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Optical photometry and spectroscopy of V612 Sct: slow classical nova with rebrightenings

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Abstract. We present the results of multicolour $UBVR_CI_C$ CCD photometry and optical echelle spectroscopy of the slow classical nova V612 Sct, discovered during its outburst on 2017 June 19.41 UT. The nova reached its brightness maximum $V_{max} = 8.42$ mag and $B_{max} = 9.53$ mag on 2017 July 29.99 UT. The light curve allows to classify it as a slow nova of the J-class with multiple peaks on the decline. We used the V and B light curves to find the rates of decline $\mathrm{t}_{3,V} = 105$ d and $\mathrm{t}_{3,B} = 224$ d. We estimated by applying MMRD relations the absolute magnitudes of the nova at maximum $MV_{max} = -6.67$ and $MB_{max} = -6.44$. The latter value yields a mass of 0.65 $\mathrm{M}_\odot$ for the white dwarf component. We estimated the colour excess $E(B-V) = 0.755$ and found the distance 3.5 kpc to the nova. The study of radial velocities of Hα and Hβ P Cyg absorptions revealed two distinct components of the expanding envelope accelerated by a variable wind with the terminal velocity up to 1900 km s^{-1}. The P Cyg absorptions were most enhanced during rebrightenings.

Key words: novae – photometry – spectroscopy

1. Introduction

Classical novae are cataclysmic variables with 6 to 19 mag brightness increase caused by a thermonuclear event on the surface of the white dwarf. They are semi-detached binaries with orbital periods less than 2 days, in which a matter from a cool component is transferred to a white dwarf. During the optically thick phase of the classical nova outburst the white dwarf photosphere expands to supergiant dimensions and engulfs the binary. Due to a strong wind from a hot source a large part of the envelope is ejected and the photospheric radius shrinks.

Classical novae are usually classified from their photometric appearance as fast or slow according to a time interval in which nova fades by 2 or 3 magnitudes

(t_2, t_3) from its maximum brightness. The fast super-Eddington novae ($t_2 < 13$, $t_3 < 30$ days) have smooth light curves (LCs) with well defined maxima. The slow Eddington novae ($t_2 > 13$, $t_3 > 30$ days) have structured LCs and many of them have standstills at the maximum and dust formation at later stages (Downes & Duerbeck 2000). According to the properties of the LCs during nova declines, Strope *et al.* (2010) proposed seven types of LCs: S (smooth), P (plateau), D (dust dip), C (cusp), O (oscillations), F (flat topped), and J (jitter).

The spectra of classical novae display at maximum light either He/N or Fe II emission lines as the most prominent non-Balmer lines. Fe II spectra are formed in a large circumbinary envelope of gas, whose origin is the secondary star, while He/N spectra are formed in white dwarf ejecta. In hybrid objects both classes of spectra appear sequentially due to changing parameters in the two emitting regions (Williams, 2012).

2. Discovery and ATels spectroscopy

The classical nova V612 Sct (Nova Scuti 2017) = ASASSN-17hx was discovered by Stanek *et al.* (2017a,2017b) with the All Sky Automated Survey for SuperNovae on 2017 June 19.41 UT at mag 14.7 at the coordinates $\alpha_{2000} = 18^h31^m45.918^s$, δ_{2000} = -14°18'55.57". According to Kurtenkov *et al.* (2017) the progenitor is the Gaia Source ID 4104113350446549888, located 0.59 arcsec from the position with $G = 19.102$ mag. According to Saito *et al.* (2017), VVVX Ks-band observations taken during July and August 2016 show the presence of a faint source 0.84 arcsec from the reported target position with the $Ks = 16.71 \pm 0.11$ mag and coincide within 0.65 arcsec with the position of the Gaia source.

