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Classical nova V339 Del (Nova Del 2013) - a short review

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Multifrequency observations of the classical CO nova V339 Del, detected in all frequencies from γ-rays to radio, are reviewed. Nova V339 Del was discovered on 2013 August 14.584 UT. The times of decline from the brightness maximum V = 4.4 mag, reached on 2013 August 16.47, UT, was estimated as $t_{2,V}$ = 10 days, $t_{3,V}$ = 18 days, so V339 Del can be classified as a fast nova with super-Eddington luminosity at maximum. The maximum-magnitude-rate-of-decline relations were used to determine an absolute magnitude at maximum $M_{V,max} = -8.70\pm$ 0.03, $M_{B,max}$ = -8.45 $\pm$0.08 and distance d = 3.2$\pm$0.3 kpc, using the interstellar extinction $E(B-V)$ = 0.184$\pm$0.035. The distance to the nova found by different methods is in the range 2.7 - 4.54 kpc. The white dwarf mass was estimated from $M_{B,max}$ as M_{wd} = 1.04$\pm$0.02 $M_\odot$. We suggest that the eruption occurred on the surface of a CO white dwarf. V339 Del is the first nova that has been observed to synthesize the element lithium. The dust consisted of amorphous carbon grains was detected in infrared region. The $UBVR_CI_C$ light curves of nova constructed from daily means of all available data, including our own observations obtained from its discovery till August 2015, are presented and used to show the track of the nova in the color-color diagram during the first 100 days. The dust particles formed in the dense clumps of ejecta were responsible for the U light curve variability. Our medium-resolution spectrum of V339 Del taken in August 2015 by the 6m SAO telescope in North Caucasus confirms a non-spherical structure of the ejected shell.

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1. Introduction

Classical novae are cataclysmic variables with outburst amplitude 6-19 mag, caused by thermonuclear runaway events on a surface of a white dwarf. The upper limit of the outburst amplitude was reached by Nova Cygni 1975 = V1500 Cyg [48]. Classical novae arise in close binaries with orbital periods of a few hours, consisting of a red dwarf filling up its Roche-lobe and mass-accreting white dwarf. After the outburst, the photosphere of the white dwarf component of the nova expands to supergiant dimensions and engulfs the binary. Due to the strong wind a large part of the envelope is ejected and the photospheric radius shrinks.

Classical novae can be divided according to their photometric and spectroscopic appearance into the fast and slow. The classification is usually based on the time interval in which a given nova fades by 2 or 3 magnitudes (t_2, t_3) below its maximum brightness. According to Downes and Duerbeck [1], the fast ($t_2 < 13$, $t_3 < 30$ days) super-Eddington novae have smooth light curves with well defined maxima. They may be classified as He/N, "hybrid" Fe II or Fe II novae. The slow ($t_2 > 13$, $t_3 > 30$ days) Eddington novae have often structured light curves and many of them have standstills at maximum and dust formation at later stages. They belong to the Fe II spectroscopic type.

2. Basic characteristics of the nova

Nova Delphini 2013 was discovered by K. Itagaki [2] on 2013 August 14.584 UT at mag 6.8 at the coordinates α_{2000} = $20^h23^m30^s.73$, δ_{2000} = $20^o46'04''.1$. The variable, preliminary designated as PNV J20233073+2046041, was named V339 Del [3]. The first spectra of the nova on August 14.909 UT [4] and August 14.87 UT [5] enabled to classify it as Fe II type CO classical nova. The high resolution spectra of the nova, taken between Aug. 14.84 - 16.86 [6] provided the equivalent width of Na I line as 0.3945(30) Å, which corresponds to a reddening $E(B-V)$ = 0.182, following the calibration by [7].

