Long-period Double-lined Eclipsing Binaries: The System V454 Aur with the Secondary Eclipse Caused by the Occultation of the Hotter Component postprint

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Abstract

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Full Text

Preamble

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Component

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Abstract

We present the results of our study of the long-period eclipsing binary star V454 Aur, based on spectroscopic data obtained with the UFES échelle spectrograph and photometric observations from the Transiting Exoplanet Survey Satellite (TESS). The derived radial velocity curve is based on 17 spectra obtained between 2021 and 2023, covering all orbital phases of this binary system. The orbital period determined from TESS data, P = 27.019803 ± 0.000003 days, agrees within uncertainties with the period established in previous studies. The model constructed for the TESS photometric light curve achieves a precision of 0.01%. The effective temperatures of both components, as well as the system metallicity, were directly derived from the spectra and are Teff,A = 6250 ± 50 K, Teff,B = 5855 ± 50 K, and [Fe/H] = −0.10 ± 0.08. Photometric and spectroscopic data allowed us to directly compute the luminosities of the components, LA = 1.82 L and LB = 1.07 L , their radii, RA = 1.15 R and RB = 1.00 R , and their masses, MA = 1.137 M and MB = 1.023 M , with uncertainties below 1%. Comparison with evolutionary tracks indicates that the system' s age is 1.18 ± 0.10 Gyr, and both components are still on the main sequence. The V454 Aur system is particularly interesting due to the partial eclipse of the primary component, which results in the "inversion" of the primary and secondary minima in the photometric light curve.

Key words: stars: luminosity function, mass function -(stars:) binaries: spectroscopic -stars: individual (V454 Aur)

1. Introduction

Double-line eclipsing binaries (DLEBs) represent an observational class of binary systems that provides the most accurate (to within 2%-3%) parameters of their components, including such critical yet challenging-to-determine parameters as mass and orbital characteristics. Large-scale studies of DLEBs began approximately half a century ago (Popper 1980; Harmanec 1988; Andersen 1991). However, current catalogs and lists of such systems still contain only about a hundred objects (Torres et al. 2010; Southworth 2015). DLEBs are an indispensable source of data for constructing fundamental relationships for main sequence (MS) stars (e.g., mass-luminosity and mass-radius relations). Consequently, the inclusion of new DLEBs in catalogs is an important and relevant task.

It should be noted that most of the studied DLEB systems are short-period binaries. For example, in the list from Torres et al. (2010), only four out of 95 DLEBs have orbital periods exceeding 15 days, and only two of these four (α Cen and AP Phe) contain MS components. In the online catalog DEBCat (Southworth 2015), there are currently more than 300 binary systems to date. However, only 150 of these, which have listed luminosities, contain MS components, and just 11 of these systems have orbital periods longer than 15 days. The study of long-period systems is indeed challenging because it requires extended observation campaigns to construct sufficiently accurate light curves and radial velocity curves. Moreover, the components of such systems exhibit smaller (and thus more difficult to observe) radial velocity variations compared to short-period DLEBs. However, these systems have several advantages over short-period DLEBs.

The large separation between components ensures that the DLEB has never been a semi-detached system, with no mass transfer having occurred. Consequently, the current masses of the components are definitively equal to their initial masses (excluding possible mass loss through stellar winds). Additionally, there is a probability that the components of such systems have not undergone significant processes of circularization and synchronization (Zahn 1975, 1977; Tassoul 1987, 1988; Khaliullin & Khaliullina 2007, 2010), at least during their time on the MS. Thus, the evolution of the components in long-period DLEBs is identical to that of single stars, making them reliable for constructing fundamental stellar relations (Malkov 2003, 2007).

