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Optical and Near-infrared High-resolution Spectroscopic Observations of Nova V2659 Cyg: Structure of Nova Ejecta and Origin of Two-distinct Velocity Systems

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Two distinct absorption-line systems distinguished by radial velocities have often been observed in the optical high-resolution spectra of classical novae during their early decline phase. The origin of these absorption-line systems is under debate. We present optical high-resolution spectroscopic observations spectra of nova V2659 Cyg and discuss the temporal evolution of those absorption-line systems observed in this nova during its early decline phase. The observed temporal evolution of absorption-line profiles with relatively higher velocities (the high-velocity component) can be explained qualitatively by the clumpy ejecta and motion of the ionization fronts in the ejecta with time. Conversely, the low-velocity component may originate in the cool region compressed by the shock caused by collision between the fast nova wind and the slow expanding, equatorially focused dense ejecta. We also present high-resolution spectra of V2659 Cyg during its nebular phase in optical and near-infrared wavelength regions. Emission lines detected during the nebular phase also showed two velocity components, suggesting that the velocity structure of the ejecta during the nebular phase is similar to that during the early decline phase. The double-horned profiles of emission lines with low velocities imply a ring-like distribution of materials with lower velocities. The observations during both the early-decline phase and the nebular phase support the multiple ejection of ejecta at a nova explosion, with different velocities.

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1. Introduction

Classical novae often display multiple absorption-line systems with different velocity components, caused by neutral atoms/ions existed in the nova ejecta along the line of sight (e.g., [1, 2, 3, 4] and references theirin), during their early-decline phase. Both spatial structure and velocity structure of the nova ejecta (especially, along the line-of-sight) could be investigated based on the absorption-line profiles of the systems. On the other hand, the emission-line profiles observed in novae during nebular phase (i.e., the nova ejecta are optically thin) also provide crucial information about the velocity structure of entire nova ejecta.

To date, several authors have proposed various physical models of nova ejecta based on observations from the gamma-ray to radio domains (e.g., [5, 6, 7, 8, 9, 10] and references therein). These models can be classified into two groups: one assumes a single eruption for each nova outburst and other assumes multiple eruptions for each nova outburst. Recently, essentially important observations were reported for novae, that is, the detection of strong gamma-ray emissions (e.g., [9], and references therein). The gamma-ray emissions in several novae strongly support the existence of shocks in nova ejecta.

Mason et al. in 2018 [10] and Shore et al. in 2011 [11] concluded that a single eruption at the nova outburst could explain the observed behavior if the temporal evolution of the recombination fronts within the nova ejecta was considered. In their scenario, materials can be ejected as multiple clumps and the nova ejecta are ballistic at the outburst. Mason et al. in 2018 [10] proposed persistent structures of nova ejecta that do not move in velocity space, i.e., in a Hubble/radial flow (or in a ballistic expansion). The density distribution of ejecta is stationary in the velocity space; their model is not compatible with the situation based on the nova wind. Even though the absorption features display apparent inward motion (or sometimes oscillations), they considered that such motion could be explained by a change in the ionization structure of the nova ejecta, i.e., moving recombination/ionization fronts in the ejecta. Their model does not require multiple ejections of shells or structures having increasing velocities. Furthermore, they claimed that collisions between clumps during the ejection and the initial expansion could explain the stochastic range of clump velocities as well as the gamma-ray emissions from novae. Shore et al. explained the change in the absorption-line systems found in the recurrent nova T Pyx [11], while Mason et al. discussed those in about V1369 Cen, T Pyx, V339 Del, and V959 Mon [10].

In contrast with the above scenario, several ejecta models have been proposed and they require multiple ejections of materials, such as the shells in the model proposed by McLaughlin [12, 13]. The most recent ejecta model explaining gamma-ray emissions from novae was proposed by Li et al. in 2017 ([9] and references therein). In their model, an isotropic nova wind with a faster expansion velocity collides with slower-velocity equatorially focused materials ejected before the initiation of the nova wind. Li et al. in 2017 [9] considered a dense and equatorially focused slow outflow (possibly due to spiral-like mass loss) through the outer L2 Lagrange point of the binary system during the pre-maximum halt phase of the nova outburst or prior to the outburst. It is likely that such mass loss is important for slow novae, in which the nova photosphere expands slowly before it reaches the visual brightness maximum (it spends a longer time in the pre-maximum phase). The shock produced by the collision between these ejecta (the equatorially focused ejecta with slow velocities and the nova wind with faster velocities) can explain the gamma-ray emissions

