Study of the Young Pre-Cataclysmic Variable SDSS J162256+473051.1

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Abstract. In this paper optical radiation and the characteristics of the eclipsing pre-cataclysmic variable (PV) SDSS J162256+473051.1 were investigated. Spectroscopic observations were carried out at BTA SAO RAS, photometric observations - at RTT-150 telescope. Numerical modeling of theoretical light curves and spectra was done taking into account the effects of nonsphericity and reflection. Sets of radial velocities of the sdB-subdwarf were measured. The fundamental parameters of the system were determined. It was shown that the previously proposed method for determining the masses of the PV components based on modeling the radial-velocity curves is effective only for systems with significant reflection effects, regardless of the temperature of the main component.

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1 Introduction

Pre-cataclysmic variables are put into separated close binary systems (CBS) that have passed the stage of a common envelope at once. PV were sorted out into a separate group by Ritter (1986). They consist of a main component, which is a hot subdwarf located on the posthorizontal or postasymptotic branch of giants, or a cooling white dwarf, and a secondary component - star of the late spectral type. PV are divided into 3 groups depending on the state of the main components: young PV with sdO - subdwarfs ($t < 10^6$ years), young PV with sdB - subdwarfs ($t < 10^7$ years), and old PV ($t > 10^7$ years) (Shimanskii et al. 2004). The group of young PV with sdB - subdwarfs (HW Vir stars) at the beginning of the 21st century remained little-studied due to the methodological difficulties of their detection and analysis. However, the search programs for binary systems with sdB - subdwarfs have expanded the group to a few dozens objects. As a result, the question about their methodically correct study and definition of characteristics have arisen. In this work, we studied the close binary system SDSS J162256 belonging to the HW Vir type (Shimanskii et al. 2012). Schaffenroth et al. (2014) performed a comprehensive analysis of SDSS J162256. During the study, the period ($P = 0.0697885^d$, the orbital inclination angle ($i = 72.°33 \pm 1.°11$), masses and radii of the components ($M_1 = 0.48 \pm 0.03 M_\odot$, $R_1 = 0.168 \pm 0.007 R_\odot$, $M_2 = 0.064 \pm 0.004 M_\odot$, $R_2 = 0.085 \pm 0.004 R_\odot$), effective temperatures ($T_1 = 29000$ K, $T_2 = 2500 \pm 900$ K), surface gravity ($\log g_1 = 5.65 \pm 0.06$) and distance between components ($a = 0.58 \pm 0.02 R_\odot$) were determined. The half-amplitude of the orbital motion velocity of the main component ($K_1 = 47.2 \pm 2.0$ km/s) and the gamma velocity, $\gamma = -54.7 \pm 1.5$ km/s, were measured by approximating the radial velocity curves. However, the modeling of reflection effects in the work of Schaffenroth et al. (2014) was done in the blackbody approximation, which can lead to errors in the parameters of the system. Therefore, in our work, we perform a reanalysis of the SDSS J162256 radiation using the method of models of atmospheres.

Obtaining and processing methods of observations are described in section 2. The modeling technique and analysis of the light curve and spectra are described in section 3. An analysis of radial velocities using the method of cross-correlation of spectra and determination of the fundamental parameters of SDSS J162256 are presented in section 4. In the Conclusion, the applicability limit of the previously proposed method of determining the parameters of systems is checked.

2 Observations

Simultaneous BVR observations of SDSS J162256 were carried out in 2017 with the RTT-150 telescope using the TFOSC instrument and the CCD matrix called CCD-447. In all, 126 images have been accumulated, of which 42 were obtained in the R-filter, 42 in the V-filter and 42 in the B-filter. The duration of observations is 1000 hours and certainly exceeds the duration of the orbital period. The Maxim DL computer package was used to process them. Secondary standards of close brightness and color in CCD images were selected as objects of comparison. Comparison of the stellar brightness in the matrix field showed that the differential photometry errors were equal to $\delta m \approx 0.01^m$ in the B, R, and V bands. Spectroscopic observations of SDSS J162256 were carried out in 2017 at the Big Azimuth Telescope of the SAO RAS using the SCORPIO (Afanasiev & Moiseev 2005) primary focus aperture ratio reducer in the mode of spectroscopy with a long slit. We used the data obtained during observations with a VPHG1200g grism (1200 lines/mm)and an EEV 42-40 CCD receiver (2048×2048 pixels, size 13.5×13.5 μm), providing a spectral resolution of $\Delta\lambda = 5.0$ Å in the wavelength range $\lambda\lambda 4050 - 5850$ Å. These observations were carried out under good astroclimatic conditions with a star image size of $2.0''$, zenith distances did not exceed 20°. The duration of the exposures was 300 seconds, which made it possible to obtain the signal-to-noise ratio $S/N = 48$. The duration of the observations was 102 minutes.