In September 2013 Chochol et al. [8] presented B,V photometry and spectroscopy of the nova V339 Del at the international workshop in Tatranská Lomnica, Slovakia. They found that nova reached brightness maximum V_{max} = 4.4 and B_{max} = 4.76 on 2013 August 16.47 (JD 2456520.97, day 0) and estimated the times of decline from brightness maximum to be $t_{2,V}$ = 10 days, $t_{3,V}$ = 18 days, which allowed to classify V339 Del as a fast super-Eddington nova. Various maximum-magnitude-rate-of-decline (MMRD) relations [1] enabled [8] to determine the absolute magnitude at maximum $M_{V,max}$ = -8.70$\pm$ 0.03, MB_{max} = -8.45 $\pm$0.08 and the distance d = 3.2$\pm$0.3 kpc, using the interstellar extinction in agreement with the value found by [6]. The mass of the white dwarf was estimated from the MB_{max} and the well known formula [9] as M_{wd} = 1.04$\pm$0.02 $M_\odot$. Burlak et al. [10] estimated the interstellar reddening $E(B-V)$ = 0.18 using maps of Galactic extinction and the MMRD relations [1] found that the distance to the nova is 2.7 - 3 kpc. Schaefer et al. [11] reported near-infrared interferometric observations of V339 Del with the CHARA Array at Mt. Wilson, which started a day after discovery and lasted during the first 43 days of the outburst. They detected an ellipticity in the light distribution, suggesting a prolate or bipolar structure that develops as early as the second day of the outburst. Combining the angular expansion rate with the outflow speed near the continuum forming layer $V_{ejection}$ = 613$\pm$79 km/s (based on an analysis

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of spectra from the archive of the Astronomical Ring for Access to Spectroscopy (ARAS)), the above authors derived a geometric distance to the nova of 4.54±0.59 kpc. The true distance of the nova depends on geometry of the expanding shell and the inclination angle of the nova binary orbit. Shore [12] estimated that the distance to V339 Del is 4.2 kpc comparing its UV spectra with those of the CO nova OS And.

The nova progenitor was found by [13] as the blue star USNO-B1 1107-0509795 (B = 17.2 - 17.4 mag), so the total outburst amplitude was $\sim$ 12.6 mag in B. The increase of brightness was very fast, because the nova was in quiescence (17.1 mag) 14 hours before its discovery. Munari and Henden [14] found the progenitor also on the Asiago 1979-82 plates: B = 17.27, V = 17.60 and in AAVSO Photometric All-Sky Survey (APASS) observations in 2012: B = 17.33. The amplitude of the variations in B was 0.9 mag with color as expected for progenitor dominated by emissions from an accretion disk. Deacon et al. [15] found observations of progenitor in the PanSTARRS 1 image archive. The data were obtained in the last 1.2 years before the nova outburst, when the nova's variability was below the upper photometric limit of the archive plate photometry [14].

3. Multifrequency observations of V339 Del and results

3.1 Gamma-rays data

V339 Del like three other classical novae V959 Mon, V1324 Sco and V1369 Cen was detected in 2012-13 by Fermi-Lat collaboration [16,17] as soft spectrum transient γ-ray sources, over 2-3 weeks duration. The Fermi-LAT high energy γ-ray telescope, covering the energy range 20MeV - 300 GeV, has been continuously scanning the sky from its launch in 2008, so it is suitable to detect transient sources. In V339 Del the maximum of γ-ray flux followed the optical maximum by 6 days. The ejected material initially blocked the high-energy photons. The gamma rays photons are absorbed via photon-atom interactions. 100 MeV emission is detected later, when the density due to the expansion of the shell drops and the ejecta become transparent for γ-rays. They are produced by collisions between relativistic protons with the nova ejecta (hadronic scenario) or Inverse Compton/bremsstrahlung emission from relativistic electrons (leptonic scenario). According to [18], the measured ratio of γ-ray and optical luminosities sets a lower limit on the fraction of the shock power used to accelerate relativistic particles, which is in favour of hadronic scenario. The strong shocks needed to accelerate particles at relativistic energies develop within a mixed and delayed torus-bipolar expansion pattern for the ejecta [19].

