A UNIVERSAL DECLINE LAW OF CLASSICAL NOVAE. IV. V838 HER (1991): A VERY MASSIVE WHITE DWARF

MARIKO KATO 1, IZUMI HACHISU 2, AND ANGELO CASSATELLA 3,4,5

1 Department of Astronomy, Keio University, Hiyoshi, Yokohama 223-8521, Japan; mariko@educ.cc.keio.ac.jp
2 Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8902, Japan; hachisu@ea.c.u-tokyo.ac.jp
3 INAF, Istituto di Fisica dello Spazio Interplanetario, Via del Fosso del Cavaliere 100, 00133 Roma, Italy
4 Departamento de Astrofisica, Facultad de Fisica, Universidad Complutense de Madrid, 28040 Madrid, Spain
5 Dipartimento di Fisica E. Amaldi, Università degli Studi Roma Tre, Via della Vasca Navale 84, 00146 Roma, Italy; cassatella@fis.uniroma3.it

Received 2009 February 23; accepted 2009 September 10; published 2009 October 6

ABSTRACT

We present a unified model of optical and ultraviolet (UV) light curves for one of the fastest classical novae, V838 Herculis (Nova Herculis 1991), and estimate its white dwarf (WD) mass. Based on an optically thick wind theory of nova outbursts, we model the optical light curves with free–free emission and the UV 1455 Å light curves with blackbody emission. Our models of 1.35 ± 0.02 M⊙ WD simultaneously reproduce the optical and UV 1455 Å observations. The mass lost by the wind is \( \Delta M_{\text{wind}} \sim 2 \times 10^{-6} M_\odot \). We provide new determinations of the reddening, \( E(B-V) = 0.53 \pm 0.05 \), and of the distance, 2.7 ± 0.5 kpc.

Key words: novae, cataclysmic variables – stars: individual (V838 Herculis) – stars: mass loss – ultraviolet: stars – white dwarfs

Online-only material: color figures

1. INTRODUCTION

V838 Her was discovered independently by Sugano (1991) on 1991 March 24.78 UT at 5.4 mag and by Alcock (1991) at ~5 mag on 1991 March 26.7 UT. Alcock’s visual discovery around the peak was made in strong twilight, so the peak magnitude was not accurate. The outburst time can be estimated from the upper limit (9 mag) predisclosure observation by Ueta (1991) on JD 2,448,339.9 and Sugano’s discovery on JD 2,448,340.281. In the present work, we adopt the outburst time JD 2,448,340.0 as day zero and the maximum magnitude \( m_{V,\text{max}} = 5.4 \) mag.

Soon after the optical maximum, the nova entered a very rapid decline phase, followed by a slight oscillatory behavior enduring several days and, later on, by a smooth decline. Infrared (IR) fluxes also showed a rapid decline, reaching a local minimum on day 6, followed by a rapid brightening. The spectral energy distribution was consistent with free–free emission from day 1.3 to 6.5, and thereafter with blackbody emission, ascribed to the formation of a hot dust shell (Chandrasekhar et al. 1992; Harrison & Stringfellow 1994; Kidger & Martinez-Roger 1993; Woodward et al. 1992). Indication of IR emission from silicate grains was reported only at a later phase (Lynch et al. 1992; Smith et al. 1995). Smith et al. (1995) suggested that silicate emission was due to a light echo by cold silicate grains deposited in a previous nova eruption.

Red and blue preoutburst magnitudes were estimated from the Palomar Sky Survey plates as 19 and 17.5, respectively, by West (1991), and 20.6 and 18.25 by Humphreys et al. (1991), but were contaminated by a closeby (~1′″) star of similar magnitude. V838 Her returned to the preoutburst magnitude \( V = 19.0 \) on day 403, and \( V = 19.2 \) on day 572 (Szkody & Ingram 1994).

In this series of papers, we have applied our universal decline law to many novae, including moderately fast novae (e.g., V1668 Cyg in Hachisu & Kato 2006, hereafter referred as Paper I) and a slow nova (GQ Mus in Hachisu et al. 2008, hereafter referred as Paper III), and have succeeded in reproducing simultaneously optical, IR, ultraviolet (UV) 1455 Å, and supersoft X-ray light curves. V838 Her is, however, one of the fastest classical novae, so it is interesting to see if the universal decline law also applied to such an extreme object. The main observational features of V838 Her are summarized in Tables 1 and 2. Section 2 reviews our observational results based on the IUE spectra. Our model light curves are briefly introduced in Section 3. The results of light-curve fitting are given in Section 4. Discussions and conclusions follow in Sections 5 and 6. In the Appendix we give several examples of nova light curves, which show high degree of homology, as predicted by our models.

2. UV OBSERVATIONS

V838 Her has been monitored by IUE from day 2 to day 831, mainly at low resolution. A gallery of UV spectra can be found in Cassatella et al. (2004a) and Vanlandingham et al. (1996).

In the following, we revisit the problem of color excess \( E(B-V) \) of V838 Her, and describe the long-term evolution of UV continuum and of emission lines. The UV spectra were retrieved from the IUE archive through the IUE Newly Extracted Spectra (INES) system, which also provides full details of the observations. The use of the IUE INES data is particularly important for the determination of reddening correction because of the implementation of upgraded spectral extraction and flux calibration procedures compared to the previously published UV spectra.

2.1. Reddening Correction

As summarized by Vanlandingham et al. (1996), the color excess of V838 Her has been determined by several authors using different methods, based on the Balmer decrement (Ingram et al. 1992; Vanlandingham et al. 1996), the equivalent width of the Na i interstellar lines (Lynch et al. 1992), the ratio of the UV flux above and below 2000 Å (Starrfield et al. 1992),

6 http://sdc.laeff.inta.cs/ines/
and the assumed intrinsic color at maximum light (Woodward et al. 1992). The mean value of these determinations, assuming to have the same weight, is $E(B - V) = 0.50 \pm 0.12$. Such a large error would cause large uncertainties on the distance and hence on the intrinsic parameters of the nova, as derived through a comparison with our models. This has driven us to revisit the problem of the reddening using an independent method that we consider more reliable than the previous ones, because of relying directly on its best detectable effect, i.e., the strength and shape of the 2175 Å broad dust absorption band.

The Galactic extinction curve (Seaton 1979) shows a pronounced broad maximum around 2175 Å due to dust absorption. Since it takes the same value $X(\lambda) = A(\lambda)/E(B - V) \approx 8$ at $\lambda = 1512, 1878$, and 2386 Å, the slope of the straight line passing through the continuum points at these wavelengths is insensitive to $E(B - V)$ in a $(\lambda, \log F_\lambda)$ plot. This circumstance can be used to get a reliable estimate of $E(B - V)$ as that in which the stellar continuum becomes closely linear in the 1512–2386 Å region, and passes through the continuum points at the above wavelengths. From eight pairs of short- and long-wavelength IUE spectra taken from day 6 to day 69, i.e., during or close to the nebular phase, we have in this way found $E(B - V) = 0.53 \pm 0.05$, a value that we adopt in the following. Examples of IUE spectra of V838 Her corrected with $E(B - V) = 0.53$ are reported in Figure 1 for days 10, 12, 15, and 22.

