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# Spectroscopic and photometric observations of symbiotic nova PU Vul during 2009–2016

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**Abstract** A new set of low-resolution spectral and *UBVJHKL*-photometric observations of the symbiotic nova PU Vul is presented. The binary has been evolving after its symbiotic nova outburst in 1977 and now it is in the nebular stage. It is found that the third orbital cycle (after 1977) was characterized by great changes in associated light curves. Now, PU Vul exhibits a sine-wave shape in all the light curves (with an amplitude in the *U* band of about 0.7 mag), which is typical for symbiotic stars in the quiescent state. Brightness variability due to pulsations of the cool component is now clearly visible in the *VRI* light curves. The amplitude of the pulsations increases from 0.5 mag in the *V* band to 0.8 mag in the *I* band. These two types of variability, as well as a very slow change in the physical parameters of the hot component due to evolution after the outburst of 1977, influence the spectral energy distribution (SED) of the system. The variability of emission lines is highly complex. Only hydrogen line fluxes vary with orbital phase. An important feature of the third orbital cycle is the first emergence of the OVI, 6828Å Raman scattering line. We determine the temperature of the hot component by means of the Zanstra method applied to the He II, 4686Å line. Our estimate is about 150 000 K for the spectrum obtained near orbital maximum in 2014. The VO spectral index derived near pulsation minimum corresponds to M6 spectral class for the cool component of PU Vul.

**Key words:** binaries: symbiotic — novae — cataclysmic variables — stars: individual (PU Vul)

## 1 INTRODUCTION

The symbiotic star PU Vul (also known as a Kuwano-Honda object) is a well-known member of the small group of symbiotic novae, which means that this system has demonstrated only one very slow and bright outburst. PU Vul exploded at the end of 1977. Near the outburst maximum, according to optical and ultraviolet (UV) data, the system was in the A-F supergiant phase and then, after a short transition period, entered the nebular phase. So, if based on the 10-year long (1977–1988) optical and UV spectroscopic and photometric observations of PU Vul, it can be classified as a single red giant (before the outburst), an A-F supergiant, a Wolf-Rayet star and finally a hot subdwarf surrounded by a gaseous nebula. A detailed bibliography concerning observations and related analysis can be found in the review of Gershberg (2000). More recent theoretical investigations of the PU Vul outburst were published in Kato et al. (2012).

The nature of the sharp and deep brightness minimum observed in 1980 (Min. I in Fig. 1) was actively debated for a long time. Spectral observations in the far UV range obtained with the *International Ultraviolet Explorer* (*IUE*) discovered the eclipsing nature of this minimum as well as that of the next one (Min. II), though not as sharp and deep, observed in 1993. Thus, the symbiotic nova PU Vul is an eclipsing variable star with a very long orbital period of $P \approx 13.4$ years (Shugarov et al. 2012). In this paper, we consider spectral and photometrical characteristics of PU Vul during a time interval near and after Min. III (2007). The preliminary version of this paper was presented at the Conference VAK-2017 (see Samus & Li 2018).

## 2 OBSERVATIONS

Our *JHKL* photometry was performed with the 1.25-m ZTE telescope of the South Station of the Sternberg Astronomical Institute, Moscow State University, with the use of a single-channel InSb photometer. The standard star was BS 7635 ($J = 0.79$, $H = 0.03$, $K = -0.16$, $L = -0.36$). The uncertainties of the photometric measurements are within 0.03 mag.

Photometrical observations in *UBV* and *BVRI* systems were obtained on the two Zeiss-600 telescopes of the South Station, equipped with the photoelectric photometer constructed by V.M. Lyuty and a CCD-photometer with an FLI PL-4022 camera, respectively. We also use photometrical observations obtained at the Skalnaté Pleso Observatory of the Astronomical Institute of Slovak Academy of Sciences (see details in Shugarov et al. 2012). The star HD 192712 was a *UBV* standard for photoelectric observations. For our CCD photometry, we used three stars, "b," "c" and "$\alpha$," from Henden & Munari (2006) as main standard stars. The observational errors do not exceed 0.01 mag for all the bands except the $U$ band (in which the errors can reach 0.03 mag).

