Complex Analysis of the Stellar Binary V446 Cep; A New Massive Eclipsing Binary in Cepheus OB2 Association

Ö. Çakırli\textsuperscript{a,*}, C. Ibanoglu\textsuperscript{a}, E. Sipahi\textsuperscript{a}, A. Frasca\textsuperscript{b}, G. Catanzaro\textsuperscript{b}

\textsuperscript{a}Ege University, Science Faculty, Astronomy and Space Sciences Dept., 35100 Bornova, İzmir, Turkey
\textsuperscript{b}Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy

Abstract

We present new spectroscopic observations of the early type, double-lined eclipsing binary V446 Cep. The radial velocities and the photometric data obtained by \textit{Hipparcos} were analysed for deriving the astrophysical parameters of the components. Masses and radii were determined as $M_p=17.94\pm1.16$ M$_\odot$ and $R_p=8.33\pm0.29$ R$_\odot$, $M_s=2.64\pm0.30$ M$_\odot$ and $R_s=2.13\pm0.10$ R$_\odot$ for the components of V446 Cep. Our analyses show that V446 Cep is a detached Algol-type system. Based on the position of the components plotted on the theoretical Hertzsprung-Russell diagram, we estimate that the age of V446 Cep is about 10 Myr, neglecting the effects of mass-loss and mass exchange between the components. Using the UBVJHK magnitudes and interstellar absorption we estimated the mean distance to the system V446 Cep as $1100\pm62$ pc.

\textit{Keywords:} stars: binaries: eclipsing -- stars: fundamental parameters --

*Corresponding author. Tel.: +902323111740; Fax: +902323731403
E-mail address: omur.cakirli@gmail.com

Preprint submitted to New Astronomy June 4, 2014
1. INTRODUCTION

High-mass stars are much less frequent than intermediate- or low-mass stars due to both the star formation process, which gives rise to an initial mass function declining with the mass (e.g. Salpeter, 1955; Kroupa, 2001), and to their shorter evolutionary times. However, high-mass stars are very important because they can affect their surroundings with their winds, their strong radiation fields, and their catastrophic death as supernovae, chemically enriching their environment and triggering star formation. They usually form within the dense cores of stellar clusters and/or associations where dynamical interactions play an important role. It is widely believed that massive stars may be the product of collisions between two or more intermediate-mass stars. This idea is supported by the fact that a large fraction of massive stars harbour close companions, as failed mergers. It has been recently estimated that at least 50% of massive stars are member of binary or multiple star system (Sana et al., 2012). This lucky occurrence allows to directly measure the masses by means of their radial velocity (RV) curves. In many cases, spectral lines of both components are visible (SB2 systems), allowing to derive the orbital parameters like the period, $P_{\text{orb}}$, the projected semi-major axes, $a_{1,2}\sin i$, and the masses, $M_{1,2}\sin^3i$, apart from the factor $\sin^3i$. If our line-of-sight is close to the orbital plane and fractional radii of the components are not too small the stars display mutually eclipses. The orbital inclination and fractional radii of the component stars can be determined by the analysis of photometric light curves. Therefore, eclipsing binaries are unique tar-
gets for determining the masses and radii from their combined light curves and radial velocities analyses. Nevertheless, absolute radii were measured only for a rather small number of early-type B-stars which are members of eclipsing binary systems [Hilditch, 2004; Torres et al., 2010; Ibanoglu et al., 2013a,b]. Thus, we started a systematic observing program devoted to the spectroscopic study of close eclipsing binary systems with at least one hot component.

1.1. V446 Cephei

The light variability of V446 Cephei (HD 210478; BD+60°2348; HIP 109311; V=7m.32, B-V=0m.08) has been discovered by the Hipparcos photometry (Perryman et al., 1997). It was classified as an Algol-type eclipsing binary (EA) from visual inspection of light variation. The orbital period of V446 Cep has been determined by the Hipparcos satellite as 3.8084 days and the ephemeris is given as follows,

\[ \text{MinI}(HJD) = 2448503.047 + 3^d.8084 \times E. \] (1)

The Hipparcos’ light curve (LC) displays a primary minimum with a depth of about 0.14 mag [Malkov et al., 2006]. Kazarovets et al. (1999) designated it as V446 Cep and classified it as an EA according to the criteria of the General Catalogue of Variable Stars. Simonson (1968) included the star in the list of probable members of the Cep OB2 association.