The first spectra of the nova, taken on June 24, 2017 by Kurtenkov *et al.* (2017) with the 2m RCC telescope at Rozhen Observatory (resolution R $\sim$ 500) exhibited Hα, Hβ, He I, He II, NII and NIII emission lines. This indicates that the nova is of He/N type, according to the classification of Williams (1992). RVs of absorptions in He I P Cyg profiles give the expansion velocity of 990 km s^{-1}. The medium-resolution (R $\sim$ 5400) spectra, taken on June 26.1, 29.02 by Williams & Darnley (2017) with the 2-m Liverpool telescope show Balmer and He I P Cyg profiles. The FWHM of Hα emission was 800 km s^{-1}. RVs of Hβ P Cyg profile absorptions were -860 and -520 km s^{-1}. The Mg II and Si II emissions were also present. The ARAS low resolution (R $\sim$ 580 - 2650) spectroscopy during June 29.8 - July 4.8 shows that He I emissions weakening is accompanied by Fe II emissions appearance. The RVs of P Cyg absorptions extended to -800 km s^{-1} (Berardi *et al.* 2017). High and low resolution spectroscopy at the brightness pre-maximum on July 10, 2018 with 1.82-m and 1.22-m telescopes in Asiago and a 1.5-m telescope at TUBITAK National Observatory shows prominent emissions of Balmer and Paschen series, FeII lines, SiII, OI and CaII lines, so it is a textbook example of the Fe II nova (Munari *et al.* 2017a). The RVs of P-Cyg absorptions of Fe II multiplet 42 are -451, -359, and -285 km s^{-1}. Interstellar reddening $E(B-V) = 0.68$ was derived from EW of the diffuse interstellar band at 6614 Å. The spectra taken on July 26.61 and 27.58 (a few days before the brightness maximum) by the 2.3-m Vainu Bappu telescope, Kavalur, India show that the P Cyg absorptions developed in Balmer and Fe II lines while the emission component strenghtened (Pavana *et al.* 2017). According to Munari *et al.* (2017b), the peak brightness was reached on July 30.1 UT at $B = 9.65$, $V = 8.44$. The spectra on Aug 12.8 were dominated by Fe II and He I emissions. A sharp absorption at velocity 250 km s^{-1} was presented in the profile of Balmer lines, superimposed on the emission component that extent at its base from about -1000 to +1000 km s^{-1}. The interstellar absorption lines of NaI D1,D2 doublet were splitted into at least 5 distinct components. The total equivalent width indicates a reddening $E(B-V) = 0.62$ following the calibration by Munari & Zwitter (1997). Kuin *et al.* (2017) started the spectroscopic observations of the nova with Swift's UVOT 30-cm telescope on June 30. They derived $E(B-V) = 0.8\pm0.1$ from a significant 2175 Å dip caused by an interstellar extinction. They found the line width FWZI 4600 km s^{-1} from NIII] 1750 Å and Mg II 2800 Å emissions with FWZI 4600 km s^{-1}. In August 9, a large Fe II curtain was present in 1800 - 3800 Å part of the spectrum. The echelle spectrum taken during rebrightening of the nova on September 11, 2017 with the Varese 0.61-m telescope show Balmer and Fe II emission lines with multi-component P Cyg absorptions (Munari *et al.* 2017c). The RVs of Hα P Cyg absorptions were -500, -875, and -1130 km s^{-1} and FWHM of Hα emission 770 km s^{-1}. The ARAS spectra from June, 29 till September, 9 with resolution from 580 to 14000, depending on the spectrograph (Alpy 600, LISA, LHIRES, eShel) covering 3800-7200 Å and S/N 50–100 showed that all lines varied in strength and profile in correlation with the LCs changes (Guarro *et al.* 2017).