Spectroscopic observations were acquired with the 2.6-m G.A. Shain reflector (ZTSh) of the Crimean Astrophysical Observatory (CrAO) by using the SPEM slit spectrograph mounted at the Nasmyth focus. The detector was a $1340 \times 100$ SPEC-10 CCD camera. The fixed 3 arcsec slit width allows spectra with a resolution of 8Å to be taken. The grating has 651 rulings mm$^{-1}$, yielding a dispersion of about 2Å pixel$^{-1}$. The primary reduction of the spectra, consisting of bias subtraction and flat-fielding, was done using the SPERED code developed by S.G. Sergeev at CrAO. The subsequent reduction of the spectra, the wavelength calibration and the spectral flux calibration were performed using the SPE code of Sergeev. The spectra were wavelength-calibrated using the exposures of the neon lamp. The flux-calibration was based on the absolute spectral energy distribution (SED) of the spectrophotometric standard star HR 7744; the calibration uncertainty is within 10% (except for the Balmer jump region, where uncertainty may be up to 30%) .

In 2016, spectroscopic observations were obtained at the 1.25-m ZTE telescope by using a slit spectrograph equipped with a diffraction grating of 600 lines per mm, and an ST-402 CCD. The dispersion for these spectra is 2.3Å pixel$^{-1}$. The standard star was 40 Cyg and the calibration uncertainty is within 10%. The primary reduction of the spectra was done using the CCDOPS program. The subsequent reduction of these spectra was also performed using the SPE code.

## 3 LIGHT CURVE ANALYSIS

As shown in Figure 1, the third eclipse differs greatly from the two previous ones . Min. I and II are sharp and contact points are well-defined, while Min. III has a sine-wave shape (with an amplitude in the $U$ band of about 0.7 mag). Such type of light curve is typical for symbiotic stars in the quiescent state. Min. I (1980) was associated with a total eclipse of the hot component in the supergiant stage (the main source of UV and optical radiation). Therefore, this minimum was deep and sharp and looked like a textbook eclipse in a binary system. However in the early 2000s, the hot component of PU Vul was in the hot subdwarf stage and its temperature was about 150 000 K (see section "Spectral Evolution"). Therefore in the third orbital cycle, the emission of an optically thin large gaseous nebula dominates the near UV and blue domains. The sine-wave shape of Min. III is related to the partial eclipse of the nebula by the orbiting cool component of PU Vul.

The orbital brightness variations are clearly visible in *UBVR* bands where the nebula provides a significant part of the total system flux and they nearly disappear in *IJHKL* bands where radiation from the cool component dominates.

During the third orbital cycle, the brightness variations, interpreted as pulsations of the cool component, are clearly visible in the *VRIJHKL* light curves (Fig. 1). The period is about 217.7 days, according to Shugarov et al. (2012), and the pulsational amplitude increases from 0.5 mag in $V$ to 0.8 mag in $I$. These variations become more prominent near the eclipse (Min. III) when the influence of the nebula radiation which veils the pulsations of the cool component weakens sufficiently. Let us note that the $R - I$ color index demonstrates a dependence that is not typical for red semiregular and Mira variables: it is redder near pulsation minima (see Fig. 2). Whereas,

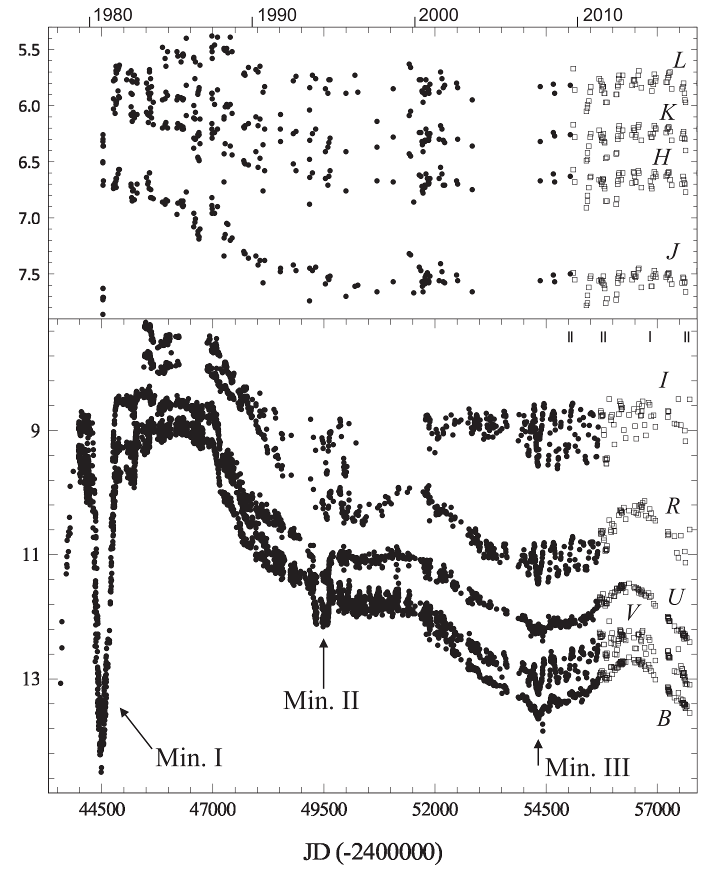


**Fig. 1** Light curves of the symbiotic nova PU Vul in 1977–2016. *Circles* are the data from Shugarov et al. (2012) and Tatarnikova et al. (2011). *Squares* are the new data. Times of our new spectroscopic observations are marked by the *vertical bars*.