In this paper we present new spectroscopic observations of V446 Cep. We evaluate effective temperatures and surface gravities of the component stars from an ad-hoc analysis of the spectra taken near the quadratures. Combining the results obtained by the analysis of RV and light curves we
determine directly absolute masses and radii of the components. We infer distance to the system, their fundamental parameters, and briefly discuss the main outcomes of this study.

2. OBSERVATIONS

Optical spectroscopic observations of V446 Cep were obtained at the TUBITAK National Observatory using the Turkish Faint Object Spectrograph Camera (TFOSC) attached to the 1.5 m telescope. The observations were made from July 22, 2012 to August 3, 2013, under good seeing conditions. Further details on 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 11 orders, with a resolving power of $\lambda/\Delta\lambda \sim 7000$ at 6500 Å. The average signal-to-noise ratio (S/N) was $\sim 120$. We also obtained high S/N spectra of early type standard stars 1 Cas (B0.5 IV), HR 153 (B2 IV), $\tau$ Her (B5 IV), 21 Peg (B9.5 V) and $\alpha$ Lyr (A0 V) which were used as templates in derivation of the radial velocities.

The echelle spectra were extracted from the raw images following standard reduction steps involving electronic bias subtraction, flat field division, cosmic rays removal, optimal extraction of the echelle orders, and wavelength calibration thanks to the emission lines of a Th-Ar lamp. The reduction was performed using tasks of the IRAF package.\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.}
3. RADIAL VELOCITIES AND ATMOSPHERIC PARAMETERS

Our spectroscopic dataset contains 15 observations for V446 Cep. We have measured radial velocities (RVs) from the spectra, focusing on spectral segments containing the He\textsc{i} $\lambda\lambda 5876$ (order 4) and $\lambda 6678$ (order 3) lines which are the most prominent un-blended features in our spectra, apart from the Balmer lines. We have employed the standard cross-correlation method for measuring the velocities of the component stars of the system. The cross-correlation technique (Simkin, 1974; Tonry & Davis, 1979) is widely used for measuring RVs from the spectra of close binary systems. Cross-correlation analyses were made using the spectra of $\tau$ Her and 21 Peg as templates. The principle spectral features showing splitting due to binarity were the He\textsc{i} lines at $\lambda\lambda 5876$ and 6678. We used also order 9, containing the He\textsc{i} $\lambda 4471$ line, for a few measurements of the radial velocities. The spectra taken close to the conjunctions, which display no double-lined feature, were disregarded. The Balmer lines were not used in the measurements of radial velocities due to their extremely broad profiles.

We obtained 15 radial velocities for each component of V446 Cep. The average radial velocities and their associated standard errors derived from the spectral segments containing He\textsc{i} $\lambda\lambda 4471, 5876$, and 6678 lines are presented in Table 1, along with the observation date and orbital phase. The mean error of radial velocities is 2.5 km s$^{-1}$ for the primary, and 3.6 km s$^{-1}$ for the secondary star of V446 Cep. The RVs are plotted against the orbital phase in Fig. 1, where the filled squares represent the primary and the empty squares the secondary stars. Examination of the Hipparcos light curve show no evidence for any eccentricity in the orbit of the system. Therefore, we have
assumed circular orbit and analysed the RVs using the RVSIM software programme (Kane et al., 2007). Final orbital parameters are presented in Table 2.

3.1. Determination of the atmospheric parameters

Intermediate-resolution optical spectroscopy permits us to derive most of the fundamental stellar parameters, such as the projected rotational velocity ($v \sin i$), spectral type ($S_p$), luminosity class, effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), and metallicity ([Fe/H]).

The width of the cross-correlation function (CCF) is a good tool for the measurement of projected rotational velocity ($v \sin i$) of a star. We use a method developed by Penny (1996) to estimate the $v \sin i$ of each star composing the investigated SB2 system from its CCF peak by a proper calibration based on a spectrum of a narrow-lined star with a similar spectral type. The rotational velocities of the components were obtained by measuring the FWHM of the CCF peak related to each component in five high-S/N spectra acquired near the quadratures, where the spectral lines have the largest Doppler-shift. The CCFs were used for the determination of $v \sin i$ through a calibration of the full-width at half maximum (FWHM) of the CCF peak as a function of the $v \sin i$ of artificially broadened spectra of slowly rotating standard star (21 Peg, $v \sin i \simeq 14$ km s$^{-1}$, e.g., Royer et al. 2002) acquired with the same setup and in the same observing night as the target system. The limb darkening coefficient was fixed at the theoretically predicted values, 0.42 for the system (van Hamme, 1993). We calibrated the relationship between the CCF Gaussian width and $v \sin i$ using the Conti & Ebbets (1977) data sample. This analysis yielded projected rotational velocities for the
components of V446 Cep as \( v_P \sin i = 120 \text{ km s}^{-1} \), and \( v_S \sin i = 44 \text{ km s}^{-1} \). The mean deviations were 3 and 9 km s\(^{-1}\), for the primary and secondary, respectively, between the measured velocities for different lines.

