Fundamental parameters for dEB SB2 binary system J064726.39+223431.6. A new challenge for stellar evolution models.

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ABSTRACT

We present a study of eclipsing binary J064726.39+223431.6 using spectra from the LAMOST-MRS and TESS photometry. We use full-spectrum fitting to derive radial velocities and spectral parameters: $T_{\text{eq}}$, $\varv$, $\log g$, $A_B$, and $[\text{Fe/H}]_{A,B}$, and their radii to be $R_{A,B}$ = 1.405 ± 0.052, 1.219 ± 0.060 $R_\odot$, and $R_{\odot}$ resulting in surface gravities $\log (g)_{A,B}$ = 4.259 ± 0.033, 4.319 ± 0.042 (cgs). Theoretical models cannot match all of these properties, predicting significantly higher $T_{\text{eff}}$ for a given metallicity. Derived age of the system 1.56 Gyr indicates that both components are younger than Sun. J064726.39+223431.6 is a good candidate for high-resolution spectroscopic analyses.

Key words: stars : fundamental parameters – binaries : spectroscopic – stars individual: J064726.39+223431.6

1 INTRODUCTION

Binary stellar systems are very important objects for astronomy, since they allow us to learn more than from single stars. For example observations of the periodic eclipses and changes in line-of-sight velocities (RV) to directly measure sizes and masses of the stellar components, if orbital inclination is high enough. Such measurements are very useful to constrain theoretical models of stellar evolution.

Many double-lined spectroscopic binaries (SB2) were identified in Kovalev (2022) based on LAMOST (Large Sky Area Multi-Object fiber Spectroscopic Telescope) medium resolution spectra (Liu et al. 2020) and we selected one previously known detached eclipsing binary (dEB) star with large RV semiamplitude based on Wang et al. (2021) to estimate physical parameters for both components in this system. Variable Star indEx (Watson et al. 2006) database contains it as Algod type variable under ID: 167003 with observations available in ZTF (Chen et al. 2020) and ASAS-SN V (Jayasinghe et al. 2018). It is included in the recent Gaia DR3 (Gaia Collaboration et al. 2022) as 337862653860701568 with $G = 13.416055±0.002923$ mag and parallax $\varpi = 0.8915±0.0177$ mas. This star is included in the TESS input catalogue (TIC Stassun et al. 2019) as TIC57046871, with no light curve (LC) data publicly available on MAST portal yet.

In this paper we use LAMOST-MRS spectra and additional photometrical data to measure physical parameters for both stars in this system. The paper is organised as follows: in Sections 2,3 we describe the observations and methods. Section 4 presents our results. In Section 5 we discuss the results in context of binary system evolution. In Section 6 we summarise the paper and draw conclusions.

2 OBSERVATIONS

2.1 Spectra

LAMOST (Large Sky Area Multi-Object fiber Spectroscopic Telescope; also known as Guo Shou Jing telescope) is a 4-meter quasi-meridian reflective Schmidt telescope with 4000 fibers installed on its 5-degree-FoV focal plane. These configurations allow it to observe spectra for at most 4000 celestial objects simultaneously (Cui et al. (2012); Zhao et al. (2012)). All available spectra were downloaded from www.lamost.org under the designa-
tion J064726.39+223431.7. We use the spectra taken at a resolving power of $R=1/\Delta \lambda \approx 7500$. Each spectrum is divided on two arms: blue from 4950 Å to 5350 Å and red from 6300 Å to 6800 Å. We convert the heliocentric wavelength scale in the observed spectra from vacuum to air using PyAstronomy (Czesla et al. 2019). Observations are carried out from 2019-11-19 till 2021-02-19, covering 16 nights with time base of 480 days. As period is short ($P = 1.217 \pm 0.029$ hrs) we analysed spectra taken during 20 individual minutes exposures, unlike Kovalev et al. (2022) where spectra stacked for the whole night were used. We discarded all spectra taken on three exposures, unlike Kovalev et al. (2022) where spectra stacked for previous stage as an input, see Section 3.1.2.

2.2 Photometry

We download publicly available ZTF light curves (LC)\(^2\). These LC contain 14444 datapoints in $r$ and 370 datapoints in $g$ bands and cover timebase 1240 d and 1125 d respectively. We also download LC in $V$ band from ASSAS-SN portal\(^3\). It contains only 183 datapoints and covers timebase 1212 d. After phase-folding of these LC with the period we found that only ZTF LC from $r$ band has good coverage of eclipses, therefore we use it only in the further analysis.

The Transiting Exoplanet Survey Satellite (TESS Ricker et al. 2015) mission observed this star in two sectors 44 and 45, which covers ~27 days each. The LCs are not available on MAST portal\(^4\), instead we used eleanor (Feinstein et al. 2019; Brasseur et al. 2019) to extract the LC datasets. We use default settings and clip the edges of the LC, as they have some processing artifacts, see Figure 1. After the clipping LCs contain 2953 and 3160 datapoints for sectors 44 and 45 respectively and have relative (non-calibrated) stellar magnitudes. The background subtraction is not optimal for these datasets, therefore we analyse them separately.

3 METHODS

3.1 Spectral fitting

Our spectroscopic analysis includes two consecutive stages:

(i) analysis of individual observations by binary and single-star spectral models, where we normalise the spectra and make rough estimation of the spectral parameters, see brief description in Section 3.1.1.