3.2 X-rays data

V339 Del was regularly monitored by the X-ray telescope on board of the Swift multi-wavelength observatory and occasionally by the Chandra and XMM satellites. The first detection of an X-ray source in the hard 1-10 keV range of an X-rays on day 33 after maximum (AM) [20], was consistent with shocked gas in an expanding nova shell with no evidence for super-soft emission. Soft X-rays in the range 0.3-1 keV were first detected by [21] on day 58 AM on very low flux level 0.0067 count/s [22]. On day 69 AM the flux level increased to 1.5 count/s, exclusively below 0.7 keV, suggesting the unveiling of the hot WD atmosphere (start of the super-soft X-ray stage). According to [23] SSS reached maximum $\sim$ 100 counts/s on day 86 AM. The rising count rate till day

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83 AM was interspersed by a few large dips. Large amplitude variations can be explained either by clumps in the ejecta, or WD photosphere temperature variations. QPO with a periodicity of 54 s, later confirmed by Newton-XMM X-ray observations for day 97 AM [24], were also present in the data and interpreted by [25] as non radial g-mode pulsations of the WD. The high resolution X-ray spectrum (22-44 Å range) taken by the Chandra observatory on day 86 revealed a rich system of absorption lines superimposed on a supersoft source continuum without any emission lines. H, He, C, and N absorption lines were blue-shifted by 1200 km/s. Modeling of the data with a blackbody indicates a photospheric temperature $\sim$ 310 000 K [26]. The blue-shift 1200 km/s of CV, CVI, NVI and NVII lines was confirmed on day 97 AM by a deep XMM-Newton observations [24]. According to [27] the last observation before the Swift satellite Sun constraint on 2014 January 6 (day 143 AM) yielded a rate $\sim$ 40 count/s. The following observation by Swift on 2014 March 4 showed the end of the SSS, because the count rate dropped to $\sim$ 0.8 count/s (day 200 AM) and further to $\sim$ 0.4 count/s on day 205 AM.

3.3 Radio data

The first detection of V339 Del in radio frequencies was done on 2013, Sep. 8 (day 22 AM) by VLA observatory in Soccoro at 28.2 GHz (flux: 0.21(3) mJy), 36.5 GHz (flux 0.32(3) mJy) and CARMA in Inyo Mountains at 95.7 GHz [28]. On Sept. 25.9 (day 40 AM), nova was detected also at 15 GHz (flux 0.68 $\pm$ 0.18 mJy) by AMI near Cambridge [29]. According to Nelson [30], the ejecta were marginally resolved in May 2014 and appeared symmetric. They expanded very slowly with a rate of $\leq$ 0.07 mas/day. Nelson suggested, that we see the object pole on.

3.4 Infrared data

Early infrared photometry in the *JHKLM* bands were published by many authors in ATels. Main results of the infrared photometry and spectroscopy can be found in [10],[31] and [32]. Analysis of the spectral energy distribution (SED) by [31] in a spectral range 0.36-5 μm has shown that the source near its optical brightness maximum mimics the emission of normal supergiant of spectral types B5 and A0 on Aug. 15.94 UT and Aug. 16.86 UT, respectively. The nova expansion velocity near its optical brightness maximum was $\sim$ 700 km/s. An infrared excess associated with the formation of a dust shell appeared in the SED one month after the nova brightness maximum. The dust component color temperature 1500 K was estimated from the $K-L$ color index on day 36 AM. The dust shell parameters were: radius $\sim 6.5\times10^{11}$ m, luminosity $\sim 4\times10^{3}$ $L_{\odot}$ and mass $\sim 1.6\times10^{21}$ kg. The rate of dust supply to the nova shell was $\sim 8\times10^{-8}$ $M_{\odot}yr^{-1}$. The expansion velocity of the dust shell was about 600 km/s. At IR maximum light (day 56 AM), the nova had a color index $J-L=6$, which corresponds to a color temperature $\sim$ 1100 K [10].

Gehrz et al. [32] derived a distance to the nova of $\sim$ 4.5 kpc adopting an expansion velocity of the principal ejecta as 505 km/s, derived from the spectrum taken on day 25 AM. This distance gives an outburst luminosity of $\sim 8.3\ \times10^{-7}L_{\odot}$ (about 13 times the Eddington limit for one solar mass WD). The ejected gas mass as estimated by the cutoff wavelength during the free-free emission phase was $\sim 7.5\times10^{-5}M_{\odot}$. On day 100 AM the dust shell temperature was $\sim$ 850 K and its mass $\sim (1.2\pm0.4)\times10^{-7}M_{\odot}$. The dust consisted of amorphous carbon grains. The surprising fact that the dust formation occurred during the super-soft stage can be explained either by dense clumps in the ejecta or with a thick equatorial density enhancement.