This work continues our series of studies on long-period DLEBs (Kniazev 2020; Kniazev et al. 2020; Pakhomova et al. 2022). Here, we present data on the long-period system V454 Aur. The variability of the bright ($V = 7.65$ mag) eclipsing binary V454 Aur = HD 44192 was discovered by the Hipparcos satellite, and the first detailed spectroscopic study of the system was conducted by Griffin (2001). In that study, radial velocity curves for both components were obtained, and both the orbital elements (period $P = 27.0197 \pm 0.0010$ days, eccentricity $e = 0.3790 \pm 0.0013$) and the spectral types of the components (F8V + G1/2V) were determined. The component masses were estimated to be MA = 1.163 M and MB = 1.035 M . Griffin (2001) also evaluated the radii and rotational velocities, highlighting the possibility of pseudo-synchronization of the components' rotation with the orbital motion, though this was not confirmed.

The parallax of V454 Aur obtained by Hipparcos (van Leeuwen 2007) is 14.4 ± 0.9 mas, whereas Gaia (Gaia Collaboration 2020) reports a value of 15.367 ± 0.022 mas. Based on data from the Geneva-Copenhagen Survey (Nordström et al. 2004), the temperature and metallicity of this system were estimated as Teff = 6064 K and [Fe/H] = −0.08 by Casagrande et al. (2011), and as Teff = 6030 K and [Fe/H] = −0.14 by Holmberg et al. (2009).

In the detailed study of V454 Aur by Yucel et al. (2024), the orbital period of the system was determined to be 27.0198177 days, with component masses of MA = 1.173 M and MB = 1.045 M , and radii of RA = 1.203 R and RB = 0.993 R , respectively. The effective temperatures of the stars were estimated as 6250 K and 5890 K. The metallicity of the system was found to be slightly above solar, and the age was estimated to be 1.19 Gyr. In the detailed study of V454 Aur by Southworth (2024), the masses and radii of the components were determined as MA = 1.161 M , RA = 1.211 R for the primary component, and MB = 1.034 M , RB = 0.979 R for the secondary component. The effective temperatures of the stars were estimated as 6170 K and 5890 K. In both detailed studies, the authors used velocity measurements from Griffin (2001) and photometric data from the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014).

In this study, we also investigate the V454 Aur system using our own spectroscopic échelle data and photometric data from the TESS survey. In Sections 2 and 3 we describe the available and obtained photometric and spectral data, as well as their processing. In Section 4 the principles of our data analysis are described. Section 5 presents the results we obtained, which are discussed in Section 6 and summarized in Section 7. In the following we will refer to the brighter and hotter star in the DLEB system V454 Aur as component A or primary and the colder star as component B or secondary.

2. Photometric TESS Data

For constructing the photometric light curve, we used data from TESS (Ricker et al. 2014). TESS is a NASA satellite designed to capture images of nearly the entire sky to search for exoplanets using the transit method. The satellite observes a designated area of the sky (referred to as a “sector”) for a duration of 30 days. Bright stars are observed with a data acquisition cadence of 2 minutes, while full-frame images are recorded every 30 minutes. Due to the satellite’ s orbit, different regions of the sky are covered non-uniformly; however, there are substantial overlaps between some regions. Most of the processed TESS data are publicly available. In this study, we utilized TESS data processed for the MIT project (“QLP” ; Huang et al. 2020a, 2020b). Photometric data for V454 Aur were obtained by TESS during observations of sectors 14, 20, 42–45, and 60, covering both primary and secondary eclipses.

The TESS photometric data set used in this paper contained approximately 48,500 data points, of which only those with a QUALITY flag value of zero were selected.

3. Spectral Observations and Data Reduction

Spectroscopic observations of V454 Aur were conducted from 2021 November to 2023 April using the fiber-fed échelle spectrometer UFES (Panchuk et al. 2011; Krushinsky et al. 2014) mounted on the 1.21 m telescope of the Kourovka Astronomical Observatory at Ural Federal University. An ANDOR DZ936N CCD-camera with back-illuminated and fringe suppression technology sensor BEX2-DD (2048 × 2048, 13.5 m) was used during these observations. The spectrograph was operated with a fiber aperture of 10 , yielding a resolution of R 12,400–13,400. Each observation consisted of three or five exposures of 1800 s each, which were subsequently median-combined to remove cosmic ray artifacts. In total, 17 observations were obtained, with the dates listed in Table 1 .

