Absolute dimensions and apsidal motion of the eccentric binary V731 Cephei

V. Bakış,1* M. Zejda,2 İ. Bulut,1 M. Wolf,3 S. Bilir,4 H. Bakış,1 O. Demircan,1 J. W. Lee,5 M. Šlechta6 and B. Kučerová2

1Çanakkale Onsekiz Mart University Observatory, Terzioglu Campus, TR-17040, Çanakkale, Turkey
2Institute of Theoretical Physics and Astrophysics, Masaryk University, Kotlářská 2, CZ-611 37 Brno, Czech Republic
3Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, V Holešovičkách 2, CZ-182 00 Praha 8, Czech Republic
4Istanbul University Science Faculty, Department of Astronomy and Space Physics, 34119, University-Istanbul, Turkey
5Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
6Astronomical Institute, Academy of Sciences, CZ-251 65 Ondřejov, Czech Republic

Accepted 2008 July 24. Received 2008 July 24; in original form 2008 April 15

ABSTRACT

A detailed analysis of new and existing photometric, spectroscopic and spatial distribution data of the eccentric binary V731 Cep was performed. Spectroscopic orbital elements of the system were obtained by means of cross-correlation technique. According to the solution of radial velocities with UBVRc light curves, V731 Cep consists of two main-sequence stars with masses \( M_1 = 2.577 \pm 0.098 \, \text{M}_\odot \), \( M_2 = 2.017 \pm 0.084 \, \text{M}_\odot \), radii \( R_1 = 1.823 \pm 0.030 \, \text{R}_\odot \), \( R_2 = 1.717 \pm 0.025 \, \text{R}_\odot \) and temperatures \( T_{\text{eff1}} = 10700 \pm 200 \, \text{K} \), \( T_{\text{eff2}} = 9265 \pm 220 \, \text{K} \) separated from each other by \( a = 23.27 \pm 0.29 \, \text{R}_\odot \) in an orbit with inclination of \( 88.70 \pm 0.03 \). Analysis of the O–C residuals yielded a rather long apsidal motion period of \( U = 10000 \pm 2500 \) yr compared to the observational history of the system. The relativistic contribution to the observed rates of apsidal motion for V731 Cep is significant (76 per cent). The combination of the absolute dimensions and the apsidal motion properties of the system yield a consistent observed internal structure parameter (\( \log \kappa_{\text{2,obs}} = -2.36 \)) compared to the theory (\( \log \kappa_{\text{2,tho} e} = -2.32 \)). Evolutionary investigation of the binary by two methods (Bayesian and evolutionary tracks) shows that the system is \( t = 133(26) \) Myr old and has a metallicity of \( [M/H] = -0.04(0.02) \) dex. The similarities in the spatial distribution and evolutionary properties of V731 Cep with the nearby (\( \rho = 3:9 \)) open cluster NGC 7762 suggest that V731 Cep could have been evaporated from NGC 7762.

Key words: binaries: eclipsing – stars: early-type – stars: evolution – stars: fundamental parameters – stars: individual: V731 Cephei.

1 INTRODUCTION

Study of eclipsing binaries is still the most effective way of determining the absolute parameters of stars, especially from the spectroscopic and photometric analysis of detached double-lined eclipsing binaries, masses and radii of the components can be obtained with a precision of \( \sim 1 \) per cent (e.g. Southworth et al. 2005; Bakış et al. 2008), the limit precision for stellar evolutionary tests (Andersen 1991). Among the stars, those in the upper main-sequence band are particularly useful in empirical tests of the convection formulae used in various evolution codes, while systems containing unevolved stars are useful in testing opacity and metallicity effects in near-zero-age main-sequence (ZAMS) models. V731 Cep, the binary discussed in this paper, is of the latter type.

The variability of V731 Cep (GSC 4288 0168; brightness at maximum \( V \sim 10.5 \) mag; orbital period \( P \sim 6.06 \) d) was discovered by Bakış et al. (2003, hereafter B03). A brief history of V731 Cep was given by Bakış et al. (2007, hereafter B07) who presented photometric light curves in \( BVRc \) and \( I \) bands and limited spectroscopic observations. Within the scope of a project to study close eclipsing binaries of SB2 type, we were able to obtain new times of minima as well as new spectroscopic data for V731 Cep.

The system has an eccentric orbit (\( e = 0.0165 \)), which makes it an important astrophysical tool for the investigation of internal structures of its components, if the rotation period of the apsides is precisely determined. The apsidal motion period together with system geometry allow the computation of the observed internal structure constant (ISC) to be compared with theoretical internal
structure computations. The primary motivation for this paper is to obtain the parameters of the close binary system V731 Cep, to discuss the evolutionary status of the system using the system parameters with the latest evolutionary models, and to investigate the apsidal motion of the orbit for the estimation of the internal structures of the component stars.

