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Multiwavelength models SED of the classical nova V339 Del (Nova Del 2013) along its age

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Classical nova V339 Del (Nova Del 2013) is a fast nova of the Fe II class, whose eruption was ignited on a CO white dwarf (WD). In this contribution we present the spectral energy distribution (SED) of the nova optical spectrum throughout its main stages of evolution: The fireball stage, transition to a harder spectrum, super-soft X-ray source phase and the nebular phase. We achieved this aim by the method of multiwavelength modelling the SED. During the fireball stage the nova spectrum was well comparable with the atmospheric models for a star of spectral type A. During two days following the fireball stage, the maximum of the WD radiation shifted out-of the optical to shorter wavelengths and a strong nebular continuum emerged and modulated considerably the whole optical to near-IR. The super-soft X-ray source phase was characterized with a flat optical continuum determined by the nebular emission. During the nebular phase, the optical spectrum was steep towards the short wavelengths reflecting a dominant contribution from the cooling WD photosphere, whereas the nebular continuum decreased by a factor of $\sim$30 with respect to the super-soft source phase. Our analysis confirmed that V339 Del is an extraordinary nova.

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1. Introduction

V339 Delphini is a classical nova that was discovered by Koichi Itagaki on 2013 Aug. 14.584 UT at the unfiltered brightness of 6.8 mag, i.e., 0.7 d after its explosion on August 13.9, 2013 [9]. After ∼1.85 days of its discovery, the nova peaked at $V \sim 4.43$ on Aug. 16.45 UT [11], and became to be an attractive target also for amateurs astronomers resulting in obtaining high-cadence photometric and spectroscopic observations in the optical. First optical spectrum was obtained on 2013 Aug. 14.844 by Olivier Garde, the observer participating in the *Astronomical Ring for Access to Spectroscopy (ARAS)* project[1] and by [7] on 2013 Aug. 14.909. Members of the ARAS project collected altogether 1152 spectra of V339 Del with the cadence of few spectra a day within 2013 and the last one obtained on September 15, 2015. A strong effort was put forth to obtain observations also in different domains of the electromagnetic spectrum, from γ-rays [1] to the radio/mm–2 cm wavelengths [5].

Early stage of the nova evolution, until emergence of first X-rays (≈ day 40), was presented by [22]. On the basis of the optical spectroscopy and near-IR photometry, the authors revealed extraordinary behaviour of the nova, focused to its long-lasting super-Eddington luminosity.

Using the near-IR photometry, [23] indicated first formation of the dust around one month after the optical maximum. Extensive studies of dust properties and its evolution were performed by [9] and [8] using the stratospheric observatory *SOFIA* and ground-based infrared observations.

V339 Del was monitored by the Swift X-ray telescope with the first detection on September 19 (day 37) at harder energies of 1–10 keV, while the super-soft emission appeared later, on October 13, 2013 (day 61) [15]. X-ray emission was gradually fading from day ∼200 to day 373, when the observations ceased (see Fig. 1 of [18]).

A short review of V339 Del was presented by [12], [8] and [4]. In this contribution we present the SED in the optical to near-IR of the nova throughout its main stages of evolution: The fireball stage, transition to a harder spectrum, super-soft source phase and in the nebular phase. Section 2 presents the used observations and their timing, Sect. 3 describes the method and results, while conclusions are found in Sect. 4.

2. Observations

Observations used to model the SED of V339 Del in this paper were collected and described in previous publications of [22] and [25], complemented with the optical low-resolution spectrum carried out at the West Challow Observatory by D. Boyd, which is available at the *ARAS* database. The spectrum was taken on November 21.857, 2013, i.e., at day ∼100, during the super-soft X-ray phase. Figure 1 shows the optical light curves of the nova in the B and I_C passbands taken from The *AAVSO* International Database[2]. Light curves cover the nova from its explosion (day 0) to day 520, i.e., throughout all its basic phases of the evolution.