In principle, we could have estimated the $E(B - V)$ color excess also from the observed relative intensities of the He II 1640 Å Balmer line, and the 2734 and 3203 Å Paschen recombination lines, compared with theoretical ratios, as done, for example in the case of GQ Mus (Paper III). Such lines were however too faint to be measured accurately.

### 2.2. Evolution of the UV Continuum

We have measured the mean flux in two narrow bands 20 Å wide centered at 1455 Å and 2855 Å, selected to best represent the UV continuum because it is little affected by emission lines (Cassatella et al. 2002). Figure 2 shows the time evolution of the $F(1455 \text{ Å})$ and $F(2885 \text{ Å})$ fluxes and of the UV color index $C(1455–2885) = -2.5 \log [F(1455 \text{ Å})/F(2885 \text{ Å})]$. The measurements were made on well-exposed low-resolution large-aperture spectra. Figure 2 reports also, for comparison, the visual light curve obtained from the fine error sensor (FES) counts on board IUE, once corrected for the time-dependent sensitivity degradation (see Cassatella et al. 2004a, for details on the FES calibration).

It appears from Figure 2 that the flux maximum is reached later in the UV 1455 Å band than in the 2885 Å and visual bands, as a result of the progressive shift of the maximum emissivity toward shorter wavelengths. The progressive hardening of the UV spectrum stops after day 10, when the $C(1455–2885)$ color index stabilizes around a value of zero. Both these features are a common property of the novae studied by Cassatella et al. (2002).

#### 2.3. Evolution of the UV Emission Lines

Figure 3 reports, as a function of time, the observed flux in the most prominent UV emission lines, as measured by us from the available IUE low-resolution spectra. The figure shows that the maximum emission progressively shifts from low to high ionization lines, such that Mg II 2800 Å is the first to reach maximum, followed by C II 1335 Å, O i 1300 Å, C iii] 1909 Å, N iv] 1487 Å, and N v 1240 Å maximum. The time delay of maximum emission, $\Delta t$, with respect to the visual maximum does in fact increase with increasing the line ionization potential $\chi$ [eV], as better shown in Figure 4 where $\Delta t$, once normalized to the $t_5$ time, is plotted as a function of $\chi$ for the different emission lines. Here, $t_5$ is the time in which the visual magnitude drops by 3 mag from the optical peak. Such a behavior is consistent with that observed in a sample of seven CO novae, whose mean data from Cassatella et al. (2005) are overplotted for comparison. In particular, note that the maximum emission in C iii] 1909 Å and

| Subject                  | Data          | Reference          |
|--------------------------|---------------|--------------------|
| Discovery                | JD 2,448,340.28 | Sugano (1991)      |
| Nova speed class         | Very fast     |                    |
| IR minimum               | JD 2,448,345.94 (day 6) | Harrison & Stringfellow (1994) |
| $t_s$                    | 5.3–6 days    |                    |
| $m_{V_{max}}$            | 5.4 mag       | Sugano (1991)      |
| $M_V_{max}$ from $t_5$   | $-9.94 \sim -9.80$ mag | Equation (3)        |
| Distance                 | 2.8–10 kpc    | Vanlandingham et al. (1996); Harrison & Stringfellow (1994) |
| Distance                 | 2.7 ± 0.5 kpc | This work          |
| FWHM of UV 1455 Å        | 4.7 days      | This work          |
| $E(B - V)$               | 0.3–0.6       | Vanlandingham et al. (1996); Harrison & Stringfellow (1994) |
| $E(B - V)$               | 0.5–0.7       | Matheson et al. (1993) |
| $E(B - V)$               | 0.53 ± 0.05   | This work          |
| Dust                     | Very thin     | See Section 5.2    |
| Orbital period           | 7.14 hr       | Ingram et al. (1992); Leibowitz et al. (1992) |
| H-burning phase          | < 1 yr        | Szkody & Hoard (1994) |

### Table 1

#### Observed Properties of V838 Herculis

| Subject       | Data         | Reference                      |
|---------------|--------------|--------------------------------|
| Object        | X            | Y                              | CNO | Ne     | Na–Fe | Reference                |
| Sun           | 0.7068       | 0.274                         | 0.014 | 0.0018 | 0.0034 | Grevesse & Anders (1989) |
| V838 Her      | 0.78         | 0.10                          | 0.041 | 0.081  | 0.003  | Vanlandingham et al. (1996) |
| V838 Her      | 0.59         | 0.31                          | 0.030 | 0.067  | 0.003  | Vanlandingham et al. (1997) |
| V838 Her      | 0.562        | 0.314                         | 0.038 | 0.070  | 0.015  | Schwarz et al. (2007)    |

### Table 2

#### Chemical Abundance by Weight

| Subject       | X            | Y                              | CNO | Ne     | Na–Fe | Reference                      |
|---------------|--------------|--------------------------------|-----|--------|-------|--------------------------------|
| Sun           |              |                                |     |        |       | Grevesse & Anders (1989)      |
| V838 Her      |              |                                |     |        |       | Vanlandingham et al. (1996)   |
| V838 Her      |              |                                |     |        |       | Vanlandingham et al. (1997)   |
| V838 Her      |              |                                |     |        |       | Schwarz et al. (2007)         |
Figure 1. *IUE* spectra of V838 Her obtained at different dates (days after the outburst). The spectra have been corrected for reddening using $E(B-V) = 0.53$. The vertical dotted lines represent the wavelengths $\lambda = 1512, 1878, \text{and} 2386 \, \text{Å}$ at which the extinction law takes the same value. With the adopted value of reddening, the stellar continuum underlying the many emission lines is well represented by a straight line all over the full spectral range. Saturated data points in the emission lines are labeled with pluses.

N iii] 1750 Å takes place after a time of $\Delta t/t_3 \approx 2$, as in CO novae. This time has been identified in Cassatella et al. as the start of the prenebular phase.

2.4. High-resolution Emission Line Profiles

Good quality *IUE* high-resolution spectra of V838 Her are available only at two dates: day 2.5 (LWP 19993) and day 15 (SWP 41317). The most prominent feature in the long-wavelength spectrum of day 2.5 is the broad P Cygni profile of the Mg ii 2800 Å doublet (Figure 5). A comparison with theoretical P Cygni profiles computed with the Sobolev Exact Integration (SEI) method (Lamers et al. 1987; Groenewegen & Lamers 1989) indicates that the terminal velocity of the wind is $\approx 3000 \, \text{km s}^{-1}$. The huge emission compared with the absorption component, usual in novae, is due to efficient population of the upper levels of the doublet by electron collisions.

Another interesting line profile is that of the C iii] 1906.68–1908.73 Å doublet shown in Figure 6, which is the strongest emission line observed in the short-wavelength spectrum of day 15. As it appears from the figure, the C iii] emission has a very complex profile. One way to interpret this profile is that the emitting region is very inhomogeneous in terms of density and velocity structure. This possibility cannot be ruled out a priori also in view of the presence of complex emission line profiles, e.g., in the hydrogen Balmer lines (see Iijima & Cassatella 2009). The other possibility is that the C iii] emission is eroded by overlying absorption from an outer shell. A likely source of overlying absorption is the principal and diffuse absorption components from the Fe iii UV 34 triplet at radial velocity of $-500 \, \text{km s}^{-1}$ and $-1600 \, \text{km s}^{-1}$, respectively. Such components have already been confidently identified to affect the C iii] emission line in V1974 Cyg (Cassatella et al. 2004b).

