A Light-curve Analysis of Gamma-Ray Nova V959 Mon: Distance and White Dwarf Mass

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Abstract

V959 Mon is a nova detected in gamma-rays. It was discovered optically about 50 days after the gamma-ray detection owing to its proximity to the Sun. The nova’s speed class is unknown because of the lack of the earlier half of its optical light curve and a short supersoft X-ray phase due to eclipse by the disk rim. Using the universal decline law and time-stretching method, we analyzed the data on V959 Mon and obtained nova parameters. We estimated the distance modulus in the V band to be \((m - M)_V = 13.15 \pm 0.3\) for the reddening of \(E(B - V) = 0.38 \pm 0.01\) by directly comparing it with novae of a similar type—LV Vul, V1668 Cyg, IV Cep, and V1065 Cen. The distance to V959 Mon is 2.5 \(\pm\) 0.5 kpc. If we assume that the early phase of the light curve of V959 Mon is the same as that of time-stretched light curves of LV Vul, our model fitting of the light curve suggests that the white dwarf (WD) mass is 0.9–1.15 \(M_\odot\), which is consistent with a neon nova identification. At the time of gamma-ray detection the photosphere of the nova envelope extends to 5–8 \(R_\odot\) (about two or three times the binary separation) and the wind mass-loss rate is \(3 \times 10^{-5} M_\odot \text{yr}^{-1}\). The period of hard X-ray emission is consistent with the time of appearance of the companion star from the nova envelope. The short supersoft X-ray turnoff time is consistent with the epoch when the WD photosphere shrank to behind the rising disk rim, which occurred 500 days before nuclear burning turned off.

Key words: novae, cataclysmic variables – stars: individual (IV Cep, LV Vul, V959 Mon, V1065 Cen) – X-rays: stars

1. Introduction

Recently, GeV gamma-rays have been detected in several classical and symbiotic novae with the Fermi/Large Area Telescope (LAT) (e.g., Ackermann et al. 2014). These gamma-ray novae show wide varieties in their speed class (fast and slow), nova type (CO and ONe), and companion type (a close binary with a red dwarf companion and a wide binary with a red giant companion). Hard X-ray emission was also detected in some gamma-ray novae. Gamma-rays could be produced in shock interactions between ejecta and companion or circumbinary matter, or in collisions between ejecta shells (internal shocks). The exact origin of gamma-rays and their relation to hard X-ray emission in the individual objects are not known.

Although gamma-rays were detected in various types of novae, the gamma-ray properties of each appear similar. Therefore, it has been argued that there is a common mechanism of gamma-ray emission independent of nova type, and thus all novae are potential gamma-ray emitters (e.g., Ackermann et al. 2014). If this is the case, the gamma-ray detection is due to close proximity and undetected novae should be more distant. Ackermann et al. (2014) concluded that all the Fermi/LAT-detected novae have estimated distances of \(\leq\) 4 to 5 kpc, i.e., V407 Cyg (2.7 kpc), V1324 Sco (4.5 kpc), V959 Mon (3.6 kpc), and V339 Del (4.2 kpc).

The distances of novae, however, are always debated. For example, Finzell et al. (2015) derived the distance of V1324 Sco to be \(d > 6.5\) kpc based on their estimated reddening of \(E(B - V) = 1.16 \pm 0.12\). This is much larger than the above distance, \(d = 4.5\) kpc, that Ackermann et al. derived from various maximum magnitude versus rate of decline (MMRD) relations. As is well known, the MMRD relations are statistical relations and not a good indicator for individual novae (see, e.g., Downes & Duerbeck 2000; Kasliwal et al. 2011; Shara et al. 2017). For V407 Cyg, Hachisu & Kato (2018) recently redetermined the distance to be \(d = 3.9\) kpc from the revised period–luminosity relation of Mira-like variables (Ita & Matsunaga 2011). This value is larger than \(d = 2.7\) kpc that Ackermann et al. adopted. To elucidate the nature of novae detected in gamma-rays, we need an accurate distance for each nova. One of the aims of this work is to obtain the distance of V959 Mon.

The classical nova V959 Mon was discovered optically by S. Fujikawa on UT 2012 August 9.8 (JD 2456149.3) at mag 9.4 (Fujikawa et al. 2012). Due to solar conjunction, the nova had already entered the nebular decline phase when it was discovered. The optical peak was possibly substantially (more than 50 days) before the discovery (e.g., Munari et al. 2013). Greimel et al. (2012) identified the progenitor of V959 Mon using images from the INT Photometric H-Alpha Survey (IPHAS) at \(r \sim 17.9\) mag and \(i \sim 17.2\) mag.

Fermi J0639+0548 is a gamma-ray source detected on UT 2012 June 22 (JD 2456100.5) (Ackermann et al. 2014), 48 days before the optical discovery of V959 Mon. Cheung et al. (2012) reported that the position of V959 Mon is consistent with that of the gamma-ray object Fermi J0639+0548 and that the spectrum of V959 Mon shows a striking resemblance to that of the fast ONe nova V382 Vel 1999 well after the optical peak. Munari (2013) suggested that V959 Mon is a neon nova because of very strong lines of [Ne III], [Ne IV], and [Ne V] in the spectrum obtained on UT 2013 January 5.938 (JD 2456298.438). Thus, V959 Mon was identified as a gamma-ray nova and also as a neon nova.
V959 Mon entered the supersoft X-ray source (SSS) phase on UT 2012 November 18 (JD 2456249.5) (Nelson et al. 2012). The UV and X-ray emission observed with Swift showed modulation that indicates an orbital period of 7.1 hr (Osborne et al. 2013). Osborne et al. (2013) argued that the orbital variation of the X-ray light curve is caused by a partial eclipse of extended emission by an accretion disk rim that is raised at the point of impact of the stream from the secondary star (see also Page et al. 2013).

Munari et al. (2013) presented the detailed photometric and spectroscopic data of V959 Mon and showed orbital light curves with the 7.1 hr period. Ribeiro et al. (2013) presented a model of the morphology of the ejected shell to reproduce line profile spectra of the [O III] λλ4959, 5007 lines and derived a probable orbital inclination angle of $i = 82^\circ \pm 6^\circ$.

Figure 1(a) summarizes the visual, V, and X-ray light curves of V959 Mon, and Figure 1(b) shows $(B - V)_0$, which are dereddened with $E(B - V) = 0.38$ after Munari et al. (2013). The lack of an optical peak and subsequent light-curve data makes this nova difficult to categorize into a particular speed class. Moreover, the supersoft X-ray phase is interrupted midway, possibly due to occultation by the disk rim, which prevents the white dwarf (WD) mass from being estimated from the SSS duration (e.g., Hachisu & Kato 2010).

In the present work, we analyze the data in Figure 1, in the context of our nova light-curve analysis for more than 60 objects (e.g., Hachisu & Kato 2006, 2010, 2014, 2015, 2016a, 2016b, 2018), and derive outburst parameters of V959 Mon as much as possible. Our paper is organized as follows. First we describe the time-stretching method of nova light curves, and derive the distance modulus in the V band, $(m - M)_V$, toward V959 Mon in Section 2. In Section 3, we show similarity in the color–magnitude diagram between V959 Mon and LV Vul (as well as IV Cep and V1065 Cen) and confirm that our obtained values of $(m - M)_V$ and $E(B - V)$ are reasonable. Section 4 describes our model light curves that fit with the V and X-ray data of V959 Mon. We derive the WD mass, $M_{WD}$, and present models for hard X-rays and a short duration of the SSS phase. We discuss the distance modulus $(m - M)_V$, extinction $E(B - V)$, and distance $d$ in Section 5. Conclusions follow in Section 6.