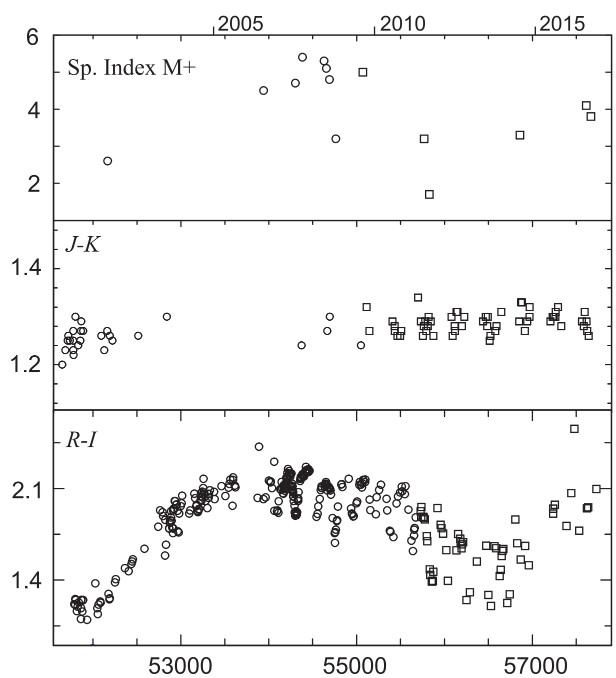


**Fig. 2** The $R-I$ and $J-K$ color curves and spectral class of the cool component. *Circles* are the data from Tatarnikova et al. (2011). *Squares* are the new data.