(ii) simultaneous fitting of multiple-epochs with a binary spectral model, using constraints from binary dynamics and values from the previous stage as an input, see Section 3.1.2.

LAMOST-MRS implementation of this method was first presented in Kovalev et al. (2022).

3.1.1 Individual spectra.

Single-star spectral model is described in Appendix A. The normalised binary model spectrum is generated as a sum of the two Doppler-shifted normalised single-star model spectra $f_{\lambda,\text{single}}$ and $f_{\lambda,\text{binary}}$ scaled according to the difference in luminosity, which is a function of the $T_{\text{eff}}$ and stellar size. We assume both components to be spherical and use following equation:

$$ f_{\lambda,\text{binary}} = f_{\lambda,\text{single}} \frac{k_4}{1 + k_4}, \quad k_4 = \frac{B_4(T_{\text{eff,1}}) M_1}{B_4(T_{\text{eff,2}}) M_2} 10^{\log(g_1)-\log(g_2)} $$

(1)

where $k_4$ is the luminosity ratio per wavelength unit, $B_4$ is the black-body radiation (Plank function), $T_{\text{eff}}$ is the effective temperature, $\log(g)$ is the surface gravity and $M$ is the mass. Throughout the paper we always assume the primary star to be brighter.

The binary model spectrum is later multiplied by the normalisation function, which is a linear combination of the first four Chebyshev polynomials (similar to Kovalev et al. 2019), defined separately for blue and red arms of the spectrum. The resulting spectrum is compared with observed one using scipy.optimize.curve_fit function, which provides optimal spectral parameters, radial velocities (RV) of each component plus mass ratio and two sets of four coefficients of Chebyshev polynomials. We keep metallicity equal for both components. In total we have 18 free parameters for a binary fit. We estimate goodness of the fit parameter by reduced $\chi^2$:

$$ \chi^2 = \frac{1}{N - 18} \sum \left( \frac{f_{\lambda,\text{observed}} - f_{\lambda,\text{model}}}{\sigma_{\lambda}} \right)^2 $$

(2)

where $N$ is a number of wavelength points in the observed spectrum. To explore whole parameter space and to avoid local minima we run optimisation six times with different initial parameters of the optimiser. We select the solution with minimal $\chi^2$ as a final result.

Additionally, every spectrum is analysed by a single star model, which is identical to a binary model when both components have all equal parameters, so we fit only for 13 free parameters. Using this single star solution we compute the difference in reduced $\chi^2$ between two solutions and the improvement factor, computed using Equation 3 similar to El-Badry et al. (2018). This improvement factor estimates the absolute value difference between two fits and weights it by difference between two solutions.

$$ f_{\text{imp}} = \frac{\sum \left( \frac{f_{\lambda,\text{single}} - f_{\lambda}}{\sigma_{\lambda}} \right)^2}{\sum \left( \frac{|f_{\lambda,\text{single}} - f_{\lambda,\text{binary}}|}{\sigma_{\lambda}} \right)^2} $$

(3)

where $f_{\lambda}$ and $\sigma_{\lambda}$ are the observed flux and corresponding uncertainty, $f_{\lambda,\text{single}}$ and $f_{\lambda,\text{binary}}$ are the best-fit single-star and binary model spectra, and the sum is over all wavelength pixels.

3.1.2 Multiple-epochs fitting.

We explore results from the fitting of the individual epochs and find that result’s quality clearly depends on separation of RVs. Clear double-lined spectra show that spectral lines are significantly broadened ($V \sin i \approx 60$ km s$^{-1}$), thus at phases near the conjunctions our fitting algorithm often cannot reliably separate primary/secondary contributions. Fortunately we can automatically separate good results with clear double-lines using $f_{\text{imp}}$. Thus we decided to use only five individual spectra with highest $f_{\text{imp}}$ in multi-epoch fitting.

If two components in our binary system are gravitationally bound, their radial velocities should agree with the following equation:

$$ \text{RV}_A = \gamma_\text{dyn}(1 + q_\text{dyn}) - q_\text{dyn}\text{RV}_B, $$

(4)

where $q_\text{dyn} = M_B/M_A$ - mass ratio of binary components and $\gamma_\text{dyn}$

\(^2\) https://irsa.ipac.caltech.edu/cgi-bin/ZTF/nph_light_curves

\(^3\) https://asas-sn.osu.edu/variables/KP24824756
- systemic velocity. Using this equation we can directly measure the systemic velocity and mass ratio. To reduce the number of free parameters in multiple-epochs fitting we use only \( \text{RV}_A \) and computed \( \text{RV}_B \) using Equation 4. The same value of mass ratio is used in Equation 1. Unlike the previous stage we fit \([\text{Fe/H}]\) for both components. In total we fit for 15 free parameters. We fit five previously normalised individual epoch’s spectra with maximal improvement factor, using their binary spectral parameters values for initialisation. We select the solution with minimal \( \chi^2 \) as a final result.