Additional multicolour photometric measurements of [11] and [3] were used to check the calibration of the spectra. Because of a strong supplement of emission lines to the continuum, we

[1] http://www.astrosurf.com/aras/Aras_DataBase/Novae/Nova-Del-2013.htm

[2] https://www.aavso.org/data-download

corrected the photometric flux-points for emission lines [20]. Finally, observations were dereddened with E_{B-V} = 0.18 [11] and resulting parameters were scaled to a distance of 4.5 kpc [17].

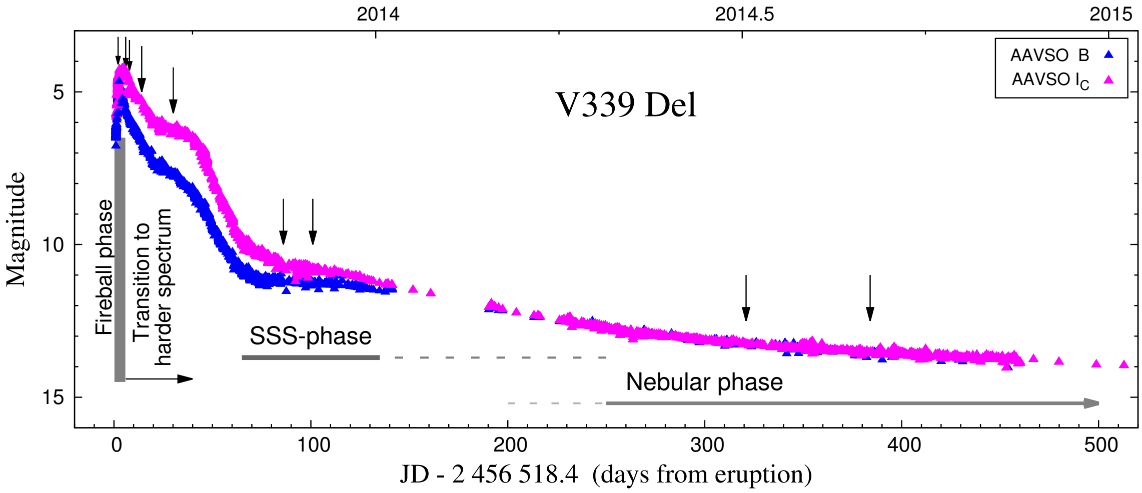

Figure 1: The B and I_C light curves of V339 Del covering 520 days of its evolution - from the eruption (August 13.9, 2013; day 0) to the nebular phase, as collected by observers in the *AAVSO* International Database. Vertical arrows mark dates with models SED presented in this paper.

3. Analysis and results

The material ejected at the nova explosion reprocesses the inner radiation, originally produced by the nuclear fusion on the white dwarf (WD) surface in the form of gamma photons. As the geometrical and optical properties of the ejecta vary with time, the observed spectrum will be a function of the nova age. In the following sections we present examples of the spectral energy distribution (SED) in the nova spectrum during its main stages of evolution.

3.1 SED during the fireball stage

During the so-called fireball stage, the expanding shell transfers the inner energetic photons to its optically thick/thin interface, which redistributes their major part into the optical. As a result, the observed spectrum resembles that produced by a star of spectral type A to F, e.g., [2]. Accordingly, the spectrum of the nova, $F(\lambda)$, as observed at the Earth, can be compared with an atmospheric model, $\mathscr{F}_\lambda(T_{\rm eff})$, i.e.,

$$F_\lambda(T_{\rm eff}) = \theta_{\rm WD}^2 \mathscr{F}_\lambda(T_{\rm eff}), \tag{3.1}$$

where $\theta_{\rm WD} = R_{\rm WD}/d$ is the angular radius of the WD pseudophotosphere and $T_{\rm eff}$ its effective temperature. Fitting parameters are $\theta_{\rm WD}$ and $T_{\rm eff}$, which define the effective radius of the shell as $R_{\rm WD} = \theta_{\rm WD} \times d$ and its luminosity $L_{\rm WD} = 4\pi d^2 \theta_{\rm WD}^2 T_{\rm eff}^4$ for the distance to the nova, d.