2 OBSERVATIONS

2.1 Photometry

As the photometric data presented by B07 are precise enough (rms scatter of $\sim 0.008$ mag) for light-curve analysis with nearly complete phase coverage of the data, apart from new times of minima observations, no new photometric observations were performed in this study. The details of the photometric observations and their reduction are given in detail by B07. The standard $UBVR_c$ and $I_c$ magnitudes of the comparison and check stars in the same CCD field with V731 Cep were derived using transformation coefficients obtained by B07, and are given in Table 1 together with near-infrared magnitudes from the Two-Micron Sky-Survey (2MASS, Cutri et al. 2003). 2MASS magnitudes in Table 1 correspond to phases where the light was at maximum.

The phasing of the photometric data in this paper was made using the updated ephemeris for primary minimum given in equation (1). This ephemeris together with the ephemeris for the secondary minimum is given in B07. In Fig. 1, the primary and secondary minima of the light curve are plotted together with $(B - V)$ colours:

$$\text{Min I (HJD)} = 2453137.4425(2) + 6.068456(2) \times E. \quad (1)$$

The difference between the periods given in equation (1) and in the ephemeris for the secondary minimum (B07) is clearly outside the observational error box, which of course indicates an apsidal motion in the system. To study apsidal motion, new times of minima for V731 Cep were obtained and are given in Table 2 together with the telescope and observatory information. During the (additional) eclipse timing observations at Ondřejov Observatory, one of the two available CCD cameras (SBIG ST-8 or Apogee AP-7) were used, while SBIG ST-10XM and ST-7 CCD cameras were employed at ČOeeně and Brno Observatories, respectively. The reduction of all photometric data was performed using C-Munipack software under GNU General Public License. The times of minima have been calculated according to the Kwee–van Woerden method (Kwee & van Woerden 1956). In addition to new times of minima observations, all available historical eclipse timings are also listed in Table 2.

2 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.
Table 2. New and historical times of minima of V731 Cep.

| HJD (-2400000) | Uncertainty | Weight | Filter | Type | Reference        |
|----------------|-------------|--------|--------|------|------------------|
| 52515.4840     | 0.0045      | 3      | clear  | sec  | B03              |
| 52560.9401     | 0.0006      | 10     | BVR, Ic| pri  | Lee, Kim & Koch (2007) |
| 52591.2817     | 0.0001      | 10     | clear  | pri  | B03              |
| 52791.5388     | 0.0003      | 3      | clear  | sec  | Bakh et al. (2005a) |
| 52864.3624     | 0.0006      | 10     | clear  | pri  | Bakh et al. (2005a) |
| 52864.3626     | 0.0019      | 5      | V      | pri  | Zejda (2004)     |
| 52864.3621     | 0.0028      | 5      | R      | pri  | Zejda (2004)     |
| 52864.3630     | 0.0028      | 5      | R      | pri  | Zejda (2004)     |

Table 3. Journal of spectroscopic observations. Date column refers to the local date of the start of night. S/N refers to the continuum near Hα.

| Numbers | Frame       | HJD (-2400000) | Date       | Phase (φ) | S/N | Exposure time (s) |
|---------|-------------|----------------|------------|-----------|-----|-------------------|
| 1       | oj090013.fit| 53653.32491    | 09.10.2005 | 0.010     | 50  | 7500              |
| 2       | pi090066.fit| 53988.61624    | 10.09.2006 | 0.262     | 65  | 7000              |
| 3       | oh290012.fit| 53612.44057    | 29.08.2005 | 0.273     | 115 | 7500              |
| 4       | pi100032.fit| 53989.50350    | 11.09.2006 | 0.408     | 100 | 7200              |
| 5       | oh300036.fit| 53613.47736    | 30.08.2005 | 0.444     | 100 | 8000              |
| 6       | oi240017.fit| 53638.33066    | 24.09.2005 | 0.540     | 125 | 7200              |
| 7       | oi070028.fit| 53621.42400    | 07.09.2005 | 0.754     | 115 | 7200              |

3 APSIDAL MOTION

The very slow apsidal motion of V731 Cep was detected and studied by means of the O–C diagram analysis. All available times of minimum were collected from the literature and are listed in Table 2 together with the new times of minima. We used the methods of Giménez & Garcia-Pelayo (1983) and Lacy Claud (1992) independently with similar results given in Table 4. All precise CCD times of minima were used with a weight of 20 or 10, less accurate measurements were assigned with weights of 5 or 3.