Each night of observations included calibrations consisting of 10 images to account for the zero level (BIAS), three flat-field lamp spectra to determine the positions of the spectral échelle orders and to correct for the spectral sensitivity (the so-called "blaze variation along each échelle order correction"), and three hollow-cathode lamp spectra (Th+Ar) for wavelength calibration. These spectra were also median-combined to remove cosmic ray artifacts.

For processing the échelle data from the UFES spectrograph, a reduction pipeline was developed based on the data reduction system of the HRS échelle spectrograph (Kniazev et al. 2016, 2019) at the Southern African Large Telescope. The reduction process included the following steps: (1) A two-dimensional background, consisting of scattered light, was determined and subtracted from each two-dimensional échelle spectrum using the algorithm described in Shergin et al. (1996); (2) The positions of 66 échelle orders were identified using flat-field lamp spectra and extracted from the two-dimensional spectra; (3) One-dimensional échelle orders were corrected for uneven brightness distribution along the orders (the blaze effect) by dividing by the extracted orders of the flat-field spectra; (4) To construct the dispersion curve, an automatic procedure identified approximately 1600 emission lines in the extracted échelle orders of the comparison spectrum. These lines were also automatically located in the two-dimensional échelle spectra, and a two-dimensional dispersion curve was constructed for each observing night using a third-order polynomial. Only about 480 emission lines were retained for the final solutions, with the remainder discarded based on various criteria by the automatic procedure. The accuracy of the constructed two-dimensional dispersion curve was approximately 0.007 Å; (5) All extracted échelle orders were resampled to a uniform wavelength scale; (6) All échelle orders were combined into a single one-dimensional spectrum.

The final spectrum covers the wavelength range of 3850–7550 Å with a reciprocal dispersion of 0.032 Å pixel^{-1}. The spectral resolution (full width at half maximum, FWHM), measured from all identified lines in the wavelength-calibrated comparison spectrum, varies from 0.30 to 0.55 Å and is shown in the left panel of Figure 1 [Figure 1: see original paper]. The behavior of the instrumental profile is well approximated by a first-order polynomial and can be expressed as FWHM = $0.05113\lambda + 0.02$ Å for the entire spectral range of 3900–7500 Å with an accuracy of 0.02 Å. This relationship is also displayed in the left panel of the figure. The resolution R = $\lambda/\delta\lambda$ as a function of wavelength is presented in the right panel of Figure 1.

4. Data Analysis

To construct the light curves and calculate the period, we used Python programs based on the algorithm from Laffer & Kinman (1965), which belongs to the class of non-parametric methods and does not require direct application of Fourier decomposition.

For the analysis of fully processed échelle spectra, we utilized the FBS package (Fitting Binary Stars; Kniazev et al. 2020; Kniazev 2020), specifically developed by our team for the analysis of binary star system spectra. FBS employs a library of theoretically computed high-resolution stellar spectra and is designed to determine radial velocities and stellar parameters (Teff, log g, v sin i, [Fe/H]) for both components of a binary system, as well as the parameter E(B − V) reddening correction and $W_{1,2}$, representing the contribution of each component to the observed spectrum ($W_1 + W_2 = 1$) at the wavelength of the V filter λ_{5550} Å. The program simultaneously fits the observed spectrum with a model spectrum obtained by interpolating the stellar model grid and convolving it with a function that accounts for instrumental resolution and rotational broadening v sin i, with a shift corresponding to the radial velocity value at a given epoch. For a binary star, the fitting involves modeling the spectra of both components, each with their own radial velocity and stellar atmospheric parameters, effectively decomposing the observed spectrum into the individual spectra of the two components. If multiple spectra of the binary system are available for different epochs, the program can determine a solution in which the parameters (Teff, log g, v sin i, [Fe/H], $W_{1,2}$ and E(B − V)) are consistent across all spectra being fit simultaneously, while the radial velocities of both components, $V_{1,2}$, are determined for each specific epoch j. The stellar models used must be pre-adjusted to match the resolution of the spectrograph in use. The FBS package has already been utilized by the authors for work with both high-resolution and low-resolution spectra (Gvaramadze et al. 2021; Muhie et al. 2021; Malkov & Kniazev 2022; Gvaramadze et al. 2023; Kniazev & Malkov 2023).