2. Time-stretching Method of Nova Light Curves

Novae show rich variety in their optical/IR light curves, but there is a strong similarity in the main decline behavior. Kato & Hachisu (1994) theoretically explained the main trend of nova light curves, i.e., a more massive WD shows a faster evolution in the decay phase of the light curve based on the optically thick wind theory. Hachisu & Kato (2006) calculated free–free emission light curves for various WD masses and chemical compositions, and found that these theoretical light curves overlap with each other as a result of time-stretching. They call this property the universal decline law. After that, these authors have analyzed a number of nova light curves and shown that observed light curves basically decay along with the light curves of the free–free model (Hachisu & Kato 2010, 2015, 2016a, 2018). Using this universal decline law and time-stretching method, they have determined the WD masses for a number of novae (e.g., Hachisu & Kato 2007, 2009, 2014, 2015, 2016a, 2018; Kato et al. 2009, 2015).
Figure 2. Optical light curves and color evolutions of V959 Mon (filled red circles) on a logarithmic timescale as well as LV Vul and V1668 Cyg. The timescales of LV Vul and V1668 Cyg are stretched by a factor of 1.38. The data on V959 Mon are the same as those in Figure 1. The LV Vul and V1668 Cyg data are taken from Figures 4 and 1 of Hachisu & Kato (2016b), respectively. In panel (a), we plot the model V (blackbody plus free–free) and X-ray (blackbody) light curves of a 1.1 $M_e$ WD (red lines) with the envelope chemical composition of Ne nova 3 (Hachisu & Kato 2016a), taking $(m - M_V) = 13.15$ for V959 Mon. Another set of model light curves of $V$, UV 1455 Å, and X-rays (black lines) are those of a 0.98 $M_e$ WD with the chemical composition of CO nova 3 for V1668 Cyg (Hachisu & Kato 2016a). The detection of gamma-rays on UT 2012 June 22 is indicated by the black arrow, which corresponds to day 34 in this figure. We depict the hard (0.8–10 keV: open cyan diamonds) and soft (0.3–0.8 keV: open magenta diamonds) X-ray fluxes separately, both of which are taken from Page et al. (2013). The open circles at the right edge of each V model light curve correspond to the epoch when optically thick winds stop. We also add the decay trend of free–free emission along the line $E \propto \tau^{-3}$ after optically thick winds stop. In panel (b), we dereddened the colors with $E(B-V) = 0.38$. The horizontal solid red lines, (b) $(B-V)_0 = -0.03$ and (c) $(U-B)_0 = -0.97$, indicate the colors of optically thick free–free emission. See the text for detail.

Figure 2(a) shows the V, soft X-ray (0.3–0.8 keV), and hard X-ray (0.8–10 keV) light curves of V959 Mon on a logarithmic timescale. We added the light curves of two classical novae, LV Vul 1968#1 and V1668 Cyg 1978, that have the most similar decline among the 60 samples that we have ever analyzed. (We show two similar novae, IV Cep and V1065 Cen, later in Figures 3 and 4, respectively.)

The light curve data of V959 Mon show good agreement with the later phase of LV Vul and V1668 Cyg. Also the evolution of $(B-V)_0$ is very similar to the upper branch of LV Vul. These similarities strongly suggest that V959 Mon follows the universal decline law, i.e., similar evolution to LV Vul and V1668 Cyg even in the early phase.

In the present paper, we consider that V959 Mon follows the universal decline law from the early phase, where we have no data, until the later nebular phase. We made this reproduction of the early light curve of V959 Mon in Figure 2. The V light curve decays along $\tau^{-3}$ after 250–300 days from the outburst. This strongly indicates that optically thick winds stopped on day 250–300 (see, e.g., Figure 25 of Hachisu & Kato 2016a). The slope of $\tau^{-3}$ usually begins after the nebular phase starts in many novae. Therefore, this nova shows the normal decline of novae.

Although their overall decline features are very similar to V959 Mon, LV Vul and V1668 Cyg evolve faster than V959 Mon by a factor of 1.38. Therefore, these two nova
light curves are time-stretched by \( f_s = 1.38 \), i.e., they are shifted toward the right by \( \Delta \log t = \log f_s = \log 1.38 = 0.14 \) in logarithmic time (see Section 2.1 for detail). In Figure 2, we assumed that the outburst day is \( \tau_{\text{OB}} = \text{JD 2456066.5 (UT 2012 May 19.0) as explained in Section 2.2. Thus, the optical light curve started from day 83.

2.1. Timescaling Factor

Now we show how to determine the timescaling (or time-stretching) factor of \( f_s = 1.38 \). We try to overlap these three novae as much as possible, by shifting the data in the vertical and horizontal directions. For the horizontal shift, we change \( \Delta \log t \) by steps of 0.01 or 0.02 and check whether the light/color curves overlap with each other. We select the best one by eye. In Figures 2(a)–(c), we dereddened the colors of IV Cep with \( E(B-V) = 0.65 \). See the text for detail.

Figure 3. Same as Figure 2, but we compare with IV Cep 1971 instead of V1668 Cyg. The timescale of IV Cep is the same as that of LV Vul, \( f_s = 1.0 \) against LV Vul. The data on IV Cep are the same as those in Figure 21 of Hachisu & Kato (2016b); the original data are taken from MacConnell & Thomas (1972) and Kohoutek & Klawitter (1973). In panels (b) and (c), we dereddened the colors of IV Cep with \( E(B-V) = 0.65 \). See the text for detail.
nebular phase started, and we fit the color curve of V959 Mon with the bluer (upper) branch of LV Vul. We explain the two separate branches later in Section 3.

We have determined the time-shift $\Delta \log t = \log f_s$ of LV Vul (open blue squares) against V959 Mon by assuming that the 10 data points of LV Vul (upper branch) overlap those of V959 Mon in the $(B-V)_0$ color curves in Figure 2(b). We shift the color curve of LV Vul in steps of $\Delta \log t = 0.01$ or 0.02 and find the best match by eye from the 10 data points between $\log t = 2.0$ and 2.5. Its allowance is about $\log f_s = 0.14 \pm 0.05$ by eye. We also estimated the error by a least-squares fit and obtained $0.14 \pm 0.06$ in the time-shift.

The vertical fit in the $V$ magnitude is also determined by eye. In the case of LV Vul and V959 Mon, we searched for a best fit by changing the vertical shift in steps of 0.1 or 0.2 mag between $\log t = 1.95$ and 2.8 in Figure 2(a). Its allowance is about 0.1 mag by eye. We checked the error by a least-squares method (for steps of 0.1 mag vertical shift) and obtained $\Delta V = 1.6 \pm 0.2$. In this case, the difference between LV Vul and V959 Mon is relatively large around the break ($\log t = 2.3-2.4$) in the $V$ light curve. Thus, the errors in determination are about $\Delta \log t = \pm 0.05$ and $\Delta V = \pm 0.1$ or $\pm 0.2$ mag unless $V$ and color data are largely scattered. These values are consistent with the fitting by eye. The least-squares

Figure 4. Same as Figure 2, but we compare with V1065 Cen 2007 instead of V1668 Cyg. The timescale of V1065 Cen is the same as that of LV Vul ($f_s = 1.0$ against LV Vul). The data of V1065 Cen are the same as those in Figure 56 of Hachisu & Kato (2016b); the original data are taken from the archive of AAVSO and SMARTS (Walter et al. 2012). In panel (b), we dereddened the colors of V1065 Cen with $E(B-V) = 0.45$. See the text for detail.
2.2. Outburst Day

We also explain how to determine the outburst day ($t_{OB} = JD 2456066.5$). The outburst day should be before the gamma-ray detection day ($t_{OB} < JD 2456100.5$). We time-stretch the light/color curves of LV Vul and V1668 Cyg with $f_e = 1.38$ on a linear timescale. Then, we overlap the V light and $(B - V)_0$ color curves of LV Vul and V1668 Cyg with those of V959 Mon. We assumed the outburst day of V959 Mon to be the same as that of LV Vul, which is time-stretched with $f_e = 1.38$.

It should be noted that the value of $t_{OB}$ is slightly dependent on the value of $\log f_e$ and vice versa. Starting from a trial value of $t_{OB} < JD 2456100.5$, we repeated twice the procedure of determining $\log f_e$ and confirmed the convergence of $t_{OB}$ (and $\log f_e$).

2.3. Time-stretched Light Curves

Figure 2(a) also shows theoretical free–free emission V and blackbody X-ray light curves of a 1.1 $M_\odot$ WD with the envelope chemical composition of Ne nova 3 for V959 Mon (red lines), which is explained in detail later in Section 4. We also add another model light curve of a 0.98 $M_\odot$ WD with the envelope chemical composition of CO nova 3 for V1668 Cyg (black lines) and LV Vul, which is time-stretched by $\Delta \log t = \log f_e = \log 1.38 = 0.14$.