Since the eccentricity is only weakly constrained by the observations in this case, we adopted a value of $e = 0.0165$ from the light-curve solutions given in Table 7. For the inclination angle, we used $i = 88.7\degree$, from the light-curve solutions. The results are given in Table 4. In this table, $(P_a)$ and $(P_s)$ are the anomalous and sidereal periods, respectively. The zero epoch is given $(T_0)$ and the corresponding position of the periastron is represented by $(\omega_0)$. The apsidal motion rate $(\dot{\omega})$ that we obtained seems to be statistically significant, $\dot{\omega} = 0.00060 (0.00015)$ degree cycle$^{-1}$. This corresponds to an apsidal period of $U = 10000 (2500)$ yr. The ephemeris curve is shown in Fig. 2, along with the residuals from the observed primary and secondary minima.

We tested the stability of the results with respect to our arbitrarily chosen weighting scheme. It turned out that the resulting parameters show some dependence on the weighting. For this reason, as well as for other reasons discussed below, the results must be considered preliminary and less certain.
Table 4. Apsidal motion elements of V731 Cep. Errors in brackets denote the last digits.

| Parameter | Unit | Value        |
|-----------|------|--------------|
| $T_0$     | HJD  | 2453137.44241(5) |
| $P_1$     | d    | 6.0684499(35)  |
| $P_2$     | d    | 6.0684600(25)  |
| $e$       |      | 0.0165        |
| $\dot{\omega}$ | $^\circ$/cycle | 0.00060(15) |
| $\omega_0$ | $^\circ$ | 29.87(42)     |
| $U$       | yr   | 10000(2500)   |

Figure 2. Ephemesis curve for V731 Cep obtained with the parameters in Table 4. Filled and open symbols represent the residuals from the primary and secondary minimum, respectively.

4 RADIAL VELOCITIES AND SPECTROSCOPIC ORBIT

The method we adopted for radial velocity (RV) measurements was the two-dimensional cross-correlation (TODCOR) of the observed spectra with two synthetically produced template spectra. The algorithm of TODCOR was developed by Zucker & Mazeh (1994) and has been efficiently applied to multiple-component spectra of late-type double-lined spectroscopic binaries (Latham et al. 1996; Metcalfe et al. 1996, among others) and more recently to short-period early-type binaries (González & Lapasset 2003; Southworth & Clausen 2007). Basically, TODCOR calculates two-dimensional cross-correlation function (CCF) from one observed and two template spectra in rebinned log $\lambda$ space and then locates the maximum of the CCF. We rebinned our observed and template spectra so that each pixel corresponded to 2.2 km s$^{-1}$. The template spectrum of each component was synthetically produced using the appropriate model atmosphere grids of Kurucz (1993) for each component’s temperature, surface gravity and projected rotational velocity values, as listed in Table 8. The two template spectra are shown in Fig. 3 together with the Si II doublets (6347.091, 6371.359 Å), which were used for RV measurement by TODCOR. The RVs of the components were computed from the two-dimensional CCFs with the highest score which is formed by combining the one-dimensional CCFs of the shifted and rescaled template spectra with the observed one. The RVs measured and their errors are presented in Table 5.

Using the TODCOR RVs, the orbital solution was performed by least-squares orbital fitting. The orbital period of $P = 6.068\,456\,d$ (equation 1) was fixed while the velocity semi-amplitudes $K_1, K_2$, systemic velocity $V_\gamma$ and the conjunction time (starting from 2453137.4425 HJD) were converged in the least-squares solution. Due to the small number of observations, the eccentricity ($e$) and the longitude of periastron ($\omega$) parameters were also fixed at the values obtained from the light-curve analysis results listed in Table 7. The RV at phase $\phi = 0.01$ was not used due to inaccurate RV reading from the blended spectra of the components. In order to avoid systematic effects in the orbital fitting due to the proximity of the components, although they are small, the effect of proximity was also considered using the system geometry obtained in Section 5.2. The orbital parameters adopted from the least-square fitting are listed in Table 6 and the orbital fitting to RVs is shown in Fig. 4.

