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Definition and analysis of the fundamental parameters of a close binary system Konkoly J064029.1+385652.2

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In this work, we studied spectroscopic and photometric observations of the close binary system Konkoly J064029.1 + 385652.2, which is a candidate for young pre-cataclysmic variables with an sdO subdwarf. Observations were obtained in 2017–19 on the Large Azimuth Telescope SAO and the Russian–Turkish RTT-150 telescope. The temperature $T^1_{\rm eff} = 46800 \pm 1600$ K and surface gravity $\log g = 6.06 \pm 0.11$ dex of the primary are determined from modeling optical spectra of KJ 064029 in an era with no reflection effects. These parameters of the star, together with the low atmospheric content of helium $He/H = 0.007 \pm 0.0007$ and other elements, make it more likely to belong to the class of sdO subdwarfs. The orbital inclination angle $i = 86.5^\circ \pm 0.2^\circ$ and the radii of the main ($R_1 = 0.104 \pm 0.008\ R_\odot$) and secondary ($R_2 = 0.212 \pm 0.009\ R_\odot$) were obtained by modeling the light curves in bands V and R. An analysis of the obtained parameters reveals a discrepancy between the dynamic mass of the main primary $M_1 = 0.567\ M_\odot$ and its estimate based on the evolutionary tracks of hot subdwarfs. This fact leads to the conclusion about the need to clarify the masses of KJ 064029 and the evolutionary status of the primary.

Keywords: Techniques: photometric – stars: spectroscopic – stars: variables: pre-cataclysmic binaries – stars: individual: Konkoly J064029.1+385652.2

1 Introduction

Pre-cataclysmic variables (PB) are detached binary systems that have once passed the stage of a common envelope (CE) [1]. Among them we distinguish old PB with cooling white dwarfs and young PB with sdO or sdB subdwarfs as the main primary paired with low-mass dwarfs of the Main Sequence (MS) as secondary [2]. Of particular interest in PB with sdO subdwarfs is the presence of an excess of cool star luminosity, due to their residual excitation after leaving the stage CE [3]. Cold stars in sdB

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subdwarf systems have an excess of radius with luminosity characteristic of MS stars [4]. Therefore, over the course of 15 years, we have completed a cycle of studies of young PBs of both types with their classification and determination of physical and chemical characteristics. In this article, we present preliminary results of the analysis of observations of a young PB, which requires a refinement of the classification and parameters of the components.

Konkoly J064029.1 + 385652.2 (further KJ 064029) was discovered by Derekas and colleagues [5] when executing an exoplanet search program as a star with a photometric deep eclipse of at least $\Delta m_R = 3.0^m$ and a sinusoidal eclipse brightness variation with amplitude $\Delta m_R = 0.3^m$. In the optical spectra of the object, the dominance of sdO dwarf radiation with $T^1_{\rm eff} = 55000$ K with the presence of emissions in the CNO lines generated by the action of reflection effects was detected. As a result, the authors of [5] classified KJ 064029 as a new young PB with an sdO dwarf and a dM dwarf. However, the mass of the primary $M_1 = 0.567 \pm 0.138\, M_\odot$ found by them from the analysis of the radial velocity curve turns out to be 20% higher than its estimate based on evolutionary tracks for the presented values of luminosity and temperature. In addition, the lifetime of such an sdO dwarf after dumping the common shell cannot exceed $\log t = 5.3$, which clearly requires the presence of a planetary nebula. However, the nebula around KJ 064029 was not detected by observations in narrow filters. As a result, we can conclude that there are internal contradictions in the set of available parameters PB and the need for their refinement.

