBITAL PERIODS

3.1 Pulsation period

Antipin et al. (2007) and Schmidt et al. (2009) have estimated the pulsation period as 4.1523 and 4.1508 d, respectively. First, because the light variation of the pulsating component dominates in the light curve, we have attempted to refine the pulsation period using the program PERIOD04 (Lenz & Breger 2005). A Fourier power spectrum of all the available V-passband data has given a spectral peak at a frequency about \( f_0 = 0.2409 \text{ c d}^{-1} \), which corresponds to 4.1581 d. This package computes the amplitudes and phases of the dominant frequency as well as simultaneous multifrequency sine wave fitting.

Because the observations were obtained with different instruments in different years under dissimilar observing conditions, many systematic observational errors and computational errors affected the data. Therefore, we have not attempted to search for the second or third frequencies for pulsation if they really do exist. As explained in Section 4, we have represented all available V data, subtracting the eclipses, with a truncated Fourier series, which includes cosine and sine terms up to second order. We have calculated the light variation originating from the oscillations of the more luminous component. We have separated all the data with an interval of about 6 d and we have determined maximum times by shifting the calculated light curve along the time axis. It should be noted here that the shape of the light curve is assumed to be more or less constant during the time base of the observations. After obtaining the best fit, we have read the times for the mid-maximum light directly from the observations, and these are presented in Table 2. Although the observations obtained by ASAS and AAVSO have relatively large scatters, we have had to use all the data because of limited observations in both the time elapsed and the continuous observations, because of the relatively longer pulsation period. Using the ephemeris given by Antipin et al. (2007),

\[
\text{Max (HJD)} = 245\,3196.529 + 4.1523 \, d \, E, \tag{1}
\]

we have obtained the residuals between the observed and calculated times of mid-maximum light, as well as the number of elapsed cycles. In Fig. 2, we plot the residuals \( O - \text{C (I)} \) versus the epoch numbers. The variation of the residuals resembles a parabolic change – in other words, TYC 1031 1262 1 appears to be undergoing a gradual period increase. A least-squares solution gives the following ephemeris:

\[
\text{Max (HJD)} = 245\,3196.201(0.061) + 4.15270(0.00061) \, d \\
\quad \times E + 9.73(2.13) \times 10^{-6} \, E^2. \tag{2}
\]

The standard deviations of the last digits are given in parentheses. In the bottom panel of Fig. 2, the deviations from the parabolic fit are also plotted. TYC 1031 1262 1 is undergoing a period increase amounting to 2.46 (±0.54) min yr\(^{-1}\). Despite the fact that the data base covers a very short time, over five years, the characteristics of the variation in the pulsation period can be revealed.
The O − C residuals obtained by equation (1) for the pulsating star of TYC 1031 1262 1 are plotted against the pulsation cycle number. A parabolic fit to the data is shown by the solid line. The deviations from the parabolic fit are plotted in the bottom panel. Open circles refer to ASAS and AAVSO, and the dots denote the data from Antipin et al. (2007) and this study.

Table 3. The times of mid-minimum light for TYC 1031 1262 1. The O − C (I) and O − C (II) residuals were computed with the ephemeris given by Antipin et al. (2007) and equation (3), respectively.