5 MODELLING OF LIGHT CURVES

5.1 Reddening towards the system

The first element needed in the light-curve modelling is an estimate of the effective temperature of the primary component. The $Q$-method of Johnson & Morgan (1953) was used with the $UBV$ indices given in Table 1. Due to unavailability of $U$-magnitudes for eclipses, the colours of the combined light ($\phi = 0.25$) were used to determine a $Q$ value of $-0.10(0.03)$. According to the relation $(B - V)_0 = -0.009 + 0.337Q$ (Johnson & Morgan 1953), one can determine the unreddened colour index of $(B - V)_0 = -0.04(0.02)$. From the
difference between the colours at 0.25 and 0.51 phases, the colour of the primary component is derived to be $(B - V)_0 = -0.07(0.02)$ which corresponds to a spectral type of B8.5V with $E(B - V) = 0.13(0.03)$ colour excess.

The reddening obtained from the $Q$-method was checked by using red clump (RC) stars in this area. RC giants have long been proposed as standard candles. They have a very narrow luminosity function and constitute a compact and well-defined clump in an Hertzsprung–Russell diagram, particularly in the infrared. Furthermore, as they are relatively luminous, they can be identified even at large distances from the Sun. The absolute magnitude ($M_K$) and intrinsic colour, $(J - K)_0$, of the RC giants are well established (Alves 2000; Grocholski & Sarajedini 2002; Salaris & Girardi 2002; Pietrzyński, Gieren & Udalski 2003). Here, we assume an absolute magnitude for the RC population of $-1.62(0.03)$ mag and an intrinsic colour of $(J - K)_0 = 0.7$ mag.

In order to make the reddening estimation in the direction of V731 Cep, the $J$, $H$, and $K_s$ magnitudes of the sources in the 1 deg$^2$ field, whose central Galactic coordinates are ($l = 115^\circ$, $b = 2^\circ$), were obtained from 2MASS point sources catalogue (Cutri et al. 2003). The isolation of the RC sources in the star field was made by using theoretical traces to define the limits of the $K$-giant branch on the colour–magnitude diagrams (CMDs), without any further implication in the method – the traces were obtained for different stellar types by using a double exponential approximation to the interstellar extinction according to the updated ‘SKY’ model (Wainscoat et al. 1992).

The maxima of the RC distribution, obtained via Gaussian fitting at different magnitude bins are shown in Fig. 5 (see López-Corredoira et al. 2002, or Cabrera-Lavers, Garzón & Hammersley 2005 for further details of the method), and the distance of RC stars in the direction of V731 Cep and their absorption on $K$ band are shown in Fig. 6. It is seen that the distance between RC stars in the direction of the star field and the Sun is $1 < d < 7$ kpc. The average absorption in the $K$ band calculated from the RC stars closest ($1 < d < 1.5$ kpc) to V731 Cep system is $A(K) = 0.279$. By using $A(K) = 0.382 \times E(B - V)$ relation, the colour excess in the direction was calculated as $E(B - V) = 0.730$ and total absorption in $V$ band was calculated as $A(V) = 2.263$. To reduce this colour excess to the V731 Cep system, we applied the following equation (Bahcall & Soneira 1980):

$$A_d(b) = A_{RC}(b) \left[ 1 - \exp\left(-\frac{|d \sin(b)|}{H}\right)\right].$$

Here, $b$ and $d$ are the Galactic latitude and distance of V731 Cep, respectively. $H$ is the scaleheight for the interstellar dust adopted as 134 pc (Drimmel, Cabrera-Lavers & López-Corredoira 2003).

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**Table 6.** Spectroscopic orbital solution adopted from the analysis of radial RVs. Parameters without errors were fixed during the solutions.

| Parameter | Value |
|-----------|-------|
| $P_0$ (d) | 6.008456 |
| $T_0$ (HJD–2453137) | 0.322 (0.030) |
| $K_1$ (km s$^{-1}$) | 85.18 (1.72) |
| $K_2$ (km s$^{-1}$) | 108.84 (1.73) |
| $q$ ($K_1/K_2$) | 0.783 (0.024) |
| $V_r$ (km s$^{-1}$) | 0.62 (0.94) |
| $e$ | 0.0165 |
| $w$ (°) | 25 |
| $m_1 \sin^2 i$ ($M_{\odot}$) | 2.575 (0.098) |
| $m_2 \sin^2 i$ ($M_{\odot}$) | 2.015 (0.084) |
| $a \sin i$ ($R_{\odot}$) | 23.26 (0.29) |

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**Figure 4.** RVs and the spectroscopic orbital solution. Primary and secondary RVs are shown with circles and diamonds, respectively. Error of each individual RV measurement is indicated with bars in RV symbols. Theoretical RV curves including proximity and eclipse effects are shown for the primary (solid line) and secondary components (dashed line).