3. Observations, data reduction and times of brightness maxima

Our $UBVR_CI_C$ CCD photometric observations of the nova were obtained with the 18-cm Maksutov telescope and the 60-cm telescope located in the pavilions G1 and G2 of the AISAS observatory at Stará Lesná as well as the 50-cm telescope at the Southern Station of the Sternberg State Astronomical Institute of the Moscow University. The data were processed by a standard way using the nearby comparison star TYC 5703 − 0153 − 1. We found its magnitudes: $U = 11.87$, $B = 11.76$, $V = 11.14$, $R_C = 10.80$, $I_C = 10.40$ adopting the sequence of 8 stars around the symbiotic star RS Oph, published by Henden & Munari (2006). All our observations were reduced to the standard Johnson-Cousins system. Our photometric data were completed by the AAVSO International Database photometry and data from other available sources. Our individual V and B observations of the nova, the data published by Munari *et al.* (2017a,b,c), Kurtenkov *et al.* (2017) and available data of P. Jordanov (http://antares48.byethost7.com/) and N. Ikonnikova (https://istina.msu.ru/conferences/presentations/90612008/) together with the AAVSO V, B and TG, TB CCD data are presented in Fig. 1. Our data show that the nova reached maximum on 2017 July 29.9886 UT (JD 2457964.4886) at $V_{max} = 8.42$ and $B_{max} = 9.53$ mag. After the main maximum I four rebrightenings of the nova, designated by Roman number II-V were detected in 2017. Their dates and JDs were as follows: (II) September 13, 2017, JD2458010.409; (III) October 6, 2017, JD2458033.271; (IV) October 24, 2017, JD2458051.194; (V) November 17, 2017, JD2458075.239. Further rebrightenings of the nova were detected in 2018 after the 3-months gap in observations caused by the position of the nova on the sky in the vicinity of the Sun. Nightly means of our $UBVR_CI_C$ and AAVSO observations taken during the year 2017 are shown in Fig. 2.

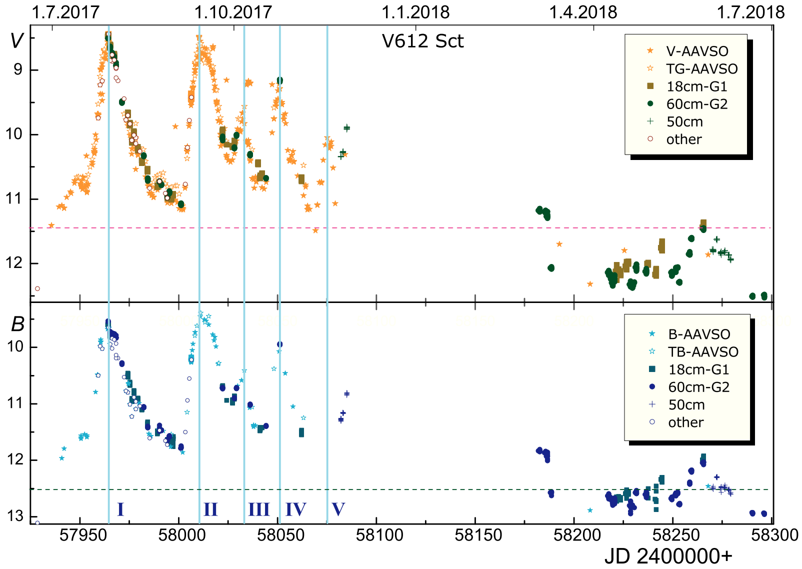

Figure 1. V and B LCs of the nova. The brightness corresponding to t_3 time is indicated by dashed lines. The vertical lines designate brightness maxima I - V.

Our optical echelle spectra in 2017 were obtained with the 60-cm telescope in G1 pavilion of the AISAS observatory at Stará Lesná (17 spectra with the resolution $R \sim 12\,000$) and the 1.3-m telescope of the AISAS observatory at Skalnaté

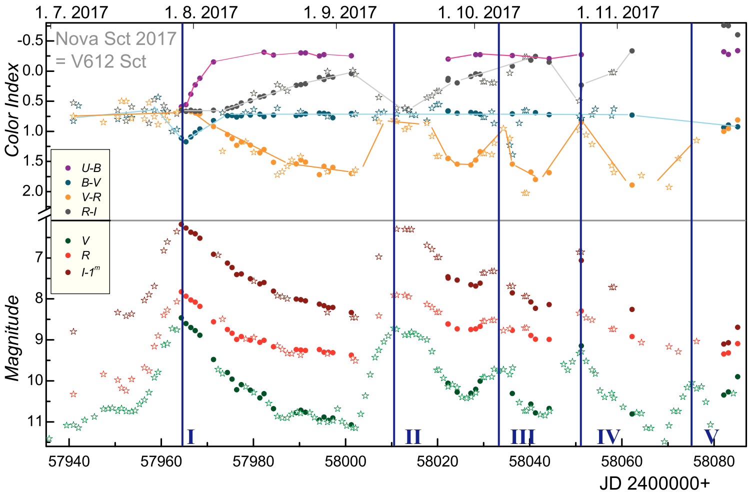

Figure 2. The $UBVR_CI_C$ photometry of the nova in 2017. The nightly means of our and AAVSO data are displayed by circles and asterisks, respectively. The vertical lines designate brightness maxima I - V.