The magnitudes of the two template novae, LV Vul and V1668 Cyg, decay along with these theoretical lines until day 90, when the two novae entered the nebular phase. In the nebular phase, strong emission lines contribute to the B and V bands, which are not included in our model light curves, so the observed V magnitude deviates much from, and decays more slowly than, the model V light curve.

After the optically thick winds stop, the observed V magnitude decays like the straight solid blue line of $F_v \propto t^{-3}$. That shows the trend of homologously expanding ejecta, i.e., the ejecta mass is constant (see, e.g., Woodward et al. 1997; Hachisu & Kato 2006). In Figure 2(a), the V light curve of V959 Mon decays along $t^{-3}$ after day $\sim$250–300. This strongly indicates that optically thick winds stopped on day $\sim$250–300 (see, e.g., Figure 41 of Hachisu & Kato 2016a for such an example). We suppose that optically thick winds stopped on day $\sim$250–300 for V959 Mon.

We also plot two more novae that show a similar decay timescale and shape to V959 Mon, that is, IV Cep 1971 and V1065 Cen 2007, in Figures 3 and 4, respectively. The timescaling factor of these two novae is the same as that of LV Vul ($f_e = 1$ against LV Vul). V1065 Cen shows a dip in the V light curve as shown in Figure 4. This is because a dust shell formed (Helton et al. 2010). Despite this, the V light curve shows a similar decay shape to that of LV Vul in the nebular phase. IV Cep and V1065 Cen follow the bluer branch of the $(B - V)_0$ color curve of LV Vul as shown in Figures 3(b) and 4(b), respectively. These figures mean that we cannot know in detail how the V959 Mon light curve behaves in the early phase from just the information from the nebular phase and later. In other words, we do not know whether V959 Mon showed a smooth decline like LV Vul, a dust dip (V1668 Cyg and V1065 Cen), or a wavy structure (IV Cep). However, we may safely assume that the main trend of the light curve is well reproduced by the model light curve.

2.4. Time-stretching Factor and Distance Modulus

Here, we obtain the distance modulus of this nova based on the time-stretching method of nova light curves. Hachisu & Kato (2010, 2015, 2016a, 2018) showed that, if the V light curves of the two nova, where one is called the template and the other is called the target, $(m[t])_V^{\text{template}}$ and $(m[t])_V^{\text{target}}$, overlap each other after a time-stretch by a factor $f_e$ in the horizontal direction and a vertical shift $\Delta V$, i.e.,

$$(m[t])_V^{\text{target}} = ((m[t \times f_e])_V + \Delta V)^{\text{template}}, \quad (1)$$

then their distance moduli in the V band satisfy

$$(m - M)_V^{\text{target}} = (m - M)_V + \Delta V)^{\text{template}} - 2.5 \log f_e. \quad (2)$$

Here, $(m - M)_V^{\text{target}}$ and $(m - M)_V^{\text{template}}$ are the distance moduli in the V band of the target and template novae, respectively. This is also written as

$$(M_V^{\text{target}}(t)]_V = (M_V(t)]_V^{\text{template}} - 2.5 \log f_e$$

$$= (M_V(t \times f_e)]_V^{\text{template}}. \quad (3)$$

This equation means that a target nova with a slower rate of decline ($f_e > 1$) than the template nova is fainter by $2.5 \times \log f_e$, i.e., $M_V(t)]_V^{\text{target}} > M_V(t)]_V^{\text{template}}$.

From Equation (2), we have the relation

$$(m - M)_V^{V959\text{ Mon}} = (m - M + \Delta V)_V^{LV\text{ Vul}} - 2.5 \log 1.38 = 11.9 + 0.2 + 1.6 + 0.2 - 0.35 = 13.15 \pm 0.3$$

$$= (m - M + \Delta V)_V^{V959\text{ Mon}} - 2.5 \log 1.38 = 14.6 \pm 0.2 - 1.1 + 0.2 - 0.35 = 13.15 \pm 0.3. \quad (4)$$

Here, we take $f_e = 1.38$ and $\Delta V = +1.6 \pm 0.2$ for LV Vul and $f_e = 1.38$ and $\Delta V = -1.1 \pm 0.2$ for V1668 Cyg as depicted in the figures “LV Vul V+1.6, 1.38 t” and “V1668 Cyg V-1.1, 1.38 t” and adopt $(m - M)_V^{LV\text{ Vul}} = 11.9 + 0.2$ and $(m - M)_V^{V1668\text{ Cyg}} = 14.6 \pm 0.2$ from Hachisu & Kato (2016b). Thus, we obtain $(m - M)_V = 13.15 \pm 0.3$ for V959 Mon. From Equations (3) and (4), we have the relation

$$(m - M)_V^{V959\text{ Mon}} = (m_V - (M_V - 2.5 \log f_e^{\text{template}}))_{V959\text{ Mon}}$$

$$= (m_V - (M_V + \Delta V))_{LV\text{ Vul}}^{\text{template}}$$

$$= 11.9 + 0.2 + 1.6 + 0.2 = 13.15 \pm 0.3. \quad (5)$$

We adopt the reddening of $E(B - V) = 0.38$ as Munari et al.'s (2013) value of $E(B - V) = 0.38 \pm 0.01$ rather than Shore et al.'s (2013) value of $E(B - V) = 0.85 \pm 0.05$ (see discussion in Section 5 for detail). We also prefer $E(B - V) = 0.38$ because it gives a good match of the color curve to that of LV Vul in Figure 2(b). The distance is calculated from

$$(m - M)_V = 3.1E(B - V) + 5 \log(d/10 \text{ pc}), \quad (6)$$

where we adopt $R_V = AV/E(B - V) = 3.1$ (e.g., Rieke & Lebofsky 1985). We obtain $d = 2.5 \pm 0.5 \text{ kpc}$, together with $(m - M)_V = 13.15 \pm 0.3$ and $E(B - V) = 0.38 \pm 0.1$. Table 1 summarizes these results.
Various Properties of V959 Mon and Selected Novae

| Object        | Outburst Year | log $f_*$ | $E(B-V)$ | $(m-M)_V$ | Distance (kpc) | $z_0$ (pc) | $M_{WD}$ ($M_\odot$) |
|---------------|---------------|-----------|---------|-----------|----------------|-----------|--------------------|
| V1065 Cen     | 2007          | 0.0       | 0.45    | 15.0      | 5.3            | 330       | 0.98a              |
| IV Cep        | 1971          | 0.0       | 0.65    | 14.5      | 3.1            | 90        | 0.98a              |
| V1668 Cyg$^d$ | 1978          | 0.0       | 0.30    | 14.6      | 5.4            | 635       | 0.98a              |
| V1974 Cyg$^d$ | 1992          | 0.03      | 0.30    | 12.2      | 1.8            | 245       | 0.98a              |
| V959 Mon      | 2012          | 0.14      | 0.38    | 13.15     | 2.5            | 3         | 0.95a              |
| V959 Mon      | 2012          | 0.14      | 0.38    | 13.15     | 2.5            | 3         | 1.05c              |
| LV Vul        | 1968#1        | 0.0       | 0.60    | 11.9      | 1.0            | 15        | 0.98a              |

Notes.

$^a$ $f_*$ is the timescaling factor against LV Vul.
$^b$ $z_0$ is the distance from the Galactic plane.
$^c$ $M_{WD}$ is obtained for the envelope chemical composition of CO nova 3, i.e., $X = 0.45$, $Y = 0.18$, $Z = 0.02$, $X_{CNO} = 0.35$, $X_{Ne} = 0.0$ (Hachisu & Kato 2016a).
$^d$ Various parameters are taken from Hachisu & Kato (2016a).
$^e$ $M_{WD}$ is obtained for the envelope chemical composition of Ne nova 2, i.e., $X = 0.55$, $Y = 0.30$, $Z = 0.02$, $X_{CNO} = 0.10$, $X_{Ne} = 0.03$ (Hachisu & Kato 2010).
$^f$ $M_{WD}$ is obtained for the envelope chemical composition of Ne nova 3, i.e., $X = 0.65$, $Y = 0.27$, $Z = 0.02$, $X_{CNO} = 0.03$, $X_{Ne} = 0.03$ (Hachisu & Kato 2016a).

