A LIGHT-CURVE MODEL OF THE SYMBIOTIC NOVA PU Vul (1979): A VERY QUIET EXPLOSION WITH LONG-LASTING FLAT PEAK

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Received 2010 July 17; accepted 2010 November 14; published 2011 January 4

ABSTRACT

We present a light-curve model of the symbiotic nova PU Vul (Nova Vulpeculae 1979) that shows a long-lasting flat peak with no spectral indication of wind mass loss before decline. Our quasi-evolution models consisting of a series of static solutions explain both the optical flat peak and ultraviolet (UV) light curve simultaneously. The white dwarf mass is estimated to be $\sim 0.6 M_\odot$. We also provide a new determination of the reddening, $E(B-V) = 0.43 \pm 0.05$, from UV spectral analysis. Theoretical light-curve fitting of UV 1455 Å provides the distance of $d = 3.8 \pm 0.7$ kpc.

Key words: binaries: symbiotic – novae, cataclysmic variables – stars: individual (PU Vul) – ultraviolet: stars – white dwarfs

Online-only material: color figures

1. INTRODUCTION

PU Vul was independently discovered by Y. Kuwano (Kozai 1979a) and M. Honda (Kozai 1979b) as a nova-like object. Subsequent observations revealed that PU Vul did not behave like a classical nova in its photometric and spectroscopic properties. After the rise to optical maximum, PU Vul maintained an almost stable maximum of $V = 8.6$ from 1979 to 1987 except for a deep minimum in 1980. It started to fade in 1988 very slowly toward the prediscov ery magnitude of $B = 14.5$–16.6 (Liller & Liller 1979) and the photographic magnitude $m_{pg} = 15.0$–16.5 (Yamashita et al. 1982). Such a long-lasting flat peak and a very slow evolution of the light curve made this object quite different from ordinary novae. PU Vul was recognized to be a binary system consisting of an M giant and an outbursting component (Belyakina et al. 1982a; Friedjung et al. 1984), with the outburst a thermonuclear runaway event on a white dwarf (WD) in a symbiotic binary (Kenyon 1986). There were debates on the origin of the deep minimum that occurred in 1980 (see discussion in Kenyon 1986). After the second eclipse in 1994, it has been clear that PU Vul is an eclipsing binary with an orbital period of 13.4 yr. The observational properties are summarized in Table 1, which shows the discovery date, nova speed class, remarkable property of the light curve, indication of dust formation, observational evidence of eclipse, orbital period, peak magnitudes of $m_V$, information of UV 1455 Å continuum-band light curve obtained from fitting of Model 1 (Section 4.1), i.e., peak value and full width at half-maximum (FWHM), extinction in the literature and our estimates, and distance to PU Vul in the literature and our estimates.

The spectral development of PU Vul was extensively studied by various authors (Yamashita et al. 1982, 1983; Iijima & Ortolani 1984; Belyakina et al. 1989; Gochermann 1991; Kanamitsu 1991a; Kanamitsu et al. 1991b; Tamura et al. 1992; Klein et al. 1994). The spectra mimicked those of an F supergiant (Yamashita et al. 1982; Kanamitsu 1991a) in the early phase and changed to A0 (Belyakina et al. 1989; Vogel & Nussbaumer 1992) from 1983 to 1986 as the excitation temperature gradually increased (Kanamitsu et al. 1991b). Yamashita et al. (1982) commented that the eruption must have been quite soft because no evidence of shell ejection, both in the emission lines and shell absorption lines, was detected. The optical spectrum was strongly absorption-dominated until 1985 but changed to a distinct nebular spectrum in the second half of 1987 (Iijima 1989; Kanamitsu et al. 1991b). In 1990, the star had shown rich emission lines in the optical and UV spectrum, which are typical in the nebular phase and associated with an extended atmosphere of a WD (Vogel & Nussbaumer 1992; Kanamitsu et al. 1991b; Tomov et al. 1991).

It is very interesting that there is no indication of strong winds in PU Vul in contrast to many other classical novae. Instead, optically thin mass ejection from the WD photosphere was suggested from P Cygni line-profiles (Belyakina et al. 1989; Vogel & Nussbaumer 1992; Sion et al. 1993; Nussbaumer & Vogel 1996) or triple structure of IR emission lines (Bensammar et al. 1991). The line width corresponds to 1100–1200 km s$^{-1}$ in average full widths at zero intensity (Tomov et al 1991), $\sim 2600$ km s$^{-1}$ in Balmer emission wings (Iijima 1989), and 550–600 km s$^{-1}$ in UV spectra (Sion et al. 1993). Mass ejection was also suggested from X-ray emission detected with ROSAT on 1992 November 10–12 UT and interpreted as thermal bremsstrahlung with a temperature of 0.22 keV (2.6 $\times$ 10$^6$ K; Hoard et al. 1996; M"urset et al. 1997). These authors suggested a collisional origin of the X-ray between a high-density, low-velocity cool wind from the M giant and a low-density, high-velocity hot wind from the WD in the context of common properties of symbiotic novae.