Pleso (1 spectrum with the resolution $R \sim 24\ 000$). Our data were completed by the Astronomical Ring for Access to Spectroscopy (ARAS) data, available at http://www.astrosurf.com/aras/Aras_DataBase/Novae/2017_NovaSct2017.htm. In the present paper, we have used 140 ARAS spectra with $R \sim 5\ 000$ - 13 000, including 71 spectra taken by the co-author (JG).

4. Basic parameters of the nova and classification

The basic parameters of the nova V612 Sct were determined using the LCs presented in Fig. 1. Due to the large V and B LCs variations after maximum I, that exceeded 2 mag, the rate of decline found from t_2 time is ambiguous. Therefore, we used t_3 time to find the rates of decline $t_{3,V}$ = 105 days and $t_{3,B}$ = 224 days from V and B LCs, respectively.

We estimated the absolute magnitude of the nova at maximum MV_{max}, MB_{max} using the MMRD (Magnitude at Maximum – Rate of Decline) relations:

1) MV_{max} - t_3 relations of Schmidt (1975)

$$MV_{max} = -11.75 + 2.5 \log t_3, \tag{1}$$

2) MV_{max} - t_3 relations of de Vaucouleurs (1978)

$$MV_{max} = -11.3 + 2.4 \log t_3, \tag{2}$$

3) MV_{max} - t_3 relations of Downes & Duerbeck (2000)

$$MV_{max} = (-11.99 \pm 0.56) + (2.54 \pm 0.35) \log t_3, \tag{3}$$

4) MB_{max} - t_3 relations of Pfau (1976)

$$MB_{max} = -10.67 + 1.80 \log t_3. \tag{4}$$

We have calculated the following values of MV_{max} using these relations: MV^1_{max} = –6.70, MV^2_{max} = –6.45, MV^3_{max} = –6.86 with the unweighted mean: MV_{max} = -6.67 ±0.09. The relation (4) provides MB^4_{max} = –6.44. Van den Bergh & Younger (1987) found that the mean intrinsic value of the $B - V$ colour index for novae at maximum is

$$MB_{max} - MV_{max} = 0.23 \pm 0.06, \tag{5}$$

which leads to the exactly same value of MB_{max} as from the MMRD relation (4). Therefore, MB_{max} = -6.44 ±0.15.

Using this value and the formula given by Livio (1992)

$$MB_{max} = -8.3 - 10.0 \log(M_{wd}/M_{\odot}), \tag{6}$$

we can estimate the mass of the white dwarf component in V612 Sct as M_{wd} = 0.65±0.02 $M_{\odot}$.

The interstellar extinction can be found:

1) from the comparison of the observed colour index at maximum $(B-V)_{max}$ = 1.11, affected by extinction, with the intrinsic colour index $(B - V)^{in}_{max}$ = 0.23. We thus find the colour excess $E(B - V) = 0.88$;

2) from the relation of van den Bergh & Younger (1987), who found that novae two magnitudes below maximum have an unreddened colour index of

$$B - V = -0.02 \pm 0.04; \tag{7}$$

The observed colour of V612 Sct two magnitudes below maximum is $B - V$ = 0.68, which thus yields $E(B - V)$ = 0.70±0.04.

3) from the 2175 Å dip caused by an interstellar extinction in UV Swift spectra (Kuin *et al.* 2017) $E(B - V)$ = 0.8±0.1,

4) from the equivalent width of the diffuse interstellar band at 6614 Å (Munari *et al.* 2017a) $E(B - V)$ = 0.68,

5) from the interstellar NaI D1,D2 doublet (Munari *et al.* 2017b) $E(B - V)$ = 0.62,

6) from the comparison of the true position (affected by interstellar reddening) of the nova Sct 2017 in the $(U - B, B - V)$ diagram with its expected

position in the classical novae sequence introduced by Hachisu & Kato (2014) $E(B-V) = 0.85$

The mean value of the reddening is $E(B-V) = 0.755 \pm 0.039$. Corresponding absorption in V is $A_V = 2.34 \pm 0.12$. The distance modulus of the nova is $V_{max} - MV_{max} = 15.08 \pm 0.08$, which yields a corresponding distance to the nova of 3.5 ± 0.3 kpc.