Figures 3 and 4 show the light/color curves of IV Cep and V1065 Cen in comparison with LV Vul. The timescales and the shapes of the $(B-V)_b$ color curve of these two novae are almost the same as those of LV Vul and V1668 Cyg. Therefore, we apply Equations (1) and (2) to Figure 3 and obtain the relation

$$(m-M)_{V,IV\ Cep} = (m-M + \Delta V)_{V,LV\ Vul} - 2.5 \log 1.0\nonumber$$

$$= 11.9 \pm 0.2 + [1.6 \pm 0.2 - (-1.0 \pm 0.2)] - 0.0
= 14.5 \pm 0.3.$$  (7)

The value of $(m-M)_{V,IV\ Cep}$ is $14.5 \pm 0.3$ is consistent with the previous estimate of $(m-M)_{V,IV\ Cep}$ of $14.7 \pm 0.2$ in Hachisu & Kato (2016b). The distance is calculated to be $d = 3.1 \pm 0.6$ kpc from Equation (6) together with $E(B-V) = 0.65 \pm 0.5$ (Hachisu & Kato 2016b).

In the same way, we obtain

$$(m-M)_{V,V1065\ Cen} = (m-M + \Delta V)_{V,LV\ Vul} - 2.5 \log 1.0\nonumber$$

$$= 11.9 \pm 0.2 + [1.6 \pm 0.2 - (-1.5 \pm 0.2)] - 0.0
= 15.0 \pm 0.3,$$  (8)

for V1065 Cen. This value of $(m-M)_{V,V1065\ Cen}$ is $15.0 \pm 0.3$ is slightly smaller than, but in reasonable agreement with, the previous value of $(m-M)_{V,V1065\ Cen}$ of $15.3 \pm 0.2$ (Hachisu & Kato 2016b). The distance is calculated to be $d = 5.3 \pm 1.0$ kpc from Equation (6) together with $E(B-V) = 0.45 \pm 0.05$ (Hachisu & Kato 2016b). These results are summarized in Table 1. Then, we have the relation

$$(m-M)_{V,V959\ Mon} = (m-M + \Delta V)_{V,IV\ Cep} - 2.5 \log 1.38\nonumber$$

$$= 14.5 \pm 0.3 - 1.0 \pm 0.2 - 0.35 = 13.15 \pm 0.3$$
$$= (m-M + \Delta V)_{V,V1065\ Cen} - 2.5 \log 1.38\nonumber$$

$$= 15.0 \pm 0.3 - 1.5 \pm 0.2 - 0.35 = 13.15 \pm 0.3,$$  (9)

from Figures 3 and 4.

In our method, there are two sources of ambiguity in $(m-M)_V$: one is the $(m-M)_V$ error of the template nova and the other is the vertical $\Delta V$ fit error. For the vertical fit, we change $\Delta V$ in steps of 0.1 mag and search for the best overlap by eye. This error is typically 0.1 or 0.2 mag unless the $V$ data are scattered. The $(m-M)_V$ errors of templates are dependent on each template (typically 0.2 mag). We checked the fit with a least-squares method and obtained errors of $\Delta V = \pm 0.2$ or $\pm 0.3$ mag. Thus, the errors in the distance modulus $(m-M)_V$ are 0.2 or 0.3 mag unless otherwise specified.

### 3. Color–Magnitude Diagram

Hachisu & Kato (2016b) analyzed 48 novae in the color–magnitude diagram, and showed that a typical nova evolves along the line of $(B-V)_b = -0.03$ in the early phase $(M_V < -4)$ of the outburst. This indicates that the optical flux is dominated by free–free emission because the intrinsic color of optically thick free–free emission is $(B-V)_b = -0.03$ (Hachisu & Kato 2014). The nebular phase begins when the nova becomes as faint as $M_V \sim -4$ (more exactly Equation (5) or (6) of Hachisu & Kato 2016b). Figure 5(a) shows the outburst evolution of V1668 Cyg and LV Vul in the color–magnitude diagram, in which they descend along the line of $(B-V)_b = -0.03$. In the nebular phase, the data of LV Vul split into two branches. This splitting is caused by slightly different responses of the V-band filters (see, e.g., Figure 1 of Munari et al. 2013). Slightly different response functions of different V filters produce large differences in the V magnitudes because of large contributions from strong emission lines of [O III] at the blue edge of the V filter (see discussion in Hachisu & Kato 2006, 2014, 2016b).

In this figure we also plot the V959 Mon data for $E(B-V) = 0.38$ and $(m-M)_V = 13.15$. The data follow the bluer branch of the LV Vul track, but are slightly fainter. In the spectra of V959 Mon obtained by Munari et al. (2012) on UT 2012 August 20, 14, the [O III] $\lambda$5007 line slightly exceeds that of H$\beta$. Therefore, we identify the start of the nebular phase at this day, i.e., $(B-V)_b = 0.269 - 0.40 = -0.13$ and $M_V = 10.022 - 13.15 = -3.128$, which is denoted by the large open red square in Figure 5(a).

The evolution of V959 Mon in Figure 5(a) does not exactly follow that of LV Vul, whereas the color evolutions of these two agree well in Figure 2(b). This is because we do not include the time-stretching effect in Figure 5(a). Here, we create another color–magnitude diagram, Figure 5(b), taking
The solid orange and green lines indicate the tracks of LV optically thick free emission respectively. The vertical solid red line indicates LV Figure 2. The data of V959 Mon into account the time-stretching effect. Remember that, in The Astrophysical Journal, V absolute magnitude, \( M_\nu \), i.e., we shift the magnitude upward by \( 2.5 \log 1.38 = 0.35 \) mag. The text \( "(m - M')_\nu = 13.5(-0.35)" \) in the figure means that \( (m - M')_\nu = 13.5 \) and \( (m - M)_\nu = 13.5 - 0.35 = 13.15 \).

Next, we obtain the intrinsic color \( (B - V)_0 \) with time-stretching effect. The stretched absolute \( B \) and \( V \) magnitudes of V959 Mon can be written against those of LV Vul as

\[
(M'_B[t])_{V959~Mon} = (M_B[t] - 2.5 \log f_s)_{V959~Mon}
\]

(10)

\[
(M'_V[t])_{V959~Mon} = (M_V[t] - 2.5 \log f_s)_{V959~Mon}
\]

(11)

Thus, we obtain

\[
(B - V)_{0,V959~Mon} = (M_B[t] - M_V[t])_{V959~Mon} = (M'_B[t] - M'_V[t])_{V959~Mon} = (M_B[t] \times f_s)_{LV~Vul} \]

(12)

This means that the intrinsic color is unchanged after the time-stretching process.

Figure 5(b) shows that the resultant track of V959 Mon overlaps well with that of LV Vul. The onset of the nebular phase of LV Vul is close to that of V959 Mon in the stretched color–magnitude diagram (see Figure 6 of Hachisu & Kato 2016b). Conversely, this agreement supports our values of \( E(B - V) = 0.38, (m - M')_\nu = 13.5, f_s = 1.38 \). Thus, we confirm that the distance to V959 Mon is \( d = 2.5 \pm 0.5 \) kpc from Equation (6) together with \( E(B - V) = 0.38 \pm 0.1 \) and \( (m - M)_\nu = 13.15 \pm 0.3 \).

We plot the color–magnitude diagrams of IV Cep and V1065 Cen in Figures 6(a) and (b), respectively. The tracks of these two novae do not move after time-stretching because the timescaling factor is \( f_s = 1.0 \) against that of LV Vul. These novae evolve along the bluer branch of LV Vul. In IV Cep, strong emission lines of [O III] appeared between UT 1971 September 12 and 22 (Rosino 1975), which is an indication of the nebular phase. We identify the start of the nebular phase at \( (B - V)_0 = -0.37 \) and \( M_V = 3.23 \), denoted by the large open red square in Figure 6(a). This starting point is close to that of LV Vul. In V1065 Cen, we specify the starting point of dust blackout (Helton et al. 2010) at \( (B - V)_0 = -0.06 \) and \( M_V = -4.06 \), denoted by the black arrow in Figure 6(b).