| HJD 245 0000 | E | O − C (I) | O − C (II) | Filter | Ref. | a |
|-------------|---|----------|------------|-------|-----|---|
| 3211.7872  | −29| −8.520 | −0.892 | V | 1 | |
| 3212.8663  | −29| −7.441 | 0.187 | V | 1 | |
| 3213.3491  | −29| −6.958 | 0.670 | V | 1 | |
| 3211.6295  | −29| −8.678 | −1.049 | V | 1 | |
| 3213.1512  | −29| −7.156 | 0.472 | V | 1 | |
| 3570.8060  | −22| −6.562 | −0.873 | V | 1 | |
| 3572.1885  | −22| −5.180 | 0.510 | V | 1 | |
| 3571.5086  | −22| −5.860 | −0.170 | V | 1 | |
| 3928.4599  | −15| −5.969 | −2.218 | V | 1 | |
| 3929.3315  | −15| −5.097 | −1.347 | V | 1 | |
| 3931.9234  | −15| −2.505 | 1.245 | V | 1 | |
| 3931.2237  | −15| −3.205 | 0.545 | V | 1 | |
| 3931.2279  | −15| −3.201 | 0.550 | V | 1 | |
| 3930.9966  | −15| −3.432 | 0.318 | V | 1 | |
| 3933.5099  | −15| −0.919 | 2.832 | V | 1 | |
| 4596.5385  | −2| −1.003 | −0.854 | V | 2 | |
| 4598.4954  | −2| 0.954 | 1.103 | V | 2 | |
| 4647.7061  | −1| −0.844 | −0.972 | V | 2 | |
| 4647.7223  | −1| −0.828 | −0.956 | V | 2 | |
| 4648.7162  | −1| 0.166 | 0.038 | V | 2 | |
| 4649.0758  | −1| 0.525 | 0.398 | V | 2 | |
| 4648.4924  | −1| −0.058 | −0.186 | V | 2 | |
| 4650.1126  | −1| 1.562 | 1.435 | V | 2 | |
| 4648.7895  | −1| 0.246 | 0.118 | V | 2 | |
| 4699.6132  | 0| 0.054 | −0.350 | V | 2 | |
| 4699.6096  | 0| 0.051 | −0.354 | V | 2 | |
| 4750.8100  | 1| 0.242 | −0.439 | V | 2 | |
| 4751.4869  | 1| 0.919 | 0.238 | V | 2 | |

* The references are: (1) Antipin et al. (2007); (2) this study.

3.2 Orbital period

Antipin et al. (2007) have estimated the orbital period of TYC 1031 1262 1 as 51.38 d. We have subtracted the intrinsic variations of the more luminous star from all the available data, and thus the remaining light variations are assumed to originate from the eclipses and proximity effects. We have revealed light variations resulting from the eclipses and proximity analysis with an analysis of these data. The shape of the primary eclipse has been revealed and compared with the observations, which fall in the ascending and descending branches of the eclipse. Using a comparison of the computed light curve with the observations, we have obtained 28 times for the mid-eclipse, as presented in Table 3. The O − C (I) residuals were computed using the first ephemeris given by Antipin et al. (2007). In Fig. 3, we plot the O − C (I) residuals versus...
Figure 3. The $O - C$ residuals obtained by equation (3) for eclipsing binary TYC 1031 1262 1 and a linear least-squares fit to the data. The deviations from the fit are plotted in the bottom panel. Open circles refer to the data from Antipin et al. (2007) and the dots denote data from this study.

the epoch numbers. A linear least-squares fit gives the following ephemeris:

$$\text{Min (HJD)} = 245 4699.964(0.279) + 51.2857(0.0174) \text{d } E.$$  (3)

The new orbital period is about 0.1 d shorter than that estimated previously.

4 ANALYSIS

4.1 Effective temperature of the primary star

We have used our spectra to reveal the spectral type of the primary component of TYC 1031 1262 1. For this purpose, we have degraded the spectral resolution from 7000 to 3000 by convolving the spectra with a Gaussian kernel of an appropriate width, and we have also measured the equivalent widths ($EW$) of the photospheric absorption lines for the spectral classification. We have followed the procedures of Hernández et al. (2004), choosing helium lines in the blue-wavelength region, where the contribution of the secondary component to the observed spectrum is almost negligible. From several spectra, we have measured $EW_{\text{He I} + \text{Fe I} \lambda 4922} = 0.81 \pm 0.07$ Å, $EW_{\text{He I} + \text{Fe I} \lambda 4144} = 0.33 \pm 0.05$ Å, $EW_{\text{Ca I} \lambda 5888} = 0.35 \pm 0.07$ Å, $EW_{\text{Ca I} \lambda 6166} = 0.35 \pm 0.07$ Å and $EW_{\text{CH (G-band)} \lambda 4300} = 1.05 \pm 0.02$ Å. From the calibration relations $EW$–spectral-type of Hernández et al. (2004), we have derived a spectral type of F8 II for the more luminous star, with an uncertainty of about one spectral subclass. In Fig. 4, we compare the spectrum of the variable, obtained on JD 245 5864, with the spectra of some standard stars.