**Figure 5.** Maxima of the RC stars for different magnitude bins and the theoretical trace for a RC star (spectral type K2-3III) obtained from the SKY model by assuming a double exponential distribution for the dust in the Galaxy.

**Figure 6.** Extinction along the line of sight ($A_K$ versus $r$) for the field ($l = 115^\circ$, $b = 2^\circ$) obtained from the RC maxima in the CMD.
5.2 Determination of the photometric elements

We performed a simultaneous analysis of the $BVR_c$ and $I_c$ light curves using the 2003 version of the Wilson–Devinney (WD; Wilson 

and Devinney 1971; Wilson 1994) program.

During the simultaneous fit with WD code, the adjustable parameters were the orbital semimajor axis ($a$), the orbital eccentricity ($e$), the longitude of periastron ($\omega$), the orbital inclination ($i$), the temperature of the secondary component ($T_{\text{eff}}^2$), surface potential of both components ($\Omega_1, \Omega_2$) and the luminosity of the primary component in each band ($L_i$). The mass ratio ($q$) was taken from the spectroscopic orbital solution (Section 3) and was used as a fixed parameter during the analysis. An eccentric orbit was adopted, and the gravity brightening coefficients and bolometric albedos were set to unity in accordance with the radiative atmospheres of the components. The limb-darkening (LD) coefficients from the logarithmic LD-law were computed at each iteration from van Hamme (1993).

All observations in each band were weighted equally. Convergence of the fits was reached rapidly and tests from different starting points indicated the uniqueness of the solution. The final residual sum of squares (rss) are similar in all bands of the light curves, 0.038 in $B$, 0.040 in $V$, 0.033 in $R_c$ and 0.042 in $I_c$. The resulting best-fitting light-curve elements are given in Table 7. The light curves with the best-fitting model curves superimposed and the O–C residuals from the fits are shown in Fig. 7.

6 DISCUSSION

6.1 Absolute dimensions and distance of the system

Combination of spectroscopic orbital elements (Table 6) with light-curve elements (Table 7) yields the absolute dimensions of the system, which is presented in Table 8. The adopted temperature $T_{\text{eff}1} = 10700$ K and mass $M_1 = 2.577$ $M_\odot$ of the primary component correspond to the spectral type of a normal B8.5-type main-sequence star, while the adopted temperature $T_{\text{eff}2} = 9265$ K and mass $M_2 = 2.017$ $M_\odot$ of the secondary component are in good agreement with the spectral type of a normal A1.5-type main-sequence star (i.e. Straižys & Kuriliene 1981). However, the radii of the components, $R_1 = 1.823$ $R_\odot$ and $R_2 = 1.717$ $R_\odot$, are in better agreement with the same spectral type stars but at closer locations to ZAMS, suggesting a young age of the system, as determined in Section 6.2.

The synchronization time-scale for the component stars of the V731 Cep system is, following Zahn (1977), of the order of 15 Myr, which is smaller than the age of 120 Myr estimated from the isochrones (see Section 6.2). To compare the observed rotational velocities with the synchronization velocities listed in Table 8, we have modelled Si II doublets (6347.091, 6371.359 Å) with model atmosphere grids using ATLAS9 and SYNTHE codes under Linux (Kurucz 1993). The modelling yielded equatorial rotational velocities of $V_{\text{rot}1} = 19(3)$ and $V_{\text{rot}2} = 18(3) \text{ km s}^{-1}$ for the primary and secondary components, respectively. Although errors in the observed rotational velocities are of the order of 15 per cent, the synchronization velocities seem to be slightly below the observational measurements. The asynchronization of the components with the orbit should be confirmed by analysing new spectra with a higher S/N and more absorption lines in a larger spectral range.

Using the brightness of the system listed in Table 1 together with the light contributions of the components listed in Table 7, the intrinsic magnitudes of the components were calculated and are presented in Table 9. During the derivation of the intrinsic magnitudes, the interstellar extinction in $B$ and $V$ bands were adopted from the $Q$-method, while the following relations of Fiorucci & Munari (2003) were used for the determination of extinction in $R_c$ and $I_c$:

$$
(R_c)_0 = R_c - 2.494 \times E(B - V),
$$

$$
(I_c)_0 = I_c - 1.753 \times E(B - V),
$$

(3)

where $(R_c)_0$ and $(I_c)_0$ are the dereddened magnitudes.