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3.5 Optical data

3.5.1 Photometry

The *UBVRI* photometric observations of the nova are available through AAVSO, VSNET and ATels. Photometric data in the first month of the outburst were gathered and analysed by [8]. Accurate and densely mapped BVR_CI_C photometry in the first 77 days AM allowed Munari et al. [33] to find characteristic decline times from $V_{max} \sim 4.46$, $B_{max} \sim 4.70$ as $t_{2,V}$ = 10.5, $t_{3,V}$ = 23.5, $t_{2,B}$ = 12, $t_{3,B}$ = 30 days, that place V339 Del in a borderline position between fast and very fast novae according to classification scheme [34]. The light curve shows a smooth decline with a small plateau soon after maximum lasting 1.5 days and a longer plateau between the days 20 and 37 after maximum. The transition from optically thick to optically thin conditions of the ejecta occurred around the day 62 AM, when the nova declined in V by 6 mag from its maximum brightness.

Highly accurate photometry obtained in the medium Stromgren y, b bands and narrow [OIII], H_α bands covering 500 days AM of the evolution of Nova Del 2013 was presented by Munari et al. [35]. These authors' comprehensive study reviews the behaviour of the nova in all regions of electromagnetic spectrum and provides unique information about extent and ionization of the ejecta, the onset of the critical phases like the transition between optically thick and thin conditions, and re-ionization by the central super-soft X-ray source. These authors explained very large variability in the super-soft X-ray emission (from day 69 to 86 AM) by clumpy ejecta passing through the line of sight.

Our $UBVR_CI_C$ CCD photometry of the nova was obtained by two 0.6m telescopes and 60/180 mm telephoto lens at the Stará Lesná Observatory (Slovakia), 0.5m, 0.6m and 1.25m telescopes in Nauchny and 0.6m and 1m telescopes at Mt. Koshka in Crimea (Russia). The back-illuminated FLI ML3041 and Vers-Array 1300 CCD camera sensitive for U band data were used at 0.6m telescope in Stará Lesná and 1.25m telescope in Nauchny, respectively. Some *UBV* observations were obtained with photoelectric photometer at 0.6m telescopes in Stará Lesná and Mt. Koshka. The data were processed in the usual way using the main standard star HD 194113 (U = 8.844(2), B = 8.319(2), V = 8.008(3), R_C = 7.768(10), I_C = 7.618(10)) and 15 check stars and reduced to the standard Johnson-Cousins system. Our observations were supplemented by all the available photometric data from AAVSO, VSNET, ATels and data from [33]. In Fig. 1 we present daily means of all data. Unusual behaviour of $V - R_C$ and $R_C - I_C$ color indices is mainly caused by an appearance and evolution of the strongest emission lines of [O III] 5007 Å in V band, H_α in R_C band and O I 7773 Å and 8446 Å in I_C band. The evolution of emission lines published by [36] fully supports this explanation.

The track of the nova in the color-color diagram with dereddened indices $(U - B)_0$, $(B - V)_0$ is shown in Fig. 2. V339 Del after maximum moved along the nova-giant sequence introduced by Hachisu and Kato [37]. This sequence is parallel to, but bluer in $(U - B) \approx$ - 0.2 mag than the supergiant sequence, because the mass of a nova envelope is 10 000 times lower than that of a normal supergiant. After the nova reached the point of free-free emission, which coincides with the intersection of the blackbody and the nova-giant sequence, it evolved leftward, due to the development of strong emission lines.