### 3.1.3 Typical errors estimation

We estimate typical errors of the multiple-epochs fitting by testing it’s performance on the dataset of synthetic binaries. We generated 3000 mock binaries using uniformly distributed mass-ratios from 0.7 to 1.0, \( T_{\text{eff}} \) from 4600 to 8400 K, \( \log (g) \) from 2.6 to 4.6 (cgs) and \( V \sin i \) from 1 to 100 km s\(^{-1}\). Metallicity was set to \([\text{Fe/H}] = 0.0\) dex in both components. For each star, we computed 5 mock binary spectra using radial velocities computed for circular orbits with the semiamplitude of the primary component 20 km s\(^{-1}\) at randomly chosen phases. These models were degraded by Gaussian noise according to \( S/N = 100 \) pix\(^{-1}\). We performed exactly the same analysis as for the observations on this simulated dataset. We checked how well the mass ratio and the spectral parameters of the primary and secondary components can be recovered by calculating the average and standard deviation of the residuals. For the primary components we have \( \Delta T_{\text{eff}} = 95 \pm 239 \) K, \( \Delta \log (g) = 0.07 \pm 0.14 \) cgs units, \( \Delta V \sin i = -1 \pm 12 \) km s\(^{-1}\) and \( \Delta [\text{Fe/H}] = -0.02 \pm 0.08 \) dex. For the secondary components we have \( \Delta T_{\text{eff}} = 35 \pm 364 \) K, \( \Delta \log (g) = 0.05 \pm 0.21 \) cgs units, \( \Delta V \sin i = -3 \pm 21 \) km s\(^{-1}\) and \( \Delta [\text{Fe/H}] = 0.04 \pm 0.18 \) dex. The mass ratio recovery has \( \Delta q = 0.05 \pm 0.15 \).

### 3.2 Orbital fitting

To get orbital solution we select 55 RVs of the primary component separated by at least 60 km s\(^{-1}\) from the systemic velocity \( \gamma \). RVs close to \( \gamma \) can be affected by the Rossiter-McLaughlin (RM) effect (Rossiter 1924; McLaughlin 1924), as several spectra were possibly taken during eclipses, thus we don’t use them in orbital fitting. We collect all RV measurements in Table 1.

In the next step, selected \( \text{RV}_A \) are used to fit circular orbits using generalised Lomb-Scargle periodogram (GLS) code by Zechmeister & Kürster (2009):

\[
\text{RV}_A(t) = \gamma - K_A \sin \left( \frac{2\pi}{P} (t - t_0) \right),
\]

where \( \gamma \) - systemic velocity, \( P \) - period, \( t_0 \) - conjunction time, \( K \) - radial velocity semiamplitude.

We also fit to a Keplerian orbit and find that eccentricity is equal to zero, so a circular orbit is a valid assumption.

### 3.3 Light curve fitting

We used JKTEBOP code (version 40)\(^4\) by Southworth (2013) to simultaneously fit the LC and RV timeseries. We used only ZTF \( r \) band and TESS datasets, because of their better coverage of the eclipses. Unlike GLS, JKTEBOP allows us to fit RVs measured for both components. Our fitting was initialised using \( P, t_0, \gamma \) values from the GLS fit. We used tables of the limb/gravity darkening coefficients from Claret & Bloemen (2011); Claret (2017) and linearly interpolated them for spectral parameters from multiple-epochs fits. We used four-parameter limb darkening coefficients \( c_i, i = 1, 4 \). We took into account useful comment by Torres (2021) on the usage of gravity darkening coefficients in JKTEBOP.

The systemic velocity was fitted for both binary components. Additionally we fit for a “third” light contribution \( L_3 \) and the nuisance parameter the out-of-eclipse magnitude \( S_0 \) for all three datasets. In total we fit for 16 parameters: \( J \) the central surface brightness ratio, \( (R_A + R_B)/a \) the ratio of the sum of stellar radii to the semimajor axis, \( R_B/R_A \) the ratio of the radii, \( i \) the inclination, \( e \cos \omega, e \sin \omega \) the eccentricity multiplied by the cosine and sine of the periastron longitude, reflected light \( i_A, i_B \), \( P \) the period, \( t_0 \), semiamplitudes and systemic velocities \( K_{A,B}, \gamma_{A,B}, L_3 \) and \( S_0 \). We use integration ring size 5º for the ZTF \( r \) and 1º for the TESS LCs.

At first we run JKTEBOP code in the mode “Task 4” to discard outliers larger than three sigma and allow it adjusting observational errors through several iterations until reduced \( \chi^2 \) will reach unity.

\(^4\) JKTEBOP is written in FORTRAN77 and the source code is available at http://www.astro.keele.ac.uk/jkt/codes/jktebop.html
This removes 24, 17, 13 datapoints from ZTF radial velocity measurements. The asterisk (*) denotes data-points which are not used in analysis with GLS and JKTEBOP. We subtract 2400000.5 days from time values.