Using the classification scheme of nova LCs (Downes & Duerbeck 2000) and Strope *et al.* (2010), the nova V612 Sct can be classified as a slow nova of J-class with multiple peaks on the decline, similar to V723 Cas, HR Del, V4745 Sgr or V5558 Sgr. The presence of Fe II emission lines (Munari *et al.* 2017b) around the maximum light allows to classify V612 Sct as the Fe II nova (Williams, 2012).

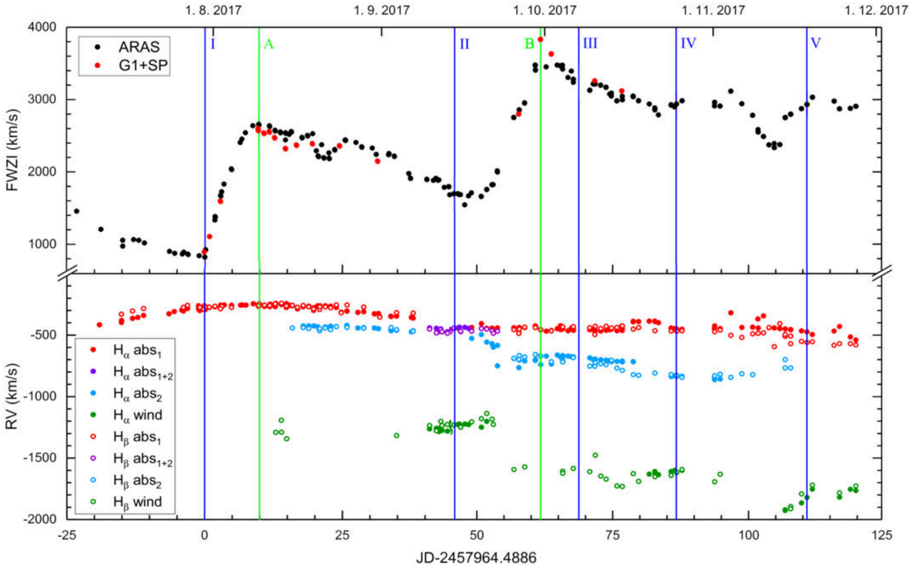

Figure 3. The FWZI of the Hα main emission peak (top). The RVs of the Hα and Hβ P Cyg absorptions (bottom). They arise in expanding inner and outer envelopes marked by the red and blue symbols, respectively. The terminal velocity of the wind is designated by green symbols. The violet symbols denoted the absorptions around maximum II without assigning them to the inner or outer envelope.

5. Hα and Hβ spectroscopy

For fitting of spectral lines and continuum we used the code `fityk` (Wojdyr, 2010). It is a general purpose peak fitting software with graphical interface. It offers many non-linear functions, subtraction of continuum, and can fit an arbitrary number of peaks simultaneously by the Levenberg-Marquardt least square method. We selected the region of spectrum around the Hα line and fitted continuum by the second-order polynomial. We added a few Gaussian peaks based on the shape of the line, emission and absorption features. The main emission peak was selected to cover the shape of the wings and the intensity at the central wavelength λ_C. We have calculated 3σ distance from λ_C and computed corresponding radial velocity to λ_C-3σ while using the laboratory wavelength for Hα. Then we measured FWZI of the main emission component and expressed it in a velocity scale.

Comparison of the brightness maxima I–V of the nova and FWZI of the Hα emission is demonstrated in Fig. 3 (top). In brightness maximum I, the FWZI of Hα emission lines reached minimum 800 km s^{-1}. The local maximum of FWZI 2600 km s^{-1} (designated as A) was reached 10 days after the maximum I on August 8, 2017 (JD2457974.441). Then the FWZI started to decline and reached the minimal values around the rebrightening maximum II. The maximum of FWZI 3830 km s^{-1} (designated as B) was reached 16 days after the rebrightening II on September 29, 2017 (JD2458026.238). The Hα and Hβ P Cyg absorptions are a useful tool to study the variable outflow from the nova. The RVs of absorptions are presented in Fig. 3 (bottom). We can easily distinguish 2 distinct components of the expanding envelope and variable thick wind with the terminal velocity up to 1900 km s^{-1}.