In the SED-fitting analysis we compared a grid of synthetic models with the observed spectrum (3.1) and selected that corresponding to a minimum of the reduced χ^2 function. The grid of atmospheric models was prepared from that of [10], for $T_{\rm eff} = 5\,000 - 15\,000$ K with the step

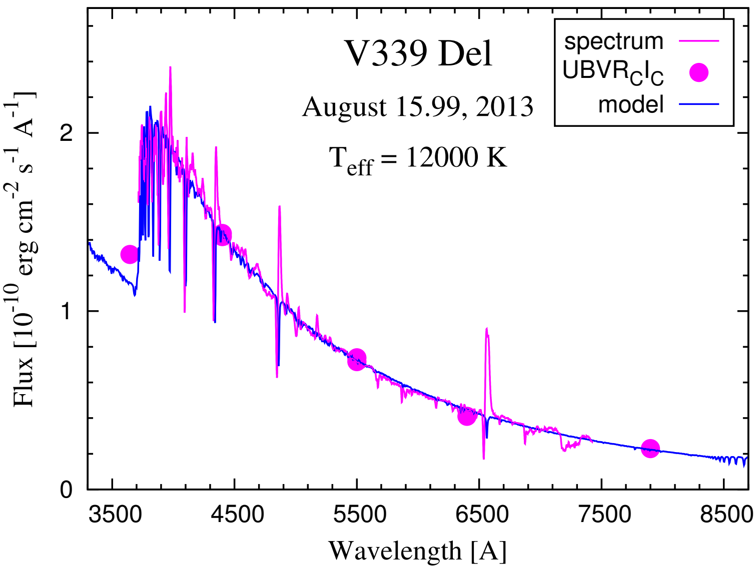

Figure 2: SED during the fireball stage. Example of the observed spectrum of V339 Del (in magenta) matched with the atmospheric model calculated for $T_{\rm eff} = 12\,000$ K (blue line). Adapted according to [22].

of $\Delta T_{\rm eff} = 250$ K and fixed other atmospheric parameters. Figure 2 shows example of the observed spectrum from August 15.99, 2013 (day 2.09). The model parameters $T_{\rm eff} = 12\,000$ K and $\theta_{\rm WD} = 8.3\times10^{-10}$ yield $R_{\rm WD} = 165\,(d/4.5\,{\rm kpc})\,R_{\odot}$ and $L_{\rm WD} = 1.9\times10^{39}\,(d/4.5\,{\rm kpc})^2\,{\rm erg\,s^{-1}}$. During the whole fireball phase the WD luminosity was a factor of $\sim$10 higher than the Eddington value for the WD mass of $1\,M_{\odot}$.

The fireball stage of V339 Del was indicated already by the first spectra taken less than 1 day after the nova explosion until August 19.9, 2013 (day 6), see [22]. Its end was indicated by a significant weakening of the H I absorption components [6] and flattening of the optical SED almost without traces of the Balmer jump on August 19.9, 2013, see [24] and [22].

3.2 SED during the transition to harder spectrum

During the transition to harder spectrum the optical depth of the shell progressively shrinks and becomes hotter on the line of sight. As a result, the spectrum significantly changes in both the continuum and lines, shifting the maximum of its SED to shorter wavelengths, beyond the optical.

The hotter WD pseudophotosphere is capable of ionizing the outer material giving rise to the nebular emission. Therefore, the nebular component of radiation starts to dominate the optical/near-IR. Because of a high $T_{\rm eff}$ of the WD pseudophotosphere, we observe only the long-wavelength tail of its radiation in the optical, which can be approximated by the black-body radiation with the temperature $T_{\rm BB}$. In this case, the observed spectrum can be modelled with

$$F_{\lambda}(T_{\rm BB}, T_{\rm e}) = \theta_{\rm WD}^2 \pi B_{\lambda}(T_{\rm BB}) + k_{\rm N}\times\varepsilon_{\lambda}(T_{\rm e}), \tag{3.2}$$

where the second term on the right represents the nebular continuum given by the total volume emission coefficient $\varepsilon_{\lambda}(T_{\rm e})$ that includes f–f and f–b transitions in the hydrogen plasma. Its scaling to the observed spectrum $k_{\rm N} = EM/4\pi d^2$, where EM is the so-called emission measure. The variables determining the model SED (3.2) are $\theta_{\rm WD}$, $T_{\rm BB}$, $k_{\rm N}$ and $T_{\rm e}$. Equation (3.2) assumes that