### Table 1 – continued

| HJD | multiple-epochs | ind. epoch | single |
|-----|-----------------|------------|--------|
|     | RVₐ, km s⁻¹      | RVₐ, km s⁻¹| RVₐ, km s⁻¹|
| 58806.74 | -169.77 ± 2.50, 98.54 ± 2.07 | -7.01 |
| 58806.76 | -159.21 ± 2.72, 103.66 ± 1.71 | -1.42 |
| 58806.78 | -159.98 ± 1.02, 106.50 ± 0.70 | -5.79 |
| 58806.79 | -158.66 ± 1.12, 106.87 ± 0.80 | 2.57 |
| 58806.81 | -158.83 ± 0.97, 103.80 ± 0.68 | -5.38 |
| 58806.82 | -155.77 ± 1.06, 103.79 ± 0.72 | -7.45 |
| 58806.84 | -152.48 ± 1.11, 103.31 ± 0.72 | -0.87 |
| 58806.86 | -151.16 ± 1.10, 96.59 ± 0.79 | -9.72 |
| 58820.77 | 124.71 ± 0.89, -141.97 ± 0.66 | -20.69 |
| 58820.78 | 124.27 ± 0.97, -139.47 ± 0.66 | -26.77 |
| 58820.79 | -140.06 ± 0.57 | -23.63 |
| 58820.80 | 123.54 ± 0.92, -140.18 ± 0.64 | -23.63 |
| 58820.81 | 121.96 ± 1.00, -139.56 ± 0.69 | -23.63 |
| 58820.82 | -129.94 ± 1.00, -139.70 ± 0.73 | -16.79 |
| 58820.83 | 123.32 ± 0.92, -138.43 ± 0.68 | -19.63 |
| 58835.74 | 121.06 ± 1.01, -137.90 ± 0.67 | -26.18 |
| 58835.75 | 3.96 ± 1.90, -40.86 ± 2.70* | -12.50 |
| 58835.77 | 24.66 ± 1.34, -45.46 ± 1.58* | -9.52 |
| 58835.78 | 22.22 ± 1.08, -64.15 ± 1.63* | -9.63 |
| 58856.64 | 30.49 ± 0.91, -74.37 ± 1.36* | -10.97 |
| 58856.66 | -149.11 ± 1.20, 96.22 ± 0.84 | 0.62 |
| 58856.67 | -154.25 ± 1.13, 98.60 ± 0.87 | -8.63 |
| 58856.68 | -157.34 ± 1.25, 105.04 ± 0.90 | -2.20 |
| 58856.69 | -157.91 ± 0.99, 105.83 ± 0.71 | -12.86 |
| 58856.70 | -158.98 ± 1.20, 105.49 ± 0.84 | -6.12 |
| 58856.71 | -158.31 ± 1.05, 106.23 ± 0.83 | -12.57 |
| 58856.72 | -27.99 ± 3.65, -9.49 ± 2.36* | -16.65 |
| 58856.68 | -39.85 ± 3.50, 0.21 ± 2.98* | -21.37 |
| 58856.70 | -41.39 ± 2.49, 9.52 ± 3.42* | -20.35 |
| 58856.72 | -43.71 ± 1.84, 25.16 ± 2.84* | -22.23 |
| 58883.56 | 100.76 ± 0.46 | -8.13 |
| 58883.57 | -154.79 ± 0.85, 101.26 ± 0.63 | -8.13 |
| 58883.58 | -151.01 ± 0.91, 98.86 ± 0.67 | -8.01 |
| 58883.59 | -145.40 ± 1.23, 93.86 ± 0.88 | -8.07 |
| 58883.61 | -140.24 ± 1.00, 88.66 ± 0.72 | -8.89 |
| 58883.62 | -132.46 ± 0.95, 83.10 ± 0.72 | -13.08 |
| 58889.54 | 155.40 ± 0.78, 100.59 ± 0.59 | -6.28 |
| 58889.55 | 157.68 ± 0.91, 103.44 ± 0.63 | -3.97 |
| 58889.57 | 158.45 ± 1.17, 106.64 ± 0.86 | -3.32 |
| 58889.58 | -157.72 ± 1.20, 105.39 ± 0.87 | -5.89 |
| 58889.60 | -159.82 ± 1.15, 106.04 ± 0.86 | -10.49 |
| 58889.62 | -157.74 ± 1.38, 104.89 ± 1.03 | -7.40 |
| 58889.63 | -157.47 ± 1.70, 103.59 ± 1.28 | -7.53 |
| 58919.48 | 120.69 ± 1.05, -134.31 ± 0.73 | -25.05 |
| 58919.50 | 115.05 ± 0.93, -131.58 ± 0.65 | -23.05 |
| 58919.52 | 115.08 ± 1.11, -127.50 ± 0.75 | -13.90 |
| 58919.53 | 103.32 ± 1.31, -120.86 ± 0.84 | -25.18 |
| 58919.55 | 100.36 ± 1.10, -116.91 ± 0.76 | -17.02 |

### Table 2. GLS orbit

| Parameter | Value |
|-----------|-------|
| P, d      | 1.217770 ± 0.000003 |
| bₒ, HJD d | 245880.8088 ± 0.0003 |
| Kₒ, km s⁻¹ | 122.80 ± 0.23 |
| Γₐ, km s⁻¹ | -16.98 ± 0.16 |