Additionally, the FBS package allows for the analysis of obtained radial velocities and, by modeling the radial velocity curve, calculates the orbital parameters of the binary system components. During its operation, FBS searches for global minima of sufficiently complex functions (Kniazev et al. 2020). The methods used for finding these minima include various numerical approaches available in the lmfit library. In the present study, theoretical stellar models from the library by Coelho (2014), adjusted to match the spectral resolution of UFES (see Section 3), were used. The FBS program was used with only one constraint: it was assumed that both components of the binary system have the same metallicity (Hawkins et al. 2020).

For further analysis of the spectroscopic and photometric data, the ELISA package (Eclipsing Binary Learning and Interactive System; Čokina et al. 2021) was used, which constructs a three-dimensional DIM model of the studied system. The ELISA package enables the determination of absolute parameters for virtually any type of binary system: detached, semi-detached, or contact. To enhance the accuracy of light curve modeling, ELISA utilizes a library of theoretical stellar spectra, although blackbody radiation models can also be used. ELISA includes an extensive set of photometric filters, including TESS, various limb darkening laws, and accounts for gravity darkening and reflection effects. For light curve modeling, ELISA implements Roche geometry and a triangulation process simulating the surface of binary star components, where the surface parameters of each surface element are treated individually. To generate a point on the light curve, the flux from the entire surface is integrated. ELISA also provides tools for solving inverse problems, including a built-in Markov Chain Monte Carlo (MCMC) method. This can be applied to determine binary system parameters based on radial velocity data sets or photometric data sets. Additionally, the package supports parallelization for optimization and MCMC computations, significantly reducing computational time when using multi-core computers or processors with many threads.

When calculating the equipotential function, ELISA uses the synchronization parameter $F_{1,2}$ (for each component), defined as the ratio $F = \omega/\omega$ b, where ω is the angular rotation velocity of the star, and ω b is the orbital angular velocity of the star. By default, it is assumed that synchronization occurs rapidly, even in the case of eccentric orbits (Zahn 1975). Due to tidal interactions, the synchronization parameter $F = 1$ for circular orbits, whereas for non-circular orbits, synchronization depends on the system' s eccentricity and is calculated using the formula from Hut (1981). However, in principle, in the case of ELISA, the synchronization value $F_{1,2}$ can be a free minimization parameter, and the hypothesis of slow or fast synchronization can be tested in the process of modeling the brightness curve.

When solving the inverse problem, both in the case of radial velocity curve analysis and light curve analysis, ELISA employs the Least Squares Trust Region Reflective algorithm. This algorithm is efficient for finding solutions in the local vicinity but does not search for a global minimum. When using the package, it is recommended to provide initial conditions sufficiently close to the true solution. For this reason, the orbital parameters of the components in the V454 Aur system obtained from Griffin (2001), their projected rotational velocities, and the physical parameters of the stellar components obtained with FBS were used as initial estimates for the ELISA package.

Thus, the sequence of steps in our analysis was as follows: (1) Using TESS photometric data, the precise period P and the epoch of the primary minimum

T_0 were calculated; (2) Using the FBS package, each observed spectrum was analyzed to obtain the stellar parameters of both components and their velocities; (3) Using the stellar parameters obtained from the previous step for each spectrum, the mean values and their uncertainties were calculated for the temperatures of each component, system metallicity, and the contributions of each component; (4) Using the FBS package, radial velocity curves were modeled for each component of the system, and initial estimates of the orbital parameters of the binary system were determined; (5) Using the ELISA package, radial velocity curves were modeled, and the final orbital parameters of the system were determined, with final uncertainties estimated using the MCMC method; (6) Using the ELISA package, TESS photometric data (Step 1), the orbital parameters of the system (Step 5), and the stellar parameters of the components (Step 3), the photometric light curve was modeled, and the absolute parameters of the binary system were determined and their final uncertainties estimated using the MCMC method.