To summarize, the outburst of PU Vul was very quiet in the first 10 years, and optically thin mass ejection arises from the WD photosphere. The outburst ended in 1990 as the nova entered a coronal phase. These spectral features as well as the long-lasting flat peak make PU Vul quite different from many other classical novae in which optical magnitude decays quickly from its peak and the spectrum indicates strong optically thick winds. This paper aims to model...
such a quite different evolution of PU Vul and to understand the cause of such properties.

Kato & Hachisu (2009) re-examined the conditions of occurrence of optically thick winds and found that optically thick winds occur in a limited range of the envelope (ignition) mass. For a relatively large envelope mass, optically thick winds are suppressed in such a way that a large density-inversion layer appears and the gas-pressure gradient balances with the radiation-pressure gradient, the driving force of the winds. In massive WDs ($\gtrsim 0.7 M_\odot$), optically thick winds always occur, because the ignition mass of the wind-suppressed solutions are too massive to be realized in the actual novae. In less massive WDs ($\lesssim 0.5 M_\odot$), on the other hand, no winds are accelerated because the radiation-pressure gradient is too weak to drive the winds. In between them, i.e., $0.5 M_\odot \lesssim M_{\text{WD}} \lesssim 0.7 M_\odot$, both types of solutions (wind and wind-suppressed) can be realized depending on the initial envelope mass. For a less massive envelope, optically thick winds are accelerated and a shell flash develops as a normal nova with strong winds. On the other hand, if the initial envelope mass is relatively large, optically thick winds are suppressed and a nova evolves without winds.

Kato & Hachisu (2009) also presented an idea that such wind-suppressed (no optically thick wind) evolution will be realized in a very slow nova that shows a long-lasting flat optical peak. If the optically thick wind occurs, as in many classical novae, the strong winds carry out most of the envelope matter in a short timescale, and the optical brightness quickly decays. Thus, the light curve has a sharp optical peak. On the other hand, in wind-suppressed evolutions, the brightness decays very slowly, because the evolution timescale is determined only by hydrogen nuclear burning. Therefore, the nova stays at a low surface temperature for a long time, which creates the long-lasting flat optical peak. PU Vul is the first example of this new type of evolution.

In Section 2, we review observational results based on the IUE spectra. In Section 3, we briefly introduce our method and assumptions of the theoretical model. Section 4 shows how to estimate the WD mass from light-curve fittings. Discussion and conclusions follow in Sections 5 and 6, respectively.

2. UV OBSERVATIONS

PU Vul had been monitored by IUE from 1979 February to 1983 September and from 1987 October to 1996 September at both low and high resolutions. A gallery of UV SWP spectra from 1992 to 1995 can be found in Nussbaumer & Vogel (1996).

In the following, we revisit the problem of the color excess $E(B-V)$ of PU Vul, and describe the long-term evolution of the emission lines. The evolution of the UV continuum will be described in Section 4.1. The ultraviolet (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 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 previously published UV spectra.

2.1. Reddening Correction

Table 1 shows that the color excess $E(B-V)$ toward PU Vul in the literature lies in the range from 0.3 to 0.5. Given the large spread of these determinations, we have directly determined $E(B-V)$ from the strength of the 2200 Å feature seen in the UV spectra of PU Vul.

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 nine pairs of short and long wavelength IUE spectra taken from JD 2,448,217 to JD 2,450,342, i.e., during the nebular phase, we have in this way found $E(B-V) = 0.43 \pm 0.05$. Examples of IUE spectra of PU Vul corrected with $E(B-V) = 0.43$ are reported in Figure 1.

Table 1

| Subject | Data | Units | Comments |
|---------|------|-------|----------|
| Discovery date | 1979 April 5.82 | UT | Kozai (1979a) |
| Nova speed class | Very slow | | |
| Light curve | Flat peak | | |
| Dust | No | | |
| Eclipse | Yes | | |
| Orbital period | 13.4 | yr | |
| $m_0$ of flat peak | 8.6 | mag | |
| Peak of UV 1455 Å flux | $6.0 \times 10^{-13}$ | erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ | This work: Section 4 |
| FWHM of UV 1455 Å | 4.4 | yr | This work: Section 4 |
| $E(B-V)$ | 0.29–0.5 | | See references$^a$ |
| $E(B-V)$ | 0.43 ± 0.05 | | This work: Section 2.1 |
| Distance | 1.6–7 | kpc | See references$^a$ |
| Distance | 3.8 ± 0.7 | kpc | This work: Section 4.4 |

Notes.