2 Observations and reduction

Spectroscopic observations of KJ 064029 were performed on the 6th Large Azimuthal Telescope (BTA) of the SAO using the SCORPIO1 [6] aperture reducer in the spectroscopic mode, EEV 42-40 CCD-matrix (2048 × 2048 pixels) and VPHG1200g grisma (1200 lines/mm). The spectral resolution was about 5 Å in the wavelength range λ = 4050–5750 Å. On the night of April 30, 2017 and May 01, 2017, 11 and 12 spectrograms with exposures of 300 seconds were obtained; and 65 spectrograms with exposures of 180 seconds were obtained on the night of January 18, 2018. The observations were carried out in satisfactory climatic conditions with weak cirrus and stellar image sizes of 1.1″, 1.7″ and 1.9″. The primary processing of the observations was performed in the Maxim DL package, and the spectra were normalized in the Origin package. The signal/noise ratio in the spectra of 2016 and 2017 amounted to S/N = 12–15 and S/N = 9–13, respectively. The low quality of observations required their partial averaging in blocks of 3–5 CCD images. The phase alignment of the spectra is based on the ephemeris from [5]:

$$HJD_{\rm min} = 2456709.5846 + 0.18728476 \times E. \quad (1)$$

As a result, 26 spectra were obtained, generally covering all phases of the orbital period. In this work, to determine the parameters of the primary, we used only observations at a minimum of brightness with no reflection effects.

Photometric observations of KJ 064029 were carried out on the night of January 17, 2019 at the 1.5th Russian-Turkish telescope (RTT-150). The TFOSK device was

used, including the CCD matrix Fairchild 447 (2048×2048 pixels) and a set of Bessel system filters (UBVRI). The observations were performed under excellent climatic conditions with stellar images of less than $1.0''$ with alternating exposures of 60 seconds in the V and R bands. A total of 176 and 174 CCD images were accumulated, respectively. When processing the observations in the Maxim DL package, 5 stars of similar brightness located in the field of the object were selected as comparison objects. An analysis of their variability showed that differential photometry errors KJ 064029 in phases outside the main eclipse were $\delta m_V = 0.^m03$ and $\delta m_R = 0.^m02$. The brightness in the total phases of the eclipses was determined by the photon statistics method and its estimates were obtained only in the R band with an accuracy of $\delta m \approx 0.^m35$.

3 Data analysis

3.1 Phenomenological analysis

The result of averaging the spectra with their transfer to the laboratory wavelength scale is shown in Fig. 1. The spectrum shows the lines of the Balmer series HI, the relatively weak lines of HeI λ4471 Å, $HeII$ λ4686, 5411 Å , $MgII$ λ4481 Å and the hood $CIII + NIII$ λ4630–4650 Å. The low intensity of non-hydrogen lines unambiguously reflects a deficiency of helium and other elements in the atmosphere of a hot star uncharacteristic of sdO dwarfs.

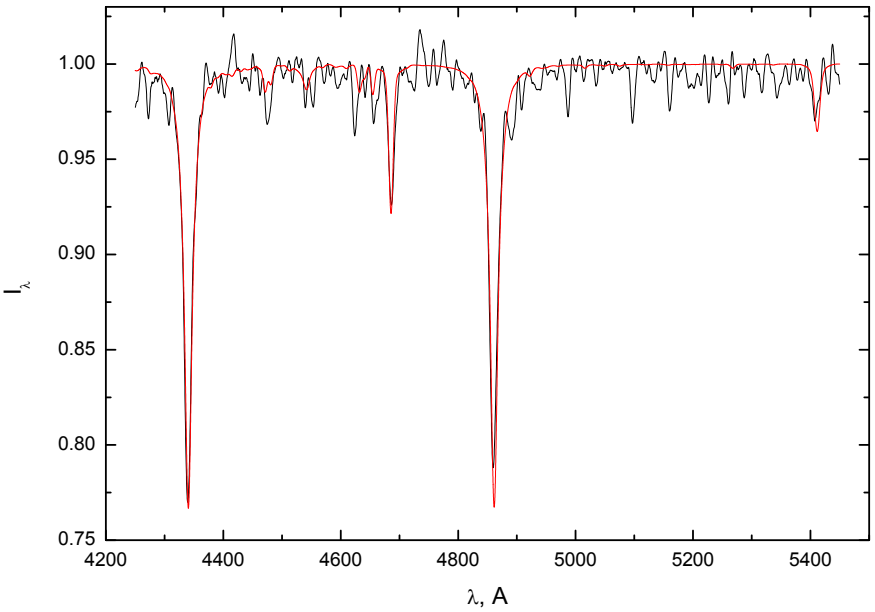


Figure 1 The observed (black line) and theoretical (red line) spectra of KJ 064029 in the flux minimum.