We have also observed the variable and comparison stars with the standard stars on the same nights. The peak-to-peak light and colour variations of the pulsating star in $V$, $B - V$ and $V - R$ are about 0.45, 0.14 and 0.09 mag, respectively. The average standard magnitudes and colours of the variable are obtained as $\langle V \rangle = 11.64 \pm 0.04$, $\langle B - V \rangle = 0.77 \pm 0.06$, and $\langle V - R \rangle = 0.50 \pm 0.05$ mag. Comparing the location of the variable in the $(B - V)$–$(V - R)$ diagram given by Drilling & Landolt (2000), we estimate a spectral type of F8–9 II, which is in good agreement with that derived from spectroscopy. The observed infrared colours of $J - H = 0.368 \pm 0.033$ and $H - K = 0.106 \pm 0.033$ are obtained using the $JHK$ magnitudes given in the Two-Micron All-Sky

Figure 4. Comparison of the spectrum of TYC 1031 1262 1 with some standard stars with similar spectral type but different luminosity.
The heliocentric radial velocities for the primary \((V_p)\) and the secondary \((V_s)\) components are listed in Table 4, along with the dates of observations and the corresponding orbital phases, computed using the new ephemeris given in Eq. 3. The radial velocities are plotted against the orbital phase in Fig. 5. The velocities in this table have been corrected for the heliocentric reference system by adopting a radial velocity of 14 km s\(^{-1}\) for the template star GJ 182.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Radial velocities folded on a period of 51.2857 d and the model. Dots (primary) and open circles (secondary) with error bars show the radial velocity measurements for the components of the system.

### 4.2 Radial velocities

To derive the radial velocities of the components, the nine TFOSC spectra of the eclipsing binary were cross-correlated against the spectrum of GJ 182, a single-lined M0 V star, on an order-by-order basis using the **FXCOR** package in IRAF. The majority of the spectra show two distinct cross-correlation peaks in the quadrature, one for each component of the binary. Thus, both peaks have been fitted independently in the quadrature with a Gaussian profile, in order to measure the velocity and errors of the individual components. If the two peaks appear to be blended, a double Gaussian was applied to the combined profile using the de-blend function in the task. For each of the nine observations, we then determined a weighted-average radial velocity for each star from all orders without significant contamination by telluric absorption features. Here, we used as weights the inverse of the variance of the radial velocity measurements in each order, as reported by **FXCOR**. We adopted a two-Gaussian fit algorithm to resolve the cross-correlation peaks near the first and second quadratures when spectral lines are visible separately.

The heliocentric radial velocities for the primary \((V_p)\) and the secondary \((V_s)\) components are listed in Table 4, along with the dates of observations and the corresponding orbital phases, computed using the new ephemeris given in Eq. 3. The radial velocities are plotted against the orbital phase in Fig. 5. The velocities in this table have been corrected for the heliocentric reference system by adopting a radial velocity of 14 km s\(^{-1}\) for the template star GJ 182.

### Table 4. Heliocentric radial velocities of TYC 1031 1262 1.

The columns give the heliocentric Julian date, the orbital phase (according to the ephemeris in equation 3) and the radial velocities of the two components, with the corresponding standard deviations.

| HJD 240 0000+ | Phase | Star 1 | Star 2 |
|---------------|-------|--------|--------|
|               |       | \(V_p\) | \(V_s\) |
| 55747.4884    | 0.4253| 4.1    | 3.5    | 29.7  | 4.2 |
| 55751.3090    | 0.4998| 2.0    | 3.3    | 45.9  | 5.6 |
| 55796.2974    | 0.3770| –5.9   | 5.4    | 22.7  | 4.8 |
| 55800.3794    | 0.4566| 5.4    | 3.5    | 48.8  | 3.6 |
| 55835.3002    | 0.1375| –7.7   | 3.6    | –35.9 | 4.8 |
| 55864.2074    | 0.7011| 35.8   | 3.4    | –35.9 | 4.8 |

The radial velocities listed in Table 4 are the weighted averages of the values obtained from the cross-correlation of orders 4, 5, 6 and 7 of the target spectra with the corresponding order of the standard star spectrum. The weight \(W_i = 1/\sigma_i^2\) has been given to each measurement. The standard errors of the weighted means have been calculated on the basis of the errors \((\sigma_i\)\) in the velocity values for each order according to the usual formula (e.g. Topping 1972). The \(\sigma_i\) values are computed by **FXCOR** according to the fitted peak height, as described by Tony & Davis (1979). The observed radial velocities correspond to the pulsation phases of 0.718, 0.627, 0.360, 0.303, 0.608 and 0.484. In these phases, the variation in the radius of the primary star as a result of oscillation is small, and therefore the radial velocity changes of the Cepheid caused by the pulsation are ignored. We have not attempted a decomposition of the radial velocity measurements of the primary star into the pulsation radial velocity and the orbital radial velocity.