$^a$ $E(B-V) = 0.4$ (Belyakina et al. 1982b), 0.49 (Friedjung et al. 1984), 0.4–0.5 (Kenyon 1986), 0.50 (Gochermann 1991), 0.4 (Vogel & Nussbaumer 1992), and 0.29 (Luna & Costa 2005).

$^b$ $d = 5$–7 kpc (Belyakina et al. 1982b), 5.3 kpc (Belyakina et al. 1984), <5.6 kpc (Gochermann 1991), 1.6–2.0 kpc (Vogel & Nussbaumer 1992), and 2.5 kpc (Hoard et al. 1996).

7 http://sdc.laeff.inta.es/ines/
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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 2885 Å, selected to provide a fairly good representation of the UV continuum because little affected by emission lines (Cassatella et al. 2002). Figure 2 shows the time evolution of the $F(1455 \, \AA)$ and $F(2885 \, \AA)$ fluxes and of the UV color index $C(1455–2885) = -2.5 \log (F(1455 \, \AA)/F(2885 \, \AA))$. The measurements were made on well-exposed low-resolution spectra. The figure shows clearly that the eclipse around JD 2,449,550 endures longer for high than for low ionization lines. This suggests that the high ionization lines are formed in the unseen side of the cool giant’s wind, thus confirming the results by Nussbaumer & Vogel (1996; see their Figure 5), who found that the UV highest excitation lines of He ii λ1640, N v λ1240, and N iv λ1718 disappeared during the second eclipse.

3. MODEL

3.1. Evolution of Nova Outburst

Nova is a thermonuclear runaway event on a WD (Nariai et al. 1980; Prialnik 1986; Starrfield et al. 1972, 1988; José et al. 1998; Prialnik & Kofetz 1995). After unstable hydrogen nuclear burning triggers a nova outburst, the envelope on the WD greatly expands to giant size. After it reaches the optical peak, the envelope expansion settles down into a steady state. The optical magnitude decreases as the envelope mass decreases and the photospheric temperature rises with time. In less massive WDs the optically thick wind does not occur as described in Section 1 and, therefore, the decay phase

Figure 1. IUE spectra of PU Vul obtained at different dates. Fluxes are in units of erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. The spectra have been corrected for reddening using $E(B-V) = 0.43$. The vertical dotted lines represent the wavelengths $\lambda\lambda$ 1512, 1878, and 2386 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 over the full spectral range. Saturated data points in the emission lines are labeled with pluses.

Figure 2. Evolution of the continuum fluxes at 1455 Å and 2885 Å of the UV color index $C(1455–2885)$, and of the V$_{FES}$ visual flux of PU Vul (see Section 2.2). Visual and UV fluxes are both in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, not corrected for reddening. Only the color index has been corrected for reddening using $E(B-V) = 0.43$ (see Section 2.1). The vertical dotted lines indicate the period of the first (JD 2,444,380–2,444,710) and the second (JD 2,449,275–2,449,608) eclipses.

Figure 3 shows, as a function of time, the observed fluxes in the emission lines of C iii] 1909 Å, C iv 1550 Å, N iv] 1487 Å, He ii 1640 Å, and N v 1240 Å, which cover a wide range of ionization conditions (the corresponding ionization energies $\chi_{\text{ion}}$ are 24.4, 47.9, 47.4, 54.4, and 77.5 eV, respectively). The flux measurements were obtained from well-exposed IUE low-resolution spectra. The figure shows clearly that the eclipse around JD 2,449,550 endures longer for high than for low ionization lines. This suggests that the high ionization lines are formed in the unseen side of the cool giant’s wind, thus confirming the results by Nussbaumer & Vogel (1996; see their Figure 5), who found that the UV highest excitation lines of He ii λ1640, N v λ1240, and N iv λ1718 disappeared during the second eclipse.
of novae can be followed by a quasi-hydrostatic sequence (e.g., Iben 1982; Kato & Hachisu 1994, 2009). We solved the equations of hydrostatic balance, radiative diffusion, and conservation of energy from the bottom of the hydrogen-rich envelope through the photosphere. The bottom radius is assumed to be the Chandrasekhar radius. The evolution of novae is followed by connecting these solutions along the envelope mass-decreasing sequence. The time evolution is calculated from the mass decreasing rate which is the summation of two mass-decreasing sequences. The time evolution is calculated to be the Chandrasekhar radius. The evolution of novae is followed by connecting these solutions along the envelope mass-decreasing sequence. The time evolution is calculated from the mass decreasing rate which is the summation of two rates, hydrogen nuclear burning and optically thin wind mass loss. We used OPAL opacities (Iglesias & Rogers 1996). The method and numerical techniques are essentially the same as those in Kato & Hachisu (1994). Convective energy transport is calculated using the mixing-length theory with the mixing-length parameter \( \alpha = 1.5 \) (see Figure 11 in Kato & Hachisu 2009 for the dependence of the model light curve on the mixing-length parameter \( \alpha \)).