### 4 RESULTS

In the Figure 2 we show the best fit by multiple-epochs binary model for epoch with maximal RV separation. We zoom into the wavelength range around the magnesium triplet and Hα and in a 70 Å interval in the red arm, where many double lines are clearly visible. Both components are on main sequence, where the primary star (Tₑff = 6104 K, log (g) = 3.86 cgs, [Fe/H] = -0.29 dex, V sin i = 58 km s⁻¹) contributes about 70% in the visible light, while the secondary star (Tₑff = 5980 K, log (g) = 4.07 cgs, [Fe/H] = 0.02 dex, V sin i = 50 km s⁻¹) and contributes to the remaining 30%. Primary RVs derived in multi epochs fit almost identical to ones estimated from individual spectra. The derived mass ratio q = 0.87 and systemic radial velocity ν = -17.63 km s⁻¹. Additionally we make another multi epochs fit assuming same metallicity for both components, finding that it caused slight change in Tₑff and log (g) with two components being metal-poor with [Fe/H] = -0.19 dex. We present all spectroscopic results in the Table 4. We can use q and Δ log (g) to estimate ratio of stellar sizes Rₛ / Rₐ = 0.73, 0.81 for solution with different and same metallicity. The errors in the
Figure 2. Example of the spectrum fitting. The observed spectrum is shown as a gray line, the best fit is shown as red line. The primary component is shown as the orange line, the secondary as a blue line. The difference O-C is shown as a green line.

spectral parameters provided by scipy.optimize.curve_fit are nominal and largely underestimated, so we omit them.

In Figures 3, 4, 5 we show best fits of the LCs (top) and RVs (bottom) by JKTEBOP. The fit residuals (O-C) are typically small ($\leq 0.10$ mag for ZTF $r$, $\leq 0.02$ mag for TESS and $\leq 5$ km s$^{-1}$ for RVs). Only one measurement for RV$_B$ is off by $\sim -15$ km s$^{-1}$. The derived systemic velocities are very similar to the values derived from multiple-epoch spectral fit. Orbital solutions for primary star from GLS and JKTEBOP agree well taking to account uncertainties. Very small value for eccentricity ($e \leq 0.002$) confirms that orbit is circular or very close to it. The orbital solution from Table 3 in Wang et al. (2021) has $e = 1$ and $K_A = 544$ km s$^{-1}$, which is wrong due to failed optimisation. Third light contributions are significant in both TESS datasets (12 and 29 per cent) and negligible in ZTF $r$. This is not surprising due small aperture of TESS cameras relative to one in telescopes used for ZTF. Oblateness of the components ($0.017, 0.007$ for ZTF $r$ and $0.013, 0.011$ for TESS) is small ($\leq 0.04$), thus JKTEBOP provides reliable solution for this system (Popper & Etzel 1981). We show “corner” plots with all RP simulations in Figures C1, C2, C3, where correlations between fitted parameters can be explored. We present results from GLS and JKTEBOP in the Tables 2, 3.

4.1 Verification with PHOEBE

We use PHOEBE (Conroy et al. 2020) to verify our results, since it allows to fit multiple LC datasets simultaneously, and updates limb darkening coefficients during the fitting. For all three LCs we convert magnitudes to fluxes and divided them by median value. We also subtract best fit $t_0$ from the timescale in all datasets. We use default Nelder-Mead optimiser and default “ck2004” atmospheres. Eccentricity, period and mass ratio were fixed, thus we

$^5$ Two additional LC datasets (ZTF $g$ and ASAS-SN $V$) were also fitted, but provided poor results not consistent with ZTF $r$, TESS and spectroscopic fits ($R_B > R_A$), possibly due to poor coverage of eclipses.
Table 3. JKTEBOP solutions

| Parameter | ZTF r | TESS 44 | TESS 45 |
|-----------|-------|---------|---------|
| fixed:    |       |         |         |
| Grav. darkening A | 0.3108 | 0.2576  |         |
| Grav. darkening B | 0.3317 | 0.2760  |         |
| Limb darkening c A, i | 0.3029, 0.8903, -0.7099, 0.2098 | 0.4002, 0.4901, -0.3288, 0.0638 |
| Limb darkening c B, i | 0.3420, 0.7173, -0.4286, 0.0838 | 0.4427, 0.3238, -0.0893, -0.0390 |

| fitted: |       |         |         |
| J   | 0.762±0.025 | 0.770±0.005 | 0.772±0.019 |
| (R A + R B)/α | 0.3935±0.0006 | 0.4063±0.0013 | 0.4052±0.0033 |
| R B/R A | 0.667±0.065 | 0.868±0.076 | 0.840±0.152 |
| i° | 83.77±1.74 | 81.66±0.29 | 81.13±0.74 |
| e cos ω | 0.0015±0.0009 | 0.0000±0.0001 | 0.0003±0.0003 |
| e sin ω | -0.0018±0.0019 | -0.0014±0.0019 | -0.0021±0.0021 |
| reflected light A, mag | 0.010±0.005 | -0.003±0.001 | 0.005±0.002 |
| reflected light B, mag | 0.010±0.005 | 0.003±0.001 | 0.010±0.002 |
| L₅, per cent | 4.33±9.87 | 12.04±1.95 | 29.49±3.93 |
| S₀, mag | 13.58±0.006 | -0.009±0.002 | -5.546±0.002 |
| Pₐ | 1.217783±0.000001 | 1.217785±0.000002 | 1.217785±0.000002 |
| t₀, HJD d | 2458808.80418±0.0000334 | 2458808.805166±0.0000972 | 2458808.805001±0.0000977 |
| K A, km s⁻¹ | 122.95±0.21 | 122.99±0.20 | 122.99±0.25 |
| K B, km s⁻¹ | 142.39±0.33 | 142.44±0.35 | 142.44±0.34 |
| γ A, km s⁻¹ | -17.15±0.13 | -17.04±0.11 | -17.06±0.13 |
| γ B, km s⁻¹ | -17.46±0.24 | -17.39±0.22 | -17.57±0.22 |

