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The determination of white dwarf parameters in dwarf novae by optical spectral modeling

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Abstract This paper presents the results of a model analysis of optical spectra and determination of the parameters of three individual SU UMa and WZ Sge type dwarf novae. The moderate resolution spectra of TY Psc, FL Psc and V455 And were obtained at the 6-m BTA of the SAO RAS in the low state of these systems with the determination of white dwarf radiation. The theoretical spectra were calculated using the grid models of hydrogen dwarf atmospheres of white dwarfs by varying the parameters ($T_{\rm eff}$ and $\log g$) to reach the best agreement with the observed ones. We highlight different effects of the parameters on the shape and intensity of the HI lines. Therefore, it is possible to unambiguously determine $T_{\rm eff}$ and $\log g$ from the analysis of observations. The fundamental parameters of white dwarfs (M and R) were found by comparing the parameters of atmospheres with theoretical models of the internal structure. The obtained parameters of the primaries of TY Psc, FL Psc and V455 And are consistent with the average values for SU UMa and WZ Sge systems. As a result, we demonstrate the efficiency of the method for determining the parameters of such systems based on the analysis of a limited set of observed optical spectra.

Key words: techniques: spectroscopic — stars: variables: dwarf novae — stars: individual: TY Psc — stars: individual: FL Psc — stars: individual: V455 And

1 INTRODUCTION

Cataclysmic variables (CVs) are semi-detached systems with short (several hour) orbital periods, consisting of a white dwarf (WD) (accretor) and a low-mass main sequence star (donor). In CVs, various effects of flare activity and unsteadiness in the course of accretion are observed. Outbursts of dwarf novae (DNe) occur at relatively low rates of accretion due to the emergence of instability in the accretion disk (AD). There is a low state of CVs with a slow matter accumulation in a cold, optically thin AD and its high state with a hot, optically thick disk that quickly transfers matter to the accretor. Among DNe, there are several groups of objects. SU UMa stars have bright and long-lasting superoutbursts with amplitudes of $\Delta m_V = 2^m - 7^m$ and more frequent normal outbursts with amplitudes $\Delta m_V = 2^m - 6^m$. After superoutbursts and normal outbursts, the system returns to a low state for 1–3 d and 10–18 d, respectively. The WZ Sge type stars only display superoutbursts with an increase in brightness by $\Delta m_V = 6^m - 9^m$ for 14–22 hr and subsequent decrease to the initial level over a period of 60 to 200 d.

A serious problem in studying CVs is the difficulty in determining the contributions of their components to the observed optical spectra. This problem is caused by observations of CVs predominantly in a high state dominated by the study of AD. As a result, it is not possible to measure the dynamic characteristics of the components and to determine their fundamental parameters. However, in the early 21st century the modeling method that relies on the HI line Lyman series was applied in DNe ultraviolet (UV) spectral analysis (Szkody et al. 2013; Godon et al. 2006). The authors confirmed the dominance of the cooling WD radiation in the UV region and the possibility of a model determination utilizing their parameters (masses, radii, effective temperatures). A small optical thickness of the AD and the dominance of WD radiation in the optical continuum were found in the later study of DN GSC 02197–00886 in the low state (Mitrofanova et al. 2014). As a result, the authors obtained estimates of the system parameters based on a model analysis of the spectra.

Table 1 Fundamental Parameters

Object	TY Psc	FL Psc	V455 And
$T_{\rm eff}$ (K)	$22\,000 \pm 1300$	$19\,000 \pm 1300$	$19\,000 \pm 1300$
$\log g$ (dex)	8.20 ± 0.09	8.30 ± 0.09	8.00 ± 0.09
M_1 ($M_\odot$)	0.72 ± 0.06	0.78 ± 0.06	0.60 ± 0.06
R_1 ($R_\odot$)	0.0111 ± 0.0007	0.0103 ± 0.0007	0.0125 ± 0.001