Helton et al. (2010) pointed out that the nova entered the early nebular phase at \( m_V \approx 12 \), about 70 days after maximum. We denote this phase by the large open red square, at \( (B - V)_0 = -0.35 \) and \( M_V = -3.42 \). This point is close to that of LV Vul.

We list our results in Table 1. These results are consistent with each other and confirm that our time-stretching method works among these nova systems.

4. Model Light Curve Fitting

4.1. WD Masses of Neon Novae

Neon novae are a subclass of classical novae that show neon emission lines stronger than the permitted lines in the nebular...
and has a thin helium-rich layer above a carbon–oxygen (CO)-
rich mantle, e.g., a 0.035 $M_\odot$ CO mantle for a 1.09 $M_\odot$ ONe core (Gil-Pons & García-Berro 2001). Such a WD may undergo a number of nova explosions before the thin helium-
rich layer is blown off. Subsequently, the WD further undergoes a number of nova explosions before the CO mantle on the ONe core is blown off. If the mass accretion rate is
$\sim 10^{-9} M_\odot$ yr$^{-1}$, the ignition mass is $\sim 10^{-3} M_\odot$, and the same amount of WD material is dredged up in every nova outburst, we can expect that 3000–4000 outbursts (in a total time of at least 30–40 Myr) must occur before the WD is deprived of its 0.035 $M_\odot$ CO-rich mantle and significant neon is detected in the ejecta. This could be a lower estimate because a CO-rich mantle is more massive for the lower mass limit of the ONe core (as massive as $\sim 0.1 M_\odot$, Gil-Pons et al. 2003). Therefore, the minimum masses of naked ONe cores could be slightly smaller than $\sim 1.0 M_\odot$.

4.2. Chemical Composition of V959 Mon Ejecta

The largest ambiguity in the WD mass determination is in the choice of the chemical composition. In many novae, the chemical composition of ejecta is not well determined. In our previous work (e.g., Hachisu & Kato 2016a), we chose several sets of chemical compositions as templates (Ne nova 1, Ne nova 2, and Ne nova 3, which are basically calculated from the degree of mixing between the hydrogen-rich envelope and WD core material).

Shore et al. (2013) obtained the chemical abundance of V959 Mon from their optical spectra. We converted their number-based abundance values to our mass-weighted values, that is, $X = 0.62$, $Y = 0.25$, $X_C = 0.002$, $X_S = 0.026$, $X_O = 0.045$, $X_{Ne} = 0.059$, and $X_{Fe} = 0.001$ by weight. Tarasova (2014) also estimated the chemical composition of V959 Mon from her optical spectra, which are converted to $X = 0.51$, $Y = 0.29$, $X_N = 0.003$, $X_O = 0.006$, $X_{Ne} = 0.10$, and $X_{Fe} = 0.001$ by weight, assuming $X_C = 0.0$ because she did not obtain the carbon abundance. In the present work, we adopt Ne nova 3 as a standard case because it is close to the abundance obtained by Shore et al. (2013), and Ne nova 2 and CO nova 3 for comparison, to examine how the WD mass depends on the chemical composition.

4.3. Multiwavelength Light Curves of V959 Mon

Figure 2(a) shows the V, visual, and X-ray data of V959 Mon. The X-ray data observed with Swift/XRT are divided into two bands, i.e., 0.3–0.8 keV (supersoft) and 0.8–10.0 keV (hard) (Page et al. 2013). In general, the main emitting wavelength region during a nova outburst shifts from optical, to UV, and to supersoft X-rays, because the WD photosphere moves inward and the effective temperature rises with time. This figure also shows the UV 1455 Å flux of V1668 Cyg observed with IUE. We have no UV 1455 Å observation for V959 Mon, but its UV phase should be the same. The supersoft X-ray flux of V959 Mon increases after the UV-
dominant phase. This is consistent with the general picture of nova evolution whereby the main emitting wavelength region shifts to a shorter one with time. Thus, we naturally consider that this supersoft X-ray emission is from the WD surface.

Hachisu & Kato (2010) calculated a number of multi-
wavelength light curves with various WD masses and chemical compositions. The V-band fluxes are dominated by free–free

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**Figure 6.** Color–magnitude diagrams of (a) IV Cep and (b) V1065 Cen. The ordinate is the absolute $V$ magnitude, $M_V$, and the abscissa is the dereddened color, $(B - V)_0$. The solid orange and green lines indicate the template tracks of LV Vul and V1668 Cyg, respectively. The vertical solid red line indicates $(B - V)_0 = -0.03$, the color of optically thick free–free emission. The onset of the nebular phase is indicated by a large open red square.

**Figure 2(a).** IV Cep (Nova Cep 1971) $E(B-V)=0.65$ $(m-M)_V=14.5$ $(B-V)_0=0.4$ $m_{V_{\text{max}}}=7.5$

**Figure 2(b).** V1668 Cyg $E(B-V)=0.45$ $(m-M)_V=15.0$ $m_{V_{\text{max}}}=7.5$

**Figure 2.** Color–magnitude diagrams of (a) IV Cep and (b) V1065 Cen. The ordinate is the absolute $V$ magnitude, $M_V$, and the abscissa is the dereddened color, $(B - V)_0$. The solid orange and green lines indicate the template tracks of LV Vul and V1668 Cyg, respectively. The vertical solid red line indicates $(B - V)_0 = -0.03$, the color of optically thick free–free emission. The onset of the nebular phase is indicated by a large open red square.

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Such neon enrichment is considered to originate from the core material of an oxygen–neon (ONe) WD (e.g., Gehrz et al. 1998). A natal ONe WD likely has a mass $\gtrsim 1.07 M_\odot$ (e.g., Umeda et al. 1999) or $\gtrsim 1.0 M_\odot$ (e.g., Weidemann 2000),...
emission. The UV 1455Å and SSS fluxes are obtained assuming blackbody emission at the photosphere. The decay timescale of their model light curves depends mainly on the WD mass and weakly on the chemical composition of the WD envelope. Assuming the chemical composition of Ne nova 3 (Hachisu & Kato 2006, 2010, 2016a), we calculated four model light curves of 1.05, 1.1, 1.15, and 1.2 $M_\odot$ WDs and chose a best-fit model of a 1.1 $M_\odot$ WD among these four model light curves as shown in Figure 7(a). We list our results in Table 1. We discuss the model light curve fitting in detail below in Section 4.4. With this 1.1 $M_\odot$ WD model and $(m - M)_V = 13.15$ for V959 Mon, we plot the model light curves of absolute $V$ (left solid red line) and arbitrarily scaled X-rays (right solid red line) in Figure 2(a). The $V$ light curve of V959 Mon is reproduced with our model light curve of a 1.1 $M_\odot$ WD until the early nebular phase.

4.4. Dependence of WD Mass on Chemical Composition

We examine the WD mass of V959 Mon in more detail, because the model light curves depend weakly on the chemical composition (Hachisu & Kato 2006). Figure 7(a) shows the model dependence of the $V$ and supersoft X-ray light curves on the WD mass for the chemical composition of Ne nova 3. Because the early phase of the $V$ light curve was not observed, we use the stretched data of LV Vul. The model light curves of 1.15 and 1.2 $M_\odot$ WDs decay too early and the supersoft X-ray light curve of 1.05 $M_\odot$ rises too late compared with the observation.

The $t^{-3}$ decay of the $V$ light curve started about day 250–300 after the outburst, as discussed in Section 2.3. This epoch corresponds roughly to the epoch when the optically thick winds stopped. The optically thick winds of 1.15 and 1.1 $M_\odot$ WDs stopped roughly on days 250 and 300, respectively. Thus,
we select the 1.1 $M_\odot$ WD for the chemical composition of Ne nova 3.

Figure 7(b) depicts four light curves of 1.0, 1.05, 1.1, and 1.15 $M_\odot$ WDs for a different chemical composition of Ne nova 2 (Hachisu & Kato 2010). The $V$ light curve of the 1.15 $M_\odot$ WD decays too early. The supersoft X-ray light curve rises too early in the 1.1 $M_\odot$ WD and too late in the 1.0 $M_\odot$ WD compared with the observation. Thus, we select the 1.05 $M_\odot$ WD for the chemical composition of Ne nova 2, although the 1.1 $M_\odot$ WD cannot be rejected.