3 Modeling and Analysis of Light Curves and Spectra

The obtained observational brightness values of SDSS J162256 refer to different phases of the orbital period of the system. The SDSS J162256 ephemeris

$$HJD = 2455359.58306(2) + 0.0697885(53)E, \tag{1}$$

proposed in Schaffenroth et al. (2014), was used to switch from the HJD heliocentric Julian date observations to the $\varphi \equiv E$ phase scale. In the orbital light curves of SDSS J162256, three regions of variability are distinguished: the primary minimum is due to the eclipse of a cold stellar part of the surface of the sdB - subdwarf, the extra-eclipse brightness change is associated with the visibility conditions change of the hot spot on the surface of the secondary component, and the secondary eclipse reproduces its partial occlusion by the sdB - subdwarf. The spectrum contains HI, HeI, HeII, CIII, NIII, OII, MgII, SiIII, SiIV, SIII lines. These absorption lines relate to the emission of only the sdB -subdwarf, i.e. primary component. The lack of information on the intrinsic radiation of the secondary component makes it difficult to find the fundamental parameters. However, a joint analysis of the light curves, spectra, and radial velocities makes it possible to determine the main parameters of the system with sufficient accuracy. On the whole, a qualitative analysis of the spectra of SDSS J162256 confirms its belonging to young PV with sdB - subdwarfs. Theoretical modeling was carried out using the SPECTR software complex. The spectra were modeled taking into account the reflection effects, according to the method of Ivanova et al. (2002). First, the surface of the stars is divided into elementary areas with the calculation of models of their atmospheres and emitted spectra. The complete spectra of the CBS are obtained by adding the spectra of all areas on the surface of both components, taking into account the conditions of their visibility. The SDSS J162256 spectra were calculated simultaneously with its light curves using the method described above. When simulating the profiles of the observed HI, HeI, HeII, CII, MgII lines, deviations from LTE were taken into account based on the level populations of these ions calculated by the NONLTE3 complex. The parameters and chemical composition of the sdB subdwarf atmosphere were obtained by matching the HI and HeI line profiles in the theoretical and observed spectra in phases close to the primary eclipse. As a result, the following values were found: $T_{eff} = 30800$ K, $\log g = 5.75$, $[He/H] = -0.62$. These parameters are generally characteristic for moderately hot sdB - subdwarfs with stratification effects in their atmospheres.

4 Analysis of Radial Velocities and Determination of System Parameters

The presence of the absorption lines of the sdB - subdwarf in the SDSS J162256 spectra makes it possible to measure the radial velocities of only its orbital motion. Their determination was carried out using the cross-correlation method. The lines H_δ (4101Å), H_γ (4341Å), HeI (4471Å), H_β (4862Å) and their combinations: $H_\delta+H_\gamma$, $H_\delta+H_\beta$, $H_\gamma+H_\beta$, $H_\delta+H_\gamma+H_\beta$ were selected for measurements. When determining the velocities, on average intervals with width of 130Å for hydrogen lines and 47Å for helium lines were cut out from the total spectra of SDSS J162256. These intervals were centered according to their laboratory wavelengths. The transition from the scale of heliocentric Julian observation dates HJD to the phase scale $\varphi \equiv E$ was made on the base on the ephemeris proposed in Schaffenroth et al. (2014) and used by us in the analysis of SDSS J162256 photometry. The radial velocity curves were approximated by the gradient descent method for the circular orbit model using a script written in the Origin software package. The obtained approximations together with the observational data are presented in Figure 1.

As seen from Fig. 1, the obtained phase curves of radial velocities differ in shape from the sinusoid characteristic for a circular orbit. However, for PV, artificial distortions of the radial velocity curves are possible due to the effects of reflection and nonsphericity of the components. The found amplitudes of V_r changes for different HI lines are 48.6 ± 0.3 km/s, and for the set of lines, 48.3 km/s.

A joint analysis of the light curves of systems of the HW Vir type in the B, V, and R bands will make it possible to find simultaneously five parameters: the temperatures T_{eff} and the radii of the components R, as well as the orbital inclination angle i. However, the effective temperature of the secondary component of SDSS J162256 has practically no effect on the light curves, and we fixed it as Teff = 3250 K. On the contrary, the temperature of the sdB - subdwarf has a major effect on the light curves. Therefore, to minimize the errors in determining the remaining parameters, we used its value $T_{eff} = 30800$ K, independently obtained from the analysis of the spectrum (see above). As a result, we matched the modeling and observed light curves by varying the component radii and the orbital inclination angle. In this matching, it was taken into account that the amplitude of reflection effects is mainly determined by the radius of the secondary component, and the amplitudes and width of eclipses are determined by the ratio R_1/R_2 and the value of i. As a result, the light curves were matched in all bands at $i = 70.^\circ0 \pm 0.^\circ3$, $R_1 = 0.195 \pm 0.01 R_\odot$, $R_2 = 0.093 \pm 0.01 R_\odot$. The presented parameter errors are due to observation errors. An example of a description of the observed V-band light curve is shown in Fig. 2.