We also performed a spectral classification for the components of the system using COMPO2, an IDL code for the analysis of high-resolution spectra of SB2 systems written by one of us (see, e.g., Frasca et al., 2006) and adapted to the TFOSC spectra. This code searches for the best combination of two reference spectra able to reproduce the observed spectrum of the system. We give, as input parameters, the radial velocities and projected rotational velocities \( v \sin i \) of the two components of the system, which were already derived. The code then finds, for the selected spectral region, the spectral types and fractional flux contributions that better reproduce the observed spectrum, i.e. which minimize the residuals in the collection of difference (observed − composite) spectra. For this task we used reference spectra taken from the Valdes et al. (2004) Indo−U.S. Library of Coude Feed Stellar Spectra (with a a resolution of \( \approx 1\AA \)) that are representative of stars with spectral types from late-O type to early-A, and luminosity classes V, IV, and III. The atmospheric parameters of these reference stars were recently revised by Wu et al. (2011).

We selected 198 reference spectra spanning the ranges of expected atmospheric parameters, which means that we have searched for the best combination of spectra among 39204 possibilities per each spectrum. The observed spectra of V446 Cep in the \( \lambda \lambda 6525–6720 \) spectral region were best represented by the combination of HD 187459 (B0.5 II) and HD 178125 (B8 III). However, we have adopted, for each component, the spectral type and luminosity class
with the highest score in the collection of the best combinations of templates, where the score takes into account the goodness of the fit expressed by the minimum of the residuals. We have thus derived a spectral types for the primary and secondary component of V446 Cep as B1 and B9 main-sequence stars, with an uncertainty of about 1 spectral subclass. The effective temperature and surface gravity of the two components of the system are obtained as the weighted average of the values of the best spectra at phases near to the quadratures combinations of templates adopting a weight \( w_i = 1/\sigma_i^2 \), where \( \sigma_i \) is the average of residuals for the \( i \)-th combination. The standard error of the weighted mean was adopted for the atmospheric parameters. Both stars appear to have a solar metallicity, within the errors. The atmospheric parameters obtained by the code and their standard errors are reported in Table 3. The observed spectra of V446 Cep at phases near to the quadratures are shown in Fig. 2 together with the combination of two reference spectra which gives the best match.

4. LIGHT CURVE ANALYSES

The light curve of V446 Cep was obtained by the Hipparcos spacecraft and is composed of 124 photometric points. The light curve is very similar to that of a detached Algol-type binary. The brightness of the system at the maximum and depth of the primary minimum were estimated by \textit{Malkov et al.} (2006) to be 7.31 and 0.14 mag, respectively. However, we estimate the brightness of the system at the maximum light as Hp=7.348 mag, with a mean error of about 0.013 mag, and the depth the primary minimum as 0.10 mag. The Hp magnitudes were transformed to the Johnson’s
V-passband using the coefficients given by Harmanec (1998). The Hipparcos light curve is plotted against the orbital phase in Fig. 3. There is no indications of any asymmetry in the LC. As the secondary minimum occurs at phase 0.5, we have adopted circular orbits for our analysis. The effective temperatures for the primary and secondary star were estimated from the spectra as 26 580±880 and 12 000±1050 K, respectively.

The apparent visual magnitude and colour indices were given by Reed (2003) as \( V=7^m.32 \), \( (U-B)=-0^m.71 \), and \( (B-V)=0^m.08 \). We obtained the reddening-free quantity \( Q=-0.768 \), which corresponds to a B1 main-sequence star (Hovhannessian, 2004) with an intrinsic colour of \( (B-V)=-0^m.273 \). This colour index corresponds to an effective temperature of 26 800±800 K (Flower, 1996), which is consistent with that obtained directly from the spectra. A preliminary analysis of the light curve gives a light ratio of \( l_s/l_p=0.014 \). Using the intrinsic colour of the primary star, the light ratio and the observed composite colour of the system an interstellar reddening of \( E(B-V)=0^m.338 \) was determined for the system.