If we further decrease the hydrogen content by weight to $X = 0.45$ (CO nova 3, see Hachisu & Kato 2016a) from $X = 0.55$ (Ne nova 2) and $X = 0.65$ (Ne nova 3), we similarly obtain a WD mass of 0.95 $M_\odot$ as the best fit among 0.9, 0.95, 1.0, and 1.05 $M_\odot$, as shown in Figure 8(a). We summarize these results in Table 1.

It should be noted that the neon content hardly affects the timescales of model nova light curves, mainly because neon is not included in the hydrogen burning (CNO cycle) and does not contribute much to the opacity. In other words, the WD mass depends weakly on the chemical composition, especially for the hydrogen content $X$.

We obtain $1.1 \pm 0.05 M_\odot$ for $X = 0.65$, $1.05 \pm 0.05 M_\odot$ for $X = 0.55$, and $0.95 \pm 0.05 M_\odot$ for $X = 0.45$, considering the relatively large ambiguity of the soft X-ray fit. This kind of dependence of WD mass on $X$ was already discussed in Hachisu & Kato (2007). Our model light curve fitting gives WD masses in the range $M_{WD} = 0.9 - 1.15 M_\odot$ for the chemical compositions of $X = 0.45 - 0.65$. This result is consistent with the above discussion on the minimum mass of naked ONe cores.

### 4.5. Emergence of a Companion Star

The hard X-ray (0.8–10 keV) flux of V959 Mon was detected by Swift (Page et al. 2013) about 85 days after the outburst, reached a maximum at day ~140, and then began to decrease until day ~350 (see Figure 2(a)). The origin of the hard X-rays was interpreted as internal shocks (Friedjung 1987) formed by a collision between two ejecta shells (Mukai & Ishida 2001), or the shock between nova winds (optically thick winds) and the companion star (see, e.g., Hachisu & Kato 2005, 2006; Hachisu et al. 2008). If it is the second case, the emergence of hard X-rays should be coincident with the emergence of the companion from the WD photosphere because hard X-rays are probably absorbed deep inside the nova photosphere.

Using the 1.1 $M_\odot$ WD model for Ne nova 3, we estimate the epoch when the companion emerges from the nova envelope. The orbital period of $P_{\text{orb}} = 0.296$ days (7.1 hr) was derived by Osborne et al. (2013) and Munari et al. (2013) from the orbital modulations of $X$-ray and optical light curves, respectively. The mass of the donor star may be estimated from Warner’s (1995) empirical formula, i.e.,

$$M_2 \approx 0.065 \left( \frac{P_{\text{orb}}}{\text{hr}} \right)^{5/4}, \quad \text{for} \quad 1.3 < \frac{P_{\text{orb}}}{\text{hr}} < 9,$$

(13)

which gives $M_2 = 0.75 M_\odot$. With the WD mass $M_1 = 1.1 M_\odot$, the separation is calculated to be $a = 2.3 R_\odot$, the effective Roche lobe radius is $R^*_h = 0.95 R_\odot$ for the primary component (WD) and $R^*_s = 0.79 R_\odot$ for the secondary component (main-sequence star). Our theoretical 1.1 $M_\odot$ WD model predicts that the photosphere of the nova envelope shrinks to the orbital size, i.e., $R_{ph} \approx a$, at $t_{\text{emerge}} \approx 65$ days and further shrinks to $R_{ph} \approx a - R^*_s$ (orbit minus the companion’s radius, i.e., the companion emerges entirely from the WD envelope) at $t_{\text{emerge}} \approx 80$ days.

In our model the companion emerges at $t_{\text{emerge}} \approx 65$–80 days, which is roughly consistent with the hard X-ray detection at 85 days. The decay of the hard X-rays may be explained as the decrease in the wind mass-loss rate. In our model, the wind mass-loss rate decreases monotonically and stops at $t_{\text{wind}} \approx 300$ days. More exactly, the wind mass-loss rate quickly decreases after $t_{\text{weak}} \approx 100$ days (see Hachisu & Kato 2006). This is consistent with the hard X-ray behavior, which peaked about $t \sim 140$ days, and subsequently decreased monotonically until $\sim 300$ days. From these coincidences, we suggest that the hard X-ray emission could originate from a shock between the ejecta and the companion.

For the chemical composition of Ne nova 2 ($M_{WD} = 1.05 M_\odot$), the time of emergence of the companion star from the WD photosphere is about $t_{\text{emerge}} = 70$ days. For CO nova 3 ($M_{WD} = 0.95 M_\odot$), the time of emergence is about $t_{\text{emerge}} = 80$ days. These values are still consistent with the above argument on the emergence of hard X-rays.

### 4.6. Epoch at Gamma-ray Detection

The gamma-rays were detected about 50 days before the hard X-ray count rate increased. Comparing with the theoretical light curve of the 1.1 $M_\odot$ WD (Ne nova 3), the photospheric radius of the nova envelope is $R_{ph} \approx 7 R_\odot$ (~3 times the separation) and the wind mass-loss rate is $M_{\text{wind}} \approx 3 \times 10^{-5} M_\odot$ yr$^{-1}$ at the time of gamma-ray detection. This may be a clue for the emission mechanism of gamma-rays. For the chemical composition of Ne nova 2, we obtain a best-fit model of $M_{WD} = 1.05 M_\odot$. The photospheric radius is $R_{ph} \approx 5 R_\odot$, and the wind mass-loss rate is $M_{\text{wind}} \approx 3 \times 10^{-5} M_\odot$ yr$^{-1}$ at the time of gamma-ray detection (day 34). For CO nova 3 ($M_{WD} \approx 0.95 M_\odot$), $R_{ph} \approx 8 R_\odot$, and $M_{\text{wind}} \approx 4 \times 10^{-5} M_\odot$ yr$^{-1}$ at the time of gamma-ray detection.

### 4.7. Short Duration of the Supersoft X-Ray Phase

Figure 2(a) also shows the model light curve of the supersoft X-ray flux. It rises before the optically thick wind stops. We suppose that in the wind phase the SSS flux may be partly blocked due to self-absorption by the wind. For example, in V1974 Cyg, only weak SSS flux was observed before the optically thick wind stopped, and the supersoft X-ray flux increases quickly after the wind stops (see Figure 41 of Hachisu & Kato 2016a). Considering these rising relations between the observed soft X-ray flux and our model soft X-ray flux, the rise of the SSS flux in V959 Mon shortly before the wind stops is consistent with our model flux.

The supersoft X-ray flux of V959 Mon decays much earlier than the model prediction, in which the X-ray turnover time is calculated from the end of hydrogen nuclear burning. This observed short SSS duration (~100 days) in V959 Mon is much shorter than the SSS duration of other classical novae with a similar timescale and WD mass. For example, V1974 Cyg shows an SSS duration of ~350 days and its WD mass is estimated to be 0.98 $M_\odot$ for the chemical composition of CO nova 3 (and $f_s = 1.08$ against LV Vul) (see, e.g., Hachisu & Kato 2016a).
V959 Mon is a high-inclination binary as mentioned in Section 1. The very short duration of the SSS phase may be naturally explained by eclipse by a flaring-up rim of the accretion disk. In other words, the WD continues to emit supersoft X-rays from its surface until the end of the nuclear burning but the WD surface is entirely obscured by a geometrically thick disk rim.

Hachisu & Kato (2003) presented a model to explain the variation in the light curve of the recurrent nova CI Aql 2000 outburst by flaring-up of the disk rim. During the optically thick wind phase, the disk rim is partially blown off in the wind, so the disk height at the rim is forced to remain small. When the wind gradually weakens and finally stops, the disk rim flares up because the wind shaping effect disappears. This change in the disk rim consistently explained the variation in the light curve of CI Aql.

As V959 Mon is a high-inclination binary ($i = 82^\circ$; Ribeiro et al. 2013), the WD and its surrounding emission region could be perfectly shielded by the flaring-up disk rim when the wind stops (see, e.g., Sala et al. 2008 for similar X-ray eclipses of V5116 Sgr). This could cause the rapid decrease in the supersoft X-ray flux.