First, we have analysed the radial velocities for the initial orbital parameters. We have used the orbital period held fixed and we have computed the eccentricity of the orbit, systemic velocity and semi-amplitudes of the radial velocities. The results of the analysis are as follows: \(e = 0.001 \pm 0.001\) (i.e. formally consistent with a circular orbit), \(\gamma = 11.07 \pm 0.85 \text{ km s}^{-1}\), \(K_1 = 27.4 \pm 1.7\) and \(K_2 = 48.1 \pm 1.7 \text{ km s}^{-1}\). Using these values, we have estimated the projected orbital semimajor axis and mass ratio to be \(a \sin i = 76.50 \pm 2.44 \text{ R}_\odot\) and \(q = M_2/M_1 = 0.570 \pm 0.041\).

### 4.3 Intrinsic variations of the primary star

The eclipsing binaries provide critical information about the orbital parameters, such as orbital inclination, fractional radii, luminosities, ratio of effective temperatures, etc. If the eclipsing binary is a double-lined binary, the masses and radii of the component stars can be determined in solar units. Using the inverse-square law, it is possible to accurately determine the distance to the system, which is independent of all distance methods.

The observed light variations are composed of the intrinsic light variations of the more luminous star and mutual eclipses. First, we have subtracted all the observations within the eclipses. The remaining observations are phased with respect to the pulsation period of 4.15270 d. The light curves of the Cepheid show a slow decline and rapid rise (i.e. an asymmetric light curve with a sharp maximum). The median magnitudes are taken as 12.408, 11.639 and 11.144 mag for the \(B\), \(V\) and \(R\) passbands, respectively. The observed magnitudes are transformed to the flux using the median magnitudes. Then, we have represented the intrinsic light variations of the primary star with a truncated Fourier series. A trial-and-error method has shown that the observed light curves can be well...
Table 5. Fourier coefficients of the oscillation light curves for TYC 1031 1262 1.

| Parameters | B         | V         | R         |
|------------|-----------|-----------|-----------|
| A0         | 1.0465 ± 0.0022 | 1.0316 ± 0.0015 | 1.0016 ± 0.0012 |
| A1         | 0.2594 ± 0.0028 | 0.1948 ± 0.0020 | 0.1504 ± 0.0016 |
| A2         | 0.0543 ± 0.0028 | 0.0366 ± 0.0020 | 0.0271 ± 0.0016 |
| B1         | −0.0019 ± 0.0032 | 0.0123 ± 0.0023 | 0.0195 ± 0.0018 |
| B2         | −0.0530 ± 0.0031 | −0.0371 ± 0.0022 | −0.0288 ± 0.0018 |

Figure 6. The B-, V- and R-passband light curves of the pulsating primary star and their Fourier representations (solid lines) with the coefficients given in Table 5. Note that the ordinates are normalized intensities.

represented by the second-order Fourier series. The coefficients are given in Table 5 and the fits are compared with the observations in Fig. 6.

4.4 Analyses of the light curves

The intrinsic light variations of the primary star have been computed for each oscillation phase using the coefficients given in Table 5. After subtracting the Cepheid light changes from the observations, we have obtained light variations consisting of those only from the eclipses and proximity effects. In Fig. 7, the eclipsing light curves in the B, V and R passbands are plotted versus the orbital phases calculated by the ephemeris given in equation (3). The light curve of the system with curved maxima resembles those of β Lyrae type binaries. The scatter in the binary light curves is mainly caused by the variations in the pulsation period.

We have used the most recent version of the eclipsing binary light-curve modelling algorithm of Wilson & Devinney (1971), with updates (hereafter W–D), as implemented in the PHOEBE code of Prša & Zwitter (2005). This uses the computed gravitational potential of each component to calculate the surface gravities and effective temperatures. The radiative characteristics of the stellar discs are determined using the theoretical Kurucz atmosphere models. The code needs some input parameters, which depend upon the physical properties of the component stars. The U-passband observations are limited and do not cover eclipses, so we have excluded these observations from the analysis of the light curves for the orbital solution.