Individual U observations are plotted in Fig. 3. During the dust formation stage that started in the middle of September and lasted till December 2013, the U light curve showed significant

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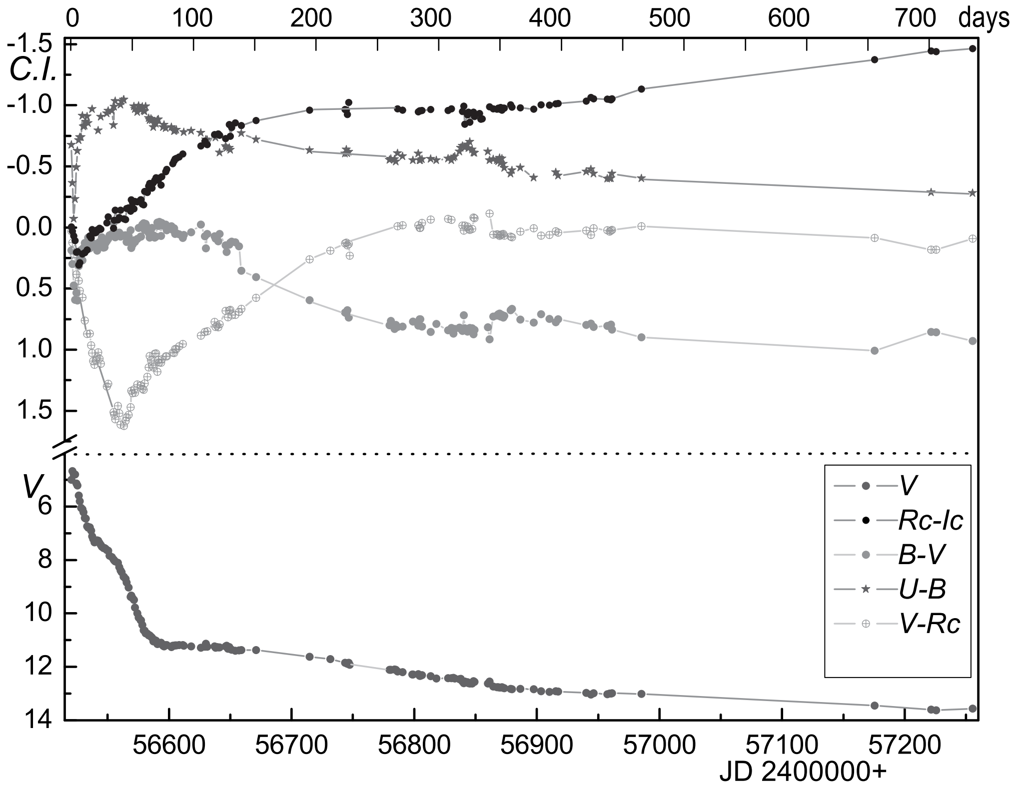

Figure 1: V light curve and color indices curves of V339 Del.

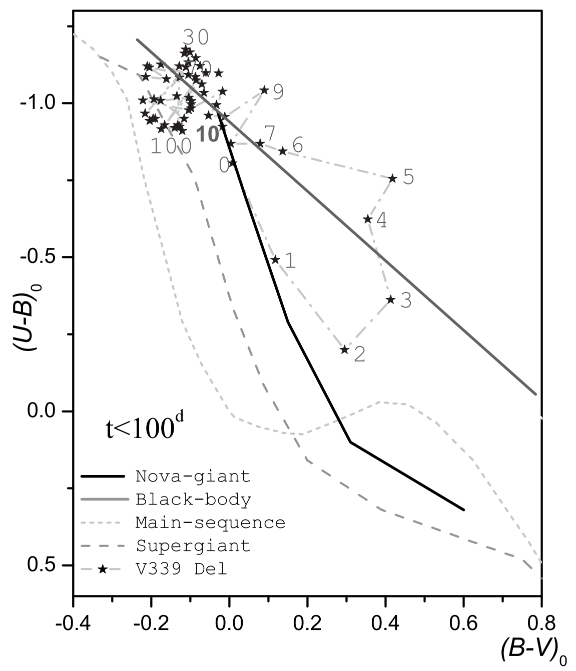

Figure 2: Track of the nova in $(U-B)_0$, $(B-V)_0$ diagram, with dereddened data assuming $E(B-V) = 0.18$.

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variations detected also during night runs. The reason of these variations could be carbon dust grains formed in the dense clumps of matter in ejecta. The large amplitude variations of X-ray flux observed between the days 69 and 83 could be explained in the same way. We present also the brightness variations of the nova in two nights during the short-term increase of *U* brightness in 2014. The graph is supplemented by the *B* band brightness variations in 2015.