It should be noted that in the case of V5116 Sgr ($P_{\text{orb}} = 0.124$ days or 2.97 hr) the SSS emission is still present during eclipse by the rim due to X-ray scattering in the surrounding material (e.g., Sala et al. 2017). The hardness of the X-ray emission barely changed during the eclipse of V5116 Sgr (Sala et al. 2008). On the other hand, if the decrease in flux is due to a turnover of hydrogen burning, one would expect the spectrum to become softer and colder during the decline of the SSS. For V959 Mon, Page et al. (2013) reported no substantial change in the X-ray spectrum in the decline phase. This may support our model of eclipse by the disk rim.

Figure 8. Model light curve fitting for the chemical composition of CO nova 3 (Hachisu & Kato 2016a). (a) All observational data are the same as those in Figure 7(a). The solid magenta, red, green, and blue lines correspond to the V and soft X-ray light curves of our 0.9, 0.95, 1.0, and 1.05 $M_\odot$ WDs, respectively. (b) The similar model light curve fitting of our 0.9 (magenta), 0.95 (blue), 0.98 (black), and 1.05 $M_\odot$ (green) WDs with V1668 Cyg, LV Vul, IV Cep, and V1065 Cen. See the text for detail.
4.8. WD Masses of LV Vul, IV Cep, and V1065 Cen

The timescales of the V and color curves of LV Vul, IV Cep, and V1065 Cen are very similar to that of V1668 Cyg. We consider that the WD masses of LV Vul, IV Cep, and V1065 Cen are also similar to that of V1668 Cyg. A comprehensive analysis of the light curve of V1668 Cyg was already presented in Hachisu & Kato (2016a), which showed that the WD mass is 0.98 ± 0.1 M_☉ for the chemical composition of CO nova 3. We reproduce their light-curve analysis and plot four model light curves for 0.9, 0.95, 0.98, and 1.05 M_☉ WDs in Figure 8(b).

5. Discussion

5.1. Reddening and Distance

We examine the distances and reddenings toward the four novae based on various distance–reddening relations. We use the following four results: Marshall et al. (2006) published a three-dimensional (3D) extinction map of our Galaxy in the direction of −100° ≤ l ≤ 100° and −10° ≤ b ≤ +10° with grids of ∆l = 0°.25 and ∆b = 0°.25. Sale et al. (2014) calculated the reddening for a region of 30° ≤ l ≤ 215° and |b| ≤ 5° based on the IPHAS photometry. Green et al. (2015) published data for the Galactic extinction map that cover a wider range of Galactic coordinates (over three-quarters of the sky) with much finer grids of 3°.4−13°.7 and a maximum distance resolution of 25%. Their values of E(B − V) could have an error of 0.05−0.1 mag compared with other two-dimensional (2D) dust extinction maps. The distance–reddening relation was recently revised by Green et al. (2018). Özdnömez et al. (2016) obtained distance–reddening relations toward 46 novae based on the unique position of the red clump giants in the color–magnitude diagram.

5.1.1. V959 Mon

Figure 9(a) shows a few distance–reddening relations toward V959 Mon, whose Galactic coordinates are (l, b) = (206°.3411, +0°.0758). The reddening of E(B − V) = 0.38 and the distance modulus of (m − M)_V = 13.15 cross at d = 2.5 kpc. The green line of Sale et al. (2014) is the nearest line-of-sight reddening of (l, b) = (206°.417, 0°.083). The solid black and orange lines denote the distance–reddening relations given by Green et al. (2015, 2018), respectively. The position of d = 2.5 kpc and E(B − V) = 0.38 is consistent with that of Özdnömez et al. (2016) but deviates slightly from those of Green et al. (2015, 2018) and Sale et al. (2014).

Munari et al. (2013) estimated the reddening to be E(B − V) = 0.38 ± 0.01 from the equivalent width of the NaI 5890 Å line and derived the distance to be ≈1.5 kpc by assuming that the companion is a K3 main-sequence star. Linford et al. (2015) obtained the distance, d = (0.9 ± 0.2)−(2.2 ± 0.4) kpc, with a most probable distance of d = 1.4 ± 0.4 kpc, using the expansion parallax method based on the radio map from the Very Large Array (VLA). On the other hand, Shore et al. (2013) derived a large reddening of E(B − V) = 0.85 ± 0.05 and a hydrogen column density of N_H = (5 ± 0.5) × 10^{21} cm^{-2} by comparing the NaI absorption line with the Leiden/Argentine/Bonn (LAB) survey λ21 cm profile of neutral hydrogen (Kalberla et al. 2005). They also obtained the distance of 3.6 kpc from the direct comparison of UV and optical fluxes of V959 Mon with those of V1974 Cyg, assuming that the distance and reddening of V1974 Cyg are 3.6 kpc and E(B − V) = 0.36. Tarasova (2014) also derived the reddening of E(B − V) = 0.85 from Balmer decrements. To summarize these previous studies, there are two distinct groups for the distance and reddening: one is (d, E(B − V)) = (1.5 kpc, 0.38) (e.g., Munari et al. 2013) and the other is (3.6 kpc, 0.85) (e.g., Shore et al. 2013). Both sets of (d, E(B − V)) are close to the distance–reddening lines obtained by Green et al. (2015, 2018) and Sale et al. (2014).

As mentioned earlier, Linford et al. (2015) obtained the distance of V959 Mon based on the motion of the ejecta along the north–south axis. The distance depends on the assumed expansion velocity of the ejecta along this axis. Their distance values are between the lower limit of d = 0.9 ± 0.2 kpc (assuming an expansion velocity of v_exp = 480 ± 60 km s^{-1}) and the upper limit of d = 2.2 ± 0.4 kpc (v_exp = 1200 ± 150 km s^{-1}) from the VLA radio map between days 126 and 199. Their upper limit is consistent with our distance of d = 2.5 ± 0.5 kpc. Linford et al. (2015) also obtained “a most probable distance of d = 1.4 ± 0.4 kpc,” assuming v_exp = 480 ± 60 km s^{-1} based on the VLA map between days 615 and 703. Note that their day 0 is defined by UT 2012 June 19 JD 2456097.5. This d = 1.4 kpc is not consistent with d = 0.9 ± 0.2 kpc from the data between days 126 and 199 (using the same v_exp = 480 ± 60 km s^{-1}). If we adopt v_exp = 1200 ± 150 km s^{-1}, their most probable distance increases to d = 3.5 ± 1 kpc for the data between days 615 and 703. Taking the arithmetic average of these two expansion velocities, we obtain “a most probable distance of (1.4 + 3.5)/2 = 2.45 kpc,” which is close to our value of 2.5 kpc. Thus, we may conclude that the distance of 2.5 ± 0.5 kpc is consistent with Linford et al.’s expansion parallax method.

5.1.2. LV Vul

For the reddening toward LV Vul, Fernie (1969) determined E(B − V) = 0.6 ± 0.2 from the color excesses of 14 B stars near the line of sight. Tempesti (1972) obtained E(B − V) = 0.55 from the color at optical maximum, i.e., E(B − V) = (B − V)_{max} − (B − V)_{0,max} = 0.9 − 0.35 = 0.55. He adopted (B − V)_{0,max} = +0.35 (Schmidt 1957) instead of (B − V)_{0,max} = +0.23 (van den Bergh & Younger 1987). The distance toward LV Vul was obtained as d = 0.92 ± 0.08 kpc by Slavin et al. (1995) from the expansion parallax method. Hachisu & Kato (2014) obtained E(B − V) = 0.60 ± 0.05 by fitting with the typical color–color evolution track of nova outbursts. These are all consistent with our set of d = 1.0 ± 0.2 kpc and E(B − V) = 0.60 ± 0.05. Thus, our set of (d, E(B − V)) for LV Vul seems to be reasonable.

Figure 9(b) shows several distance–reddening relations toward LV Vul, (l, b) = (63°.3024, +0°.8464). We plot Marshall et al.’s distance–reddening relations of four directions close to LV Vul: (l, b) = (63°.25, 0°.75) (open red squares), (l, b) = (63°.50, 0°.75) (filled green squares), (l, b) = (63°.25, 1°.00) (blue asterisks), and (l, b) = (63°.50, 1°.00) (open magenta circles). We added (l, b) = (63°.250, 0°.917) from Sale et al. We also add Green et al. and Özdnömez et al.’s distance–reddening relations. In this way, various distance–reddening relations are not converged.