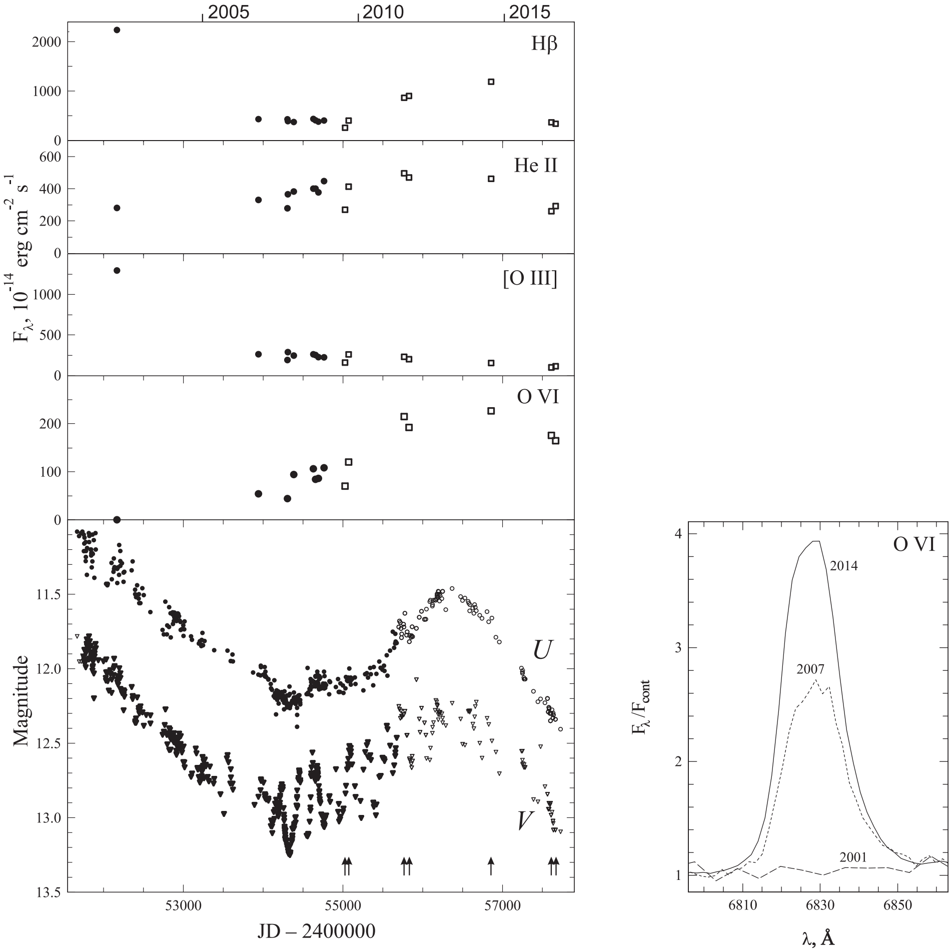


**Fig. 3** *Left column*: Light curves of the symbiotic nova PU Vul in *U*, *V* filters and some emission lines: H$\beta$, HeII (4686Å), [OIII] (5007Å) and OVI (6828Å) (*filled symbols* are the data from Tatarnikova et al. (2011), *open symbols* are the new data and *arrows* mark the dates of our spectroscopic observations). *Right column*: Variations in the OVI line profile.

the $J - K$ color index is barely dependent on the pulsation phase. The reason is that the nebular radiation contributes to the total flux (including the strong H$\alpha$ emission) more essentially in the *R* band than in the *IJHK* bands. Consequently, the star, according to the $R - I$ color index, is redder near pulsation maxima than it is near pulsation minima due to the relative contribution of the red giant emission to the *R* band being larger at those moments.

In addition to orbital brightness variations and cool component pulsations, a long-term brightness evolution after the outburst in 1977 can be traced in Figure 1.

## 4 SPECTRAL EVOLUTION

Flux variations for some optical lines are shown in Figure 3. Only the H$\beta$ emission line demonstrates strong orbital variations. Maybe the fluxes of He II, 4686Å and Raman scattering line OVI, 6828Å also correlate with the orbital phase, but the very slow evolution of the hot component after the outburst (its temperature has increased since 1985) affects these emission line fluxes and distorts phase correlation. For example, two spectra (14.09.2001 (see Tatarnikova et al. 2011) and 18.07.2014) were obtained at nearly the same orbital phase ($\varphi \approx 0.56$ and $\varphi \approx 0.51$ accordingly, see the ephemeris in Shugarov et al. 2012), however the emission feature OVI was absent in 2001 but it was one of the strongest emission lines in the spectrum in 2014.

The TiO 6180, 7100Å absorption bands are often used to estimate the spectral class for cool components of symbiotic stars. However, all these estimates yield an earlier spectral class for PU Vul than the real one. The reason is that the blue nebular continuum veils the true depths of TiO bands.

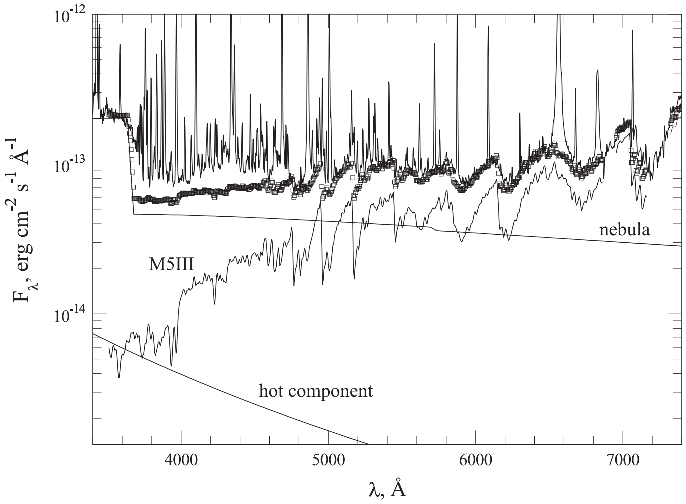


**Fig. 4** Interstellar-reddening-corrected spectrum of PU Vul obtained on 2014 July 18 (*solid line*). The *squares* signify the model continuum SED consisting of light from the hot component ($T_{\rm hot} = 147\,000$ K), the optically thin nebula ($T_{\rm e} = 20\,000$ K) that absorbs all Lc-quanta and the cool component (spectral type M5III).

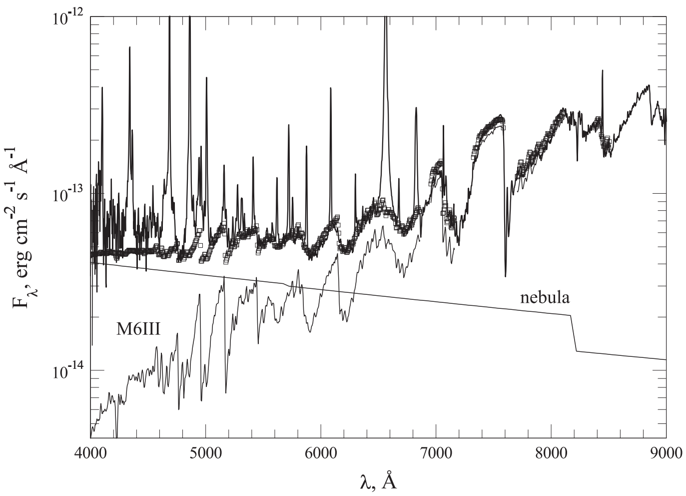


**Fig. 5** Interstellar-reddening-corrected spectrum of PU Vul obtained on 2016 August 11 (*solid line*). The *squares* signify the model continuum SED consisting of light from the cool component (spectral type M6III) and optically thin nebula ($T_{\rm e} = 20\,000$ K).