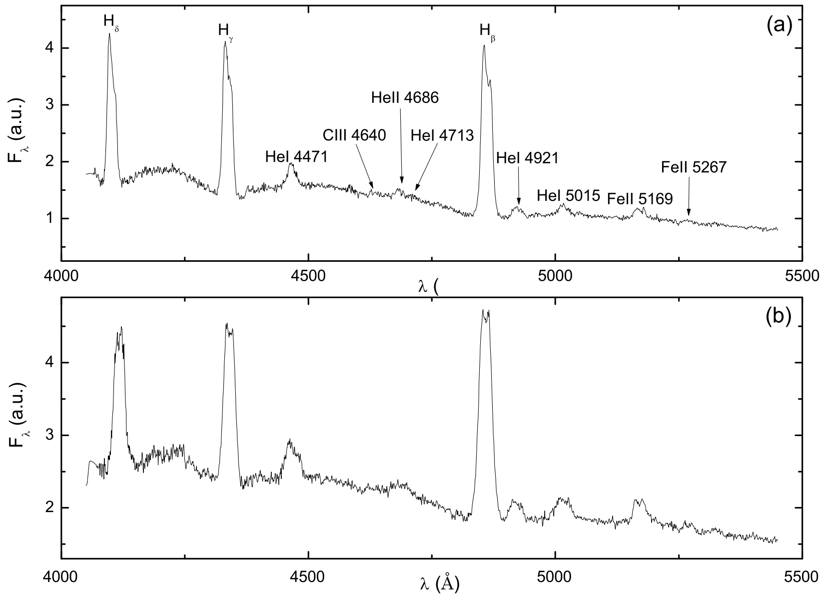

Fig. 1 The observed FL Psc (a) and TY Psc (b) spectra.

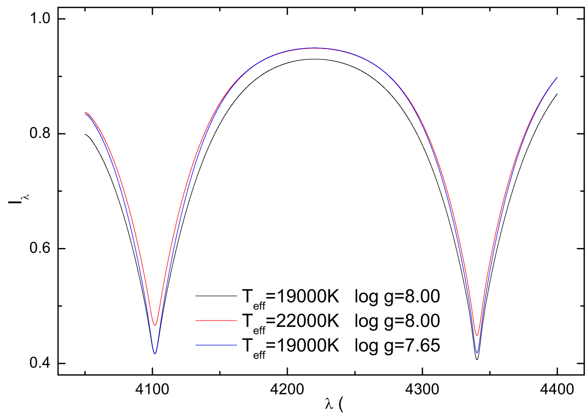

Fig. 2 The theoretical WD spectra for different atmospheric parameters.

However, WD parameters were determined by Mitrofanova et al. (2014) through the analysis of a large number of spectra observed in two states of the system. This approach requires long-term observations on large telescopes. Therefore, the aim of our work is to study the efficiency of similar analysis of short observation blocks of three–four spectra. This number of spectra allows for checking the stability of the radiation of the system during 0.3–0.4 of orbital period and to establish its presence in a low state with an optically thin disk. For the study we selected three DNe (TY Psc, FL Psc and V455 And) which are SU UMa and WZ Sge types (Ritter & Kolb 2011)

2 OBSERVATIONS AND DATA REDUCTION

Spectroscopic observations were carried out during the night of 2013 September 11 at the Big Azimuth Telescope of the Special Astrophysical Observatory of the Russian Academy of Science (SAO RAS) using the primary focus aperture reducer SCORPIO-1 (Afanasiev & Moiseev 2005), grism VPHG1200G and CCD-matrix EEV42-4. The final spectral resolution was $\lambda = 5.0$ Å in the investigated wavelength range $\lambda = 4050 - 5450$ Å. Observations were carried out under good weather conditions with seeing $\sigma = 1.3''$. For each object, three spectra with an equal exposure time of 300 s were obtained. In the spectra of all systems, the signal-to-noise ratio (S/N) exceeded 100. Simultaneously with the objects, the standard star HZ 44 and the spectrum of the helium-neon-argon lamp were observed (Bohlin 1996). Primary reduction of spectra is performed by specialized programs for reduction of astronomical observations in the IDL environment.

Standard processing included the following operations: cleaning of cosmic rays, wavelength calibration utilizing an He-Ne-Ar filled lamp, the approximate elimination of sky background by a two-dimensional polynomial along the entire CCD image, and selecting the vector of a one-dimensional spectrum. At the end of processing, the observed spectrum of the system was divided into the observed spectrum of the standard star multiplied by the known tabular values of its calibrated fluxes carried beyond the Earth's atmospheric boundary. As a result, one-dimensional spectra were obtained in units of absolute flow.