T_e and thus $\varepsilon_\lambda(T_e)$ are constant throughout the nebula. The SED modelling is described in more detail by [19] and [21].

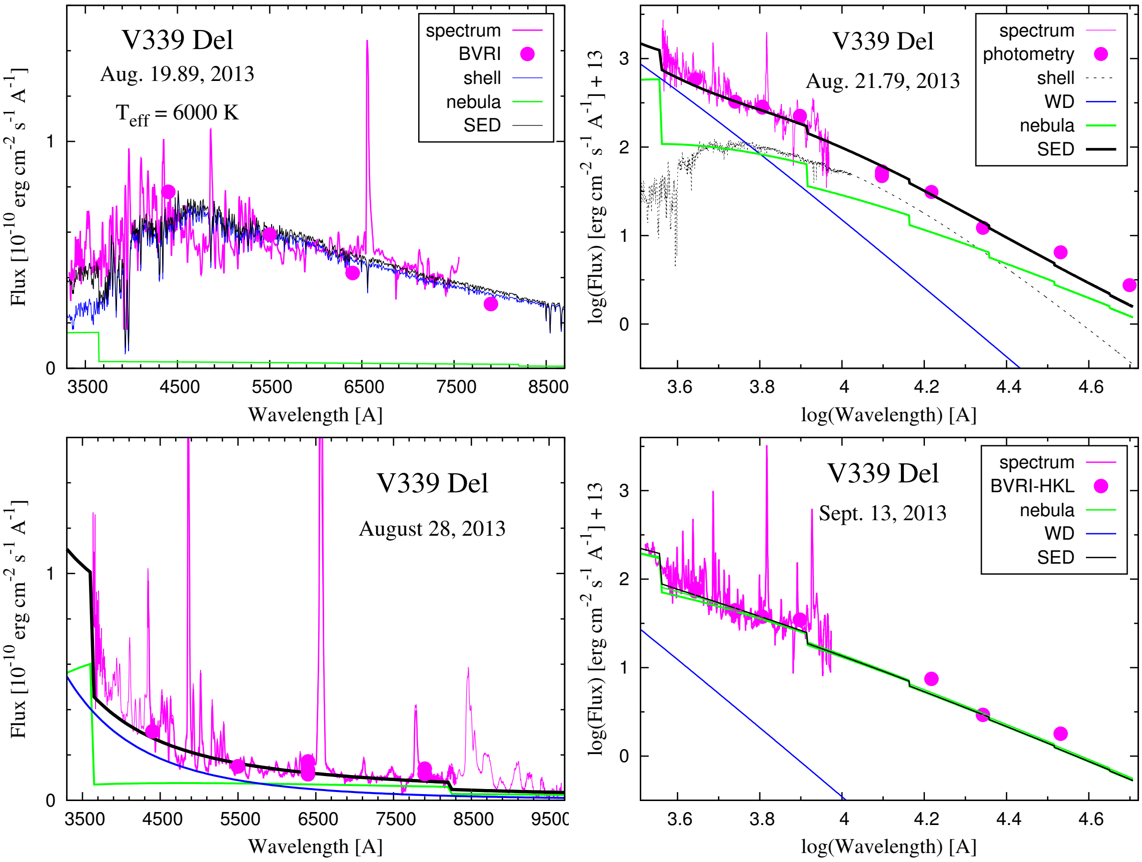

Figure 3: SEDs during the transition to harder spectrum. The observed spectra are in magenta and their model SED is denoted with black line. The top left panel shows the last spectrum from the fireball stage, while the top right panel represents the first spectrum with the maximum shifted to the UV. Bottom panels depict typical SEDs during the transition to harder spectrum with strong nebular component and a hot WD pseudophotosphere. Adapted according to [22].