Figure 2 gives evidence that the estimates of the red giant spectral class depend not only on the orbital phase but also on the pulsation phase. The VO, 7865Å absorption band index provides a more reliable method for spectral class estimation due to the longer wavelength of the band. Only the spectra obtained in 2016 include this band. The spectral class of the cool component estimated from VO is about M5.7–M6. A lack of spectral data prevents us from investigating the possible real variability of the cool component's spectral class. We used M5III and M6III standard SEDs to model the total continuum emission during the whole period of spectral observations. The model SEDs for red giants of various spectral types were taken from the spectral library by Silva & Cornell (1992).

Figures 4 and 5 display spectra of PU Vul dereddened with $E(B-V) = 0.4$ mag (Vogel & Nussbaumer 1992) and appropriate model SEDs consisting of radiation from the hot component, optically thin radiation from the nebula, which absorbs all the Lc-photons, and radiation from a standard red giant (see Esipov et al. 2000 for details). The adopted electron temperature of the nebula was about 20 000 K. The temperature of the hot component was estimated by means of the modified Zanstra method (see Tatarnikova et al. 2011) applied to the modified equivalent width of the He II, 4686Å line (the flux in the He II emission line was divided by the

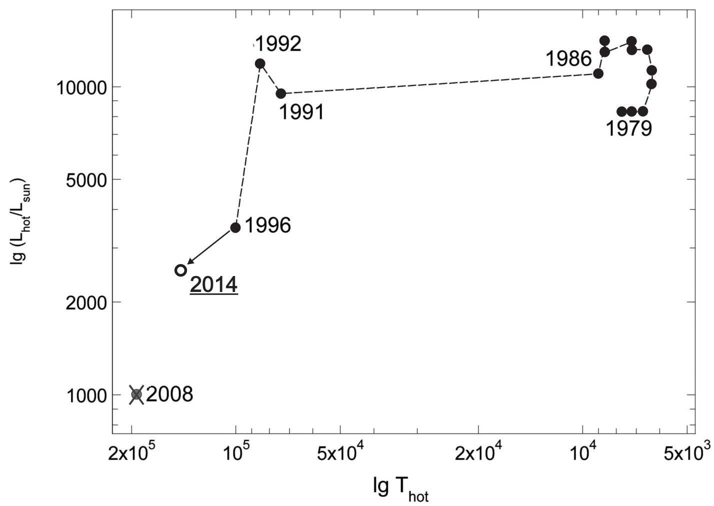


**Fig. 6** Positions of the hot component of PU Vul in the Hertzsprung–Russell diagram in 1979–2014. The star positions in 1979–1996 were taken from Tatarnikova & Tatarnikov (2009) (see also references therein).

flux in the blue continuum near 3600Å). We determined the hot component's luminosity from its bolometric flux (we estimated it when modeling the SEDs) and distance to the system ($D = 3.5$ kpc, Tatarnikova & Tatarnikov 2009). Note that our previous estimate of the hot component's temperature (see Tatarnikova et al. 2011) was not correct because it was obtained in 2008 when a significant part of the nebula was eclipsed by the cool component. But by that time, our photometrical observations had covered only half of the third orbital cycle and therefore the light curves looked like a gradual brightness decrease, not like a third eclipse. New spectral observations allow us to determine the location of PU Vul in the temperature-luminosity diagram in 2014 when the effect of the cool component eclipsing the nebula was negligible (see Fig. 6).

## 5 CONCLUSIONS

The analysis of our spectral and photometric observations of PU Vul reveals the presence of three types of variability: (1) the variability related to orbital motion, (2) the cool component pulsations, and (3) the brightness variations due to slow after-outburst evolution of the hot component.

During the third orbital cycle, the *UBVR* light curves demonstrated a sine-wave shape, which is typical for symbiotic stars in the quiescent state.

The temperature of the hot component is still gradually increasing whereas its luminosity is simultaneously decreasing. Therefore, the hot component of PU Vul is not on the cooling curve yet.

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