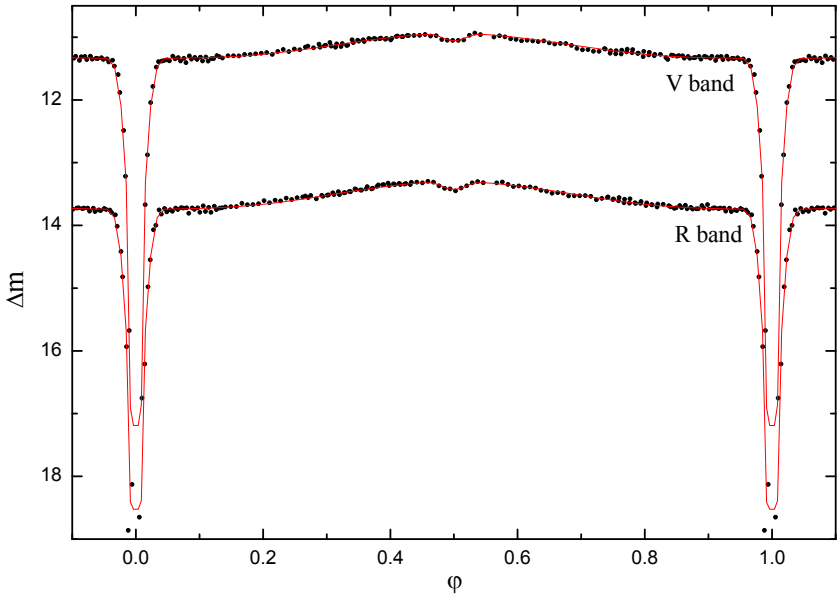


Figure 2 Observed (points) and theoretical light curves of KJ 064029.

The observed phase light curves of KJ 064029 in both bands are shown in Fig. 2. They have a main eclipse with an amplitude $\Delta m_R > 5.^m3$ and a secondary eclipse with amplitudes of $\Delta m_V = 0.^m097$ and $\Delta m_R = 0.^m12$. Outside of the eclipses, the brightness variations of the correct form with amplitudes $\Delta m_V = 0.^m42$ and $\Delta m_R = 0.^m44$ and a maximum near the phase $\varphi = 0.50$ are due to the corresponding reflection effects. Their symmetry with respect to the moments of the eclipses indicates the circular orbit of the system and the orientation of the hot spot on the surface of the secondary strictly in the direction of the irradiating star. The latter fact indirectly indicates the synchronism of rotation of the secondary with its orbital motion. A slight increase in the brightness amplitude with increasing wavelength corresponds to the effects of reflection in a young PB with a moderately hot subdwarf ($T_{\rm eff}$ = 40000–60000 K).

3.2 Numerical analysis

To determine the KJ 064029 fundamental parameters, we used the software package *SPECTR* [2, 7] for modeling light curves and spectra of binary stars with the reflection effects and non-sphericity of the components. The grid of atmospheric models [8] were taken as models of unirradiated atmospheres of MS stars. We obtained atmospheric models of hot subdwarfs using the *ATLAS*12 complex [8]. To construct the structure of the irradiated atmospheres, we used the method of balancing the functions of heating and cooling of stellar gas [9].