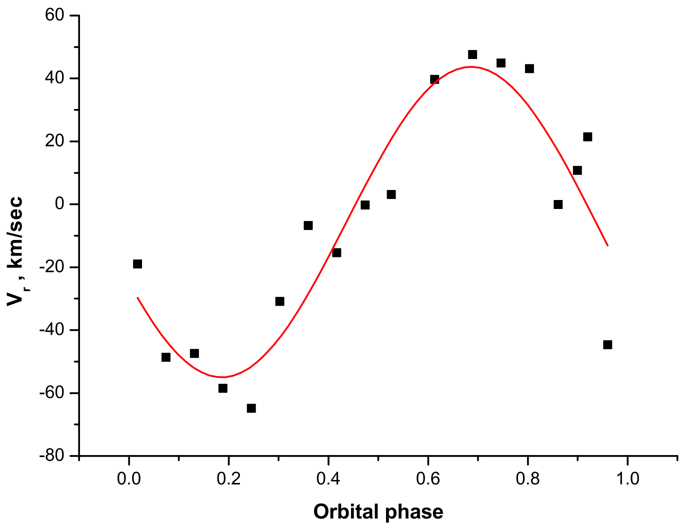

Fig. 1. Approximation of the radial velocity curve for the H_β line (4862Å.)

The values of the mass of the secondary component $M_2 = 0.065 \pm 0.001 M_\odot$ and the semi-major axis of the orbit $a = 0.580 \pm 0.01 R_\odot$ were calculated from the found mass function with the adoption for the primary component of the mass estimate $M_1 = 0.47 M_\odot$, which is considered standard for all sdB - subdwarfs on the post- horizontal branch (Heber 2016). The M_2 presented value corresponds to the masses of brown dwarfs. This result is of particular interest, since indicates the possible belonging of our star to the predecessors of dwarf novae with an ultrashort period of the AM CVn type. These systems are characterized by significant excesses of the helium content in the matter of the accretion disks and, hence, in the secondary components. Therefore, an analysis of the emission components of the HeI lines formed by the reflection effect can provide important information on the chemical composition of the brown dwarf.

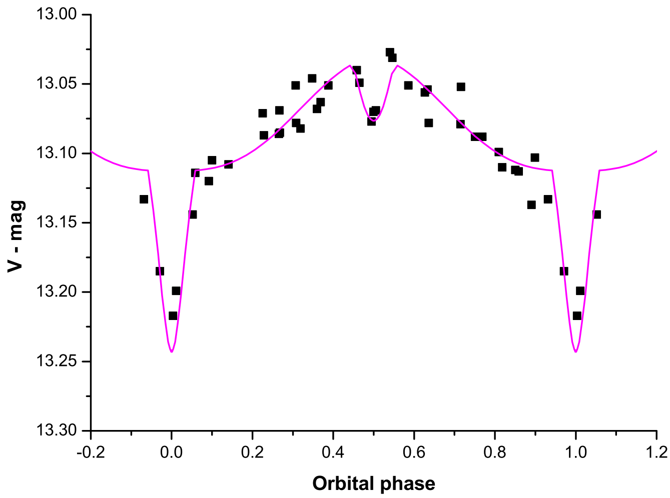

Fig. 2. Light curve of SDSS J162256 in the V-band (squares - observational data, line - theoretical curve).

5 Conclusion and Analysis of Results

The method of modeling the radial-velocity curves for determining the masses of the components, proposed in Shimanskii et al. (2012), assumed the formation of rather strong HI emission lines on the surface of the secondary component. Their blending with absorption lines in the spectrum of the sdB subdwarf leads to a weakening and artificial shift of the latter, i.e. to distortions of the shape of the radial velocity curves. It was shown that the final shape of this curve depends on both the amplitude of the reflection effects and the ratio of the masses of the components. Therefore, preliminary modeling of the reflection effects in the light curves made it possible to find the mass ratio from the analysis of the radial velocity curves, which, at a known inclination angle of the system, ensured the determination of their masses. Analyzing the conditions for the applicability of the new method, Shimanskii et al. (2012) assumed that it is effective for systems with temperatures of the primary components above $T_{eff} = 32000$ K. However, our analysis of the radiation of NSVS 14256825 (Deminova et al. 2017) with a hot primary component ($T_{eff} = 40000$ K) showed that this method cannot be applied to systems with weak reflection effects ($\Delta m_{<} 0.^{m}3$). Therefore, when studying subsequent systems of the HW Vir type and determining their parameters, we use a fixed value of the mass of the main component $M_1 = 0.47 M_{\odot}$. The study Deminova et al. (2017) showed that in this case the analysis of photometric and spectroscopic observations of such systems makes it possible to unambiguously find the remaining parameters and ensure the methodological uniformity of their determination. In this work, on the basis of the described method, we studied the SDSS J162256 system and obtained a full set of its fundamental parameters. They are in good agreement with the characteristics of other HW Vir type PV with brown dwarfs. It should be noted that the secondary component of SDSS J162256 has a noticeable radius excess relative to MS stars. Similar excesses were previously found in most systems of the HW Vir type, which makes it possible to unambiguously consider SDSS J162256 a member of this group of CBS.

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