The dereddened visual apparent magnitude and optical absolute magnitude presented in Table 8 allowed us to derive a distance of 809(30) pc to the system. To compare the distance of V731 Cep system using a different method, a luminosity–colour relation (Bilir et al. 2008) which has been formed for detached binary systems with main-sequence components was used in this study. The near-infrared magnitudes of the system were taken from the 2MASS point sources catalogue of Cutri et al. (2003) and are shown in Table 1. For dereddening near-infrared magnitude and colours of the system, the following formulae (Bilir, Güver & Aslan 2006; Ak

### Table 7. Results from the simultaneous solution of $BVR_c$ and $I_c$-band light curves of V731 Cep system. Adjusted and fixed parameters are presented in separate panels of the table.

| Parameter | Value |
|-----------|-------|

**Adjusted parameters**

- $T_{\text{eff1}}(K)$: 9265 (20)
- $L_1/L_{1+2}(B)$: 0.639 (0.008)
- $L_1/L_{1+2}(V)$: 0.620 (0.008)
- $L_1/L_{1+2}(R_c)$: 0.613 (0.008)
- $L_1/L_{1+2}(I_c)$: 0.604 (0.008)
- $\Omega_1$: 13.24 (0.12)
- $\Omega_2$: 11.75 (0.08)
- $r_1$ (mean): 0.0805 (0.0008)
- $r_2$ (mean): 0.0738 (0.0005)
- $i$ (°): 88.70 (0.03)
- $e$: 0.0165 (0.0005)
- $w$ (°): 25 (2)

**Fixed parameters**

- $A_1 = A_2$: 1.0
- $g_1 = g_2$: 1.0
- $T_{\text{eff1}}(K)$: 10700
- $q$: 0.783
- $x_1(B, V, R_c, I_c)$: 0.678, 0.581, 0.496, 0.396
- $y_1(B, V, R_c, I_c)$: 0.338, 0.290, 0.246, 0.195
- $x_2(B, V, R_c, I_c)$: 0.733, 0.630, 0.534, 0.425
- $y_2(B, V, R_c, I_c)$: 0.325, 0.286, 0.249, 0.201
- $F_1 = F_2$: 1.034
- $\chi^2_{\text{min}}$: 0.149

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Figure 7. Theoretical model fits to the light curves of V731 Cep (upper panel). O–C residuals from the theoretical fits (lower panel).

Table 8. Close binary stellar parameters of V731 Cep. Errors of parameters are given in parenthesis.

| Parameter                                      | Symbol | Primary       | Secondary      |
|------------------------------------------------|--------|---------------|----------------|
| Mass ($M_\odot$)                               | $M$    | 2.577(0.098)  | 2.017(0.084)   |
| Radius ($R_\odot$)                             | $R$    | 1.823(0.030)  | 1.717(0.025)   |
| Separation ($R_{\odot}$)                       | $a$    | 23.27(0.29)   | 23.27(0.29)    |
| Surface gravity (cgs)                          | $\log g$ | 4.304(0.011) | 4.273(0.011)   |
| Integrated visual magnitude (mag)              | $V$    | 10.54 (0.01)  | 10.54 (0.01)   |
| Integrated colour index (mag)                  | $B-V$  | 0.09 (0.01)   | 0.09 (0.01)    |
| Colour excess (mag)                            | $E(B-V)$ | 0.13 (0.03)  | 0.13 (0.03)    |
| Visual absorption (mag)                        | $A_V$  |                | 0.40           |
| Intrinsic colour index (mag)                   | $E(B-V)_0$ | -0.04 (0.02) | -0.04 (0.02)  |
| Component intrinsic colour index (mag)         | $(B-V)$ | -0.073(0.020) | 0.016(0.020)   |
| Temperature (K)                                | $T_{\text{eff}}$ | 10700(200) | 9265(220)  |
| Spectral type                                  | Sp     | B8.5 V        | A1.5 V         |
| Luminosity ($L_\odot$)                         | $\log L$ | 1.618(0.035) | 1.292(0.043)   |
| Computed synchronization velocities (km s$^{-1}$) | $V_{\text{synch}}$ | 15.6(0.2) | 14.3(0.2)  |
| Observed rotational velocities (km s$^{-1}$)   | $V_{\text{rot}}$ | 19(3) | 18(3) |
| Bolometric magnitude (mag)                     | $M_{\text{bol}}$ | 0.705(0.088) | 1.519(0.108) |
| Velocity amplitudes (km s$^{-1}$)              | $K_{1,2}$ | 85.18(1.72) | 108.84(1.73) |
| Absolute visual magnitude (mag)                | $M_V$  | 1.104(0.054)  | 1.631(0.070)   |
| Bolometric correction (mag)                    | $B_C$  | -0.399        | -0.112         |
| Distance (pc)                                  | $d$    | 809(30)       | 809(30)        |
| Systemic velocity (km s$^{-1}$)                | $V_s$  | 0.62 (0.94)   | 0.62 (0.94)    |
| Parallax (mas)                                 | $\pi$  | 1.236(0.044)* | 1.236(0.044)* |
| Proper motion (mas yr$^{-1}$)                  | $\mu_\alpha \cos \delta, \mu_\delta$ | -1.5 (2.6), -3.1 (2.5)** | -1.5 (2.6), -3.1 (2.5)** |
| Space velocities (km s$^{-1}$)                 | $U, V, W$ | 7.59(9.03), 4.71(4.31), -9.75(9.62) | 7.59(9.03), 4.71(4.31), -9.75(9.62) |