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observed in novae ([9, 14] and references therein). Their model also explains the formation of dust grains in novae during their early decline phase [15]. A dense region compressed by the shock could become cool enough to form dust grains in the later phase. That is, the ionization degree of the materials in this region is low during the early decline phase prior to the dust formation. In contrast with the equatorially focused ejecta, the materials blown with the nova wind may be diffuse and in lower densities unless they collide with the equatorially expanding ejecta. A wide range of ionization degrees could be achieved at different distances from the central nova in such a diffuse region [16]. The clumpiness of the nova ejecta could be employed to explain the fine structure of the emission/absorption-profiles in velocity space.

In this article we report the temporal evolution of the absorption-line systems observed in V2659 Cyg after its outburst in 2014. This nova was discovered by Nishiyama and Kabashima [17] on UT Mar 31.79, 2014. Initial low-resolution spectroscopic studies [17, 18] revealed that it is an Fe II-type nova according to the classification by Williams [19]. This nova displayed P-Cygni profiles for low-ionized species such as H I, Fe II, and O I with radial velocities -480 – $-650\,\mathrm{km\,s^{-1}}$. The slow decline rate of the optical light curve of this nova (Figure 2), in addition to the slow expansion velocities, indicates that V2659 Cyg is a slowly evolving nova. The optical light curve is complicated and is classified as a “jitter” type [20]. Arai et al. in 2016 [4] have already reported a detailed analysis of the absorption lines found in the high-resolution spectra taken on May 13, 2014 (33 days after the visual brightness maximum). The authors argued for two distinct absorption-line systems in velocity space: a “low-velocity component (LVC)” and a “high-velocity component (HVC)”. Here, we also report the high-resolution spectra taken on other dates, not only during the early decline phase but also during the nebular phase. We discuss the structure of the nova ejecta based on the observational features of the absorption-line systems in this nova from the viewpoints of two different models (single and multiple ejection scenarios).

2. Observations

High-resolution spectroscopic observations of the nova V2659 Cyg were conducted using several instruments, as summarized in Table 1. During the early decline phase, we used the HDS [21] mounted on the 8-m Subaru telescope and the BOES [22] mounted on the 1.8-m telescope at BOAO in Korea, to obtain high-resolution spectra in the optical wavelength region. During the nebular phase of the nova, we also used the WINERED [23] mounted on a 1.3-m Araki telescope in Kyoto, Japan, to perform high-resolution near-infrared spectroscopic observations in addition to the optical observations by the BOES. We used the astronomical software package IRAF [1] to reduce the spectroscopic data obtained by the BOES, based on the standard procedures for high-resolution echelle spectra. In the case of WINERED data, we used the customized pipeline software that has a capability to remove telluric absorption lines. The detail of the reduction process is described elsewhere (e.g., [24, 25]).

[1]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

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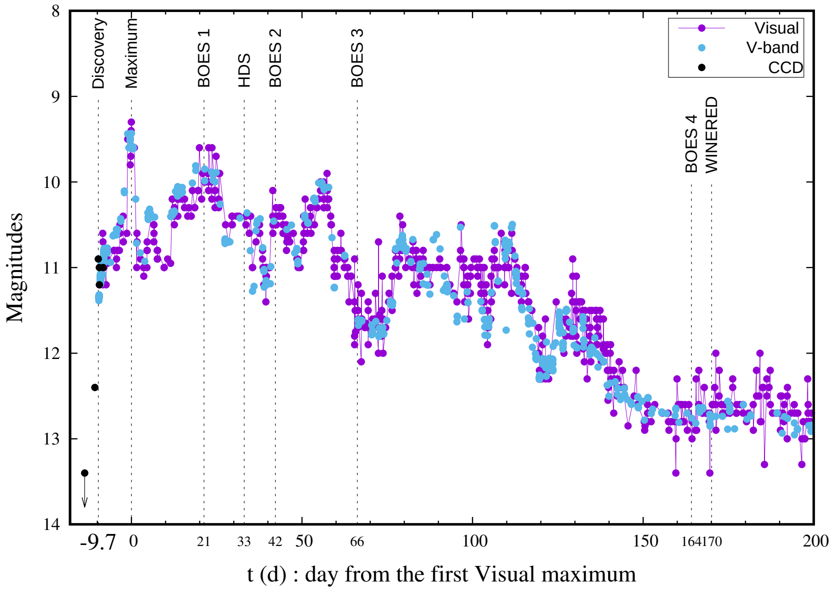

Figure 1: Optical light curves of V2659 Cyg. Labels with dotted line denote the dates of the discovery, the maximum, and our observations The labels "BOES1" – "BOES4" show the dates of our time-series observations with the BOES.