In the rising phase, the envelope does not yet settle down to thermal equilibrium, i.e., the nuclear energy generation is larger than the radiative loss. We have approximated such a stage by a sequence of static solutions of constant mass without thermal equilibrium. These solutions may not approximate well the rising phase, but are enough for our purpose, because the rising phase plays no important role in the determination of physical values such as the WD mass and distance.

### 3.2. Wind Mass-loss Rate

In the later phase of the outburst (after 1986), optically thin wind may arise because many emission lines had appeared in the spectra. We cannot calculate such wind mass loss, however, because radiative transfer in the optically thin region is not included in our model calculation. Therefore, we take the wind mass-loss rate as a model parameter. This optically thin wind does not affect the envelope structure below the photosphere, but speeds up the nova evolution because the mass decrease rate of the envelope is accelerated by this wind mass loss.

In line-driven winds, the mass-loss rate \( \dot{M} \) is limited by photon momentum; the wind cannot get momentum that exceeds the momentum of photon flux by much. This is in contrast to optically thick winds in which the mass-loss rate could be much larger than the momentum of photon flux (Kato & Iben 1992). Therefore, we assume the condition, that the momentum of wind is smaller than that of photon flux, of

\[
\dot{M} v_{\text{wind}} < \frac{L_{\text{ph}}}{c},
\]

where \( c \) is the speed of light. We get an upper limit of the wind mass-loss rate as

\[
\dot{M} < 1.6 \times 10^{-6} \left( \frac{L_{\text{ph}}}{6 \times 10^{37} \text{erg s}^{-1}} \right) \left( \frac{v_{\text{wind}}}{200 \text{km s}^{-1}} \right)^{-1} M_\odot \text{yr}^{-1}.
\]

Here we take \( L_{\text{ph}} = 6 \times 10^{37} \text{erg s}^{-1} \) from a bolometric luminosity of a 0.6 \( M_\odot \) WD (which will be shown later as Model 2 in Table 2), and assume a relatively small value of \( v_{\text{wind}} = 200 \text{ km s}^{-1} \) for a safe upper limit.

Bensammar et al. (1991) estimated the mass-loss rate of PU Vul to be about \( 4 \times 10^{-6} M_\odot \text{ yr}^{-1} \) from emission measure on 1988 April 30 and May 1 with a wind velocity of 70 km s\(^{-1}\) and a hot star radius of 3.9 \( \times 10^{12} \) cm (56 \( R_\odot \)). Sion et al. (1993) set an upper limit of the mass-loss rate, \( 1 \times 10^{-5} M_\odot \text{ yr}^{-1} \). Skopal (2006) estimated the mass-loss rate from H alpha line luminosity of 144 \( L_\odot \) on 1988 September 28, assuming optically thin fully ionized winds. With a terminal velocity 2100 km s\(^{-1}\) of a given velocity profile, Skopal obtained the mass-loss rate to be \( \dot{M} = 5 \times 10^{-6} M_\odot \text{ yr}^{-1} \). These values, however, may be a little bit larger than our momentum condition (1).

In our model, we assume no wind mass loss during the optical flat peak because no emission lines are observed or they are very weak. We assume that optically thin wind begins when the photospheric temperature rises to \( \log T_{\text{ph}} \) (K) \( \sim 4.0 \). This wind seems to have much weakened sometime around 1999–2001, because, after that, the optical light curve changes its shape and seems to decay as \( r^{-3} \), where \( r \) is the time after the decay started. In classical novae, the \( r^{-3} \) decay is often observed in the later phase of the outburst, and is interpreted as emission from homologously expanding optically thin plasma with a constant mass, which indicates that the mass supply had stopped (Hachisu & Kato 2006, 2010). In the case of PU Vul, the wind had not stopped entirely since the P Cyg profiles are still observed in 2004 (Yoo 2007). Therefore, we assume that the optically thin wind begins at \( \log T_{\text{ph}} \) (K) = 4.0 and continues until \( \log T_{\text{ph}} \) (K) = 5.05 at a rate shown later, and after that the wind mass-loss rate drops to \( \dot{M} = 1.0 \times 10^{-7} M_\odot \text{ yr}^{-1} \).