5. Results

(1) Using TESS data and a program based on the algorithm from Laffer & Kinman (1965), the orbital period was determined to be P = 27.019803 ± 0.000003 days, and the epoch of the primary minimum in the system was calculated as BJD $T_0 = 2458850.801464 \pm 0.000105$.

(2) The result of analyzing one spectrum of V454 Aur is shown as an example in Figure 2 [Figure 2: see original paper]. The top panel of the figure displays the modeling result in the spectral range of 3900–6800 Å, while the bottom panel shows the modeling result for the region around the Mg I line. In each panel, the black and red lines correspond to the observed spectrum and its modeled fit, respectively. The blue and orange spectra represent modeled spectra of components A and B, respectively. The lower part of each panel shows the difference between the observed and modeled spectra, including the uncertainties obtained during the data processing, which are shown in green.

(3) Experience with FBS shows that the most robust and accurate results in terms of finding the global minimum are obtained using the "differential evolution" method. Unfortunately, the time required to find the global minimum with this method, even for a single échelle spectrum, is substantial and increases nonlinearly when working simultaneously with more than one spectrum. This issue also prevents error estimation via the Monte Carlo method. For this reason, a "pseudo" -statistical approach was used to determine the stellar parameters. In this approach, all observed spectra were paired iteratively, and the pairs were processed by the program. With 17 observed spectra, 136 pairs were analyzed. For each solution, the mass ratio q was calculated using the formula $q = (V_1 - \gamma)/(\gamma - V_2)$, where γ is the systemic heliocentric velocity of the V454 Aur system, and V_1 and V_2 are the measured velocities of each star for

each observation pair. Unstable solutions that deviated significantly from the mean value of q were discarded (approximately 30% of the solutions) through iterative filtering at the 2.5σ level. The remaining solutions were used to calculate the means and their uncertainties for the parameters of each component: temperature Teff, projected rotational velocity v sin i, metallicity [Fe/H], and contribution to the flux at a wavelength of 5500 Å. The physical parameters of the stellar components and their uncertainties determined in this way are presented in Table 2 .

(4) The calculated barycentric velocities for both components of the V454 Aur system at specific epochs, along with their associated uncertainties, are presented in Table 1 . The results of modeling these velocities with the FBS program, in the form of calculated radial velocity curves as a function of the observational phase, are shown in Figure 3 [Figure 3: see original paper]. The derived orbital parameters of the V454 Aur system components and their uncertainties are listed in Table 3 . We also utilized published orbital velocities from Griffin (2001) and modeled the parameters of the V454 Aur components using the FBS program, comparing them with the parameters obtained from our observations. The results of modeling these velocities with the FBS program are also shown in Figure 3, and the derived orbital parameters of the V454 Aur components are listed in Table 3. The comparison shows that the orbital parameters of the system agree well within the uncertainties. However, the data from Griffin (2001) exhibit twice the scatter compared to our data, despite having a significantly larger number of observational points–52 measurements versus 17. The epoch of the primary minimum also agrees very well within the uncertainties, indicating that no significant apsidal motion is observed in the spectral data over the past 22 yr.

(5) As the first step in working with ELISA, the radial velocity curve data provided in Table 1 were analyzed. Unlike the FBS package, ELISA uses the mass ratio $q = M_2/M_1$ and the parameter F as input and output parameters. Initial values for these parameters were taken from the results of the FBS analysis, as shown in the corresponding column. The results of ELISA for modeling radial velocity curves and estimating parameter uncertainties based on posterior distributions using MCMC are also presented in Table 3 . To ensure good statistical reliability in evaluating parameter values and their uncertainties, 400,000 solutions were generated with MCMC. The first 100,000 generations were discarded to eliminate autocorrelation effects, and the remaining generations were used to calculate mean values and confidence intervals. The orbital parameter values from both programs agree within the uncertainties. The corner plot of the posterior distributions for the determined orbital parameters is shown in Figure 4 [Figure 4: see original paper]. It reveals that most parameters exhibit weak correlations with each other, with the exception of the pairs e-ω and e-F which show moderate correlation coefficients of approximately 0.5 and −0.5, respectively.