The BVR photometric observations for the system have been analysed individually. We have fixed some parameters whose values have been estimated from spectra, such as the effective temperature of the hotter component and the mass ratio of the system, which are the key parameters in the W–D code. The effective temperature of the primary star has already been derived from various spectral type–effective temperature calibrations as 5880 K, and the mass
The adjustable parameters in the differential correction calculation are the orbital inclination, the dimensionless surface potentials, the effective temperature of the secondary and the monochromatic luminosity of the hotter star. Our final results are listed in Table 6 and the computed light curves (solid line) are compared with the observations in Fig. 7. The secondary minimum appears to be not very well reproduced. This is mainly because of the light variation of the pulsating star, which is in front of the less massive secondary star at the secondary minimum. We have assumed that light variation of the pulsating star is repeated with the same amplitude and that the shape of its light curve is not changed with time. The uncertainties assigned to the adjusted parameters are the internal errors provided directly by the W–D code. The last three lines of Table 6 give the sums of the squares of residuals ($\chi^2$), the number of data points (N) and the standard deviations (σ) of the observed light curves, respectively. Taking weight inversely proportional to σ, the adopted parameters given in the last column of Table 6 are obtained.

### 5 RESULTS AND DISCUSSION

A comparison of the results obtained in the three light curves reveals some differences in the inclination angle and, especially, in the fractional radii of the stars. The B and R light curves are constructed only using our own observations. The scatter in the B-passband observations is significantly larger compared to the other bands, because of its faintness. By combining the spectroscopic results along with the photometric solutions, as listed in the last column of Table 6, we obtain the absolute masses, radii, luminosities and surface gravities of the stars, which are presented in Table 7. The mass and radius of the pulsating component have been determined, for the first time, directly from the radial velocities and multicolour light curves. These are unexpectedly large compared to Type II Cepheids. The luminosity and absolute bolometric magnitude $M_{\text{bol}}$ of each star have been computed from their effective temperatures and radii. The bolometric magnitude and effective temperature for the Sun are taken as 4.74 mag and 5770 K (Drilling & Landolt 2000). A comparison of its location in the HR diagram, constructed for metal-poor Cepheids by Gingold (1985), see their fig. 1, indicates that TYC 1031 1262 1 is in the IS of Type II Cepheids, about 20 times more luminous than RR Lyrae stars. It seems to have the same luminosity and effective temperature as a Type II Cepheid, having pulsation periods of about 10 d, closer to the blue edge of the IS. When we compare with solar composition models (e.g. Baraffe et al. 1998), the primary star appears to be an evolved 5-M$_\odot$ star and the secondary is consistent with an evolved 3-M$_\odot$ star.

After applying bolometric corrections to the bolometric magnitudes, we obtained absolute visual magnitudes of the components. Taking into account the light contributions of the stars and total apparent visual magnitude, we have calculated their apparent visual magnitudes. The light contribution of the secondary star $L_2/(L_1 + L_2) = 0.02$, 0.04 and 0.08 are obtained directly from the B-, V- and R-bandpass light-curve analyses, respectively. This result shows that the light contribution of the less massive component is very small, indicating that its effect on the colour at out-of-eclipse is almost negligible for the shorter wavelengths. For the bolometric corrections given by Drilling & Landolt (2000), we have calculated the

| Parameters | TYC 1031 1262 1 | TYC 1031 1262 1 |
|-------------|----------------|----------------|
| Spectral type | Primary | Secondary |
| Mass (M$_\odot$) | 1.640 ± 0.151 | 0.934 ± 0.109 |
| Radius (R$_\odot$) | 26.9 ± 0.9 | 15.0 ± 0.7 |
| $T_{\text{eff}}$ (K) | 5880 ± 200 | 4890 ± 125 |
| Luminosity (L$_\odot$) | 764 ± 144 | 109 ± 26 |
| Gravity (gs) | 62 ± 3 | 114 ± 11 |
| $a$ (R$_\odot$) | 79.58 ± 2.54 | |
| $V_0$ (km s$^{-1}$) | 11.07 ± 0.85 | |
| $i$ (◦) | 74.0 ± 0.4 | |
| $q$ | 0.570 ± 0.041 | |
| $d$ (pc) | 5070 ± 250 | |
| $\mu_\alpha \cos \delta$, $\mu_\delta$ (mas yr$^{-1}$) | 2.7 ± 0.8, 0.8 ± 0.8 | |
| $U$, $V$, $W$ (km s$^{-1}$) | −14.5 ± 13.0, 47.7 ± 14.9, −47.2 ± 19.1 | |