Table 1: Observational conditions.

Date (UT)	t (days)[a]	Total integration time (s)	Spectral resolving power ($R = \lambda/\Delta\lambda$)	Instrument
May 1, 2014	21	1,200	27,000	BOES
May 13, 2014	33	600	72,000	HDS
May 22, 2014	42	1,200	27,000	BOES
Jun 15, 2014	66	1,200	27,000	BOES
Sep 21, 2014	164	1,200	27,000	BOES
Sep 27, 2014	170	4,400	20,000	WINERED

[a] $t = 0$ for the visual brightness maximum.

3. Results and Discussion

3.1 Line identification

Arai et al. in 2016 [4] reported line identifications for the spectrum of V2659 Cyg, which was taken on May 22, 2014 ($t = 33$d). Here, in addition to this previous report, we report the line identifications of the nova for the high-resolution spectra taken by the BOES at other epochs (i.e., $t = 21$ d, 42 d, and 66 d) during the early decline phase in Figure 3.1. The high-resolution spectra of the nova during the nebula phase, taken by both the BOES and the WINERED, are also shown with line identifications in Figure 3.1.

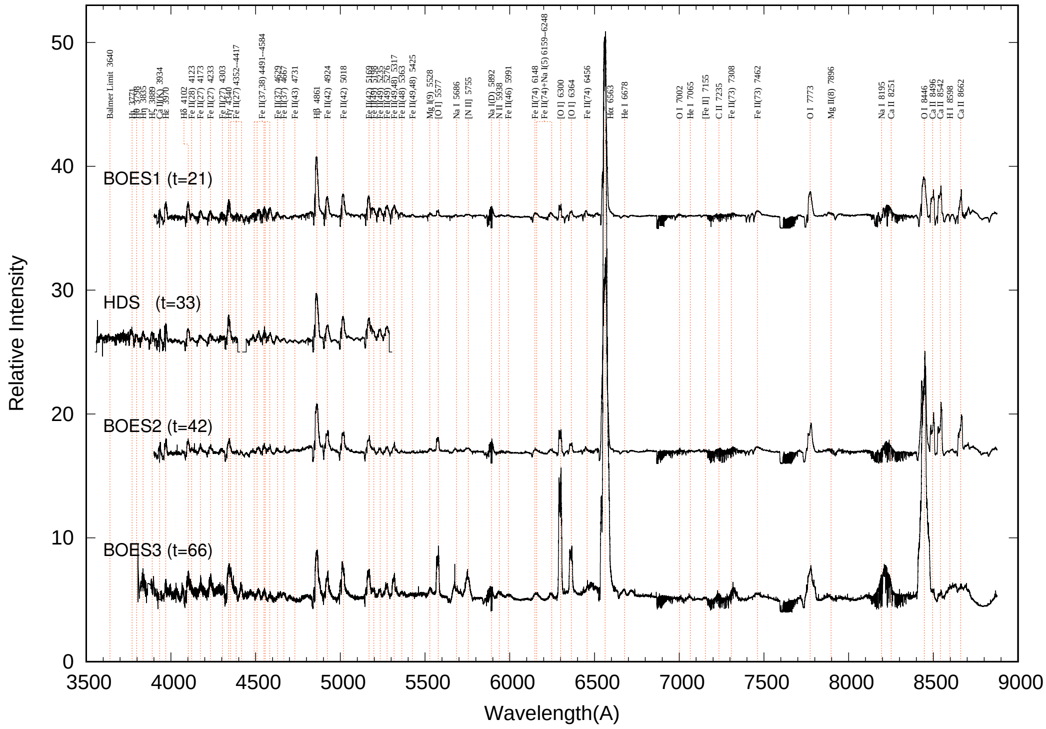

Figure 2: Optical spectra of the early decline phase of V2659 Cyg at $t = 21$ d, 33 d, 42 d, and 66 d. The dashed vertical lines indicate the positions of the identified emission lines.