(6) Using the derived orbital parameters, the calculated mass ratio q = M_2/M_1, and the physical parameters of the components such as metallicity, Teff, and log g, the TESS light curve was analyzed. The temperatures of the components and the metallicity were considered fixed and taken from Table 2, with the components assumed to be synchronized in the sense of Equation (3). The variable parameters included the surface potential of each component $\Omega_1,_2$, the inclination angle of the system i, as well as the system' s eccentricity e and longitude of periastron ω. While the values of e and ω were already known from modeling the radial velocity curves, the high-precision TESS light curve allowed for their refinement, despite the known correlation between these parameters, as illustrated in Figure 4.

The orbits of the components of the V454 Aur system are shown in Figure 5 [Figure 5: see original paper], and the brightness curve is displayed in Figure 6 [Figure 6: see original paper]. In Figure 5, the observer views the system from the left, and phase 0 (eclipse of the hotter component) corresponds to the alignment of both components along the Y-axis at Y = 0.

Modeling of the brightness curve reveals that the eclipse of the hotter component A of the V454 Aur system is "more partial" than the eclipse of the cooler component B. As a result, the "true" primary minimum, corresponding to the hotter component, is not as deep as the secondary minimum. Consequently, the minima appear "switched" on the brightness curve, as shown in Figures 6 and 5. Once this fact was understood, further modeling posed no difficulties. Using only five variables ($\Omega_1,_2$, i, e, ω), we were able to construct a model with a precision of approximately 0.1% (^{2} = 0.999). The use of various limb darkening laws available in ELISA led to differences in the model fit only in the fifth decimal place. Ultimately, we chose the "square root" law, which performed slightly better than the linear or logarithmic options. The reflection parameter (albedo) was used with its default value, as it did not affect the model quality, which is reasonable in this case.

Subsequently, uncertainties were estimated based on posterior distributions constructed using the MCMC method with 400,000 model generations. The first 150,000 generations were discarded and the remaining generations were used to calculate mean values and confidence intervals. The final results and their confidence intervals are presented in Table 4 . The resulting model, based on these parameter values, is shown in Figure 6, and the posterior distributions of the fitted parameters ($\Omega_1,_2$, i, e, ω) are displayed in Figure 7 [Figure 7: see original paper].

6.1. Comparison of Obtained Parameters for V454 Aur System

Figure 8 [Figure 8: see original paper] shows a comparison of the luminosities, masses, and radii of MS stars from Southworth (2015) with the derived values for both components of the V454 Aur system from this work and the NN Del system (Kniazev 2020). The comparison of our derived characteristics for the V454 Aur components with published data demonstrates that the properties of V454 Aur fully align with the masses, luminosities, and radii of previously studied stars.

We also independently estimated the distance to V454 Aur and compared it with the distance derived from the latest Gaia satellite data (Gaia Collaboration et al. 2016, 2023). The Gaia parallax (Gaia Collaboration 2020) translates to a distance of DistGaia = 65.07 ± 0.09 pc. We used the V = 7.65 ± 0.01 mag value for V454 Aur from the Tycho-2 catalog (Høg et al. 2000), bolometric corrections interpolated from Straizys & Kuriliene (1981), bolometric luminosities from Table 4, and extinction E(B − V) from Table 2. The calculations were performed in Python using the uncertainties package, which facilitates the computation of output parameter uncertainties while accounting for input parameter errors. The resulting distance, DistOur = 65.17 ± 0.32 pc, agrees very well with the distance calculated from Gaia data, within the uncertainties. The primary source of error in this estimation is the precision of the photometric data.