Figure 3 shows example of models SED just at the transition from the end of the fireball stage (top left panel) to the beginning of SEDs with harder spectrum, with the maximum radiation at shorter wavelengths. The transition was very short, it happened during ~2 days, from August 19.9 to August 21.8, 2013. The former spectrum was still dominated by a cool (~6000 K) shell, but for the first time with identifiable contribution of the nebular emission in the continuum, whereas the latter spectrum was already dominated by a strong nebular emission with $EM \sim 2\times10^{62}$ cm^{-3}. In addition, the optical to near-IR observations still required a contribution from a warm pseudophotosphere, which was not possible to recognize on a few days later spectra (see Fig. 3).

Modelling the SED after the fireball stage is not unambiguous in determining properties of the hot WD pseudophotosphere, because its maximum of radiation is located far beyond the optical, at much higher energies. An estimate of its luminosity can by made by using the well measured nebular component of radiation under assumption that this component represents the reprocessed WD's radiation for $\lambda < 912$ Å. The high values of $EM \sim 10^{62}$ cm^{-3}, derived from models SED during this period of nova evolution, require the WD luminosity to be of $\sim 10^{39}\,\mathrm{erg\,s^{-1}}$, i.e., still about of a factor of ∼10 above the Eddington limit, as during the fireball phase (see [22] for details).

3.3 SED during the super-soft X-ray source phase

According to the development of the X-ray emission from V339 Del (see Fig. 1 of [18]), the super-soft source (SSS) phase began at day ∼66, when the absorbing column density of hydrogen atoms decreased to $\sim 1.8 \times 10^{21}\mathrm{cm^{-2}}$ (see [14]), which can be attributed to the interstellar quantity, because it is relevant to the extinction to the nova $E_{\mathrm{B-V}} = 0.18$ mag (e.g., [16]). This means that the veiling of the WD photosphere by the circumstellar matter was rather small, allowing us to detect the super-soft X-ray component of the nova spectrum. On the basis of the *Chandra* X-ray spectrum, [13] estimated its photospheric temperature to ∼310 000 K at day 89. Such the hot WD then ionizes the circumbinary material giving rise to a strong nebular emission.

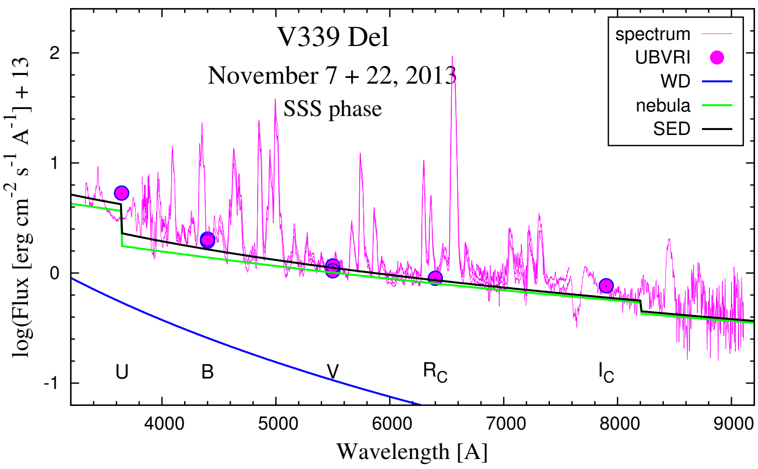

Figure 4: SED during the super-soft X-ray source phase. It is characterized with a strong nebular radiation dominating the optical. The spectra are from [25] (November 7, 2013; day 86; 320–750 nm) and Fujii Kurosaki Observatory (November 22, 2013; day 101; 450–965 nm; see [22]).