3. THE MODEL OF NOVA LIGHT CURVES

In this and previous papers, we have presented a unified model for the IR, optical, UV, and supersoft X-ray light curves of several classical novae. Our models are based on the optically thick wind theory of nova outbursts as described in Kato & Hachisu (1994) and Paper I.

3.1. Optically Thick Wind Model

After a thermonuclear runaway sets in, the photosphere of the white dwarf (WD) envelope expands greatly to a giant size with $R_{\text{ph}} \gtrsim 100 \, R_\odot$. The envelope settles into steady state around the
Figure 3. Evolution of the observed fluxes in the most prominent emission lines of V838 Her, in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Open dots in the N iv and N v panels refer to features not due to these transitions.

Figure 4. Delay of the flux maximum of the emission lines, normalized to the $t_3$ time, as a function of the corresponding ionization potential for V838 Her (filled circles). The emission lines considered, in order of increasing ionization potential, are Mg ii 2800 Å, C ii 1335 Å, O i 1300 Å, C iii 1909 Å, N iii 1750 Å, N iv 1487 Å, and N v 1240 Å. We also show, for comparison, the average values of CO novae (crosses) in Cassatella et al. (2005). In this case, the x-axis has been shifted by 0.5 eV to make the error bars visible and the O iii 1660 Å line is added between the N iii and N iv lines.

Figure 5. P Cygni profile of the Mg ii 2800 Å doublet from the IUE spectrum LWP 19993 of V838 Her taken on day 2.5. The observed profiles have been fitted with a theoretical P Cygni profile, obtained through the SEI method (Lamers et al. 1987; Groenewegen & Lamers 1989), indicated as a thick line. The derived wind terminal velocity is $\approx 3000$ km s$^{-1}$. Fluxes are normalized to the local continuum. Note the presence of the narrow interstellar components of the doublet at about the laboratory wavelength.

The UV 1455 Å flux is estimated directly from blackbody emission instead of modeling WD atmosphere. This approximation is reasonably accurate in a very narrow wavelength range around UV 1455 Å flux (Cassatella et al. 2002; Paper III) near its peak. IR and optical fluxes are calculated from free–free emission by using physical values of our wind solutions. Physical properties of these wind solutions are given in our previous papers (Hachisu et al. 1999; Kato 1983, 1997, 1999; Kato & Hachisu 1994).

We neglect helium ash layer which may develop underneath the hydrogen burning zone in mass increasing WDs as in RS Oph (see Hachisu et al. 2007). We suppose that the WD mass is decreasing in V838 Her, because metal enhancement is observed in V838 Her (see Table 2). Metal enrichment is an indicator of decreasing WD mass (e.g., Prialnik 1986; Prialnik & Kovetz 1995).
respectively, $V$ is the emitting volume, $R_{\text{ph}}$ is the photospheric radius, $M_{\text{wind}}$ is the wind mass-loss rate, and $v_{\text{ph}}$ is the velocity at the photosphere. We also assume that $N_e \propto \rho_{\text{wind}}$, $N_i \propto \rho_{\text{wind}}$, and use the continuity equation, i.e., $\rho_{\text{wind}} = M_{\text{wind}}/4\pi r^2 v_{\text{wind}}$, where $\rho_{\text{wind}}$ and $v_{\text{wind}}$ are the density and velocity of the wind, respectively. Finally, we assume that $v_{\text{wind}} = \text{const.} = v_{\text{ph}}$ outside the photosphere.

This equation has successfully reproduced the optical and IR light curves of several novae in outburst (see papers of this series; Hachisu & Kato 2006, 2009; Kato et al. 2008). In the case of V838 Her, the early decay (until day 6) of $J$, $H$, and $K$ bands are almost parallel to each other as shown later in Figure 8, whereas $J$ is not shown for clarity; this is one of the characteristic properties of free–free emission (see the appendix of Paper III). Also the spectrum of V838 Her is consistent with that of free–free emission as mentioned in Section 1. Thus, we can safely apply our method to V838 Her.

After the optically thick wind stops, the total mass of the ejecta remains constant with time. The flux from such homologously expanding ejecta is

$$F_{\nu} \propto \int N_e N_i dV \propto \rho^2 V \propto \frac{M^2}{V^2} \propto R^{-3} \propto t^{-3},$$

where $\rho$ is the mean density and $M_0$ is the ejecta mass. We assume that the ejecta are expanding at a constant velocity, $v$. So we have $R = vt$, where $t$ is the time after the outburst. The proportionality constants in Equations (1) and (2) cannot be determined a priori because radiative transfer is not calculated outside the photosphere; these were determined using the procedure described below. $F_2$ is also represented by Equations (1) and (2), but the proportionality constant depends on wavelength since $F_2 \propto \lambda^{-2} F_{\nu}$.

If we assume an expanding shell with constant thickness, the flux is proportional to $F_{\nu} \propto t^{-2}$ as discussed in V723 Cas (Evans et al. 2003). In V1500 Cyg and V1974 Cyg, however, we found that the flux decline rate can be well represented by $t^{-3}$ (see Paper I). As we will see later, the decline rate of V838 Her is consistent with $t^{-3}$.

As the proportionality constant in Equation (2) cannot be determined theoretically, and there is no representative timescale, this later part of the light curve does not contain any information on the WD mass. Therefore, we do not use this part in our light-curve fitting.

### 3.4. System Parameters of Optically Thick Wind Model

The light curves of our optically thick wind model are parameterized by the WD mass ($M_{\text{WD}}$), chemical composition of the envelope ($X, Y, Z, X_{\text{CNO}}, X_{\text{Ne}}$), and the envelope mass ($M_{\text{env,0}}$) at the time of outburst (JD 2,448,340.0). Note that the metal abundance, $Z$, includes carbon, nitrogen, oxygen, and neon with solar composition ratios and that $X_{\text{CNO}}$ and $X_{\text{Ne}}$ denote additional excesses.

Table 2 summarizes the chemical abundance determinations so far available for V838 Her, as first provided by Vanlandingham et al. (1996), superseded by the later re-determinations by Vanlandingham et al. (1997), and extended by Schwarz et al. (2007) from spectra taken at four epochs (days 28, 60, 79, and 148). We thus assume the chemical composition of V838 Her to be $X = 0.55$, $Y = 0.33$, $X_{\text{CNO}} = 0.03$, $X_{\text{Ne}} = 0.07$, and $Z = 0.02$. We call it the “standard” composition set. We also assumed two other sets of composition for comparison. The first case is $X = 0.65$, $Y = 0.27$, $X_{\text{CNO}} = 0.03$, etc.
0.35, and $Z = 0.02$, expressing less enrichment of heavy elements such as in V382 Vel and QU Vul, and the second case is $X = 0.35$, $Y = 0.33$, $X_{\text{CNO}} = 0.2$, $X_{\text{Ne}} = 0.1$, and $Z = 0.02$ which may be an extreme case of metal enrichment for V838 Her but appropriate composition for V1974 Cyg and V351 Pup, which may be an extreme case of metal enrichment for V838 Her but appropriate composition for V1974 Cyg and V351 Pup, although abundance estimates are very different among different authors (see Table 1 in Paper I which lists observational estimates of abundance of nova ejecta).

