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# Determination of QW Ser and QZ Lib parameters from optical spectra

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**ABSTRACT**

The paper investigates a new technique for determining dwarf nova parameters based on the analysis of their optical spectra with a signal-to-noise ratio $S/N \approx 80$. We have determined parameters for the QW Ser and QZ Lib systems related to the SU UMa and WZ Sge dwarf novae. Moderate resolution spectra of both systems were obtained at BTA SAO during their low state with an optically thin accretion disk and the dominance of white dwarf radiation. As a result of the model analysis of the spectra, the parameters of the accretor atmosphere of QW Ser ($T_{\rm eff} = 23500 \pm 400$ K and $\log g = 8.36 \pm 0.05$ dex) and constraints on the parameters for QZ Lib ($T_{\rm eff} = 9500 \pm 300$ K and $\log g > 8.55$ dex) were found. The presence of moderate noise in the studied spectra is not shown to affect the accuracy of determining parameters. The low temperature of the white dwarf does not allow to obtain a correct estimate of its surface gravity. Based on the determined parameters of the accretor atmospheres, a complete set of QW Ser parameters and estimates of QZ Lib parameters were found. The secondary components of both systems are defined to be red dwarfs of spectral type M.

**Key words:** cataclysmic variables, dwarf novae, white dwarfs, optical spectra

## 1 Introduction

Cataclysmic variables (CV) are semi-detached systems consisting of a low-mass main-sequence star (donor) and a white dwarf (accretor) with an orbital period of no more than a few hours. Brightness variations of CVs are associated with the orbital motion of the components and with changes in their projection onto the tangential plane, with different types of flare activity and the nonstationarity mass transfer from the donor to the accretor.

The flare activity of dwarf novae (DN) is caused by changes in the accretion rate from the accretion disk (AD) on the surface of a white dwarf (WD). In a low state, the flowing matter of the secondary component gradually accumulates in a cold, optically thin AD. The corresponding increase of optical thickness and density of the gas leads to its heating. From some point, the heating produces a burst since an increase in temperature causes a rapid increase of opacity and turbulent viscosity of matter. As a result, intensive accretion to the surface of the WD occurs, continuing until the complete depletion of the AD. When the optically thin state is reached, the disk rapidly cools down and enters the accumulation stage (Guillaume, Otulakowska-Hypka, 2018).

The SU UMa-type stars are a group of dwarf novae with random superflares ($\Delta m_v = 4^m$–$7^m$), brighter and longer-lasting than normal flares (with $\Delta m_V = 2^m$–$6^m$). The process of relaxation of such systems into a calm state after superflares and normal flares lasts 10–30 and 2–5 days, respectively. The WZ Sge-type systems show only superflares with an increase in brightness amplitude of $\Delta m_V = 6^m$–$9^m$ in 14–22 hours and its decrease to the initial level in 60–200 days. This process includes the stages of uniform brightness decreasing and its abrupt reduction $\Delta m_V = 2^m$–$3^m$ in 2–3 days. In the flare phase, the SU UMa and WZ Sge DNs show periodic brightness fluctuations with an amplitude of $\Delta m_V = 0.2^m$–$0.4^m$ that are called superhumps. The periods of superhumps are close to the orbital ones (Katysheva et al., 2015), which for both types of DNs do not exceed $P_{\rm orb} = 2^h$.

The masses of the main and secondary components of about 30 studied SU UMa and WZ Sge systems are $M_1 = 0.76 \pm 0.19\ M_\odot$ and $M_2 = 0.10 \pm 0.04\ M_\odot$, respectively (Mitrofanova, 2019).These estimates were obtained using various methods and are characterized by strong heterogeneity. The main problem in determining the parameters of DNs is the dominance of AD radiation in the optical range, which prevents the analysis of donor and accretor radiation. However, after the end of the flare, the cooling WD begins to dominate in the UV range of the spectrum (Szkody et al., 2013). The numerical modeling of its radiation makes it possible to determine the parameters of the donor atmosphere and its fundamental parameters (Szkody et al., 2013). Later, a similar analysis of the optical spectra of DNs with cold, optically thin ADs was carried out, which turned out to be an effective tool for finding their parameters (Mitrofanova et al., 2014).

Based on these results, we have developed and implemented a new method for the extensive determination of the parameters of DNs using their optical observations in a low state (Dudnik et al., 2021).This method was used in the study of TY Psc, FL Psc, V355 And systems with moderately hot WDs and showed high efficiency. Its development made it possible to simultaneously determine the fundamental parameters of both the main and secondary components.