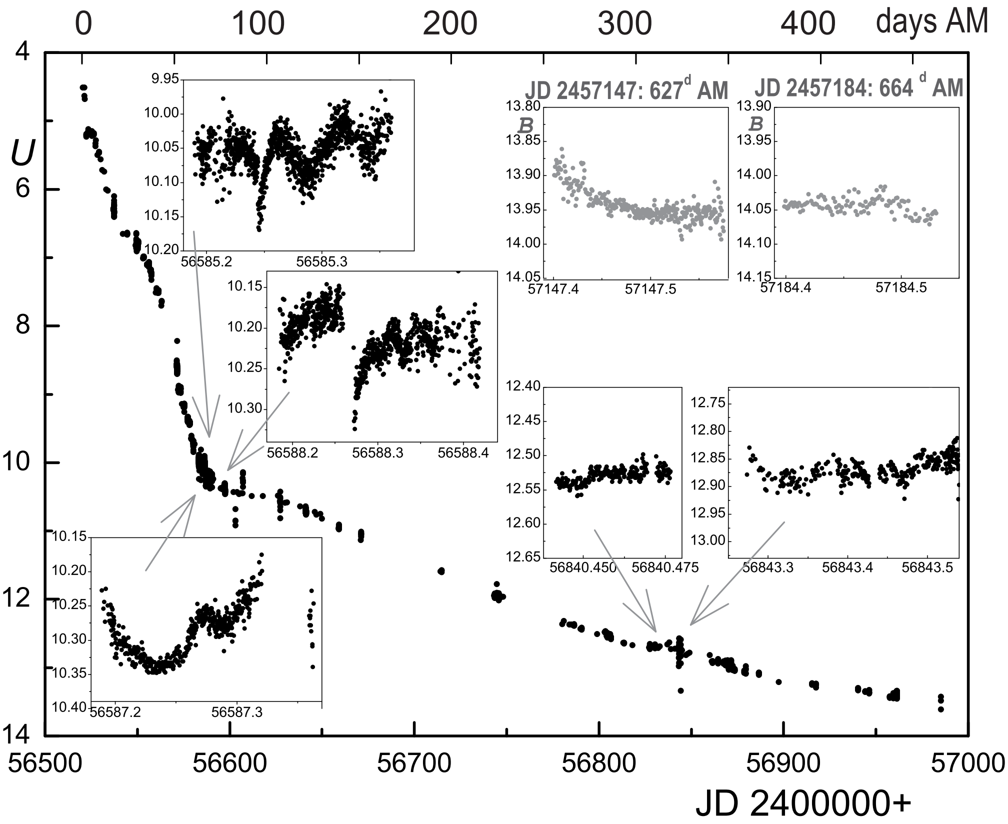

Figure 3: *U* light curve and strong brightness variations on days 64, 66 and 67 AM. The monitoring was done in *U* band on days 319 and 322 AM and *B* band on days 627 and 664 AM.

Short-term *U* light curve variability was caused by screening of the object by the dust clumps of the ejecta. In addition, there may have been effects related to the orbital motion. In the *U* light curve taken between the days 50 to 76 AM (JD24456571-97) we removed the declining trend of the nova and searched for periods in residuals by Fourier period analysis. We found that the most likely period is 3.154 hours (Fig. 4), about half of the period of 6.43 hours found [8] in the B,V data. The phase diagram in Fig. 5 was constructed using the ephemeris HJD_{min} = 2456575.397 + 0.13140 $\times$E. The brightness variations probably reflect the orbital motion in the binary system V339 Del.

3.5.2 Spectroscopy

A large amount of spectroscopic observations of the nova were gathered by astronomers. The spectra taken during the first month of the outburst was described in [8]. The evolution of the nova was followed by amateurs of the ARAS group. They obtained and made publicly available 1151

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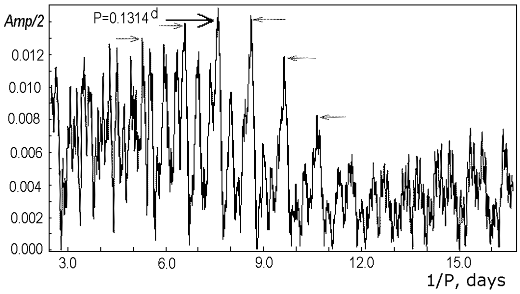

Figure 4: Fourier period analysis of U data from day 50 to 76 AM (JD24456571 - 97).