Table 6. Results of the BVR light-curve analyses for TYC 1031 1262 1.
distance to TYC 1031 1262 1 as \( d = 5074 \pm 207 \) pc. However, the infrared JHK magnitudes give a distance of 5040 ± 255 pc. The estimations of distances to the stars strongly depend on the bolometric corrections. If we adopt the bolometric corrections given by Code et al. (1976) and Bessell, Castelli & Plez (1998), the distances to TYC 1031 1262 1 are obtained as 5082 ± 540 and 5110 ± 650 pc, respectively. The average distance to the system is obtained as 5070 ± 250 pc. The distance from the Galactic plane is calculated as 970 pc using the Galactic latitude of 11 degrees, about 14 times larger than the mean scaleheight of a Type I Cepheid. In the last line of Table 7, we list the Galactic space–velocity components of the system, which have been calculated using the coordinates, distance, systemic radial velocity and proper motions. Here, \( U, V \) and \( W \) are velocities towards the Galactic Centre, towards the direction of Galactic rotation and towards the North Galactic Pole, respectively. With planer and vertical eccentricities of 0.50 and 0.26 and the velocity components, the system most probably belongs to the thick-disc population. This result confirms the earlier suggestion of Harris & Wallerstein (1984) that many field Type II Cepheids are metal-rich and have kinematic properties similar to those of the old-disc or thick-disc population.

The pulsation period of TYC 1031 1262 1 has shown a secular period increase of 2.46 (±0.54) min yr\(^{-1}\). Vinko, Szabados & Szatmary (1993) have investigated the secular period change in AU Peg, another Type II Cepheid that belongs to a binary system. The observed rate of the period increase in TYC 1031 1262 1 is about five times larger than that of AU Peg. Within the globular cluster NGC 5466, McCharty & Nemec (1997) have observed a decrease in the pulsation period of V19, which is known as an AC with a mass of 1.66 M\(_{\odot}\) and a pulsation period of 0.82 d. They have proposed that this is an indication of blueward evolution. In contrast, TYC 1031 1262 1 shows a period increase, and its large magnitude should indicate a faster evolutionary time-scale redward. Sandage, Diethelm & Tammann (1995) and Diethelm (1996) have proposed that all of the BL Her Cepheids appear to have increasing periods and are consistent with the post-blue horizontal branch models of Population II stars. The observed period increase in TYC 1031 1262 1 appears to confirm this suggestion. Unlike the BL Her Cepheids, TYC 1031 1262 1 has a companion very close to it. Period change rates have been determined for only a few ACs. Yet, the cause of such a relatively large pulsation period change in a Type II Cepheid is not obvious. Observations covering a long time-span are crucially needed for a better understanding of such a large rate of increase in the pulsation period of TYC 1031 1262 1, as well as for other Type II Cepheids.

As mentioned in Section 1, Type II Cepheids are divided into three subclasses: BL Her, W Vir and RV Tau. All three classes are characterized by the presence of Balmer emission, especially H\(_\alpha\), during some parts of their pulsation cycle. An evolutionary scheme of these classes has been suggested by Gingold (1985). In this scheme, the BL Her stars are evolving from the horizontal branch towards the lower asymptotic giant branch. However, the W Vir variables are on loops to the blue from the asymptotic giant branch. The RV Tau stars are moving to the blue in a post-asymptotic giant branch phase. Gingold has investigated the evolutionary status of Type II Cepheids as post-horizontal-branch stars and he has called attention to a different structure and evolution for ACs. He has estimated the masses of Type II Cepheids to be around 0.6 M\(_{\odot}\) with a radius of about 8 R\(_{\odot}\) in the post-horizontal-branch phase. Bono, Caputo & Santolamazza (1997a) have suggested masses between 0.52 and 0.59 M\(_{\odot}\) for Type II Cepheids, using their pulsation properties rather than evolutionary tracks. Now, there is a consensus that Type II Cepheids are fundamental pulsators with masses below 0.8 M\(_{\odot}\).