The large discrepancies among the distance–reddening relations can be understood as follows. The 3D dust maps essentially give an averaged value of a relatively broad region, and thus the pinpoint reddening could be different from the value of the 3D dust maps, because the resolutions of these dust
maps are considerably larger than molecular cloud structures observed in the interstellar medium. Özdoğmez et al. (2016) used red clump giants. The number density of red clump giants is smaller than that of giants, which Marshall et al. used. Therefore, the angular resolution of Özdoğmez et al. (2016) could be less than that of Marshall et al. (2006), although Özdoğmez et al. (2016) claimed the accuracy for the distance–reddening relation toward WY Sge, which is not significantly different for the four resolutions of 0°.3, 0°.4, 0°.5, and 0°.8. (WY Sge is not included in the present analysis.) The angular resolution of the map of Marshall et al. is 0°.25 = 15′.0. Marshall et al. used only giants (or post-main-sequence stars) in their analysis, and thus the dust map they produced has little information for the nearest kiloparsec. Among these relations, only the orange line (Green et al. 2018) is consistent with our estimates of \( d = 1.0 \pm 0.2 \) kpc and \( E(B - V) = 0.60 \pm 0.05 \).

5.1.3. IV Cep

The reddening toward IV Cep was estimated to be \( E(B - V) = 0.8 \) (Sato et al. 1973) from the interstellar absorption in the Cepheus region, and \( E(B - V) = A_V/3.1 = 1.8/3.1 = 0.58 \).
(Thomas et al. 1973) and \( E(B - V) = A_V/3.1 = 1.7/3.1 = 0.55 \) (Kohoutek & Klawitter 1973), both from the absorption–distance relation given by Neckel (1967). Hachisu & Kato (2016b) obtained \( E(B - V) = 0.65 \pm 0.05 \) by fitting with the typical color–color evolution track of nova outbursts. All these values are roughly consistent with our estimate of \( E(B - V) = 0.65 \pm 0.05 \).

Figure 9(c) shows several distance–reddening relations toward IV Cep. \((l, b) = (99°/6137, -1°/6381)\). We plot four relations given by Marshall et al. (2006) in directions close to IV Cep: \((l, b) = (99°/5, -1°/5)\) (open red squares), \((99°/75, -1°/5)\) (filled green squares), \((99°/75, -1°/75)\) (blue asterisks), and \((99°/75, -1°/75)\) (open magenta circles). We add \((l, b) = (99°/583, -1°/583)\) from Sale et al. We also add Green et al. and Özdöreme et al.’s relations. Among these relations, Marshall et al.’s relation of open red squares is consistent with our set of \( d = 3.1 \pm 0.6 \) kpc and \( E(B - V) = 0.65 \pm 0.05 \).

5.1.4. V1065 Cen

Figure 9(d) shows various distance–reddening relations toward V1065 Cen. \((l, b) = (293°/9836, +3°/6129)\). We plot Özdöreme et al.’s relation, and four distance–reddening relations given by Marshall et al. (2006): \((293°/75, 3°/75)\) (open red squares), \((294°/00, 3°/75)\) (filled green squares), \((293°/75, 3°/50)\) (blue asterisks), and \((294°/00, 3°/50)\) (open magenta circles). The closest ones of Marshall et al. (2006) are those denoted by filled green squares and open magenta circles. Our values of \( d = 5.3 \pm 1.0 \) kpc and \( E(B - V) = 0.45 \pm 0.5 \) are midway between them.

The reddening for V1065 Cen was obtained as \( E(B - V) = 0.50 \pm 0.10 \) by Helton et al. (2010) from an average of three estimates, i.e., \( E(B - V) = (B - V)_{\text{max}} - Q(B - V)_{\text{hel}} \), with \( Q = 0.52 \pm 0.04 \) (\( Q = 0.23 \pm 0.06 \) of Helton et al.). \( E(B - V) = (B - V)_{\text{hel}} - (B - V)_{\text{obs}} \). The reddening relation in the \( B \) band as \( (m - M)_{\text{V}} = 7.6 \pm 0.2 \) is \( 0.162 \pm 0.06 \) from the MMRD relation together with \( t_2 \) days. This gives a distance of \( d = 8.77^{+2}_{-1} \) kpc. Note, however, that the distance estimate from the MMRD relation is not so accurate (see, e.g., Downes & Duerbeck 2000). Hachisu & Kato (2016b) obtained \( E(B - V) = 0.45 \pm 0.05 \), assuming that the intrinsic \( (B - V)_{\text{hel}} \) color evolution of V1065 Cen is identical with that for similar novae of type IIa, i.e., LV Vul and V1668 Cyg. This value is consistent with the estimate of Helton et al.

To summarize, our obtained distances and reddening for the four novae are broadly consistent with other estimates. We conclude that the distance of V959 Mon is \( d = 2.5 \pm 0.5 \) kpc for \( E(B - V) = 0.38 \pm 0.01 \).

6. Conclusions

Our main results are summarized as follows:

1. The \( V \) light curves of V959 Mon and LV Vul overlap each other, if we stretch the timescale of LV Vul by a factor of \( f_s = 1.38 \). Applying the time-stretching method to the \( V \) light curves of V959 Mon and LV Vul, we obtain the distance modulus of V959 Mon in the \( V \) band, \( \mu_V = (m - M)_V = 13.15 \pm 0.3 \). The distance is calculated to be \( d = 2.5 \pm 0.5 \) kpc for the reddening of \( E(B - V) = 0.38 \pm 0.01 \). We also apply the time-stretching method for other sets of V959 Mon versus V1668 Cyg, IV Cep, and V1065 Cen, and obtain similar values for the distance modulus \( (m - M)_V \) for V959 Mon.

2. The stretched color–magnitude track of V959 Mon just overlaps with that of LV Vul in the diagram of \( (B - V)_0 \) versus \( (M_V - 2.5 \log f_s) \). This strongly supports our adopted values of \( E(B - V) = 0.38 \pm 0.1 \) and \( (m - M)_V = (m - (M_V - 2.5 \log f_s)) = 13.5 \pm 0.3 \). The color–magnitude track of IV Cep and V1065 Cen also overlap with that of LV Vul, which may indicate a common track in the stretched color–magnitude diagram.

3. The various distance–reddening relations toward V959 Mon are consistent with our obtained values. Thus, we confirm \( d = 2.5 \pm 0.5 \) kpc, \( E(B - V) = 0.38 \pm 0.1 \), and \( (m - M)_V = 13.15 \pm 0.3 \).

4. The model light curve fitting suggests the WD mass of \( M_{\text{WD}} = 0.9-1.15 M_\odot \), depending weakly on the assumed chemical composition. This range of WD mass is consistent with the claim that V959 Mon is an ONe nova. If we adopt the model chemical composition of Ne nova 3, which is close to the abundance obtained by Shore et al. (2013), the WD mass is \( M_{\text{WD}} = 1.1 \pm 0.05 M_\odot \).

5. The period of hard X-ray emission is consistent with the time of appearance of the companion star from the nova envelope. Thus, the hard X-rays could originate from a shock between the ejecta and the companion.

6. The supersoft X-ray flux increases in the later phase of a nova outburst when the extended WD envelope becomes transparent to soft X-rays. The X-ray turn-on time of V959 Mon is quite consistent with the theoretical model, which is confirmed by a number of classical novae. In other words, no diagnostics can be found for the X-ray turn-on time. This is a typical event in the evolution of a nova.

7. The very short supersoft X-ray phase in V959 Mon (~100 days) can be explained as occultation by the disk rim. Our theoretical model indicates that the WD radius becomes as small as \( R_{\text{wd}} = 0.08 \) R_\odot at the observed X-ray turn-off time, which can be easily hidden by the disk rim \( (i = 82^\circ) \). In short, the X-ray turn-off is due to the occultation by the disk rim rather than nuclear burning turnoff.

8. Our WD models suggest that, at the time of gamma-ray detection, the photosphere of the nova envelope extends to \( 5-8 \) R_\odot (about two or three times the binary separation) and the wind mass-loss rate is \( (3-4) \times 10^{-5} M_\odot \) yr^{-1}. This may be a clue to the emission mechanism of gamma-rays.

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