3.2 LVCs and HVCs during the Early Decline Phase

Using the multi-epoch observations taken during the early decline phase of V2659 Cyg, the temporal evolution of the absorption-line systems of the LVCs and HVCs could be revealed. Figure 4 shows the absorption line systems of Fe II at 5018 Å. A comparison between Fe II at 5018 Å and Na I at 5889 Å are also shown in Figure 4. The LVC (from $-600\,\mathrm{km\,s^{-1}}$ to $-800\,\mathrm{km\,s^{-1}}$) and HVC (from $-1000\,\mathrm{km\,s^{-1}}$ to $-1600\,\mathrm{km\,s^{-1}}$) are clearly recognized at all dates. The absorption-line profiles of both velocity systems changed during the early decline phase.

For the LVC, the absorption-line was relatively sharp earlier (FWHM $\sim$ 60kms^{-1} at $t = 21$ d), became wider (FWHM $\sim$ 100 kms^{-1} at $t = 33$ d), and then took on a double-peaked shape later (at $t = 42$ d and 66 d), as demonstrated in Figure 5 for Fe II at 5018 Å. Even for the large difference in the excitation potential of the lower energy levels for Fe II at 5018 Å (10.3 eV) and for Na I at 5889 Å (0.0 eV), the absorption-line profiles are very similar on the same dates, as shown in Figure 4. This indicates that the absorption lines formed via optically thick gas and that the absorption was saturated. Further, the bottom of the absorption did not reach the zero level, i.e., the covering factor of the gas was not unity. It is likely that dense blobs of nova ejecta absorbed

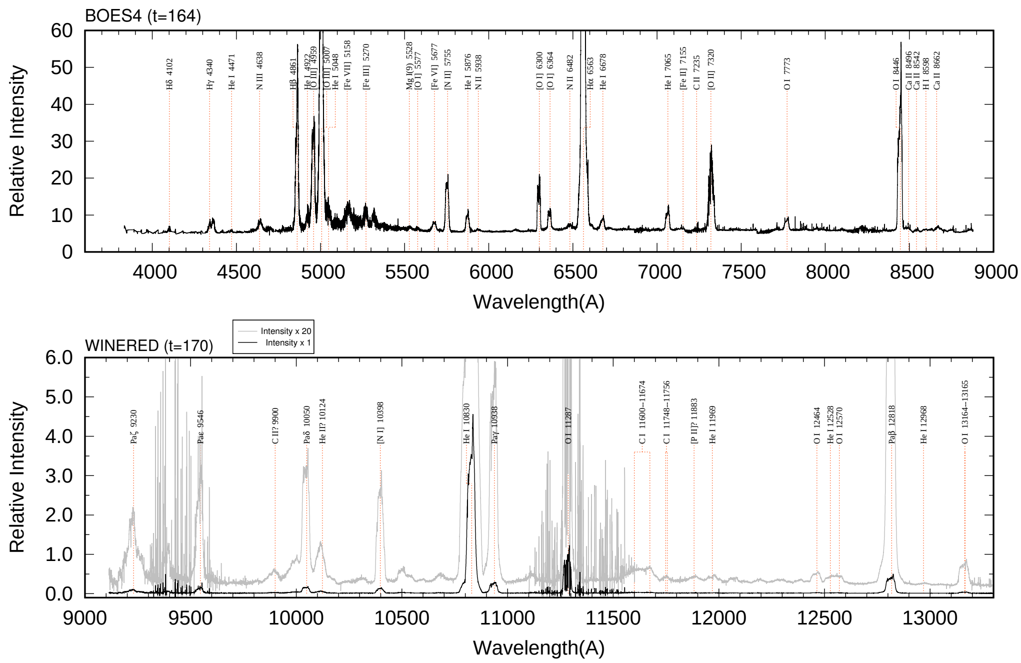

Figure 3: Optical and near infrared spectra of the nebular phase of V2659 Cyg at $t = 164$ d and 170 d. The dashed vertical lines indicate the positions of the identified emission lines. The grey spectrum in the bottom panel shows the relative flux of nearinfrared data scaled by 20 times. Line idenifications of the near-infrared spectrum was refered to [26, 27, 28, 29].