With a mass of about 1.640 M\(_{\odot}\), a luminosity of 760 L\(_{\odot}\) and a radius of 27 R\(_{\odot}\), the pulsating primary component of TYC 1031 1262 1 cannot be a Type II Cepheid. If it were a Type I Cepheid, its mass would be greater than 4 M\(_{\odot}\), according to the models given by Bono, Castellani & Marconi (2000) for \( Z = 0.02 \) and even for \( Z = 0.004 \). However, the ACs are usually accepted to be metal-poor horizontal branch stars with masses above 1.5 M\(_{\odot}\). Soszynski et al. (2008) have presented 83 ACs in the LMC and have shown that ACs are located between Type I and Type II Cepheids in the P–L diagram. They are found in every dwarf spheroidal galaxy and, unlike Type II Cepheids, are absent in globular clusters, except for a few ACs in ω Cen. As for their origin, Demarque & Hirschfeld (1975) have proposed that they are young single stars, as a result of recent star formation. In contrast, Renzini, Mengel & Sweigart (1977) have suggested that they are formed as a consequence of mass transfer in binary systems with the same age as the stellar systems to which they belong. Bono, Caputo & Santolamazza (1997b) have examined the evolution and pulsation properties of ACs and have concluded that models of masses between 1.5 and 2.2 M\(_{\odot}\) fit most of the stars. Concerning the origin of ACs, as single young stars or old binary systems, they have noted that their results do not support a single interpretation. The mass, luminosity, kinematic properties and light curves of TYC 1031 1262 1 fulfil most of the properties of ACs. As pointed out by Soszynski et al. (2008) and Fiorentino & Monelli (2012), the mode identification of an AC is very complex and cannot be based only on their light curves. However, Soszynski et al. (2008) have compared the light curves of the ACs in the LMC. They have proposed that the ACs pulsating in the first overtone have generally smoother light curves than for the fundamental-mode pulsators with rounded maxima and minima. The shape of the light curve of the pulsating star looks like those of fundamental-mode pulsators. If we compare its location on the \( M_\bullet-log P \) plane given by Fiorentino & Monelli (2012) for the ACs in the LMC, whose pulsating periods are shorter than 2.4 d, the pulsating star is located on the extension of fundamental-pulsators, as though its classification as a fundamental-pulsator is supported. In Fig. 8, we compare the position of TYC 1031 1262 1 on the colour–magnitude diagram with other ACs taken from Harris, Olszewski & Wallerstein (1984) and Nemec, Nemec & Lutz (1994).
It is located among the brightest ACs close to the blue edge, with a luminosity of about 800 times solar. The binary Cepheid ST Pup, with a pulsation period of about 18.47 d, is located very close to TYC 1031 1262 1. In contrary, the binary Cepheids TX Del, with a pulsation period of 6.2 d, and AU Peg, with a period of 2.4 d, are located at the red-edge of the IS, with lower luminosity.

6 CONCLUSIONS

We have obtained the multicolour light curves and radial velocities of the eclipsing binary system TYC 1031 1262 1, of which the luminous component is a Cepheid. The astrophysical parameters of the component stars were obtained directly by analysing the light curves and radial velocities. In earlier studies, the brighter star has been classified as a metal-poor Type II Cepheid. However, some investigators have included it among the classical Cepheids. The mass of the pulsating primary star of 1.64 M\(_\odot\) indicates that its structure and evolution are different from those of RR Lyrae and W Vir stars. The Galactic velocity components U, V and W have been determined to be −14.5, 47.7 and −47.2 km s\(^{-1}\), respectively, and the distance from the Galactic plane to be about 970 pc. All these properties and the asymmetric pulsating light curve lead us to classify the Cepheid as an AC. The pulsation period appears to be increasing at a rate of 2.46 ± 0.54 min yr\(^{-1}\), the largest period observed for Type II Cepheids so far. This observed rate of increase indicates that the star evolves redward in the IS with shorter time-scales.

The pulsating primary star fills almost 85 per cent of its corresponding Roche lobe, while the less massive star fills 61 per cent. The pulsating component in TYC 1031 1262 1 is very close to its Roche lobe, and therefore mass loss or transfer to its companion has taken place. Both components are supergiants, and the separation is only two times the sum of their radii. The companion should unexpectedly affect both pulsation and evolution of the Cepheid. However, it is not clear how such a close companion can cause any period variation on pulsation by tidal interaction alone. Most of the ACs are faint stars and have relatively longer orbital periods. Therefore, measurements of the radial velocities of ACs in binary systems are very difficult. In addition, the velocity variations resulting from the orbital motion might be affected by the pulsation, depending on the inclination of the orbits. In the case of TYC 1031 1262 1, the orbital inclination is sufficiently large to separate the orbital velocities of both components. If mass loss or transfer from the pulsating star has taken place, the orbital period of the system would be changed, which might be revealed by observations to be made in the coming years. This will provide us with some clues about the further evolution of ACs in binary systems.

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