We started to analyze the light curve using the Wilson-Devinney code (hereafter WD; e.g., Wilson & Devinney, 1971; Wilson, 1979, 2006) as implemented in the software PHOEBE (Prša & Zwitter, 2005). The WD code is widely used for determination of the orbital parameters of the eclipsing binaries. To run the code we need some initial parameters. The initial logarithmic limb-darkening coefficients were taken from the tables given by van Hamme (1993) as \( x_1=0.41 \) and \( x_2=0.62 \), \( y_1=0.24 \), \( y_1=0.30 \) and are automatically interpolated at each iteration by PHOEBE. The effective temperature of the primary star is taken as 26 600 K and the ratio of the masses of two compo-
nents $q=0.147$. We have started with $Mode - 2$ meant for detached binary systems, keeping the temperature of the primary and the mass-ratio as fixed parameters. According to the WD code we adjusted the following parameters: $i$ (the orbital inclination), $\Omega_1$ (the potential for the primary), $\Omega_2$ (the potential for the secondary), $T_{\text{eff}2}$ (the effective temperature of the cool star), $L_1$ (the luminosity of the primary), and the zero-epoch offset. The luminosity of the secondary star, $L_2$, was constrained by the model. After a few numbers of runs of the DC program in $Mode - 2$ the sum of residuals squared showed a minimum and the corrections to the adjustable parameters became smaller than their probable errors. The results are given in the Table 4. The corresponding computed light curve is shown in Fig. 3 as a continuous line.

5. Results and discussion

Based on the results of radial velocities and light curves analyses we have calculated the physical properties of the V446 Cep. For this purpose, we used the $JKTABSDIM$ code developed by Southworth et al. (2005). This code is now widely used for derivation of the absolute parameters of the eclipsing binary stars' components. It calculates complete error budgets using a perturbation algorithm. The fundamental stellar parameters for the components such as masses, radii, luminosities and their standard deviations have been derived using this code. The astrophysical parameters of the components, and other properties for the stars of V446 Cep is presented in Table 5.

The separation between the components was found to be $28.10\pm0.63$ R$_{\odot}$ for V446 Cep. The masses were measured to precision of about 6–7\%, apart
from the mass of the secondary star of V446 Cep, which has an uncertainty of about 11%. On the other hand the radii of the stars have been derived with a precision of better than 5%. The accuracy of any parameter of an eclipsing binary system depends mainly on the coverage of the both spectroscopic and photometric observations and their precision. In addition, the LC solutions are more accurate for totally eclipsing systems. The light curve of V446 Cep shows total eclipses, but the precision of the photometric measurements is not sufficiently high. Despite these drawbacks, the physical parameters of the components of system could be determined with sufficient precision. We note that the effective temperature of the secondary star derived from the spectra is in good agreement with that obtained from the light curve analysis.

The luminosities and absolute bolometric magnitudes are calculated directly from the radii and and effective temperatures of the components. The effective temperature of 5777 K and the absolute bolometric magnitude of 4.74 mag were adopted for the Sun (e.g., Drilling & Landolt, 2000). The bolometric corrections were interpolated from the tables of Flower (1996). The V-band magnitude of the system at out-of-eclipse phases is taken as 7.32 for V446 Cep. We have calculated the absolute visual magnitudes for the components using the fractional luminosities and bolometric corrections given in Table 4 and 5. Combining these values with the interstellar absorption of 1.09 mag for V446 Cep we have estimated the distance to the system as 1100±62 pc.

In the log $T_{\text{eff}}$–log $L/L_\odot$ (left panel) and log $T_{\text{eff}}$–log $g$ planes (right panel) of Fig. 4 we have plotted the positions of the components, with 1-σ error bars. The filled and empty circles represent the primary and secondary star
of V446 Cep. The evolutionary tracks and isochrones for the non-rotating single stars with solar composition are taken from Ekström et al. (2012).