light from the nova photosphere. Arai et al. in 2016 [4] proposed the same picture because the absorption-line profiles of Fe II with different gf-values displayed similar profiles at $t = 33$ d (see Figure 4 in [4]). The acceleration of the absorption profile was recognized as observed in other novae [1], as shown in Figure 5. Note that the fastest velocity of the LVC appears to terminate as approximately $-900\,\mathrm{km\,s^{-1}}$ at $t = 66$ d, in contrast to the monotonic increase in the slowest velocity of the LVC during the period of our observations.

Regarding the origin of LVC in V2659 Cyg, absorption lines of LVC originated from energy levels with low excitation potential (≤ 4 eV) of lowly-ionized Fe-peak and s-process elements as also reported in other novae, e.g., Sc II, Ti II, V II, Cr II, Fe II, Sr II, Y II, Zr II, Ba II, and Mn II in optical spectra ([1, 2, 30, 3, 4] and references therein) together with Fe II, Si II, and Al II in UV spectra [31]. Strong emission lines in novae such as H I, He I, Na I, Mg I, Mg II, Ca II, O I, also show the absorption system with similar velocities in the novae including V2659 Cyg.

The ”low-ionization” is probably a key to understand the origin of LVC. The multiple ejection scenario proposed by Li et al. in 2017 [9] assumed a dense and equatorially focused slow outflow and an isotropic nova wind with faster velocities (leading to the collision between the slow outflow and the nova wind). The equatorially focused region is compressed and becomes cool due to the shock at the collision, sometimes followed by the dust formation during early decline phase [15].

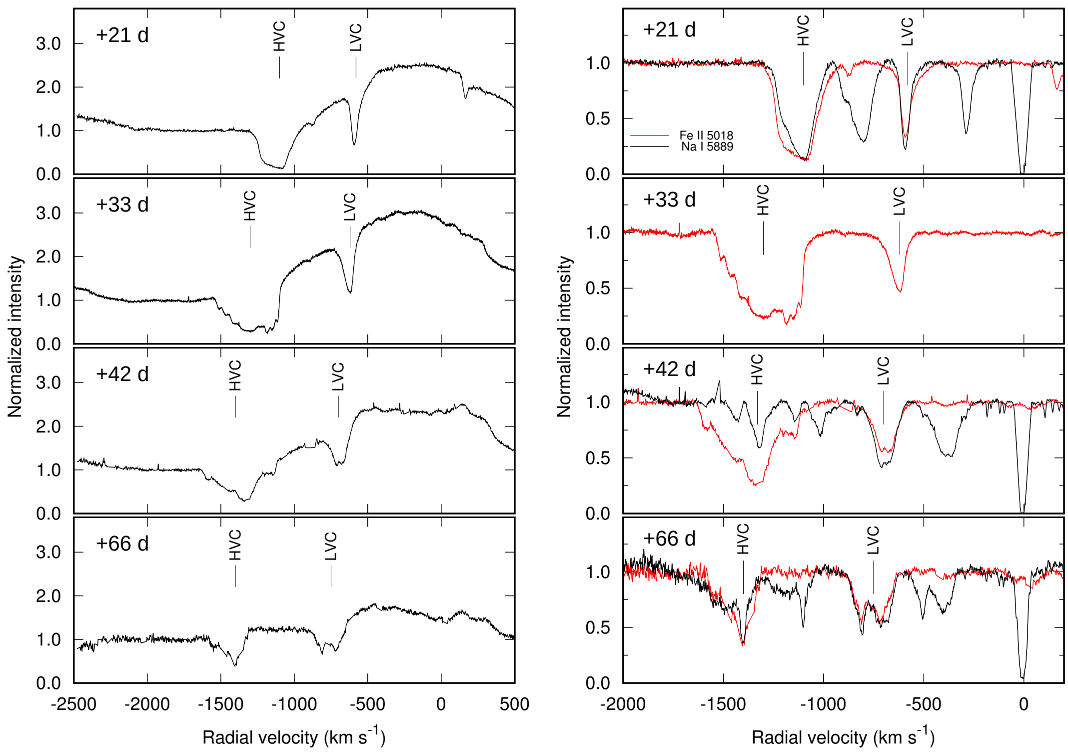

Figure 4: The left panel shows absorption systems (LVCs and HVCs) of Fe II 5018 Å. The right panel shows a comparison of LVCs and HVCs between Fe II 5018 Å and Na I 5889 Å. In the right panel, spectra are normalized by the polynomical functions fit with the emission profile.