We have selected spectra taken by our co-author (JG) for the investigation of the evolution of Hα and Hβ profiles. This subset provided good resolution (R = 9000) spectra with large coverage (4050–7500 Å). Also the number of spectra and their temporal cadence (with mean 4 days) was ideal for tracking changes in the line profiles. The evolution of the Hα and Hβ profiles in a normalized intensity scale are displayed in Fig. 4. The evolution of selected Hα profiles around the brightness maximum I and rebrightenings II and III are shown in Fig. 5.

6. Discussion

Appearance of the strong P Cyg absorptions in Balmer lines during the brightness maximum and rebrightenings maxima of the nova V612 Sct can be explained by re-expansion of its photosphere as suggested by Tanaka *et al.* (2011) for V5558 Sgr and similar novae. Csák *et al.* (2005) proposed for the nova V4745 Sgr that the repetitive instabilities of the hydrogen shell burning on the surface of the white dwarf cause a majority of spectral lines to switch back to strong P-Cyg profiles during mini-outbursts similar to their profiles from the main outburst. Episodic fuel burning during rebrightenings was discussed by Pejcha (2009).

The expanding shell of the nova V612 Sct consists of two major components: an inner slow main high-mass envelope in the form of an equatorial ring and an

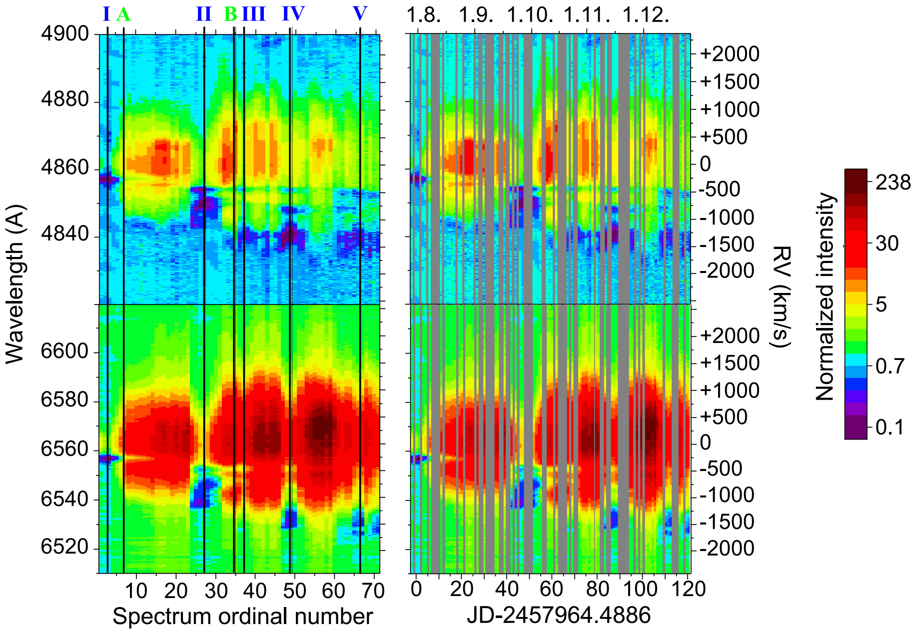

Figure 4. The evolution of the Hα and Hβ profiles in a normalized intensity scale. The profiles on the right side are expressed in a time scale, the missing dates of observations are marked by neutral wedges. The profiles on the left side are expressed in ordinal numbers of the spectra. The brightness maxima I–V and FWZI maxima A, B are marked.

outer fast tenuous low-mass envelope shaped and accelerated by spherical and polar winds. Chochol *et al.* (1997) proposed a similar structure of the expanding shell for the nova V1974 Cyg. Unfortunately, the interpretation of absorptions before the maximum II is not unique. The long-term behaviour of absorptions (red symbols before the maximum II and blue symbols after the maximum II in Fig. 3) could indicate a long-term change of an inclination of the polar outflow, suggesting the precession of the accretion disk with the period of about 170 days. The exact kinematical model of the expanding shell requires the high-resolution spectroscopy in a nebular stage of the nova and direct radio and optical images of the expanding shell.