Table 4. Spectral parameters.

| Parameter | Star A | Star B |
|-----------|--------|--------|
| multy-epochs fit with free [Fe/H] |       |        |
| γ, km s⁻¹ | -17.61±0.28 | -17.54±0.28 |
| q_syn | 0.87 | 0.87 |
| T eff, K | 6104 | 6177 |
| log (g), cgs | 3.86 | 3.88 |
| [Fe/H], dex | -0.29 | -0.19 |
| V sin i, km s⁻¹ | 58 | 59 |

| multy-epochs fit, assuming same [Fe/H] |       |        |
| γ, km s⁻¹ | -17.54±0.28 |
| q_syn | 0.87 |
| T eff, K | 6104 |
| log (g), cgs | 3.88 |
| [Fe/H], dex | -0.19 |
| V sin i, km s⁻¹ | 59 |

| single-star fits of separated spectra |       |        |
| T eff, K | 6384 | 6384 |
| log (g), cgs (fixed) | 4.26 | 4.26 |
| [Fe/H], dex | 4.32 | 4.32 |
| V sin i, km s⁻¹ | 58 | 58 |

insignificant. All parameters agree with JKTEBOP values for TESS datasets, therefore our usage of fixed limb darkening coefficients is reasonable. The best fit T eff, B of the secondary agrees with spectroscopic estimate, but T eff, A is 250 K higher. Computed V sin i are in excellent agreement with spectroscopic values. We don’t use any sampling techniques to estimate errors as PHOEBE calculations are very computationally expensive in comparison with JKTEBOP.

4.1.1 RV during eclipses

By phase-folding the whole RV dataset we find that several spectra were taken exactly during eclipses. In Figure 6 we show RVs measured from these spectra together with the flux-weighted RV curves computed by PHOEBE using the best parameters. We can see that RM effect is not very strong, but it can be barely seen in our RVs data for primary eclipse.

4.2 Spectral separation.

We used “shift and add” algorithm described in González & Levato (2006) to extract rest-frame spectra for both components. We selected 24 spectra with S/N ≥ 40 and ΔRV > 180 km s⁻¹. All these spectra were previously normalised during binary model fitting as described in Section 3.1.1. Radial velocities were computed using
Figure 4. Phase-folded LC from TESS44 (top) and orbit (bottom) fits with JKTEBOP. In the bottom panels we show fit residuals O-C. The magnitudes are not calibrated.

Table 5. Parameters derived by PHOEBE.

| Parameter       | Star A | Star B |
|-----------------|--------|--------|
| fixed           |        |        |
| $q$             | 0.87   |        |
| $P d$           | 1.21778|        |
| $e$             | 0.00   |        |
| fitted          |        |        |
| $\gamma$, km s$^{-1}$ | -17.25 |        |
| $i^2$           | 81.63  |        |
| $a \sin i$, $R_\odot$ | 6.421  |        |
| $R_A$, $R_B$    | 1.427  | 1.219  |
| $T_{EB}$, K     | 6414   | 5873   |
| $L_3$ ZTF r, per cent | 0.0    |        |
| $L_3$ TESS 44, per cent | 12.0   |        |
| $L_3$ TESS 45, per cent | 30.4   |        |
| derived         |        |        |
| $M_A$, $M_B$    | 1.323  | 1.151  |
| log (g), cgs     | 4.251  | 4.327  |
| $V \sin i$, km s$^{-1}$ | 58.67  | 50.10  |

The seven iterations were enough to clearly reveal both spectral components, except for the spectral edges, where solutions start to oscillate around baseline. These separated spectra can be fitted by single-star spectral model. We fixed log (g) to values derived based on TESS 44 LC fit, as broad spectral features were poorly recovered in resulted spectra (González & Levato 2006). Additionally we fitted for four normalisation coefficients for each spectral arm and residual Doppler shift. Spectral errors were assigned to values corresponding to S/N = 100 for primary and S/N = 80 secondary. Regions at the spectral edges ($\lambda > 6770$ Å and $\lambda < 5000$ Å) and 40 Å around H$\alpha$ were assigned infinite errors. We show resulting best fits in Figure 7. Residual Doppler shifts were negligible $\Delta RV \leq 0.4$ km s$^{-1}$, as expected. For primary component we got $T_{eff} A = 6384$ K, [Fe/H]$_A = 0.02$ dex and $V \sin i_A = 58$ km s$^{-1}$ which is similar to results from multiple-epochs fit. Even masked H$\alpha$ region is modelled well. However we were unable to find good solution for secondary component which is consistent with results from multiple-epochs fit. We got much higher temperature $T_{eff} B = 6583$ K, probably due to masked H$\alpha$ line wings, although [Fe/H]$_B = -0.22$ dex and $V \sin i_B = 51$ km s$^{-1}$ were similar to results from multiple-epochs fit. We tried to fit these spectra again with H$\alpha$ region and found $T_{eff} A,B = 6407, 5920$ K, [Fe/H]$_A = 0.05, -0.81$ dex and $V \sin i_B = 57, 51$ km s$^{-1}$. This solution for secondary have acceptable temperature, but its metallicity is very small. Note that $V \sin i_A$ almost unchanged, therefore our spectroscopic analysis can provide stable recovery of this parameter.