Thus, the feature of "low-ionization" is consistent with the hypothesis that the LVC originates from such equatorially focused outflow compressed by the collision between the slow outflow and the fast nova wind.

In contrast to the LVC, the HVC displayed very different, complicated line profiles. The existence of different velocity components (a multi-peak profile) is indicative of clumpy structure of the nova ejecta. Figure 5 shows the temporal change in the absorption-line profile in the LVC and the HVC. An apparent acceleration of the absorption-line profiles was recognized for the LVC; however, a much more complicated situation exists for the HVC. Note that the step-like features for the range from $-1400\,\mathrm{km\,s^{-1}}$ to $-1600\,\mathrm{km\,s^{-1}}$ (likely composed of multiple absorption lines) shows similar velocities at each peak between $t = 42$ d and 66 d. Stationary velocity structure of the nova ejecta is supported by this observational fact. As discussed by Mason in 2018 [10] and Shore et al. in 2011 [11], the apparent change of the absorption-line system may be explained by the moving recombination/ionization fronts in the nova envelope.

The slowest velocity of HVC absorption increased monotonically although the fastest velocity terminated in later epochs as for the LVC (Figure 5a). The fastest velocity in the latest epoch ($\sim -1600\,\mathrm{km\,s^{-1}}$) may indicate the maximum velocity of the ejecta. Regarding the origin of HVC in the nova, HVC has a wide range in ionization in novae (e.g., C IV, N V, Al III, C II and O I

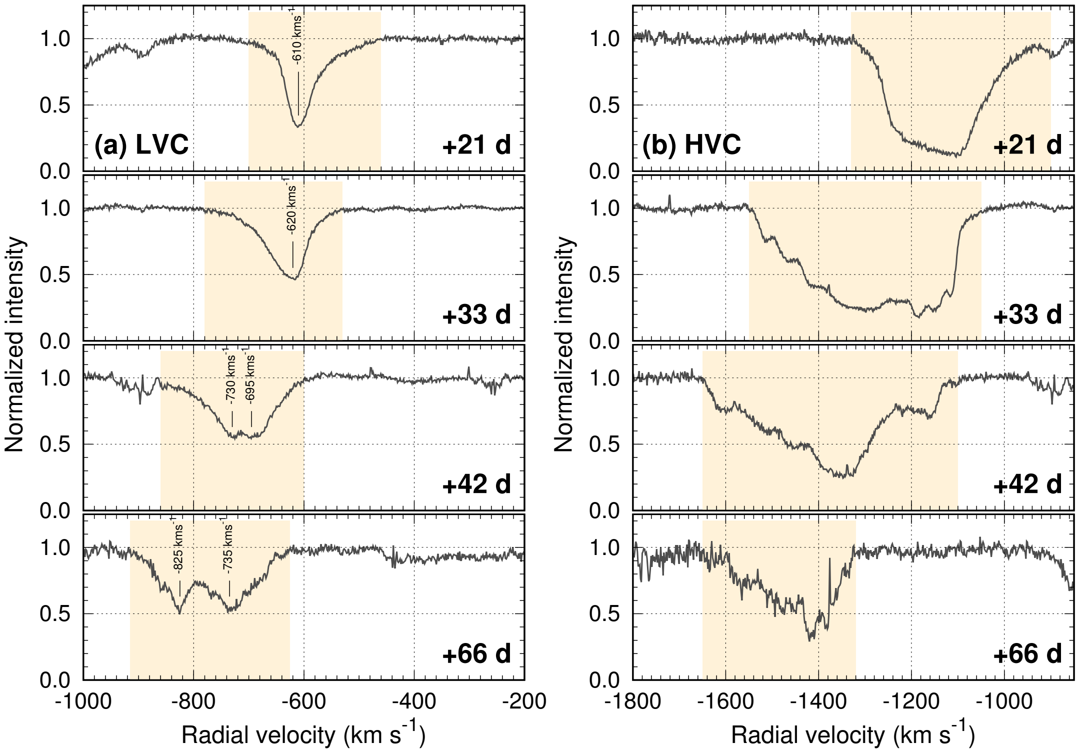

Figure 5: Temporal developments of (a) the LVC and (b) the HVC at Fe II 5018 Å from $t = 21$ d to 66 d. Shaded region (in orange) denote the approximate widths of the velocity range for each absorption feature.