The latter two recent determinations both indicate an excess of helium with respect to hydrogen, i.e., $X/Y = 1.9$ (Vanlandingham et al. 1997) and 1.8 (Schwarz et al. 2007), against the solar value of 0.7/0.28 = 2.58. In massive WDs, about one-tenth of hydrogen is consumed by nuclear burning to produce thermal and gravitational energy during the early phase of the outburst (Politano et al. 1995; Prihlik & Kovetz 1995). Supposing that $\Delta X = 0.1$ of hydrogen is converted into helium, the hydrogen/helium ratio becomes $X/Y = (0.7 - 0.1)/(0.28 + 0.1) = 1.6$. If, in addition, a fraction of 10% of the envelope mass is dredged up and mixed into the envelope, the above envelope composition is further changed to $X = 0.545$, $Y = 0.345$, and $X_{\text{CNO}} + X_{\text{Ne}} + Z = 0.11$. This is very consistent with the observational results by Vanlandingham et al. (1997) and Schwarz et al. (2007) in Table 2.

Figure 7. UV 1455 Å light-curve fitting for V838 Her. Large open circles with error bar: observed UV 1455 Å flux and root mean square of errors (units of the left-hand side axis). Three different sets of chemical composition are assumed. (a) $X = 0.55, X_{\text{CNO}} = 0.03, X_{\text{Ne}} = 0.07$, and $Z = 0.02$, (b) $X = 0.65, X_{\text{CNO}} = 0.03, X_{\text{Ne}} = 0.03$, and $Z = 0.02$, and (c) $X = 0.35, X_{\text{CNO}} = 0.2, X_{\text{Ne}} = 0.1$, and $Z = 0.02$. The WD mass is attached to each light curve. Theoretical flux $F_{\lambda}$ is presented for an arbitrarily assumed distance of 1.0 kpc and no absorption (the scale in the right-hand side is for normalized arbitrarily). For other curves scales are normalized arbitrarily.

(A color version of this figure is available in the online journal.)

$X_{\text{Ne}} = 0.03$, and $Z = 0.02$, expressing less enrichment of heavy elements such as in V382 Vel and QU Vul, and the second case is $X = 0.35$, $Y = 0.33$, $X_{\text{CNO}} = 0.2$, $X_{\text{Ne}} = 0.1$, and $Z = 0.02$ which may be an extreme case of metal enrichment for V838 Her but appropriate composition for V1974 Cyg and V351 Pup, although abundance estimates are very different among different authors (see Table 1 in Paper I which lists observational estimates of abundance of nova ejecta).

The latter two recent determinations both indicate an excess of helium with respect to hydrogen, i.e., $X/Y = 1.9$ (Vanlandingham et al. 1997) and 1.8 (Schwarz et al. 2007), against the solar value of 0.7/0.28 = 2.58. In massive WDs, about one-tenth of hydrogen is consumed by nuclear burning to produce thermal and gravitational energy during the early phase of the outburst (Politano et al. 1995; Prihlik & Kovetz 1995). Supposing that $\Delta X = 0.1$ of hydrogen is converted into helium, the hydrogen/helium ratio becomes $X/Y = (0.7 - 0.1)/(0.28 + 0.1) = 1.6$. If, in addition, a fraction of 10% of the envelope mass is dredged up and mixed into the envelope, the above envelope composition is further changed to $X = 0.545$, $Y = 0.345$, and $X_{\text{CNO}} + X_{\text{Ne}} + Z = 0.11$. This is very consistent with the observational results by Vanlandingham et al. (1997) and Schwarz et al. (2007) in Table 2.
Figure 9. Same as Figure 8, but for logarithmic time. The AAVSO data (small dots) are plotted only until day 68, because after that time the nova becomes fainter than 14 mag, i.e., the brightness of a closeby star. The optical data for the late phases (filled squares) are taken from Ingram et al. (1992) and Szkody & Ingram (1994). The IR data denoted by the asterisk are taken from Harrison & Stringfellow (1994). The emergence time of companion for the 1.35 $M_\odot$ WD model (day 9) and the first eclipse observation (day 21) are also indicated by the small and large downward arrows.

(A color version of this figure is available in the online journal.)

Figure 8 reports the model fits to the visual and IR light curves for the standard composition set. We have assumed that, at these wavelengths, the light curve is dominated by free–free emission (i.e., can be calculated from Equation (1)). Since its shape does not depend on wavelength, one can apply the same light-curve model to the optical and IR data. Figure 8 shows indeed that, if suitably upward shifted, the optical light curve also fits the IR fluxes, at least until day 6, when an IR flux minimum was reached (indicated as a vertical dashed line in Figure 8), owing to thermal emission from dust (see Sections 1 and 5).

Figure 9 provides, in logarithmic time, another view of the model fit to the data. This figure shows that, at very late phases, optical and IR fluxes decay along with the $F_\lambda \propto t^{-3}$ line as predicted from Equation (2). This circumstance does not bring, however, any information on the WD mass. As shown in Figures 8 and 9, among models with the WD mass of 1.33, 1.35, and 1.37 $M_\odot$, the 1.35 $M_\odot$ WD provides a best-fit representation of the UV light curves as well as the optical and IR light curves.

Figures 10 and 11 show the model fits for the other two sets of chemical composition. In Figure 10, we get the best-fit models of 1.35 $M_\odot$ WD from fitting optical, IR and UV fluxes. In Figure 11, however, we cannot fit both of the UV and optical fluxes simultaneously. When we fit the optical, the model UV flux rises too earlier, and then we cannot obtain a good fit in the UV. This indicates that the assumed composition, i.e., $X = 0.35$, $X_{\text{CNO}} = 0.2$, and $X_{\text{Ne}} = 0.1$ is too metal rich and not appropriate for V838 Her.

To summarize we may conclude that the WD mass is $M_{\text{WD}} = 1.35 \pm 0.02 M_\odot$. The model parameters and the main results are summarized in Table 3.

5. DISCUSSION

5.1. “Optical Drop” in Woodward et al. (1992)

Woodward et al. (1992) and Harrison & Stringfellow (1994) claimed that the rise of IR fluxes starting on JD 2,448,346 (day 6) was accompanied by a sudden drop of the visual magnitude by $\Delta V \sim 0.9$. Woodward et al. (1992) proposed that the sudden drop of the visual flux was caused by an optically thick clump of matter ejected toward the earth on day 6 (indicated by the vertical dotted line in Figure 12). Afterwards, the optical flux continued to decline but at a substantially lower level than extrapolated from the light curve of previous days, shown by a dash-dotted line in Figure 12 (which mimics the dashed curve in Figure 1 of Woodward et al. 1992).