Spectral separation results are less reliable in comparison with multiple-epochs fits, since they have lost information on relative contribution of the components and broad spectral features. We therefore don’t use them in further analysis.
The spectroscopic solution computed with assumption of the same sight, therefore we have Algol type variable, with partial eclipses. Physical parameters of the components suggest that system consists of two fast rotating stars, which are heavier and larger than Sun. They form close system with circular orbit, slightly inclined to the line of sight, therefore we have Algol type variable, with partial eclipses. Both components are on the main sequence, mass transfer is not started yet, as both components are smaller than their Roche lobes. The spectroscopic solution computed with assumption of the same [Fe/H] for both components have $R_B/R_A = 0.81$ which is very close to the value $R_B/R_A = 0.868 \pm 0.076$ from the TESS LC fit. Relatively large projected rotational velocities measured from the spectra are in perfect agreement with $V \sin i_{sync,A_B} = 57.8 \pm 2.0, 50.0 \pm 2.5 \text{ km s}^{-1}$ computed using TESS LC fit parameters, suggesting spin-orbit synchronisation.

Surface gravities derived by JKTEBOP are significantly larger than spectroscopic ones. There is a bias of $A \log(\gamma) = 0.3 - 0.4$ dex, which is larger than expected $\log(\gamma)$ uncertainties given in Section 3.1.3. Similar bias was observed in Kovalev et al. (2019) for open cluster NGC 2243, where stars near the turn-off have spectroscopic $\log(\gamma)$ smaller than $\log(\gamma)$ from the PARSEC isochrone (Marigo et al. 2017). Thus such bias can be related to inaccuracy of the spectral models. Note that difference of spectroscopic surface gravities $\log(\gamma)_B - \log(\gamma)_A = 0.12$ is comparable to difference $(\log(\gamma)_B - \log(\gamma)_A = 0.06)$ from the TESS LC fit, because we use it to scale relative contribution of the components in the spectrum.

We explore previously reported measurement for this system and collect them in Table 6. Orbital periods from ZTF and ASAS-SN.
SN V are in good agreement with our estimations, although they are slightly shorter. Recent Gaia DR3 presents very interesting estimates by Multiple Star Classifier (MSC) Gaia Collaboration et al. (2022), where they tried to model observed low resolution BP, RP spectra using two stellar components. These estimates agree very well with our \( T_{\text{eff}} \) from multiple-spectra fit and \( \log g \) from TESS 44 dataset, although our \([\text{Fe/H}]\) is 0.3 dex smaller. This is well-behaved solution based on goodness-of-fit score logposterior_msc=4956. We also retrieve all their 100 Monte Carlo samples and plot them in Figure D1.

Xiong et al. (submitted) also used LAMOST MRS, ZTF, ASAS-SN data to analyse this system with PHOEBE. For primary star in the system they got \( M_A \) and \( R_A \) larger than our estimates, but their \( T_{\text{eff}}A \) agrees with our value. For the secondary star their \( M_B \) is higher, but \( R_B \) and \( T_{\text{eff}}B \) are significantly smaller than our estimates. Their [Fe/H] for the system is slightly smaller than our estimate. We think that disagreement is due to their usage of less precise LC datasets and usage of spectral parameters from the second minimum for initialisation. Likely they underestimated orbital inclination, which led to much larger masses.

We take parameters from TESS 44 fit by JKTEBOP together with \( T_{\text{eff}} \) and [Fe/H] from multiple-spectra fit, assuming same [Fe/H] as a final solution.

5.2 Age determination

We use the grid of PARSEC isochrones (Marigo et al. 2017), computed at metallicity [Fe/H] = −0.19 dex, together with masses and radii from all RP simulations for TESS 44 dataset to derive system’s age, assuming that two stars evolve separately, but have the same age. All fitted age solutions have median \( \log t = 9.19^{+0.230}_{-0.220} \) yr (1.56 Gyr) with 16 and 84 percentiles, which is significantly younger than Sun. This is very different from the single star age values \( t \approx 5.66^{+0.417}_{-0.483} \) Gyr from GDR3 FLAME (Gaia Collaboration et al. 2022) and \( \log t = 9.572 \pm 0.246 \) (3.73 Gyr) from (Mints & Hekker 2017). The theoretical circularisation time for orbit with given \( q \) and \( P \), using Formula 6.2 from Zahn (1977): \( \log t_{\text{circ}} = 9.47 \) yr (2.95 Gyr) is larger than our estimate of the system’s age, therefore tidal friction was very efficient, possibly was also accompanied by strong magnetic interactions.

However we should note, that theoretical models have difficulty to describe this system. In Figure 8 we plot grid of PARSEC isochrones computed for [Fe/H] = −0.6, −0.2, 0.2 dex and five ages in range from 1 to 5 Gyr. Our best fit ([Fe/H] = −0.19 dex, age 1.57 Gyr) isochrone is also shown (red dot-dashed line), together with our best estimates and primary parameters from Xiong et al. submitted.