As noted earlier in Section 1, two recent papers (Southworth 2024; Yucel et al. 2024) have been published with a detailed study of the V454 Aur system. Both studies used radial velocity and TESS photometric data, which are also utilized in our work. Table 5 summarizes the main parameters of the V454 Aur system obtained in all three studies. Since both earlier studies were based on the same spectroscopic data, the mass ratio, and consequently the stellar masses derived, are similar and differ from those obtained in our study. However, this difference does not exceed $2{-}3\sigma$ of the total error for component A and $1.5{-}2\sigma$ for component B. Similarly, the size of the semimajor axis (a), and the derived radii and inclination are in comparable agreement. Overall, this is an excellent match, given that all three studies used different software packages for modeling binary systems.

The situation is notably worse for the determined orbital period, where the difference between the value obtained in our work and that from Yucel et al. (2024) corresponds to 4.9σ of the total error. The comparison of the system’ s eccentricity is even more striking: the difference between our value and that of Yucel et al. (2024) amounts to 18σ, while the difference between our value and that of Southworth (2024) reaches 28σ. This discrepancy may stem from methodological differences, or the reported uncertainties in those studies may be underestimated. The comparison of the temperatures of both system components, which were determined from échelle spectra in our study, from photometric data in Yucel et al. (2024), and using the surface brightness ratio in Southworth (2024), shows agreement within less than one σ of the total error.

Our spectroscopic data allowed us to directly determine the metallicity of V454 Aur as [Fe/H] = −0.17 ± 0.02 dex. This value agrees well with the metallicity [Fe/H] = −0.14 reported by Holmberg et al. (2009) and somewhat less so with [Fe/H] = −0.08 determined by Casagrande et al. (2011) based on spectroscopic and photometric data from the Geneva-Copenhagen Survey (Nordström et al. 2004). These values are notably different from the metallicity determinations of [Fe/H] = −0.02 dex and [Fe/H] = 0.0 dex reported by Yucel et al. (2024) and Southworth (2024), respectively, where the authors derived the metallicity of V454 Aur using evolutionary tracks, i.e., by an indirect method.

6.2. Is the System V454 Aur Synchronized?

We began our study of long-period DLEB systems under the assumption that these systems are examples where the components do not influence each other' s evolution, and therefore, the stellar evolution in such systems serves as a true representation of single-star evolution. According to this assumption, we are particularly interested in systems that are neither synchronized nor circularized. The V454 Aur system is certainly not circularized, as it has a significant eccentricity, but what can we say about its synchronization?

As mentioned in Section 4, the ELISA package includes a parameter responsible for synchronization and, by default, assumes that the stars are synchronized. In our modeling, the value of this parameter was found to be F = 2.4414 ± 0.0015, as derived from Equation (3), suggesting that the stars in V454 Aur are either already synchronized or close to synchronization. Attempts to treat the parameter F as a free variable in the modeling did not lead to changes in its value, and adjusting F far from the initial value resulted in a deterioration of the model. Thus, we conclude that our initial assumption of entirely independent evolution for each component in this system appears to be incorrect, as synchronization is a result of tidal interactions between the stars. This naturally raises the question: how does synchronization affect the evolution of both components, and can we observe its influence in some way?