The visual magnitudes used by Woodward et al. (1992) and by Harrison & Stringfellow (1994) were taken from IAU Circulars. These data were, however, obtained by different observers. We have tested self-consistency of the different sets by connecting the data obtained by the same observer (Figure 12). It clearly appears from the figure that there are systematic differences between the data sets from different observers, and also that no observer reported the sudden drop at JD 2,448,346, in agreement with the smooth decline shown by the homogeneous set of the IUE $V_{\text{FES}}$ magnitudes, also given in the same figure. Moreover, the magnitudes corresponding to just before and after
IUE V = digit number, the magnitude should dropped by 0.006 day observers. If we take the reported observation time as a three-March 30.466 UT, respectively, which are obtained by different the sudden drop are 8.5 mag at March 30.46 UT and 9.54 mag at 1683

Table 3
Summary of the Present Model

| Subject                | Units | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|-----------------------|-------|---------|---------|---------|---------|---------|
| Outburst day (t₀)     | JD    | 2,448,340 | ←       | ←       | ←       | ←       |
| E(B−V)                |       | 0.53    | ←       | ←       | ←       | ←       |
| H                    |       | 0.55    | ←       | ←       | 0.65    | 0.35    |
| Y                    |       | 0.33    | ←       | ←       | 0.27    | 0.33    |
| CNO                   |       | 0.03    | ←       | ←       | 0.03    | 0.2     |
| Ne                   |       | 0.07    | ←       | ←       | 0.03    | 0.1     |
| Z                    |       | 0.02    | ←       | ←       | ←       | ←       |
| Distance from UV fit  | kpc   | 2.7     | 2.7     | 2.6     | 2.6     | 2.8     |
| Mₓ,max from UV fit    | mag   | −8.41   | −8.40   | −8.32   | −8.32   | −8.48   |
| WD envelope mass      | Mₓ    | 2.5 × 10⁻⁶ | 2.9 × 10⁻⁶ | 3.5 × 10⁻⁶ | 2.6 × 10⁻⁶ | 2.9 × 10⁻⁶ |
| Mass lost by winds    | Mₓ    | 2.3 × 10⁻⁶ | 2.6 × 10⁻⁶ | 3.0 × 10⁻⁶ | 2.2 × 10⁻⁶ | 2.5 × 10⁻⁶ |
| Wind phase            | days  | 37      | 52      | 68      | 58      | 39      |
| Secondary mass        | Mₓ    | 0.76a   | ←       | ←       | ←       | ←       |
| Separation            | Rₓ    | 2.4     | 2.4     | 2.4     | 2.4     | 2.4     |
| Rₓ₁                   |       | 1.0     | 1.0     | 1.0     | 1.0     | 1.0     |
| Rₓ₂                   |       | 0.8     | 0.8     | 0.8     | 0.8     | 0.8     |
| Companion’s emergence | days  | 10      | 15      | 19      | 15      | 14      |

Note. a Estimated from Equation (10).

5.2. Dust Formation: Comparison with V1668 Cyg

After the local minimum on day 6, the IR fluxes increased to reach a local maximum around day 12 (in the H band), being ascribed to thermal emission from an optically thin dust shell (Chandrasekhar et al. 1992; Woodward et al. 1992; Kidger & Martinez-Roger 1993; Harrison & Stringfellow 1994). As shown in Figure 8, however, there is no clear evidence for a corresponding decrease in the UV fluxes. In this subsection, we make a comparison with nova V1668 Cyg in order to understand to what extent dust absorption can cause significant effects on the UV and optical fluxes in the case of V838 Her.

V1668 Cyg is a well-studied moderately fast nova. It developed an optically thin dust shell giving rise to the IR second maximum ~60 days after the optical peak (Stickland et al. 1981). In correspondence with the second IR maximum, the UV 1455 Å flux suddenly dropped by 1/2 ~ 1/3 of what expected from a linear decline law (Kato & Hachisu 2007). The evolution of V1668 Cyg (t₁ ~ 23 days) was much slower than that of V838 Her, due to its smaller WD mass (~ 0.95 Mₓ, see Paper I). Consequently, the ejected mass of V1668 Cyg is expected to be much larger than that of V838 Her. Namely, since the ejected mass of V1668 Cyg is estimated to be 5.8 × 10⁻⁵ Mₓ (Kato & Hachisu 2007), while we estimate that it was 2–3 × 10⁻⁶ Mₓ for V838 Her from our best-fit models (see Table 3). One should thus expect that the dust mass of V838 Her was roughly 10 times smaller.

Observationally, Gehrz et al. (1980) estimated for V1668 Cyg the mass of dust (condensed carbon) to be 2.5 × 10⁻⁸ Mₓ and shell mass of hydrogen to be 2 × 10⁻⁷ Mₓ, which is consistent with the above value of total ejecta mass 5.8 × 10⁻⁵ Mₓ.

Figure 12. Optical and IR light curves. The optical data are shown separately to assess their homogeneity. From bottom to top, IAUC+3: data from IAU Circulars, shifted by 3 mag downward, in which all the data are connected along the reported observing time. IAUC: same data of IAU Circulars but are connected between points only obtained by the same observer. IAUC+3: data connected by a dashed line (shifted 2 mag upward). K − 1 and H − 1.5: IR K and H data, shifted by 1.0 and 1.5 mag upward, respectively. The time of the “drop in optical magnitude” proposed by Woodward et al. (1992) is indicated with a vertical dashed line, and their “unabsorbed light curve” with a dot-dashed line.

(A color version of this figure is available in the online journal.)

The sudden drop are 8.5 mag at March 30.46 UT and 9.54 mag at March 30.466 UT, respectively, which are obtained by different observers. If we take the reported observation time as a three-digit number, the magnitude should dropped by 0.006 day = 8.6 minutes. This is too short to have some significant change in stellar luminosity. Therefore, we conclude that the claimed V magnitude drop is an artifact caused by connecting the different data set with systematic difference.

Should the 0.9 mag optical drop be real and due to dust absorption from a clump of matter ejected along the line of sight, one would expect to observe a simultaneous strong absorption of the UV flux. The decrease in the UV flux is estimated to be a factor of 10^(8.3/3.1) × 9 = 257. Figure 8 shows, however, no indication of such a drastic decrease in the UV flux.
Also, Chandrasekhar et al. (1992) estimated the total grain mass of V838 Her to be $1.6 \times 10^{-8} M_\odot$ assuming distance of $d = 8.3$ kpc. As the mass estimate is proportional to $d^2$, where $d$ is the distance to the star, this corresponds to $1.7 \times 10^{-9} M_\odot$ for $d = 2.7$ kpc here adopted (see Section 5.3 below). Harrison & Stringfellow (1994) estimated the dust mass of V838 Her to be $1.1 \times 10^{-8} M_\odot$ at dust shell maximum for $d = 5.5$ kpc, which is proportional to the IR luminosity, therefore, a smaller value $2.7 \times 10^{-9} M_\odot$ is derived for $d = 2.7$ kpc.

In any case, the dust mass of V838 Her appears to be one-tenth of the dust mass of V1668 Cyg, a value that is not expected to affect significantly the UV fluxes even at the time of the second IR maximum, explaining then the absence of any quick drop in the UV 1455 Å light curve.

### 5.3. Distance

The interstellar extinction and the distance were estimated with various methods (Harrison & Stringfellow 1994; Vanlandingham et al. 1996, for summary), the values of which are largely scattered as $E(B - V) = 0.3 - 0.6$ and $d = 2.8 - 10$ kpc (see Table 1). One of the typical ways to estimate the distance is to use $t_3$ time or using statistical properties such as a given magnitude at a certain stage of light curve.