absorption lines were recognized in UV spectra [31]) as pointed out by Williams & Mason (2010). A wide range of ionization degrees could be achieved in nova envelope (without compression by the shock) at different distances from the central nova [16].

3.3 Emission Profiles of the Nebular Phase Spectra

Basically the nebular phase is observationally defined as the period when the [O III] emission lines are stronger than the Hβ emission, indicating the nova ejecta is optically thin. In the case of V2659 Cyg, at $t = 164$ d, the nebular lines such as [O III] lines of the nova had already been stronger than the Hβ. Here we present the high-resolution spectra of the nova on $t = 164$ and 170 d.

The spatial distribution of the nova ejecta of V2659 Cyg during the nebular phase can be inferred from the emission-line profiles. Figure 6 and 7 show the emission-line spectra of [O I] at 6300 Å [O III] at 5007 Å ($t = 164$ d), and He I at 10830 Å ($t = 170$ d). Note that the telluric absorption lines were not corrected in Figure 6 (for [O I] and [O III]), but almost corrected in Figure 7 (for He I). The peaks at -450 kms^{-1} and $+170$ kms^{-1} are clear in these emission-line profiles. Here we concentrate on the emission-line profile of He I because the telluric absorption lines are well corrected and the continuum fitting is easier due to less contamination by other emission lines for the He I emission. The observed emission-line profile of He I is double-horned and it can be decomposed by two velocity components (with FWHMs of ~ 700 and $\sim 1700\,\mathrm{kms}^{-1}$) along with a double-peaked profile as shown in Figure 7. The expansion velocities estimated from these FWHMs are in good agreement with the terminal velocities of the fastest edge in LVCs ($\sim -900\,\mathrm{km\,s}^{-1}$) and in HVCs ($\sim -1600\,\mathrm{km\,s}^{-1}$) at $t = 66$ d, respectively (as mentioned in the previous section, see Figure 5). These results indicate the existence of two distinct velocity systems for the nova ejecta.

Mason et al. in 2018 [10] calculated the emission-line profiles of the nova during the nebular phase for ejecta distributions with various opening angles as observed from various lines-of-sight with respect to the orbital plane of the central binary system of the nova. Based on a comparison with their results, the ejecta distribution of V2659 Cyg might have a nonspherical biconical structure. Further, the emission-line profiles of [O I], [O III] and He I display complicated velocity structures (especially multiple velocity peaks for the narrower component) and suggest of a clumpy, multiple ring structure of the nova ejecta.

As mentioned in Section 3.2, a complicated multi-peak structure for the HVC was seen during the early decline phase. However, these systems were not seen during the nebular phase. This difference is probably explained by the difference in the contributing regions of the ejecta for absorption and emission. The absorption seen during the early decline phase was caused by the gas along the line-of-sight only (almost moving toward the observer) against the background light source. On the other hand, the emission seen during the nebular phase was produced from the gas of entire ejecta (not limited for the line-of-sight). Therefore, only smaller number of clumps contributed to the absorption during the early decline phase (these clumps could be distinguished in the velocity space, as multiple absorption peaks) while all clumps contributed to the emission during the nebular phase (those clumps could not be separated). This hypothesis should be reexamined for future observations of different novae.

In summary, our observational facts strongly indicate that two distinct velocity components (the LVC and the HVC) of the nova envelope of V2659 Cyg existed until its nebular phase, at least. The origin of those ejecta might be a multiple eruption of materials from the nova, with different velocities.