3.3 Spectrum analysis

The depth of the main eclipse KJ 064029 shows that the radiation of the primary dominates in the spectra of neighboring phases with an insignificant (less than 1%) contribution of the cool star radiation. Therefore, a model analysis of the spectra makes it possible to determine with good accuracy the main parameters of the subdwarf atmosphere: effective temperature $T_{\rm eff}$, surface gravity $\log g$ and helium content He/H. They were found by calculating the grids of theoretical spectra with varying all parameters and calculating their standard deviations from the observed in the range $\lambda = 4300$–5450 Å. As a result, we found the optimal values: $T^1_{\rm eff} = 46800 \pm 1600$ K, $\log g = 6.06 \pm 0.11$ dex, $He/H = 0.007 \pm 0.0007$. At the same time, estimates of the content of light elements were obtained: $[C/H] = -0.6$ dex, $[N/H] = -0.3$ dex, $[O/H] = -0.2$ dex. The parameters that we found of the atmosphere of the subdwarf differ markedly from those presented in [5]: $T^1_{\rm eff} = 55800 \pm 3000$ K, $\log g = 5.97 \pm 0.30$ dex, $He/H = 0.0057 \pm 0.0035$. Of particular note is the difference in the values of the temperature of the star, because it has a strong influence on the amplitude of reflection effects. In addition, for different estimates of $T^1_{\rm eff}$, the primary can be assigned to sdO or sdB subdwarfs. The significant deficit of helium and CNO elements found allows us to classify the star as an sdB subdwarf, which is consistent with our value of $T^1_{\rm eff}$. The final agreement between the theoretical and observed spectra is shown in Fig. 1.

3.4 The analysis of the light curves

Most of the KJ 064029 parameters are determined based on the optimal agreement between the theoretical and observed light curves in the V and R bands. The mass values of the components are $M_1 = 0.567 \pm 0.138\ M_\odot$, $M_2 = 0.177 \pm 0.051\ M_\odot$ and the semimajor axis $A = 1.228 \pm 0.010\ R_\odot$ are taken fixed according to [5], and the subdwarf temperature $T^1_{\rm eff} = 46800 \pm 1600$ K according to our analysis of the spectra. The estimates [5] of the remaining parameters of KJ 064029 were considered initial when modeling the light curves. The main influence on the amplitude of extraterrestrial changes in brightness is exerted by the radius of the secondary R_2, the ratio of the radii of the components $\dfrac{R_2}{R_1}$ and the angle of inclination of the system i, and to the depth of the main eclipse, the ratio $\dfrac{R_2}{R_1}$ and the temperature of the secondary $T^2_{\rm eff}$. The width of the eclipses is determined by the ratio of the radii to the semimajor axis $\left(\dfrac{R_1}{A} \text{ and } \dfrac{R_2}{A}\right)$ and the angle of inclination of the orbit. Thus, the observed indicators in the light curves of the system are enough to uniquely determine its parameters. The condition for optimal agreement between the observed and theoretical data was considered to be the absence of systematic deviations between them at O–C curves at a level higher than the observation errors (see above). The resulting standard deviations were $\sigma m_V = 0.^m036$ and $\sigma m_R = 0.^m025$. A comparison of the theoretical and observed light curves is shown in Fig. 2, and the system parameters we found in Table 1.

The presence of narrow and deep eclipses at KJ 064029 allows us to determine with good accuracy the orbital inclination angle $i = 86.5^\circ \pm 0.2^\circ$ and the relative

Table 1 KJ 064029 parameters.

Star	Primary	Secondary
$T_{\rm eff}$ (K)	46800 ± 1600	4200 ± 200
$\log g$ (dex)	6.06 ± 0.11	4.82 ± 0.01
$\frac{M}{M_\odot}$	0.567 ± 0.138	0.177 ± 0.051
$\frac{R}{A}$	0.083 ± 0.007	0.170 ± 0.008
$\frac{R}{R_\odot}$	0.104 ± 0.008	0.212 ± 0.009
$\frac{A}{R_\odot}$	1.228 ± 0.010	
i°	86.5 ± 0.2	