Let us begin with the distance estimate using the Maximum Magnitude versus Rate of Decline (MMRD) law. The absolute $V$ magnitude at maximum $M_{V, \max}$ can be estimated from the $t_3$ time through Schmidt–Kaler’s MMRD relation (Schmidt 1957):

$$M_{V, \max} = -11.75 + 2.5 \log t_3.$$

Then the distance is obtained from

$$(m - M)_{V, \max} = -5 + 5 \log d + 3.1 E(B - V),$$

if $E(B - V)$ is known. If we adopt $t_3 = 5.3$ from the optical maximum of $m_V = 5.4$ (Harrison & Stringfellow 1994), this equation gives $M_V = -9.94$. With the apparent visual magnitude of $m_V = 5.4$ and $E(B - V) = 0.53$, we get $d = 5.49$ kpc. If $E(B - V)$ is not fixed, we have

$$(m - M)_{V, \max} = -5 + 5 \log d + 3.1 E(B - V) = 15.34,$$

which is plotted in Figure 13 (labeled “MMRD1”).

The Schmidt–Kaler law (Equation (3)) yields a bit larger magnitudes for a faster nova. Della Valle & Livio (1995) derived the following MMRD relation which is a good representation of fast novae:

$$M_{V, \max} = -7.92 - 0.81 \arctan \frac{1.32 - \log(t_3)}{0.23}.$$  (6)

For $t_3 = 1.4$ (Harrison & Stringfellow 1994), this equation gives $M_V = -9.04$. With the apparent visual magnitude of $m_V = 5.4$ and $E(B - V) = 0.53$, we get $d = 3.6$ kpc. If $E(B - V)$ is not fixed, we have

$$(m - M)_{V, \max} = -5 + 5 \log d + 3.1 E(B - V) = 14.44,$$

which is plotted in Figure 13 (labeled “MMRD2”).

Another way to estimate the distance to V838 Her comes from comparing the observed light curve of 1455 Å band with the corresponding model fluxes (see Paper I; Paper III; Kato & Hachisu 2005, 2007). We show that the calculated flux at $\lambda = 1455$ Å at a distance of 1 kpc for Model 2 is $F_{\lambda}^{mod} =$...
for the distance to V838 Her, which is \( d > 2.46 \) kpc for the particular value of \( E(B - V) = 0.53 \).

As shown in Table 1, the distances in literature are very scattered. The distance obtained from MMRD tends to be larger than ours as shown in Figure 13. Starrfield et al. (1992) obtained a distance of \( \sim 3.4 \) kpc and \( E(B - V) \sim 0.6 \) from the comparison of total UV flux (LWP/SWP) including both of line and continuum emission with that of nova LMC 1991 showing a similar spectrum development. This is similar but contrasted to our method in the sense that we use only continuum emission around 1455 Å and compare it with the theoretical value. Their value \( \sim 3.4 \) kpc is larger than ours, but closer than other estimates using the MMRD relation.

### 5.4. Emergence of the Companion

In the early phase of the outburst, the photosphere of the WD envelope extends beyond the size of the binary orbit. The companion is deeply embedded inside the WD photosphere. After maximum expansion, the photospheric radius shrinks owing to wind mass loss. We can estimate the epoch when the companion appears from the photosphere.

From Warner’s (1995, p.111) empirical formula the mass of the donor star (companion) is expressed as

\[
\frac{M_2}{M_\odot} \approx 0.065 \left( \frac{P_{\text{orb}}}{\text{hr}} \right)^{5/4}, \text{ for } 1.3 < \frac{P_{\text{orb}}}{\text{hr}} < 9, \tag{10}
\]

which gives \( M_2 = 0.76 M_\odot \) for \( P_{\text{orb}} = 0.2976 \) days (7.14 hr), in good agreement with the value \( M_2 = 0.73-0.75 M_\odot \) obtained by Szkody & Ingram (1994), although they could not well constrain the mass of the primary component \( (M_{\text{WD}} > 0.62 M_\odot) \).

The binary separation is obtained from Kepler’s law to be \( a = 2.41 R_\odot \) for \( M_{\text{WD}} = 1.35 M_\odot \). The effective radius of the Roche lobe is \( R_1^* = 1.0 R_\odot \) for the primary component (WD), and \( R_2^* = 0.80 R_\odot \) for the secondary. Here we use an empirical formula of \( R_1^* \) and \( R_2^* \) given by Eggleton (1983). In our model, the companion emerges from the WD envelope when the photospheric radius of the WD shrinks to \( R_{\text{ph}} \sim 3.2 R_\odot \) (the separation plus \( R_2^* \)), \( \sim 2.4 R_\odot \) (the separation), or \( 1.6 R_\odot \) (the separation minus \( R_1^* \)). This occurs on days 7, 9, and 11, respectively, in our Model 2. The emergence time of the companion (the central time) is shown in Table 3 and also indicated by a small arrow in Figures 9, 10, and 11. As the eclipse is due to the occultation of the WD, or of the central part of the accretion disk by the companion, the eclipse must occur after the above three epochs of emergence. Our estimated time of companion emergence is a rough estimate, but it is well before the first eclipse observation (day 21), so consistent with observation.

### 5.5. Mass Determination from the Duration of the 1455 Å Maximum

The duration of a UV nova outburst, as measured by the full width at half-maximum \( t_{\text{FWHM}} \) of the 1455 Å light curve (Cassatella et al. 2002) is tightly correlated with the nova decay time \( t_1 \) which, in turn, is a primary indicator of the WD mass (Livio 1992). Detailed model calculations by Hachisu & Kato (2006) have confirmed the primary dependence of \( t_{\text{FWHM}} \) on \( M_{\text{WD}} \) and have shown, in addition, that there is secondary, weaker, dependence on chemical composition. These results imply that the duration of a UV nova outburst can be used as a useful tool to estimate the WD mass in nova systems.

In Figure 14, we compare the theoretical relation of \( t_{\text{FWHM}} \) versus WD mass (Hachisu & Kato 2006) with those obtained from the measured values of \( t_{\text{FWHM}} \) (Cassatella et al. 2002) and from the WD masses of seven classical novae, including V838 Her, estimated from the previous works (namely, from Paper I for V1668 Cyg and V1974 Cyg; from Kato & Hachisu 2007) for V351 Pav, OS And, and V693 CrA, and from this paper for V838 Her). We adopt Model 2. For GQ Mus, we used the results in Paper III. For V1668 Cyg and V1974 Cyg, the results in Paper I. For V351 Pav, OS And, and V693 CrA, the results in Kato & Hachisu (2007). Novae named in the upper side of the figures are Ne novae whereas those in the lower side are CO novae.

(A color version of this figure is available in the online journal.)
formation took place shortly after the UV 1455 Å maximum, so making the measured $r_{\text{FWHM}}$ significantly smaller than expected. In the case of V838 Her, in spite of being a dust forming nova, the mass of dust was too small to affect the UV light curve, as discussed in Section 5.2.

Note that the mass determination of our light-curve analysis is based not only on the UV data fittings, but also on the optical and IR fittings, so the error in UV fitting does not directly reflect to the resultant $M_{\text{WD}}$.