V446 Cep was included in the list of probable members of the Cep OB2 association (e.g., Simonson, 1968, and reference therein). According to Patel et al. (1998) the distance to the Cepheus OB2 association is \( \sim 900 \) pc and it is embedded in the Cepheus bubble, a giant shell structure of atomic and molecular gas extending in a radius of about 120 pc, which is believed to be generated by an earlier generation of hot and massive stars in NGC 7160. Garmany & Stencel (1992) derived a reddening in the range 0.29–1.12 for the stars in the Cep OB2 field, with a mean value of 0.59 for the members of the association. The interstellar reddening that we estimated for V446 Cep, \( E_{(B-V)} = 0.34 \), is lower than the value estimated for the association, but it is consistent with the value of 0.32 derived by Harries et al. (1998) for the binary system LZ Cep in this association.

This result suggests that the binary is located near the NGC 7160 in the border of Cepheus Bubble (Kun et al., 2008). The open clusters Tr 37 and NGC 7160 with the ages of 4 and 12 Myr locate in the association (Sicilia-Aguilar et al., 2004). Our distance of V446 Cep agrees quite well with those distance values of Cep OB2 association. Both components of V446 Cep appear to have an age of about 10 Myr which is consistent with the age of stars in the open cluster NGC 7160.

As seen from Fig. 4, components of the system are located on the main-sequence, i.e. in the central hydrogen burning phase. They are still inside their lobes, corresponding to the detached Algols. Ibanoglu et al. (2006) collected the physical parameters of 74 detached Algols, mainly composed
of hot (BAF-type) stars. Their mass-ratios, $M_2/M_1$, are generally larger than 0.5, with a mean value of 0.88. The binary system AR Cas has the smallest mass-ratio in their Table 1, with a value of 0.315. We find V446 Cep as a detached Algol with a lower mass-ratio. $M_2/M_1 = 0.147$, which is among lowest values found for this class of binaries. The less massive stars in the semi-detached binaries fill their corresponding Roche lobes and are oversized and over-luminous relative to a zero-age main-sequence star of the same mass (Harries et al., 1998). Although the less-massive secondary star of V446 Cep does not fill its respective Roche volume it is seen as oversized and over-luminous with respect to its mass, similar to the secondaries of the semi-detached systems.

6. Summary

V446 Cep is close eclipsing binary containing high-mass star. We carried out spectroscopic observations of the system. The atmospheric parameters of the stars in the eclipsing pair have been determined from its spectra. The spectra were analyzed using cross-correlation for measuring the radial velocities of both components and with an ad-hoc code for deriving their atmospheric parameters. Moreover, HIPPARCOS light curve was modeled using the WD code. The physical parameters for the system are measured to accuracies of 6-7\% in mass, apart from the secondary of V446 Cep, and 5\% in radius. The distance to the system V446 Cep was estimated as 1100±62 pc. A comparison of physical parameters of the components with the theoretical models of single stellar evolution models has been made and an age of about 10 Myr for V446 Cep has been derived. Both the estimated age and distance
of V446 Cep confirm its membership of Cepheus OB2 association, locating close to the open cluster NGC 7160.

Acknowledgments

We thank to TÜBİTAK National Observatory (TUG) for a partial support in using RTT150 telescope with project number 11BRTT150-198. We thank to EBİLTEM Ege University Research Center for a partial support with project number 2013/BIL/018. We also thank to the staff of the Bakırlıtepe observing station for their warm hospitality. This study is supported by Turkish Scientific and Technology Council under project number 112T263. This research was also partly supported by the Scientific Research Projects Coordination Unit of Istanbul University. Project number 3685. We thank Canakkale Onsekiz Mart University Astrophysics Research Center and Ulupinar Observatory together with Istanbul University Observatory Research and Application Center for their support and allowing use of IST60 telescope. This work was partially supported by the Italian Ministero dell’Istruzione, Università e Ricerca (MIUR). The following internet-based resources were used in research for this paper: the NASA Astrophysics Data System; the SIMBAD database operated at CDS, Strasbourg, France; and the arχiv scientific paper preprint service operated by Cornell University.