The developed method for determining parameters of DNs currently has a number of limitations. First of all, it assumes the use of spectra with a high signal-to-noise ratio $S/N > 100$ (Dudnik et al., 2021). Meanwhile, the most number of SU UMa and WZ Sge objects of DW types in the low state have a weak brightness less than $m_V = 18^m$. Obtaining their spectra with a high $S/N$ ratio requires a lot of time for large telescopes. Secondly, some systems of the WZ Sge type do not experience superflares for a long time (more than 10 years) and contain cooled WDs with a temperature below $T_{\rm eff} = 15000$ K. The presence of convection in the atmospheres of such WDs leads to a noticeable change in their structure, as well as the emitted spectra. Such changes can have a serious impact on the accuracy of parameter determination when using our methodology. Therefore, within the framework we analyzed its applicability for studying noticeably noisy spectra and systems with cold WDs. The analysis was performed for the QW Ser and QZ Lib DNs that belong to the SU UMa type.

The QW Ser was discovered by Takamisawa and noted in Takamizawa (1998). The relation of QW Ser to dwarf novae was confirmed by Kato and Uemura (1999), and its identification with the X-ray source 1RXS J152613.9+081845 was carried out by Voges et al. (2000). In 2003, 2009 and 2013, the system experienced superflares with the appearance of superhumps (Nogami et al., 2004; Patterson et al., 2003). In the review of photometric variability of QW Ser, Kato et al. (2014) noted the presence of 4 long and many short flares throughout the period 2000–2003 with amplitudes $\Delta m_V \approx 5.5^m$, lasting up to 14 days and a periodicity of 50–240 days. The orbital period of the $P_{\rm orb} = 0.^d07457(2)$ system is represented by Uemura et al. (2010). There is no information in the literature on the determination of its fundamental parameters.

QZ Lib was classified by Schmidtobreick et al. (2004) as a SU UMa-type dwarf nova with a photometric period of superhumps $P_{\rm ph} = 0.^d06501$ during the flare in February 2004. In the paper of Pala et al. (2018), the parameters of WD atmospheres were determined from the analysis of optical and infrared spectra ($T_{\rm eff} = 10500 \pm 1500$ K, $\log g = 8.35$ dex, $R_1 = 0.01\ R_\odot$) and its temperature change was shown in one, two, and six months after the flare ($T_{\rm eff} = 17000$ K, 14000 K, 11700 K). A close value of $T_{\rm eff} = 11300$ K was obtained in Pala et al. (2017). They determined the amplitude of the radial velocities of WDs ($K_1 = 20$ km/sec) and the angle of inclination of the orbit $i = 30°$. Based on these data, an estimate of the masses of the accretor ($M_1 = 0.8\ M_\odot$) and the donor ($M_2 = 0.032\ M_\odot$) with the temperature of the latter $T_{\rm eff} < 1700$ K was found. Zorotovic et al. (2014) obtained a close value of the WD mass ($M_1 = 0.83 \pm 0.23\ M_\odot$). Several estimates are presented for the mass ratio of the QZ Lib components: $q = 0.04019$ (Pala et al., 2018), $q = 0.020 \pm 0.017$ (Patterson et al., 2005).

## 2 Observations and reduction

The QW Ser and QZ Lib spectra were obtained at BTA SAO during the nights of April 29/30, 2020 and July 3/4, 2021, respectively. During the observations, a SCORPIO-1 (Afanasyev, Moiseev, 2005) focal reducer in the long-slit spectroscopy mode, a *VPHG*1200*G* grisma (1200 strokes/mm), and an *EEV CCD*42-40 *CCD* receiver (2048 × 2048 pixels) were used. For QW Ser and QZ Lib, 5 and 6 exposures were performed with the same duration of 300 seconds. The final signal-to-noise ratio of the total spectra in the studied wavelength range $\Delta\lambda = 3970$–$5770$ Å was $S/N = 87$ and $S/N = 59$, respectively.

For the data reduction, which includes all standard procedures, a software package implemented in the *IDL* environment was used. As a result, we obtained the spectral distributions of QW Ser and QZ Lib radiation in units of absolute fluxes on the accepted wavelength scale. The subsequent normalization of the spectra was carried out in the process of their model analysis. The main requirement of normalization was the coincidence of the radiation level of the observed and model spectra in the ranges free of emission lines and absorption wings of *HI* lines. The obtained normalized spectra of QW Ser and QZ Lib are shown in Figs. 1 and 2.