Figure 14 indicates that less-massive WDs ($\lesssim 1 M_\odot$) are systematically CO-rich, while more-massive WDs ($\gtrsim 1 M_\odot$) are neon-rich. It has been argued that heavy element enrichment of nova ejecta is caused by dredge-up of WD core material so that, for example, C and O enrichment is an indication of a CO WD. An ONe WD is born in massive stars after ignition of a CO core and, therefore, ONe WDs are usually more massive than CO WDs when they are just born. Our results are consistent with this.

The mass boundary of CO WDs and ONe WDs is suggested to be 1.0–1.1 $M_\odot$. Iben (1990) summarized that a star of initial mass 5–10 $M_\odot$ leaves a CO WD of mass 0.75–1.1 $M_\odot$ and a star of 10–12 $M_\odot$ becomes ONe WD. García-Berro et al. (1997) calculated stellar evolution of 9 $M_\odot$ star which finally becomes a $\sim 1.08 M_\odot$ ONe core surrounded by a CO envelope of $\sim 0.08 M_\odot$. Umeda et al. (1999) calculated stellar evolution until CO core ignition with fine grid of initial stellar mass and concluded that the mass of CO WDs born in binaries is less massive than 1.07 $M_\odot$ of which initial mass is $\sim 8 M_\odot$ for $Z = 0.02$. Meng et al. (2008) obtained CO core mass consistent with Umeda et al.’s value. These predictions are consistent with our results in Figure 14.

5.6. X-ray Observations

X-ray emission from V838 Her has been detected with ROSAT as early as 5 days after the discovery (Lloyd et al. 1992; O’brien et al. 1994), and was found to be consistent with emission from shocked plasma with $T \sim 10$ keV (O’brien et al. 1994). According to these authors, the shock could originate from within the ejected material itself or by interaction of the ejecta with pre-existing circumstellar matter. In our Model 2, the optically thick wind lasts until day $\sim 52$ days (see Table 3 for other models); this is consistent with the picture that the wind collides with circumstellar matter to produce the observed X-ray flux.

5.7. Quiescent Phase

The presence of an accretion disk has been suggested from the long duration of the eclipse (Ingram et al. 1992), and from the depth of eclipse at minimum (Leibowitz 1993). The absolute magnitude of a disk, seen at an inclination angle $i$, is approximated by

$$M_V(\text{obs}) = -9.48 - \frac{5}{3} \log \left( \frac{M_{\text{WD}}}{M_\odot} \right) \left( \frac{M_{\text{acc}}}{M_\odot \text{yr}^{-1}} \right)$$

$$- \frac{5}{2} \log (2 \cos i),$$

where $M_{\text{WD}}$ is the WD mass and $M_{\text{acc}}$ is the mass accretion rate (Equation (A6) in Webbink et al. 1987). Szkody & Ingram (1994) estimated the inclination of the disk to be $i = 78^\circ - 90^\circ$. Assuming $M_{\text{WD}} = 1.35 M_\odot$ and $i = 80^\circ$, we get $M_V = 6.5$, 4.8, and 3.1 for the mass accretion rates of $1 \times 10^{-9}$, $1 \times 10^{-8}$, and $1 \times 10^{-7} M_\odot \text{yr}^{-1}$, respectively. The corresponding apparent magnitudes, as calculated from Equation (4) with $E(B-V) = 0.53$ and $d = 2.7$ kpc are $m_V = 20.3$, 18.6, and 16.9. Considering the ambiguity of assumed accretion rates and the inclination angle, these values are consistent with the preoutburst magnitude reported in Section 1.

The contribution of a companion star to the quiescent luminosity is estimated as follows. Patterson (1984) gives an empirical relation between the absolute magnitude of a Roche lobe filling companion and its orbital period as

$$M_V = 22 - 17.46 \log P(\text{hr}),$$

for $0.7 < \log P(\text{hr}) < 1.1$. For $P(\text{hr}) = 7.14$ hr (Ingram et al. 1992; Leibowitz et al. 1992) we get $M_V = 7.1$ and $m_V = 20.6$. Thus, the companion star would be fainter than the accretion disk although there are ambiguity in the mass accretion rate and the inclination angle. This is also consistent with a faint companion suggested from a small upper limit of $\sim 0.05$ mag on the depth of the secondary minimum (Leibowitz 1993) and from no visible evidence in the spectrum (Szkody & Ingram 1994).

6. CONCLUSIONS

We have applied the “universal decline law” of classical novae described in Section 3.3 to one of the fastest novae V838 Her and derived various parameters. Our main results are summarized as follows.

1. An analysis of the IUE reprocessed data of V838 Her indicates $E(B-V) = 0.53 \pm 0.05$.
2. The $1.35 \pm 0.02 M_\odot$ WD model reasonably reproduces the light curves of V838 Her both in the optical and in the UV 1455 Å band as well as in the IR $H$ and $K$ bands at the early stages, until dust formation takes place. Model 2 in Table 3 is the best-fit model.
3. The distance is estimated to be $d \sim 2.7 \pm 0.5$ kpc from the UV 1455 Å light-curve fitting.
match is excellent for the y light curve, because this band is little contaminated by strong emission lines (Hachisu et al. 2008). As one may appreciate from the figure, there is a good overlap between the light curves of V1668 Cyg (y-magnitude, connected by solid line), V1500 Cyg (y-magnitude), and the initial phase of V1974 Cyg (V magnitude). It also appears from the figure that, whenever strong emission lines provide the dominant contribution to the magnitude, the data deviate above the V1668 Cyg line. In the case of V838 Her the data are scattered compared with the above three objects, therefore, we fit its lowest boundary of the data with the V1668 Cyg line. We can see excess of the visual magnitudes between day 3 and day 6.

Four UV 1455 Å light curves also show a good agreement with each other, although V1668 Cyg shows a drop at 0.37 in the normalized time due to dust formation (Gehrz et al. 1980). We do not see any indication of sharp drop like this in V838 Her.

APPENDIX

Figure 16 demonstrates a “universality” of nova light curves, in which five classical novae are shown in the visual (V and y) and UV 1455 Å band (except V1500 Cyg: no UV 1455 Å band is available). Each peak of the UV 1455 Å flux is normalized in order to match the peak of V838 Her. Also, the timescale of each nova is normalized so that each UV 1455 Å light curve is overlapped with that of V838 Her. The same normalizing factor is applied to both the UV and the optical light curves. These normalizing factors, obtained by eye fitting, are summarized in the figure caption.

Our universal decline law predicts that the light curves, normalized in this way, should merge into one, independent of the WD mass and chemical composition (see Paper I). This

Figure 16. Scaling of five nova light curves. The observed light curve of classical novae, V693 CrA, V1974 Cyg, V1668 Cyg, and V1500 Cyg are overlapped to that of V838 Her. For V838 Her only the optical data in IAU Circulants and IUE V838s data are shown. Optical data are y magnitudes for V1668 Cyg (connected by a solid line) and V1500 Cyg, V for V1974 Cyg (for the references, see Paper I), V and visual for V693 CrA (Kato & Hachisu 2007). The scale for the UV Flux (on the left-hand side), the magnitude, and the time after outburst refer to V838 Her. The scale of the other nova is normalized as follows: the upper limit in the UV flux scale (in erg s⁻¹ cm⁻² Å⁻¹), the lower limit in the magnitude, the upper limit in the magnitude, and the timescale normalized to unity (abscissa) have been set to (3.9E⁻¹2, 16.8, 1.8, 25) for V838 Her, (1.9E⁻¹2, 18, 3, 54) for V693 CrA, (4.4E⁻¹1, 14.8, 0.2, 202) for V1974 Cyg, (4.4E⁻¹2, 18, 3, 200) for V1668 Cyg, and (no data, 16.1, 1.1, 162.8) for V1500 Cyg.