References

Conti, P. S., & Ebbets, D., 1977, ApJ, 213, 438

Drilling J. S., Landolt A. U., 2000, Allen’s astrophysical quantities, 4th ed.
Ekström S., Georgy C., Eggenberger P., et al., 2012, A&A, 537, A146

Flower, P. J., 1996, ApJ, 469, 355

Frasca, A., Guillout, P., Marilli, E. 2006, A&A, 454, 301

Garmany, C. D., & Stencel, R. E., 1992, A&AS, 94, 211

Harmanec, P. 1998, A&A, 335, 173

Harries, T. J., Hilditch, R. W., & Hill, G., 1998, MNRAS, 295, 386

Hilditch, R. W., 2004, ASPC, 318, 198

Hovhannessian R. K., 2004, Ap, 47, 499

Ibanoglu C., Çakırlı, Ö., & Sipahi, E., 2013a, MNRAS, 436, 750

Ibanoglu, C., Çakırlı, Ö., & Sipahi, E., 2013b, NewA, 25, 68

Ibanoglu, C., Soydugan, F., Soydugan, E., & Dervişoğlu, A., 2006, MNRAS, 373, 435

Kane, S. R., Schneider, D. P., & Ge, J., 2007, MNRAS, 377, 1610

Kazarovets E. V., Samus N. N., Durlevich O. V., et al., 1999, IBVS, 4659, 1

Kun, M., Kiss, Z. T., & Balog, Z. 2008, Handbook of Star Forming Regions, Volume I, 136

Kroupa, P. 2001, MNRAS, 322, 231
Malkov, O. Y., Oblak, E., Snegireva, E. A., & Torra, J., 2006, A&A, 446, 785

Patel, N. A., Goldsmith, P. F., Heyer, M. H., Snell, R. L., & Pratap, P., 1998, ApJ, 507, 241

Penny, L. R., 1996, ApJ, 463, 737

Perryman M. A. C., Lindegren L., Kovalevsky J. et al., 1997, A&A, 323, L49

Prša A., Zwitter T., 2005, ApJ, 628, 426P

Royer F., Gerbaldi M., Faraggiana R., & Gomez A. E. 2002, A&A, 381, 105

Reed, B. C., 2003, AJ, 125, 2531

Sana, H., Dunstall, P. R., Hénault-Brunet, V., et al. 2012, Proceedings of a Scientific Meeting in Honor of Anthony F. J. Moffat, ASPC, 465, 284

Salpeter, E. E. 1955, ApJ, 121, 161

Sicilia-Aguilar, A., Hartmann, L. W., Briceño, C., Muzerolle, J., & Calvet, N., 2004, AJ, 128, 805

Simkin, S. M., 1974, A&A, 31, 129

Simonson, S. C., III, 1968, ApJ, 154, 923

Southworth, J., Maxted, P. F. L., & Smalley, B., 2005, A&A, 429, 645

Tonry, J., & Davis, M. 1979, AJ, 84, 1511

Torres G., Andersen J., & Giménez A., 2010, A&ARv, 18, 67
Valdes, F., Gupta, R., Rose, J. A., Singh, H. P., & Bell, D. J., 2004, ApJS, 152, 251

van Hamme, W., 1993, AJ, 106, 2096

Wilson, R. E., 1979, ApJ, 234, 1054

Wilson, R. E., 2006, Astrophysics of Variable Stars, ASPC, 349, 71

Wilson, R. E., & Devinney, E. J., 1971, ApJ, 166, 605

Wu, Y., Singh, H. P., Prugniel, P., Gupta, R., & Koleva, M. 2011, A&A, 525, 71
Figure 1: Radial velocities for the components of V446 Cep. Filled squares correspond to the radial velocities for the primary and the empty squares for the secondary star. Error bars are shown by vertical line segments, which are smaller than symbol sizes. The solid lines are the computed radial velocity curves for the component stars.
Figure 2: Comparison between the observed spectra of V446 Cep and the best-fitting spectra around He\textsc{i} λ4471 (left panel) and the H\textalpha{} and He\textsc{i} λ6678 lines (right panel).
Figure 3: The *Hipparcos* light curve of V446 Cep. The continuous line shows the best-fit model.
Figure 4: Positions of the components of the system in the luminosity-effective temperature and gravity effective temperature planes are plotted. The filled and empty circles represent the primary and secondary stars, respectively, of V446 Cep. The solid lines show evolutionary tracks for single stars with masses of 20, 15, 10, 5 and 2 solar masses for solar composition taken from Ekström et al. (2012). The positions of the components of V446 Cep are consistent with an age of \( \sim 10 \) Myr.
Table 1: Heliocentric radial velocities of V446 Cep. The columns give the heliocentric Julian date, orbital phase and the radial velocities of the two components with the corresponding standard deviations.