4. Conclusions

We report the high-resolution spectra of the nova V2659 Cyg from the early decline phase to the nebular phase and discuss the velocity structure of the nova envelope. During its early decline phase, the nova displayed absorption-line profiles corresponding to two-distinct velocity components (the LVC and the HVC) along with sub-peaks indicative of a clumpy nova envelope structure. The velocities for the absorption components changed during our observations. In general, the apparent outward motion of the absorptions, i.e., their acceleration, was recognized. However, the fastest velocities of the LVC and HVC components appear to terminate at $\sim 900\,\mathrm{km\,s}^{-1}$ and $\sim 1600\,\mathrm{km\,s}^{-1}$ in the later phase. The emission-line profiles seen during the nebular phase of

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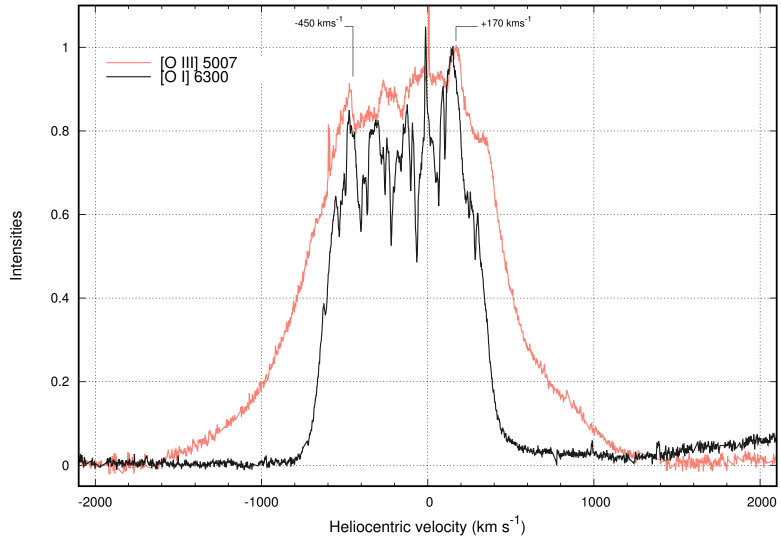

Figure 6: Forbidden emission lines, [O I] 6300 Å and [O III] 5007 Å on $t = 164$ d obtained by the BOES. Telliric absorption lines are not corrected for those profiles.

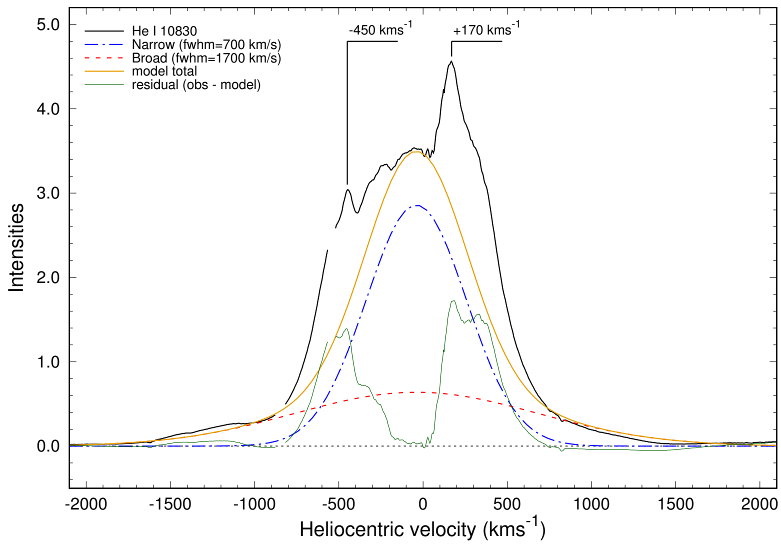

Figure 7: Line profile of He I 10830 Å on $t = 170$ d. The dashed blue and red lines are narrow ($FWHM$ of 700 kms^{-1}) and broad ($FWHM$ of 1700 kms^{-1}) components de-composed by Gaussian fittings, respectively.

V2659 Cyg also indicate the existence of two velocity components with FWHMs of $\sim 700\,\mathrm{km\,s^{-1}}$ and $\sim 1700\,\mathrm{km\,s^{-1}}$, consistent with the terminal velocities found during the early-decline phase as described above. A clumpy structure is also implied for the envelope materials in the LVC system (but not obviously for the HVC system).

We conclude that the nova envelope of V2659 Cyg has two-distinct velocity components and is thought to be clumpy. The velocity structure might be stationary, and the apparent motion of the absorption lines during the early decline phase may be explained by the changing recombination/ionization fronts in the nova envelope as the envelope thinned out.

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