(A color version of this figure is available in the online journal.)

4. We have estimated ejecta mass ΔMₚₜₜld ~ (2–3) × 10⁻⁶ M☉ lost by winds.

The authors are grateful to Takashi Iijima for fruitful discussion, and also to the anonymous referee for useful comments to improve the manuscript. We also thank the American Association of Variable Star Observers (AAVSO) for the visual data of V838 Her. This research has been supported in part by the Grant-in-Aid for Scientific Research (20540227) of the Japan Society for the Promotion of Science.

REFERENCES

Alcock, G. 1991, IAU Circ.No. 5222
Cassatella, A., Altamore, A., & González-Riestra, R. 2002, A&A, 384, 1023
Cassatella, A., Altamore, A., & González-Riestra, R. 2005, A&A, 439, 205
Cassatella, A., González-Riestra, R., & Selvelli, P. 2004a, INES Access Guide No. 3 Classical Novae (Noordwijk: ESA)
Cassatella, A., Lamers, H. J. G. L. M., Rossi, C., Altamore, A., & González-Riestra, R. 2004b, A&A, 420, 571
Chandrasekhar, T., Ashok, N. M., & Ragland, S. 1992, MNras, 255, 412
Della Valle, M., & Livio, M. 1995, ApJ, 452, 704
Della Valle, M., & Evans, A., et al. 2003, AJ, 126, 368
Evans, A., et al. 2003, AJ, 126, 1891
García-Berro, E., Ritossa, C., & Iben, I., Jr. 1997, ApJ, 485, 765
Gehrz, R. D., Hackwell, J. A., Grasdalen, G. L., Ney, E. P., Neugebauer, G., & Seligren, K. 1980, ApJ, 239, 570
Grevesse, N., & Anders, E. 1989, in Cosmic Abundances of Matter, ed. C. J. Waddington (Melville, NY: AIP), 1
Greene, A. & M. R., & Lamers, H. J. G. L. M. 1989, A&A, 79, 359
Hachisu, I., & Kato, M. 2006, ApJS, 167, 59, (Paper I)
Hachisu, I., & Kato, M. 2009, ApJ, 694, L103
Hachisu, I., Kato, M., & Cassatella, A. 2008, ApJ, 687, 1236 (Paper III)
Hachisu, I., Kato, M., & Luna, G. J. M. 2007, ApJ, 659, L153
Hachisu, I., Kato, M., & Nomoto, K. 1999, ApJ, 522, 487
Harrison, T. E., & Stringfellow, G. S. 1994, ApJ, 437, 827
Hauschildt, P. H., Shore, S. N., Schwarz, G. J., Baron, E., Starrfield, S., & Allard, F. 1997, ApJ, 490, 803
Humphreys, R. M., Zunach, W., & Stockwell, T. 1991, IAU Circ.No. 5224
Iben, I., Jr. 1990, in ASP Conf. Proc. 11, Confrontation between Stellar Pulsation and Evolution, ed. C. Cacciari & G. Clementini (San Francisco, CA: ASP), 483
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Iijima, T., & Cassatella, A. 2009, A&A, submitted
Ingram, D., Garnavich, P., Green, P., & Skzody, P. 1992, PASP, 104, 402
Kato, M. 1983, PASJ, 35, 507
Kato, M. 1997, ApJS, 113, 121
Kato, M. 1999, PASJ, 51, 525
Kato, M., & Hachisu, I. 1994, ApJ, 437, 802
Kato, M., & Hachisu, I. 2005, ApJ, 633, L117
Kato, M., & Hachisu, I. 2007, ApJ, 657, 1004
Kato, M., Hachisu, I., Kiyota, S., & Saito, H. 2008, ApJ, 684, 1366
Kato, T., & Hirata, R. 1991, IAU Circ.No. 5262
Kidger, M. R., & Martinez-Roger, C. 1993, A&A, 267, 644
Lamers, H. J. G. L. M., Cerruti-Sola, M., & Perinotto, M. 1987, ApJ, 314, 726
Leibowitz, E. M. 1993, ApJ, 411, L29
Leibowitz, E. M., Mendelson, H., & Mashal, E. 1992, ApJ, 385, 49
Livio, M. 1992, ApJ, 409, 803
Lynch, D. K., Hackwell, J. A., & Russell, R. W. 1992, ApJ, 398, 632
Matheson, T., Filippenko, A. V., & Ho, L. C. 1993, ApJ, 418, L29
Meng, X., Chen, X., & Han, Z. 2008, A&A, 487, 625
Neckel, Th., & Klar, G. 1980, A&AS, 42, 251
O'Brien, T. J., Lloyd, M. H., & Bode, M. F. 1994, MNRAS, 271, 155
Patterson, J. 1984, ApJS, 54, 443
Politano, M., Starrfield, S., Truran, J. W., Weiss, A., & Sparks, W. M. 1995, ApJ, 448, 807
Prialnik, D. 1986, ApJ, 310, 222
Prialnik, D., & Kovetz, A. 1995, ApJ, 445, 789
Schmidt, Th. 1957, Z. Astrophys., 41, 181
Schwarz, G. J., Shore, S. N., Starrfield, S., & Vanlandingham, K. M. 2007, ApJ, 657, 453
Seaton, M. J. 1979, MNRAS, 187, 73
Smith, C. H., Aitken, D. K., Roche, P. F., & Wright, C. M. 1995, MNRAS, 277, 259
Starrfield, S., Shore, S. N., Sparks, W. M., Sonneborn, G., Truran, J. W., & Politano, M. 1992, ApJ, 391, L71
Stickland, D. J., Penn, C. J., Seaton, M. J., Snijders, M. A. J., & Storey, P. J. 1981, MNRAS, 197, 107

Sugano, M. 1991, IAU Circ.No. 5222
Szkody, P., & Hoard, D. W. 1994, ApJ, 429, 857
Szkody, P., & Ingram, D. 1994, ApJ, 420, 830
Ueta, E. 1991, IAU Circ.No. 5265
Umeda, H., Nomoto, K., Yamaoka, H., & Wanajo, S. 1999, ApJ, 513, 861
Vanlandingham, K. M., Starrfield, S., & Shore, S. N. 1997, MNRAS, 290, 87
Vanlandingham, K. M., Starrfield, S., Wagner, R. M., Shore, S. N., & Sonneborn, G. 1996, MNRAS, 282, 563
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)
Webbink, R. F., Livio, M., Truran, J. W., & Orio, M. 1987, ApJ, 314, 653
West, R. M. 1991, IAU Circ.No. 5224
Woodward, C. E., Gehrz, R. D., Jones, T. J., & Lawrence, G. F. 1992, ApJ, 384, L41