| HJD 2400000+ | Phase | V446 Cep |
|--------------|-------|----------|
|              | Vp    | σ       | Vs      | σ     |
| 56132.3303   | 0.2778| −61 2   | 289 2   |
| 56134.4239   | 0.8276| 25 2    | −291 2  |
| 56135.5843   | 0.1323| −49 3   | 221 4   |
| 56136.5042   | 0.3738| −49 3   | 205 3   |
| 56137.4177   | 0.6137| 13 3    | −223 8  |
| 56162.5807   | 0.2209| −67 2   | 299 2   |
| 56162.5890   | 0.2231| −69 2   | 289 2   |
| 56168.3798   | 0.7436| 35 2    | −334 2  |
| 56506.5293   | 0.5341| −5 4    | −88 7   |
| 56506.5444   | 0.5380| −7 4    | −98 9   |
| 56507.3464   | 0.7486| 33 2    | −341 3  |
| 56507.3596   | 0.7521| 29 2    | −335 3  |
| 56507.3739   | 0.7558| 40 2    | −345 2  |
| 56507.3895   | 0.7599| 34 2    | −330 3  |
| 56507.4025   | 0.7633| 35 2    | −335 2  |
Table 2: Results of the radial velocity analysis for V446 Cep.

| Parameter                  | V446 Cep |         |         |
|----------------------------|----------|---------|---------|
|                            | Primary  | Secondary |
| $K$ (km s$^{-1}$)          | 47±4     | 319±7   |
| $V_\gamma$ (km s$^{-1}$)   | −18±3    |          |
| Average O-C (km s$^{-1}$)  | 2.5      | 3.6     |
| $a \sin i$ ($R_\odot$)     | 3.51±0.27| 24.03±0.49|
| $M \sin^3 i$ ($M_\odot$)  | 16.86±1.08| 2.48±0.28|

Table 3: Spectral types, effective temperatures, surface gravities, and rotational velocities of components estimated from the spectra of V446 Cep.

| Parameter                  | V446 Cep |         |         |
|----------------------------|----------|---------|---------|
|                            | Primary  | Secondary |
| Spectral type              | B(1±0.5) V | B(9±0.5) V |
| $T_{\text{eff}}$ (K)       | 26 580±880 | 12 000±1050 |
| log $g$ (cgs)              | 3.77±0.05 | 3.95±0.17 |
| $v \sin i$ (km s$^{-1}$)   | 120±3     | 44±9     |
Table 4: Final solution parameters for the semi-detached model of V446 Cep.

| Parameters | V446 Cep |
|------------|----------|
| $i^\circ$  | 78.36±0.22 |
| $T_{\text{eff}1}$ (K) | 26 600[Fix] |
| $T_{\text{eff}2}$ (K) | 11 900±1 500 |
| $\Omega_1$ | 3.452±0.132 |
| $\Omega_2$ | 3.217±0.119 |
| $r_1$ | 0.2962±0.0118 |
| $r_2$ | 0.0756±0.0046 |
| $\frac{L_1}{(L_1+L_2)}$ | 0.9858±0.0036 |
| $\sum (O - C)^2$ | 0.0108 |
| $N$ | 124 |
| $\sigma$ | 0.0097 |
Table 5: Absolute parameters, magnitudes and colours for the components of V446 Cep.

| Parameter       | Units | V446 Cep          |   |   |
|-----------------|-------|-------------------|---|---|
|                 |       | Primary           | Secondary |   |
| Mass            | M<sub>☉</sub> | 17.94±1.16        | 2.64±0.30  |
| Radius          | R<sub>☉</sub> | 8.33±0.29         | 2.13±0.10  |
| T<sub>eff</sub> | K     | 26 600±1000       | 11 900±1050 |
| log(L/L<sub>☉</sub>) |       | 4.500±0.056      | 1.904±0.118 |
| log g           | cgs   | 3.850±0.023       | 4.205±0.050 |
| Sp.Type         |       | B1V               | B8IV       |
| M<sub>bol</sub> | mag   | −6.51±0.14        | −0.02±0.30  |
| BC              | mag   | −2.58             | −0.66       |
| M<sub>V</sub>   | mag   | −3.93±0.08        | 0.64±0.17   |
| v sin i<sub>cal</sub> | km s<sup>−1</sup> | 108±4 | 28±1 |
| v sin i<sub>obs</sub> | km s<sup>−1</sup> | 120±8 | 44±7 |
| d               | pc    | 1 100±62          | 1 120±40   |