Therefore, we used Eq. (3.2) to model the SED also during the SSS phase. Figure 4 shows example of the observed and model SED in the optical around the middle of the SSS phase of V339 Del (day 86 and 101). The nebular continuum strongly dominates this domain. It corresponds to $T_{\mathrm{e}} = 50\,000 \pm 5000$ K and $EM = (8.5 \pm 0.9) \times 10^{60}\,\mathrm{cm^{-3}}$. For the stellar radiation from the WD photosphere we adopted $T_{\mathrm{BB}} \equiv 310\,000$ K (see above) and scaling $\theta_{\mathrm{WD}} \sim 10^{-12}$, which influences only marginally the short-wavelength part of the optical spectrum (see Fig. 4). However, determination of the hot WD radiation is not unambiguous, because at temperatures $\gtrsim 10^5$ K we observe only its small long-wavelength tail, which is hardly to identify in the optical.

3.4 SED during the nebular phase

According to [25], spectrum of V339 Del exhibited characteristics of nebular phase already at the spectrum from April 25, 2014 (day 255), being unchanged to their last spectrum on September 1, 2014 (day 384). Nebular lines of [O III] 5007, 4958 Å represented the strongest emission lines in the spectra, complemented with other forbidden lines as [Ne III] 3869, 3968 Å, [Ar III] 7136 Å and

[Ar IV] 7237+7263 Å lines. Also forbidden lines of highly ionized elements like [Fe VI] 5176 Å, [Ca V] 5309 Å, [Fe VII] 6087 Å and [Ne V] 3346, 3426 Å were present. Well recognizable were also permitted lines; those of hydrogen Balmer series, He I 5775 Å and relatively faint He II 4686 Å line (around one third of the Hβ flux).

We modelled the optical continuum as a superposition of the nebular component of radiation and that produced by the WD photosphere, i.e., using Eq. (3.2). Similarly to modelling SED during the SSS phase, determination of the WD parameters ($T_{\rm BB}$ and $\theta_{\rm WD}$) is not unambiguous. However, fading of the super-soft X-ray photons below 0.01 counts s^{-1} (see [18]) and the presence of a faint He II 4686 Å emission during the nebular phase, constrain $T_{\rm BB}$ to be around of 50 000 K.

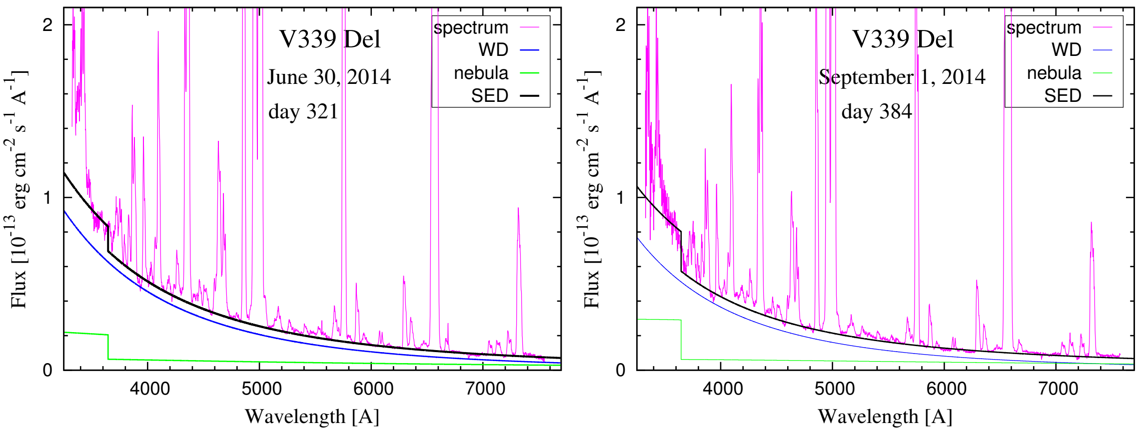

Figure 5: SED of V339 Del during the nebular phase. It is characterized with a dominant contribution from the WD photosphere within the optical.