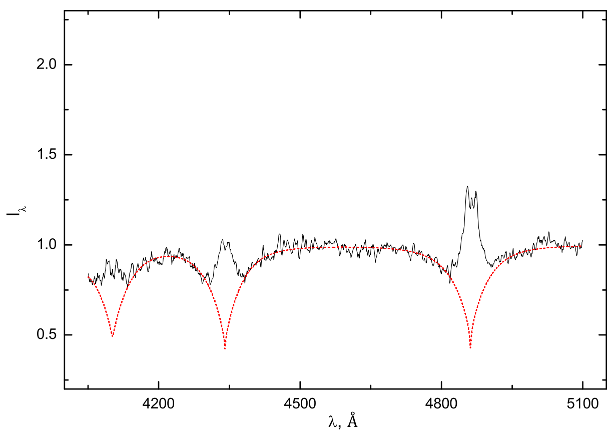


**Fig. 1.** The observed (solid lines) and theoretical (dashed lines) QW Ser spectra.

Two-peak emission lines *HI* and *HeI* with a half-width of 15–40 Å and a separation of peaks up to 10 Å and wide absorption wings of Balmer lines are distinguished in them. The observed spectra are characteristic of low-state DNs with the dominance of WD radiation in the continuum and optically thin ADs in emission lines. Deep and moderately wide ($\Delta\lambda \approx 70$ Å) absorption wings of *HI* lines in the QW Ser spectrum indicate an effective temperature of the WD of above $T_{\rm eff} = 20000$ K. In the QZ Lib spectrum, these lines are weakly expressed, which corresponds to the literature data on the low temperature WD in this system.