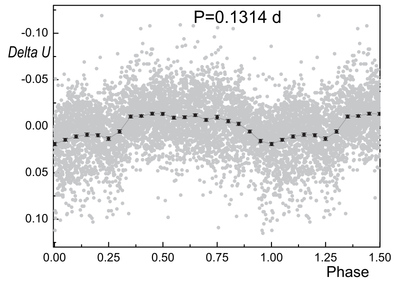

Figure 5: Phase diagram for the best period 3.154 hours.

spectra of V339 Del with spectral resolution ranging from 500 to 10 000 during the time 2013 Aug 14 - 2015 Aug 17. The observations were described by Shore et al. [38], [39], [40] and used by Skopal et al. [41] to study the temporal evolution of the luminosity, radius and effective temperature of the nova shell from discovery to around day 40. The above authors modelled the optical/near-IR spectral energy distribution (SED) using low-resolution spectroscopy (3500 - 9200 Å), $UBVR_CI_C$ and $JHKLM$ photometry and found that during the fireball stage (2013 Aug. 14.8 - 19.9), T_{eff} was in the range of 6000 -12 000 K, the radius was expanding non-uniformly in time from ($\sim$ 66 to $\sim$ 300)($d/3$ kpc) R$_\odot$, while the luminosity was super-Eddington. The maximum of bolometric luminosity $\sim 9\times10^{38}$ $(d/3\ \mathrm{kpc})^2$ erg/s occurred around Aug. 16.0, at maximum of T_{eff}, half a day before the visual maximum. The profile of the H$_\alpha$ line and its relative high flux during the fireball phase suggest a low-density optically thin part of the envelope, which is ionized and has a bipolar shape. The optically thick/thin interface represents the warm expanding pseudo-photosphere. A gradual increase of the nebular contribution during the last day of the fireball stage (Aug. 18.9 - 19.9) may be caused by a gradual opening and enlargement of the H II zone and narrowing of the H I zone. The optically thick pseudo-photosphere was therefore transformed into a disk-like shape. After the fireball stage the mass of the ionized region was a few $\times10^{-4}$ M$_\odot$ and mass loss rate between the days 5.5 AM and 35 AM decreased from $\sim$ 5.7 to $\sim 0.71\times10^{-4}$ M$_\odot$. At the same time the temperature of the burning white dwarf increased from $\sim$ 37 000 K to $\sim$ 150 000 K and its radius decreased from 19 to 0.6 R$_\odot$. On day 35 AM the model SED indicated a dust emission component in the spectrum. The dust was located beyond the H I zone, where it was shielded from the radiation of the burning WD.

The emission feature around 6830 Å observed in the spectra of nova from day 3 to 37 AM was identified by [41] as the Raman-scattered O VI 1032 Å line because of similarity of its line profile with Raman 6825 Å line profile in the spectrum of the symbiotic star Z And. Shore et al. [42] identified this emission as the C I 6828 Å line, by comparing its profile with the profile of C I 8335 Å line.

The observed galactic lithium abundance and theoretical predictions suggest that a significant amount of ^{7}Li could be produced in classical nova explosions. Tajitsu et al. [43] detected in high-resolution spectra of V339 Del taken 38-48 days after its explosion by 8.2m Subaru telescope highly blue-shifted ($\sim$ 1 000 km/s) absorption resonance lines of singly ionized radioactive isotope of beryllium ^{7}Be (3130.583 and 3131.228 Å). Production of the unstable isotope ^{7}Be by the reaction ^{3}He$(\alpha,\gamma)^7$Be in nova explosions was theoretically predicted by [44]. According to [45],

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^{7}Be decays to form ^{7}Li within a short time (half-life 53.22 days). Therefore, the detection of ^{7}Be in an expanding ejecta of the nova means, that it will soon decay to ^{7}Li on a time scale given by the half-life of ^{7}Be. Hernanz et al. [46] showed that lithium production is favored for novae with underlying CO white dwarf. V339 Del is the first nova that has been observed to synthesize the element lithium.