Using this condition we re-analyzed two spectra from [25] made on June 30, 2014 (day 321) and September 1, 2014 (day 384) for $T_{\rm BB} = 50\,000$ K. Figure 5 shows the results. The former spectrum was fitted with $\theta_{\rm WD} = 3.6 \times 10^{-12}$ (i.e., $L_{\rm WD} \sim 1.1 \times 10^{37}\,(d/4.5\,{\rm kpc})^2\,{\rm erg\,s^{-1}}$ or $2900\,L_{\odot}$) for the WD radiation, and $T_{\rm e} \sim 30\,000$ K and $EM \sim 2.9 \times 10^{59}\,(d/4.5\,{\rm kpc})^2{\rm cm}^{-3}$ for the nebular continuum. The latter spectrum is characterized with $\theta_{\rm WD} \sim 3.3 \times 10^{-12}$ (i.e., $L_{\rm WD} \sim 9.2 \times 10^{36}\,(d/4.5\,{\rm kpc})^2\,{\rm erg\,s^{-1}}$ or $2400\,L_{\odot}$), $T_{\rm e} \sim 22\,000$ K and $EM \sim 3.0 \times 10^{59}\,(d/4.5\,{\rm kpc})^2{\rm cm}^{-3}$. In both cases the reduced $\chi^2 \sim 1$ for 7% errors of the continuum and d.o.f. around of 40. Although there are larger uncertainties in the physical parameters determined by modelling only the optical spectrum, it is clear that the WD radiation dominates this region (Fig. 5), decreased significantly with respect to the SSS phase in both the temperature and the luminosity. Therefore, the very slow weakening of the nova optical brightness during the nebular phase (see Fig. 1) is given by a gradual cooling of the WD photosphere after its burning phase.

4. Conclusions

Using the method of multiwavelength modelling the SED we fitted the observed spectrum of the classical nova V339 Del (Nova Delphini 2013) by the radiation from the WD photosphere and the nebular hydrogen continuum along its evolution.

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During the fireball stage (day 0 to 6 after the nova explosion) the spectrum was well comparable with the atmospheric models calculated for $T_{\rm eff} = 6\,000 - 12\,000$ K. Example at the maximum effective temperature of the fireball, 12 000 K (day 2.1), is shown in Fig. 2.

Figure 3 shows example of SEDs during the transition to harder spectrum. A dramatic and fast change in the spectrum composition happened during two days following the fireball stage (day 6 – 7.9). The maximum of the nova radiation rapidly shifted from the optical to shorter wavelengths, and a strong nebular continuum ($EM \sim 2 \times 10^{62}\,{\rm cm}^{-3}$) started to modulate the optical to near-IR with a remnant of the warm fireball radiation (see top panels of the figure).

During the SSS phase, the WD photosphere was purged of the absorption by the circumstellar matter. Maximum of its radiation was located within the super-soft X-rays, reducing considerably its contribution in the optical. However, the nebular continuum strongly dominated the optical making its SED rather flat. Figure 4 shows example of such the model SED around the maximum rate of the super-soft photons.

During the nebular phase, the photospheric temperature of the WD had to decrease to around 50 000 K, not to be capable of producing the super-soft X-ray photons, but still giving rise to a faint He II 4686 Å line. As a result, the emission measure decreased by a factor of ∼30 with respect to the SSS phase. The optical spectrum was steep towards the short-wavelengths, which reflects a dominant contribution from the cooling WD photosphere. Example of models SED during the nebular phase is shown in Fig. 5.

Acknowledgments

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DISCUSSION

IZUMI HACHISU: Theoretically, 100 times super-Eddington luminosity should expand the WD surface to a large size, because of radiation pressure. I think not consistent with the SSS phase.

AUGUSTIN SKOPAL: Probably, yes. However, in the case of V339 Del we indicate luminosities in order of $10^{39}\,\mathrm{erg\,s^{-1}}$, i.e., a factor of $\sim$10 above the Eddington value.