radii of the components $\frac{R_1}{A} = 0.083 \pm 0.007$ and $\frac{R_2}{A} = 0.170 \pm 0.008$. The relative radii obtained by us are 9–10% higher than the data of [5], which is less than the total errors in their determination in two works. The corresponding absolute radii were $R_1 = 0.104 \pm 0.008\ R_\odot$ and $R_2 = 0.212 \pm 0.009\ R_\odot$. The noticeable uncertainty in estimating the temperature of a cold star $T^2_{\rm eff} = 4200 \pm 200$ K is associated with large photometric errors of the object in the phase of total eclipse and recording its depth only in the R band. The temperature value $T^2_{\rm eff} = 4648 \pm 55$ K found from the analysis of infrared photometry [5] is much higher, but it was obtained using the blackbody approximation to describe star radiation. We consider our estimate of $T^2_{\rm eff}$ to be more correct, since it corresponds better to the temperatures of red dwarfs with a mass of $M \approx 0.18 M_\odot$.

4 Discussion and conclusion

The new values of the primary temperature and radius determine its luminosity $\log(L/L_\odot) = 1.668 \pm 0.004$. On the evolutionary tracks of the hot subdwarf [10] the star is located significantly below the track with $M = 0.524\, M_\odot$ and its position as a whole corresponds to the mass $M \approx 0.46\, M_\odot$. Such mass values are characteristic of sdB subdwarfs lying on a post-horizontal branch, which is consistent with the deficiency of helium and light elements in the atmosphere of the primary described above. Therefore, we speculate about the possible presence in KJ 064029 of not an sdO subdwarf but of an sdB subdwarf and the corresponding belonging of the system to the old galactic population. However, this assumption partially contradicts the subcarlik mass value obtained in [5] $M_1 = 0.567 \pm 0.138\, M_\odot$. Note that a large error of the presented measurement allows us to consider our assumption admissible.

For the secondary component of KJ 064029 we obtained an estimate of the bolometric luminosity $\log(L/L_\odot) = -1.901 \pm 0.099$. On evolutionary tracks [11] a MS star with a mass of $M = 0.177\ M_\odot$ and a solar chemical composition must have the luminosity $\log(L/L_\odot) = -2.35$ and radius $R = 0.195\ R_\odot$. In this way the cold

star in KJ 064029 may have excesses of radius and luminosity relative to stars of MS with a similar mass. Such excesses are more characteristic of young PBs with sdO subdwarfs [12], and only an excess of radius [4] was found in the components of PB with sdB dwarfs. However, we note that this conclusion was made by us using the mass estimate M_2 from [5] and needs additional verification. In general, we state that the problem of the mismatch of the KJ 064029 fundamental parameters persists and requires further research.

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References

[1] Ritter H., Kolb U., 2014, Cataclysmic binaries, LMXBs, and related objects, 1, 1
[2] Shimansky V.V., Borisov N.V., Shimanskaya N.N., 2003, Astron. Rep., 47, 763
[3] Shimansky V.V., Mitrofanova A.A., Borisov N.V. et al., 2016, Astroph. Bull., 71, 371
[4] Deminova N.R., Shimansky V.V., Borisov N.V. et al, 2017, ASP Conf. Series, 510, 420
[5] Derekas A., Nemeth P., Southworth J. et al., 2015, Astroph. J., 808, 179
[6] Afanasev V.L., Moiseev A.V., 2005, Astr. Lett., 31, 194
[7] Shimanskii V.V., Karitskaya E.A., Bochkarev N.G., et al., 2012, Astron. Rep. 56, 741
[8] Castelli F., Kurucz R. L., 2003, Proc. of IAU Symp. 210, 1
[9] Ivanova D.V., Sakhibullin N.A., Shimanskii V.V., 2002, Astron. Rep., 46, 390
[10] Blocker T., 1995, Astron. Astrophys., 299, 755
[11] Girardi L., Bressan A., Bertelli G. et al., 2000, Astron. Astrophys. Suppl. Ser., 141, 371
[12] Shimansky V.V., Pozdnyakova S.A., Borisov N.V. et al., 2009, Astroph. Bull., 64, 349