Examples of the obtained spectra are featured in Figure 1. They contain radiation in the WD continuum with wide absorption of HI. In their center there are intense two-peak emissions with a half-width of $\lambda \approx 30$ Å. Similar profiles have weaker HeI, HeII, CIII and FeII lines. The intensity and width of the emissions indicate their formation in the optically thin AD. In general, the observed spectra correspond to the DN spectra in a low state with the dominance of WD radiation.

Normalization of spectra is complicated by the large width of the HI lines and by the absence of continuum sections with an intensity near 1. Therefore, we normalized the observed spectra by their agreement with the theoretical ones in the process of determining the WD parameters. For this purpose, we have allocated ranges of a conditional continuum in which the requirement of equality of averages of theoretical and observed fluxes was set.

3 MODELING AND ANALYSIS

The parameters were determined by numerical simulation of absorption lines in the DN spectra according to the Mitrofanova et al. (2014) method. Using the ATLAS12 (Castelli & Kurucz 2003) program complex, we calculated grids of WD hydrogen atmosphere models with parameters: $T_{\rm eff} = 10\,000 - 90\,000\,K$ with step $\Delta T_{\rm eff} = 2000\,K$, $\log g = 6.5 - 9.5$ dex with step $\Delta \log g = 0.25$ dex, $[\mathrm{He/H}] = -3$ dex and $[\mathrm{Fe/H}] = -5$ dex (Suleimanov 1996). Models of atmospheres for intermediate parameters were obtained by the method of their interpolation presented in Suleimanov (1996).

Synthetic spectra were calculated by the STAR program (Menzhevitski et al. 2014). Test calculations of atmospheric models for $T_{\rm eff} = 20\,000\,K$ and $\log g = 8.20$ dex with an increase in the helium content to $[\mathrm{He/H}] = -0.5$ dex and metallicity to $[\mathrm{M/H}] = -0.7$ dex demonstrated their effect up to 0.004 on the residual intensities in the HI line wings. This effect is significantly lower than the noise level and we did not take this aspect into account in this work.

The parameters of the WD atmospheres ($T_{\rm eff}$ and $\log g$) in the studied DNe were determined by modeling the theoretical spectra to optimal agreement with the observational data. Figure 2 shows an example of the influence of WD parameters on the profiles of HI Balmer lines. Their amplification occurs almost uniformly along the profile, when $T_{\rm eff}$ is lowered. With the growth of $\log g$, the half-width of the lines increases with a weak increase in their intensity. Thus, we could simultaneously determine both parameters by matching the observed and theoretical profiles of the HI lines.

The parameters were varied to achieve the best matching of spectra according to the following criteria:

1. A detailed fitting of the distant absorption wings of the HI lines.

2. The absence of absorption parts and symmetry of the profiles of emission lines after subtracting the observations with the theoretical spectrum of a WD.

When the temperature decreases, there is an almost uniform strengthening of the lines along the entire profile. A stronger influence of $T_{\rm eff}$ is seen in the transition to the late Balmer lines. The change in the width of the profiles with temperature variations is insignificant. With an increase in $\log g$, there is a predominant growth in the wings of the HI lines, which leads to an increase in their half-width with a slight change in the intensity in the nuclei.

The final optimal spectrum matching is displayed in Figure 3, and the parameters of the WD atmospheres are in Table 1.

The masses and radii of WDs were determined by comparing the parameters of WD atmospheres with the model three-parameter mass-radius-temperature (M-R-T) relation from the paper by Panei et al. (2000). On the mass-radius relation that is the closest to the observed value of $T_{\rm eff}$, there is a point where the combination of mass and radius corresponds to the observed value of $\log g$. We employed models by Panei et al. (2000) with carbon and oxygen nuclei expected for the obtained estimates of WD masses in the studied DNe. The results of determination of the fundamental parameters are presented in Table 1.