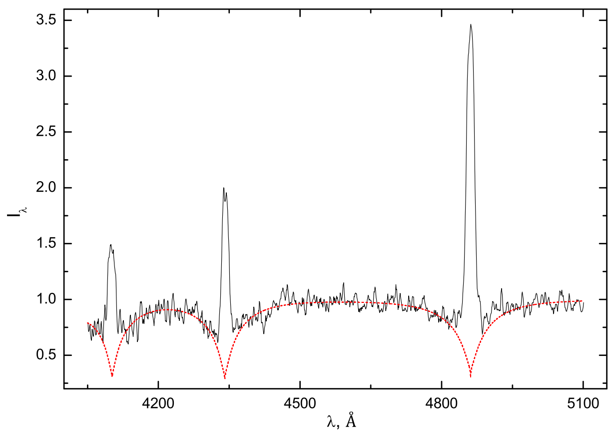


**Fig. 2.** The observed (solid lines) and theoretical (dashed lines) QZ Lib spectra.

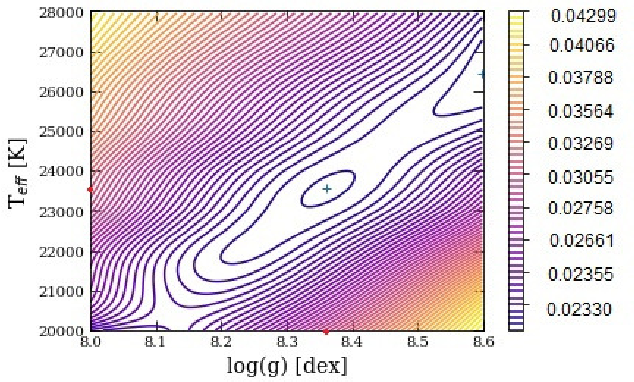


**Fig. 3.** The map of $\sigma$ distributions for QW Ser.

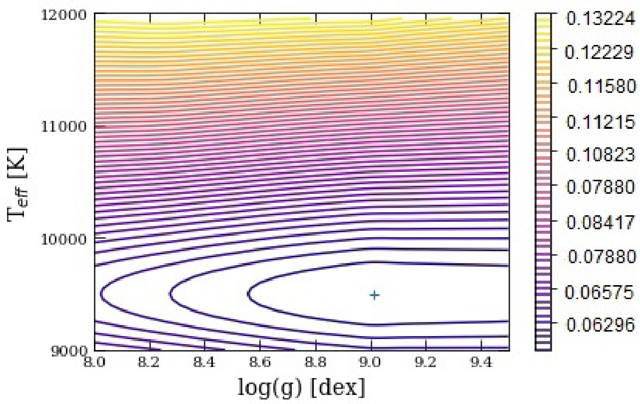


**Fig. 4.** The map of $\sigma$ distributions for QZ Lib.

## 3 Parameters of WD atmospheres

The characteristics of the observed QW Ser and QZ Lib spectra make it possible to analyze them according to the standard method (Dudnik et al., 2021; Mitrofanova et al., 2014) with a numerical simulation of WD radiation and determination of the fundamental parameters of the systems. Grids of WD atmospheric models with radiant and convective transport in the range of parameters $T_{\rm eff}$ = 10000 − 90000 K, $\log g$ = 6.5–9.5 dex, at $[He/H] = -3$ dex and $[M/H] = -5$ dex were obtained in Mitrofanova et al. (2014) using the $ATLAS12$ software package (Piskunov, 1992). On their basis, grids of synthetic spectra in the wavelength range $\lambda$ = 3900–5400 Å were calculated using the STAR software package (Menzhevitski et al., 2014). To obtain the atmospheric spectrum with arbitrary $T_{\rm eff}$ and $\log g$ values, a linear interpolation of grid spectra for both parameters was used.

A comparison of the model spectrum of WDs and the observed spectrum of DNs was carried out after their transition into a single wavelength scale and the selection of ranges free from emission lines of ADs. The correspondence of the spectra was determined by calculating their standard deviations ($\sigma$) in the selected ranges. The described procedure was carried out on a dense grid of atmospheric parameters $T_{\rm eff}$ and $\log g$ to obtain two-dimensional distributions of root-mean-square deviations for these parameters. The distributions ($\sigma$) were processed by the specialized Contour Paradise V 1.0 utility to form their two-dimensional maps in the form of sets of isolines. At the same time, the position of the global minimum of distributions corresponding to the desired values of the parameters of the WD atmosphere was found. The obtained maps for QW Ser and QZ Lib are shown in Figs. 3 and 4, and a comparison of their observed and model spectra is shown in Figs. 1 and 2.

The deviation distribution for QW Ser contains a clearly defined minimum at $T_{\rm eff}$ = 23500 ± 400 K and $\log g$ = 8.36 ± 0.05 dex. The alternative minimum at $\log g > 8.8$ dex was excluded from consideration because of too large final estimate of the WD mass. A comparison of the model and observed spectra shows their good agreement in the wings of all *HI* lines but with standard deviations of 1.8 − 2.0 times the average noise level. The excess value is probably due to the incomplete exclusion from consideration of the areas with weak emission lines and inaccuracies in the normalization of the spectrum. Therefore, we concluded that noise had a non-critical effect on the results of the DN spectra analysis with moderately hot WDs ($T_{\rm eff}$ = 20000–25000 K) at a ratio of $S/N \approx 70$–100.

The analysis of the model spectra of cold WDs shows a very strong influence of the effective temperature on them with a weak influence of the surface gravity. Therefore, in QZ Lib deviation distributions, the values of $\sigma$ are almost insensitive to $\log g$. This circumstance causes the low accuracy of the $\log g$ determination with the high accuracy of $T_{\rm eff}$ value at the same time. The accretor temperature $T_{\rm eff}$ = 9500 ± 300 K found by us turns out to be 1800 K and 2200 K lower than the estimates in the literature (Pala et al., 2017, 2018). This result is expected due to the continued cooling of the WD in the absence of QZ Lib flares. However, the presented $T_{\rm eff}$ value is beyond the limits of the synthetic spectrum grid and contains additional uncertainties. Estimation of the surface gravity of WDs $\log g$ = 9.0 ± 0.45 dex leads to abnormally high values of its mass (see below).Therefore, for an accretor in QZ Lib, only the lower bound of $\log g > 8.55$ dex values and the corresponding limits of its mass and radius can be set. In general, we came to the conclusion about the low efficiency of our technique for analyzing the spectra of DNs containing WDs with $T_{\rm eff} < 13000$ K. A comparison of the model (at $T_{\rm eff} = 9500$ K, $\log g = 9.0$ dex) and the observed QZ Lib spectra in Fig. 2 shows their satisfactory agreement. Therefore, we carried out further determination of the system parameters using the obtained parameters of the WD atmosphere.