6.3. Evolutionary Status and Age of V454 Aur

Assuming that the studied binary star is a detached system where the components do not influence each other' s evolution, the evolutionary status of the components can be assessed based on single-star evolutionary models. In Gallenne et al. (2019), it was demonstrated that the results from the PARSEC (PAdova and TRieste Stellar Evolution Code; Bressan et al. 2012), BaSTI (Bag of Stellar Tracks and Isochrones; Pietrinferni et al. 2004), and MIST (MESA Isochrones and Stellar Tracks; Choi et al. 2016) models are very similar. Therefore, in this work, we used only the MIST models. Given that the masses of the V454 Aur components are known with high accuracy, we extracted evolutionary tracks for stars of these masses from the MIST database and analyzed the positions of each component on these tracks for metallicities [Fe/H] = −0.17 dex, −0.10, and 0.0. The results are presented in Figure 9 [Figure 9: see original paper], which displays sections of the evolutionary tracks in coordinates log Teff-log L, log g-log Teff, and log R-log Teff, along with the positions of both components of V454 Aur. From the figure, it is evident that to match the evolutionary tracks for the given mass and metallicity, both components need to be approximately 200–300 K hotter. Since we know with certainty that no mass transfer occurred between the components, it is reasonable to hypothesize that this offset results from the influence of synchronization on the evolution of the components. It should be noted that the differences between MIST models with v/vcrit = 0 and v/vcrit = 0.4 are minimal, and these tracks are indistinguishable.

How observable is the discovered effect in other binary systems similar to V454 Aur? We examined all DLEBs listed in Table IV of Griffin (2001), which includes 14 binary systems with properties similar to those of V454 Aur. The V454 Aur system itself is also included in this table. Upon analysis, approximately half of the systems listed have only indirect metallicity estimates and can therefore be excluded from the comparison. All other DLEBs in this table, where metallicity was determined directly using spectroscopy, exhibit, to varying degrees, a similar type of offset toward cooler temperatures relative to the evolutionary track for the given mass and metallicity. Since we hypothesize that this effect may reflect the degree of synchronization within the system, this is quite logical. Additionally, in our study of the long-period system NN Del (P = 99.25 days; Kniazev 2020), consisting of two F-type stars, we also observed the same temperature offset for both components. In Kniazev (2020), we also verified that the determined metallicity is independent of the stellar models used in the FBS program.

A comparison of Figures 9 with 8 suggests that such a temperature offset should not result in significant deviations in radius or luminosity. Therefore, we attempted to estimate the age of the system by minimizing the following function:

$^{2} = \Sigma$ [(log L ,obs - log L ,mod)$^{2}/\sigma^{2}$log L + (log R ,obs - log R ,mod)$^{2}/\sigma^{2}$log R]

where the summation is over both components (i = 1, 2), Δ represents the logarithmic difference between the model and the observed value, and σ is also used in logarithmic scale. The search was performed for each model metallicity under the assumption that both components of the system share the same metallicity. For a metallicity of [Fe/H] = -0.17 dex, the age of the V454 Aur system is estimated to be 1.18 ± 0.10 Gyr, while for [Fe/H] = 0.0 dex, the age is estimated at 2.77 ± 0.30 Gyr. In both cases, as shown in Figure 9, both components are on the MS. Our age estimate agrees very well with the age of 1.19 ± 0.09 Gyr derived by Yucel et al. (2024), where the authors performed evolutionary modeling for the binary system with parameters of V454 Aur.

7. Conclusions

The long-period eclipsing binary star V454 Aur was studied using spectroscopic data obtained with the échelle spectrograph UFES, mounted on the 1.21 m telescope of the Kourovka Astronomical Observatory at Ural Federal University, and photometric data from the TESS satellite. A radial velocity curve was constructed based on 17 spectra obtained between 2021 and 2023, covering the entire phase space of velocity variations for this binary system. Spectral data, radial velocity curves, and photometric data were modeled, and the orbital and absolute parameters of the V454 Aur system components were determined. Using spectroscopic data, the effective temperatures of both components and the system' s metallicity were directly estimated. Our modeling based on TESS photometric data suggests that both components in the system are synchronized or close to synchronization. The obtained parameters of the V454 Aur system components were compared with the evolutionary tracks of MIST models, and the age and evolutionary status of both components were evaluated. Comparison with model tracks revealed a systematic offset toward cooler temperatures relative to the evolutionary tracks for the given mass and metallicity. It was found that a similar temperature offset exists in a significant number of binary systems with properties similar to V454 Aur, and it was proposed that this offset is a result of the interaction between the components due to synchronization.

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