*In this study.

**NOMAD catalogue (Zacharias et al. 2005).
et al. 2007; Bilir et al. 2008) were used:

\[
\begin{align*}
J_0 &= J - 0.884 \times E(B - V), \\
(J - H)_0 &= (J - H) - 0.322 \times E(B - V), \\
(H - K)_0 &= (H - K_s) - 0.187 \times E(B - V).
\end{align*}
\]

All the colours and magnitude with subscript ‘0’ show the dereddened ones. The colour excess \(E(B - V) = 0.13\) was estimated in a direction to V731 Cep by using Q-method (see Section 5.1). The near-infrared absolute magnitude of V731 Cep system was estimated by the luminosity–colour relation, \(M_J = 5.228(J - H)_0 + 6.185(H - K)_0 + 0.608\), of Bilir et al. (2008) and the distance of the system calculated as 733(50) pc by using the photometric parallaxes method. The photometric distance of 809(30) pc given in Table 8 is consistent with the 733(50) pc distance estimated by luminoity–colour relation obtained for detached binary systems.

### 6.2 Internal structure

Binary systems with apsidal motion allow us to determine the ISC, which is an important parameter of stellar evolution models. The observed apsidal motion period of \(U = 100000(2500)\) yr, corresponding to a total rate of \(\dot{\omega} = 0.00060(0.00015)\) cycle\(^{-1}\) was obtained in Section 6. The relativistic contribution to the apsidal motion in case of V731 Cep is substantial \(\dot{\omega}_{\text{rel}} = 0.00045\) cycle\(^{-1}\), or about 75 per cent of the total observed rate (Giménez 1985). After correcting for this effect, an average ISC was derived to be \(\log \dot{\omega}_{\text{obs}} = -2.36\) under the assumption that the component stars rotate pseudo-synchronously. This value is in very good agreement with the theoretical prediction of \(\log \dot{\omega}_{\text{theo}} = -2.34\) according to new evolutionary models of Claret (2004) with the standard chemical composition of \((X, Z) = (0.70, 0.02)\). It should, however, be noted that the present apsidal motion solution is still tentative due to relatively short observational history of V731 Cep compared to the apsidal motion period. Therefore, accurate eclipse timings are strongly needed in a decade or more in order to say more definite on the apsidal motion parameters and the related ISC.

### 6.3 Evolutionary stage and age of the system

We investigated the evolutionary status of the system by means of the Bayesian method and constructing an HR diagram for the component masses in log \(T_{\text{eff}} - \log L\) plane. We used a slightly modified version of the Bayesian estimation method idealized by Jørgensen & Lindegren (2005), which is designed to avoid statistical biases and to take error estimates of all observed quantities into consideration. Estimation of age and metal abundance of the components was made by using the web interface\(^3\) based on the Bayesian method of da Silva et al. (2006). Including their errors, the effective temperatures, visual brightness, metal abundance of components and distance to the system were the parameters used in the web interface to obtain the best-matching model parameters [i.e. surface gravity (\(\log g\)), radii (\(R_1, R_2\)), masses (\(M_1, M_2\)) and age of components \((t_1, t_2)\)] to Padova isochrones by the Bayesian method. Since the metal abundance of the components was initially not known, a range of metal abundance (i.e. \(-0.10 < [\text{M/H}] < +0.10\) dex) was selected and the values in this range were used with 0.02 dex steps. The output model parameters for each component were compared by means of \(\chi^2\) test with the absolute dimensions of the components listed in Table 8. Consequently, the minimum \(\chi^2\) yielded simultaneously the metal abundance and age of the components as \([\text{M/H}]_1 = -0.06(0.02)\) dex and \(t_1 = 116(15)\) Myr for the primary, and \([\text{M/H}]_2 = -0.02(0.02)\) dex and \(t_2 = 150(15)\) Myr for the secondary component. From these values, we adopted the mean metal abundance and mean age of the system to be \([\text{M/H}] = -0.04(0.02)\) dex and \(t = 133(26)\) Myr, respectively.