Kato & Hachisu (2011) proposed two types of nova evolution that can occur in low-mass white dwarfs of $\sim$ 0.5 - 0.7 M$_{\odot}$. The flat peak around maximum, lasting about 9 years, in the symbiotic nova PU Vul suggests evolution with no indication of strong winds. The multipeak, lasting a few hundred days, for slow novae V723 Cas, V5558 Sgr, and HR Del suggest the presence of a transition from static evolution with no optically thick wind to usual evolution with the

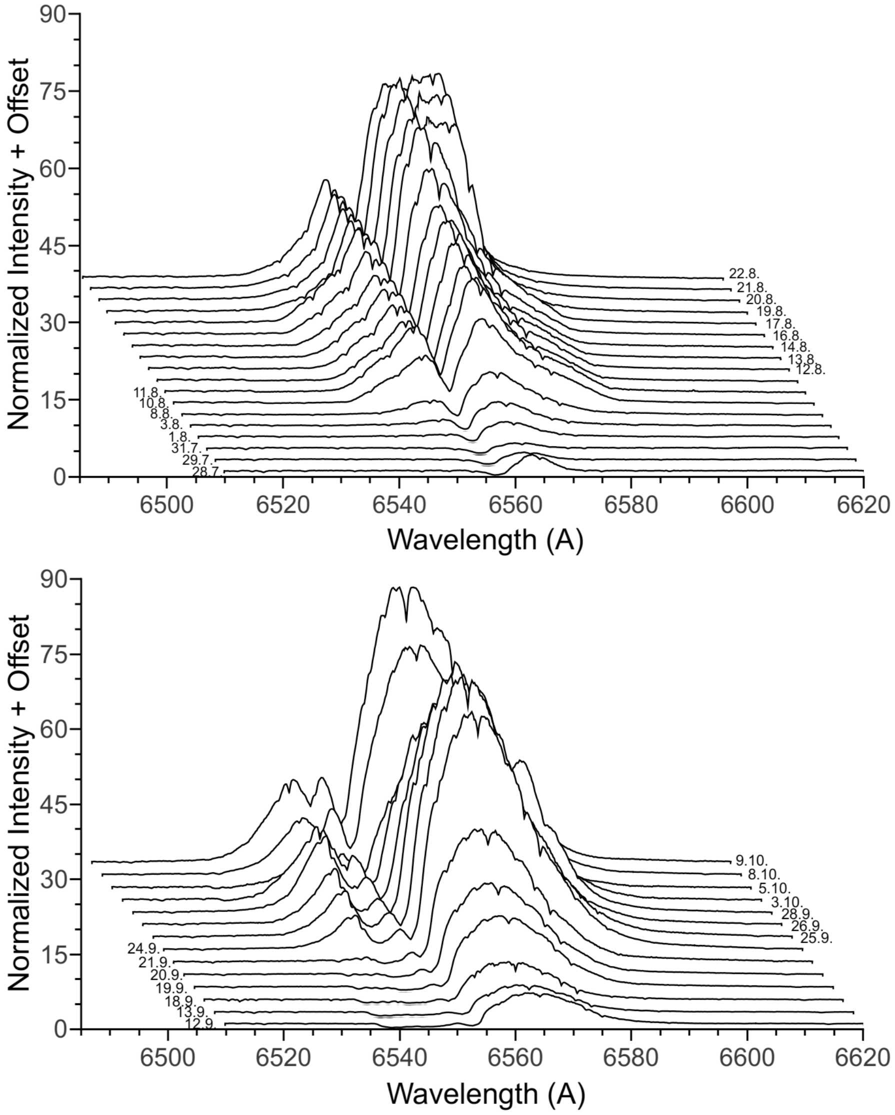

Figure 5. The evolution of selected Hα profiles around the brightness maximum I (top) and rebrightenings II and III (bottom). Individual spectra are shifted in wavelength and normalized intensity for better visibility.

optically thick winds. The presence of a companion deep inside the envelope triggers this transition, accompanied by oscillatory behaviour caused by a relaxation process. The LCs can be fitted by the model of a 0.6 $M_\odot$ WD with solar composition envelope. Our findings of the existence of thick winds in nova V612 Sct and its WD mass of 0.65 $M_\odot$ suggest that it belongs to the same group of slow novae.

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