Values of the mass of WD TY Psc, FL Psc and V455 And presented in the literature differ within $\Delta M = -0.10 - 0.15\,M_{\odot}$. Our values of M_1 for all systems are consistent with the literature values in the range of errors. The parameters of the WD atmosphere for TY Psc obtained by us are close to those found by Araujo-Betancor et al. At the same time, we determined a significantly higher WD temperature than in the work by Szkody et al. This may indicate a shorter time elapsed after the V455 And superburst before our observations.

Our results for WD parameters are generally consistent with the literature data for SU UMa and WZ Sge

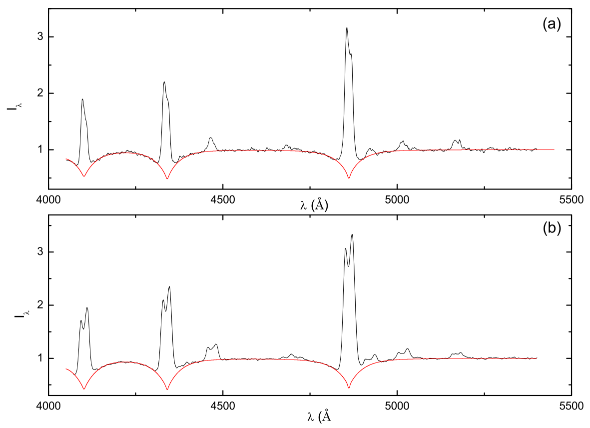

Fig. 3 The observed (*solid lines*) and theoretical (*dashed lines*) FL Psc (a) and V455 And (b) spectra.

type DNe. According to the review by Ritter & Kolb (2011), WD mass estimates in 34 SU UMa type systems are $M_1 = 0.76 \pm 0.19\, M_\odot$. For 17 systems with short orbital periods (2–3 h), the WD mass values are reduced to $M_1 = 0.69 \pm 0.19\, M_\odot$. However, our estimate of the mass of the WD ($M_1 = 0.59\, M_\odot$) in V455 And remains below the average. In general, we conclude that the characteristics of the primaries of FL Psc and TY Psc are typical representatives of SU UMa type DNe. Verification and refinement of V455 And parameters should be performed using additional observations and more effective criteria for matching theoretical and observed spectra. Errors in the WD parameters are mainly caused by inaccuracies in the model description of the observed spectra in the presence of their noise. The obtained estimates of parameter errors are determined by the requirement that the root-mean-square deviations of the theoretical and observed spectra exceed the existing noise level. As a result, the uncertainties of the WD atmospheric parameters are $\sigma T_{\rm eff} \approx 1300\, K$ and $\sigma \log g \approx 0.09$ dex. An additional source of parameter error can be the difference in the structures of atmospheres and of inner layers in single WD and DN components. In the works of Chen et al. (2019) and Wolf et al. (2014), it is shown that in novae, for repeated novae and nova-like cases with accretion rates above $10^{-9}\, M_\odot\, {\rm yr}^{-1}$, WDs experience strong changes in their internal structure and in fundamental characteristics ($T_{\rm eff}$, R_1). However, the rate of accretion is much lower in the DNe studied by us (10^{-12} – 10^{-11}) and does not lead to nuclear fusion on the surface of a WD or change their chemical composition. Therefore, we assume that the application of atmospheric models and the internal structure of a single WD in our work will lead to smaller parameter errors than the errors of observations and their theoretical description.

4 DISCUSSION AND CONCLUSION

The main aim of this work was to investigate the possibility of mass determination for the parameters of the primaries of SU UMa and WZ Sge type DNe on the basis of model analysis of small sets of their optical spectra in the low state. The method of analysis as a whole was developed and applied by us in Mitrofanova et al. (2014). We found different effects of WD atmospheric parameters ($T_{\rm eff}$ and $\log g$) on the shape and intensity of the wings of HI lines free from blending by emission components. As a result, it is possible to simultaneously determine all WD parameters on the basis of matching the unblended parts of the HI line profiles in the observed and theoretical spectra. Estimates for the parameters of the primaries of the SU UMa and WZ Sge type DNe found in this way correspond to the average for such objects. Note that the method we used involves short observations on large telescopes. However, observation candidates must be pre-selected on the basis of their presence in the low state. Such selection is possible through monitoring observations with medium and small telescopes.

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