The comprehensive high-resolution optical spectroscopy in the range 3800 and 8800 Å , taken by 1.2m telescope TIGRE during the first 121 days of the outburst, was published by [47]. Their spectral line profiles atlas covers four different expansion phases of the ejecta. In *optically thick phase* H I, C I, Ca II, Fe II, O I exhibit clear P-Cyg profiles. Lowly ionized lines of Cr II, Fe I, Mg II, Na I, Sc II, Si II, Sr II, Ti II, show only narrow absorption features with radial velocities covering a narrow range between - 500 and - 800 km/s. H I P-Cyg profile show absorption with terminal velocity - 2000 km/s. During the *transition phase* that started on day 13 AM the spectrum exhibited strong H I lines with a weak P-Cyg absorptions that spans a velocity range from - 700 to - 1350 km/s. The terminal velocities of the strongest Fe II transitions were - 1200 km/s. The emission line profiles were asymmetric with the red side brighter than the blue one. The appearance of [N I] and [O I] lines marked the transition towards *optically thin phase* or nebular phase observed from day 40 AM. The P-Cyg absorptions disappeared. The ionization level of the gas increases as seen from appearance of He I lines and [O III] 5007 Å line. The emission lines of H I, He I, C II, Fe II, O I and [O I] show double-peaked profile with separation of peaks 1400 km/s. It is clear signature of the non-spherical structure of the ejecta. During the *bright X-ray central source phase* covered by observations from day 70 AM the appearance of high ionization N III, O III, He II and [Fe VII] emission lines suggests re-ionization of expanding ejecta by highly energetic radiation from the remnant white dwarf.

The medium-resolution spectrum of V339 Del that we obtained in August 2015 with the SCORPIO spectrograph of the 6m telescope in North Caucasus is shown in Fig. 6. Double-peaked profile of emission lines confirms a non-spherical structure of the ejecting shell.

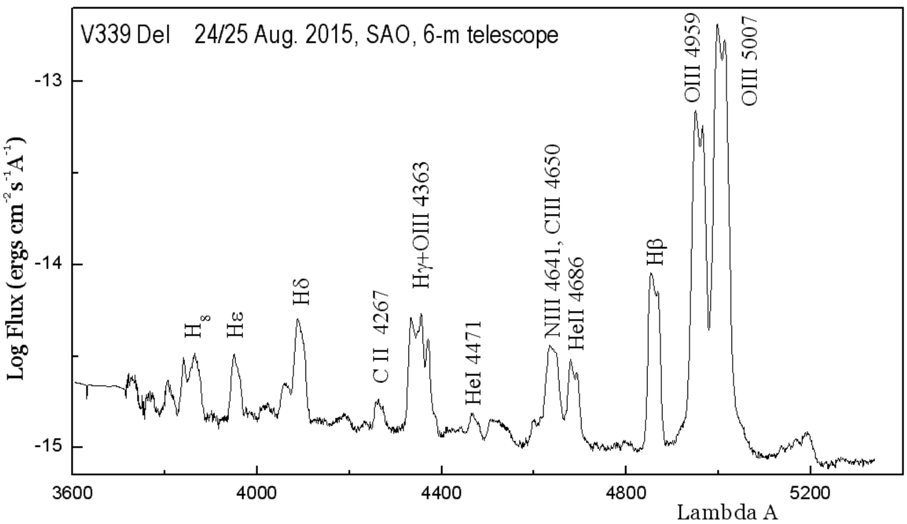

Figure 6: Medium resolution spectrum of V339 Del.

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DISCUSSION

VOJTECH ŠIMON: You showed also pre-outburst phase of the optical activity of V339 Del. Can you please compare the optical brightness in the phases before and after the outburst of V339 Del.

DRAHOMÍR CHOCHOL: The brightness of the nova in quiescence was $B \sim 17.2$ mag. At present the nova is still in outburst, because we found B =14.3 mag from our last photometric observations obtained on 2015 August 20.

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