## 4 Fundamental parameters of the systems

The method of subsequent obtaining estimates of the fundamental parameters of the components is described in detail in Dudnik et al. (2021). To determine the masses and radii of accretors, the authors used the theoretical three-parameter temperature - mass - radius dependencies for WDs of different chemical composition from Panei et al. (2000). The high total WD masses in both systems determined the choice of dependence for WDs with an oxygen core. For the given values of $T_{\rm eff}$, according to these dependencies, pairs of values of mass M and radius R were iteratively found corresponding to the observed $\log g$ estimates by the formula:

$$\log \frac{g}{g_\odot} = \log \left( \frac{\frac{M}{M_\odot}}{\left(\frac{R}{R_\odot}\right)^2} \right). \quad (1)$$

As a result, the following estimates of the fundamental parameters of WDs are obtained: $M_1 = 0.82 \pm 0.03\ M_\odot$, $R_1 = 0.0099 \pm 0.0004\ R\odot$ for QW Ser and $M_1 > 0.93\ M_\odot$, $R_1 = 0.0085\ R_\odot$ for QZ Lib. The accuracy of the first-found values of the mass and radius of the QW Ser accretor generally corresponds to the accuracy of determining the parameters of the main components of the DN in Dudnik et al. (2021).

The fundamental parameters of the secondary components and the large semi-axes of the systems were found by the joint application of Kepler's third law, the Eggleton formula (Eggleton, 1989) for calculating Roche lobes, and the theoretical mass-radius dependencies for low-mass main-sequence stars from the classes of red (Girardi et al., 2000) and brown (Baraffe et al., 2003) dwarfs of solar chemical composition. The donor parameters were determined from the assumption $R_{L2} = 1.05\ R_2$, where $R_2$ is the radius of the Roche lobe, and $R_2$ is the radius of the star from the dependencies (Panei et al., 2000). As a result, the following values were obtained: $M_2 = 0.16 \pm 0.01\ M_\odot$, $R_2 = 0.18 \pm 0.01\ R_\odot$, $A = 0.757 \pm 0.009\ R_\odot$ for QW Ser, $M_2 > 0.13\ M_\odot$, $R_2 > 0.15\ R_\odot$, $A > 0.687\ R_\odot$ for QZ Lib. Thus, the secondary components of both systems are red dwarfs of spectral type M.

The values of the QW Ser parameters found by us correspond well to the published estimates for similar systems. Dudnik et al. (2021) performed a statistical analysis of the literature data of Ritter, Kolb (2011) for 34 SU UMa-type DNs. This analysis shows the average mass of their accretors $M_1 = 0.76 \pm 0.19\ M_\odot$ and the average mass of their donors $M_2 = 0.12 \pm 0.04\ M_\odot$. The application of the method of model study of optical spectra of 3 DNs in Dudnik et al. (2021) allowed us to determine the masses of their WDs with an average value of $M_1 = 0.70 \pm 0.08\ M_\odot$. Therefore, we consider the obtained QW Ser parameters to be reliable. At the same time, the boundary estimates of the mass of the WD in QZ Lib ($M_1 > 0.93\ M_\odot$) and the red dwarf ($M_2 > 0.13\ M_\odot$) significantly exceed the average values of the component masses in the WZ Sge-type systems. In addition, they do not correspond to the QZ Lib parameters presented in the literature: $M_2 = 0.032\ M_\odot$ (Zorotovic et al., 2014), $R_1 = 0.01\ R_\odot$ (Pala et al., 2017), $q = 0.04019$ (Pala et al., 2018). As a result, we came to the conclusion that the results obtained by us are doubtful for this system.

## 5 Conclusions

The analysis of the QW Ser and QZ Lib systems was performed with the determination of the parameters of DW atmospheres, as well as a set of fundamental parameters. Both systems were in a low state, which showed the presence of the WD spectrum. It is shown that the presence of moderate noise in the studied spectra does not affect the accuracy of determination of the parameters. The low temperature of the WD does not allow to obtain a correct estimate of its surface gravity. We came to the conclusion that our program for cold WDs ($T_{\rm eff} < 13000$ K) is not very effective. The analysis of the applicability of the method of determining parameters for the study of noticeably noisy spectra and systems with cold WDs was carried out. Some limitations have been described. The technique involves the use of spectra with a moderate signal-to-noise ratio $S/N < 100$ for the studied systems $S/N = 87$ (QW Ser), $S/N = 59$ (QZ Lib). For QW Ser, taking into account the literature data, the obtained parameters are correct. However, the parameters we determined for QZ Lib turned out to be overestimated.

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