![Figure 8. The grid of PARSEC isochrones computed for [Fe/H] = −0.6 (solid lines), −0.2 (dashed lines), 0.2 dex (dotted lines) and five ages in range from 1 to 5 Gyr. Our best fit ([Fe/H] = −0.19 dex, age 1.57 Gyr) isochrone is also shown (red dot-dashed line), together with our best estimates and primary parameters from Xiong et al. submitted.](https://gea.esac.esa.int/archive/documentation/GDR3/Data_analysis/chap_cuSpar/sec_cuSpar_apsis/ssec_cuSpar_apsis_msc.html)

of well studied dEBs to test PARSEC isochrones, using Bayesian framework to infer masses, distances and ages, taking radii, \( T_{\text{eff}} \) and [Fe/H] as input. They found that PARSEC models systematically underestimate masses, although discrepancies are not so important for main sequence. For example for close dEB system UZ Dra with similar parameters to J064726.39+223431.6 \( (P = 3.261 \, \text{d}, R_{A,B} = 1.31 \pm 0.03, 1.15 \pm 0.02 \, R_\odot, T_{\text{eff}}_{A,B} = 6209 \pm 114, 5984 \pm 110 \, \text{K}, M_{A,B} = 1.34 \pm 0.02, 1.23 \pm 0.02 \, M_\odot, \) no estimate of [Fe/H] yet) they inferred \( M_{A,B} = 1.13 \pm 0.09, 1.04 \pm 0.09 \, M_\odot, \) assuming solar metallicity for this system.

Additionally we check another two sets of theoretical models by Dotter (2016) and Claret (2019), but find no improvement relative to PARSEC.

6 CONCLUSIONS

We present a study of dEB SB2 J064726.39+223431.6 system using spectra from the LAMOST-MRS survey and photometrical data. We use full-spectrum fitting to derive radial velocities and spectral parameters. The orbital solution and light curves from ZTF and TESS suggests, that it is a close pair on circular orbit. We have measured the masses of the stars to accuracies of 1 per cent and the radii to accuracies of 5 per cent. System shows strong evidence for spin-
orbit synchronisation. We find discrepancy between spectroscopic $\log(g)$ and $\log(g)$ calculated using parameters from LC fitting. Theoretical isochrones also unable to model measured mass-$T_{\text{eff}}$ relations at derived metallicity. Derived age of the system indicates that both components are still on the main sequence.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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between −0.9 and +0.9 dex. The model is computed only if linear interpolation of MAFAGS-OS (Grupp 2004a, b) stellar atmosphere is possible for a given point in parameter space. Micro-turbulence is fixed to $V_{\text{mic}} = 2 \text{ km s}^{-1}$ for all models. The grid is randomly split on training (70%) and cross-validation (30%) sets of spectra, which are used to train The Payne spectral model (Ting et al. 2019). The neural network (NN) consists of two layers of 300 neurons each with rectilinear unit (ReLU)$^8$ activation functions. We train separate NNs for each spectral arm. The median approximation error is less than 1% for both arms. We use output of The Payne as single-star spectral model.

APPENDIX B: PHOEBE BEST FIT SOLUTION

We show best fit LC solution obtained with PHOEBE in Figure B1.

APPENDIX C: RESIDUAL-PERMUTATION SIMULATIONS

In Figures C1, C2, C3 we show corner plots (Foreman-Mackey 2016) with all residual-permutation simulation results for $J$, $R_B/R_A$, $i$, $L_B/L_A$, and log ($g$)$_{A,B}$ for ZTF $r$ and TESS LCs. There is strong correlation between $J$ and $R_B/R_A$ clearly visible for all datasets, which can propagate into other parameters like $L$ and log ($g$). However the most precise TESS 44 dataset is less affected.

APPENDIX D: GAIA DR3 MONTE CARLO MULTIPLE STAR CLASSIFIER SAMPLE

In Figure D1 we show corner plot (Foreman-Mackey 2016) with Monte Carlo Multiple Star Classifier sample from Gaia Collaboration et al. (2022). We select subsample with $A_0 > 0.2$ mag (70 datapoints). These results have higher log$_{\text{post}}$. We compute 16, 50 and 84 percentiles for them and median values are comparable to out final parameters, however metallicity and log ($g$)$_B$ are higher. The remaining 30 datapoints have smaller log$_{\text{post}}$ and have log ($g$)$_A, B \sim 4.7$ cgs. This is probably solutions from local maximum of the posterior.

This paper has been typeset from a TeX/LaTeX file prepared by the author.

\footnote{We used [Fe/H] as a proxy of overall metallicity, abundances for all elements are scaled with Fe.}

\footnote{ReLU(x)=$\max(x,0)$}

Figure B1. The best fit PHOEBE model for ZTF $r$ (top), TESS 44 (middle) and TESS 45 (bottom) LCs.
Figure C1. Corner plot for the residual-permutation simulations of ZTF $r$ solution. Titles show 16, 50 and 84 percentiles.
Figure C2. Corner plot for the residual-permutation simulations of TESS 44 solution. Titles show 16, 50 and 84 percentiles.
Figure C3. Corner plot for the residual-permutation simulations of TESS 45 solution. Titles show 16, 50 and 84 percentiles.
Figure D1. Corner plot for Gaia DR3 Multiple Star Classifier sample. Titles show 16, 50 and 84 percentiles for subsample with $A_V > 0.2$ mag.