Interpretation of the evolutionary status of V731 Cep requires also the construction of HR diagrams using the latest theoretical evolutionary models. In Fig. 8, the components of V731 Cep are shown in the \(T_{\text{eff}} - \log L\) plane together with Yonsei–Yale (Y2) evolutionary tracks (Yi et al. 2001; hereafter YDK) for different masses. Evolutionary tracks for the exact masses of the components were also computed using the code provided by YDK. Among the tracks computed for the exact masses with their errors, those with \([\text{M/H}] = -0.024\) dex (\(Z = 0.0172\)) metallicity models match the locations of the components within the error limits in the \(T_{\text{eff}} - \log L\) plane. We also computed a set of isochrones using a metallicity of \([\text{M/H}] = -0.024\) dex in Y2 models. In Fig. 8, two isochrones \((t = 100\) and 120 Myr) are plotted for comparison. It was found that 120 Myr age is the best-fitting isochrone to the locations of both components. Although, the most reliable method of metal abundance determination is the atmosphere modelling of spectral lines, in this study, it seems fair to conclude that the two methods (Bayesian methods and evolutionary tracks) used for estimation of the metallicity and age of the system are in excellent agreement within the error limits. The metallicity we found for the components should be confirmed with the atmosphere modelling of metallic absorption lines in spectra taken in wider wavelength range.

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**Table 9.** Dereddened magnitudes of stars in V731 Cep system.

|       | \(B\)  | \(V\)  | \(R_c\) | \(I_c\) | Errors |
|-------|-------|-------|-------|-------|-------|
| Primary | 10.59 | 10.66 | 10.67 | 10.74 | 0.02  |
| Secondary | 11.21 | 11.19 | 11.17 | 11.20 | 0.02  |

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\(^3\) [Link](http://stev.oapd.inaf.it/~igirardi/cgi-bin/param)

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![Figure 8](http://example.com/figure8.png)

**Figure 8.** Evolutionary tracks for individual component masses and isochrone curves best matching the location of the components in log \(T_{\text{eff}} - \log L\) plane. The primary and secondary stars are shown with filled and empty circles, respectively.

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6.4 Possible origin of V731 Cep

One of the formation regions of early-type stars is open clusters. To find a possible formation region for V731 Cep, nearby young open clusters were investigated. Among others, NGC 7762 was found to be the closest open cluster and the most similar in chemical composition to V731 Cep. Chincarini (1966) estimated the distance of NGC 7762 to be 750 pc and the age 266 Myr. In a more recent study relating on the cluster, Patat & Carraro (1995) proposed a similar distance of 800 pc to NGC 7762. Nevertheless, Patat & Carraro (1995) estimated an older age for the cluster at 1.8 Gyr and less metallicity compared to the Sun. The age (133 Myr) we adopted for V731 Cep system seems to agree more with the age (266 Myr) that Chincarini (1966) calculated for NGC 7762. In addition to this, the distance and metal abundance estimation of NGC 7762 by Patat & Carraro (1995) are in agreement with the distance and metal abundance of V731 Cep found in this study. The most reliable evidence that V731 Cep is evaporated from NGC 7762 can be obtained from the spatial distribution and the metallicity of V731 Cep.

In calculation of the kinematical properties of V731 Cep, the systemic velocity, distance and proper motion components listed in Table 8 were used in the algorithm given by Johnson & Soderblom (1987). The computed space velocity components with their errors are given in Table 8. The total space velocity of 14 km s$^{-1}$ for V731 Cep is in agreement with the space velocities of young stars. Although the space velocity of the cluster could not be computed due to its unavailable RV data, the distance of 55 pc between V731 Cep and NGC 7762, and similar age and metallicity distribution of V731 Cep with NGC 7762, suggest that V731 Cep could be evaporated from NGC 7762. However, it is necessary to carry out precise photometric and spectroscopic observations of the member stars of NGC 7762 in order to form more definite conclusions on the history of V731 Cep in relation with NGC 7762.

ACKNOWLEDGMENTS

The authors would like to thank Dr Antonio Cabrera-Lavers for his help in extracting extinction data from RC stars and to the referee, Professor E. F. Guinan, for his useful comments that improved the readability of this paper. This study is part of a project funded by ÇOMU Scientific Research Foundation under project code BAP2008/37. The research of MW was supported by the Refunded by C¸ OMU Scientific Research Foundation under project 2008 RAS, MNRAS 390, 407.

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