### 3.3. Multiwavelength Light Curves

After the maximum expansion of the photosphere, the photospheric radius (\( R_{\text{ph}} \)) gradually decreases keeping the total luminosity (\( L_{\text{ph}} \)) almost constant. The photospheric temperature \( (T_{\text{ph}}) \) increases with time because \( L_{\text{ph}} = 4\pi R_{\text{ph}}^2 \sigma T_{\text{ph}}^4 \). The maximum emission shifts from optical to supersoft X-ray through...
UV. This causes the luminosity decrease in the optical and increase in UV and finally the increase of supersoft X-ray. We assume that photons are emitted at the photosphere as a blackbody with a photospheric temperature $T_{\text{ph}}$. The light curve of optical ($V$) and UV 1455 Å fluxes are estimated from the blackbody emission.

### 3.4. Chemical Composition

Belyakina et al. (1989) obtained the chemical composition of the atmosphere of the hot component of PU Vul, in which iron is depleted by a factor of 0.3–0.5 relative to the Sun. The number ratio of He/H is estimated to be 0.31 (Andrillat & Houziaux 1994) and 0.146 (Luna & Costa 2005) from emission line ratios, which shows helium overabundance from the solar value (He/H $\sim$ 0.08). Another suggestion comes from the location in the Galaxy. Belyakina et al. (1982b) suggested that PU Vul belongs not to the planar component of the Galaxy because the star is off the galactic plane by 0.7–1.0 kpc, based on their derived distance of 5–7 kpc. This value, however, reduces to 0.5 kpc if we adopt the distance of $\sim$3.8 kpc as we will obtain later.

With the information above we assume the mass fraction of hydrogen, helium, and heavy elements of the envelope to be $(X, Y, Z) = (0.5, 0.494, 0.006)$. For comparison, we further assume additional sets of composition, i.e., $(0.5, 0.49, 0.01)$, $(0.7, 0.28, 0.02)$, and $(0.7, 0.29, 0.01)$. We simply assumed that the chemical composition of the envelope is uniform and constant with time.

### 4. LIGHT-CURVE FITTING

#### 4.1. UV Light-curve Fitting and the WD mass

The UV 1455 Å flux provides a good representation of the continuum level in novae, because it coincides with a local minimum of line opacity (Cassatella et al. 2002). In previous papers (Hachisu & Kato 2006; Hachisu et al. 2008; Kato et al. 2009), we have shown that the UV 1455 Å continuum light curve is very sensitive to model parameters, especially the WD mass.

Figure 4 shows time evolution of the UV 1455 Å continuum flux as well as our theoretical light curves. Figure 4(a) shows the dependence on the WD mass for a given set of the wind mass-loss rate of $1 \times 10^{-7} M_\odot$ yr$^{-1}$ (arbitrarily chosen but not too small compared with the nuclear burning rate of $3 \times 10^{-7} M_\odot$ yr$^{-1}$) and chemical composition of $X = 0.5$ and $Z = 0.006$. We see that the UV peak is narrower in more massive WDs, because the nova evolves faster owing to a less massive envelope and a high nuclear burning rate. Figure 4(b) depicts four light curves with different wind mass-loss rates for a given WD mass and chemical composition. As the assumed wind mass-loss rate is comparable to the nuclear burning rate ($3 \times 10^{-7} M_\odot$ yr$^{-1}$), the evolution speed of the nova is sensitive to the mass-loss rate. Figure 4(c) shows five light curves with different sets of chemical composition. The nova evolves faster for smaller X, because of less nuclear fuel, and also faster for larger Z because of a smaller envelope mass.

In this way we can choose a WD mass in reasonable agreement with the UV data for a given parameter set of the wind mass-loss rate and composition, $(X, Y, Z) = (0.5, 0.494, 0.006)$. Table 2 shows two such models, one is a 0.57 $M_\odot$ WD with the wind mass-loss rate of $5 \times 10^{-7} M_\odot$ yr$^{-1}$ (Model 1) and the other is a 0.6 $M_\odot$ WD with $3 \times 10^{-7} M_\odot$ yr$^{-1}$ (Model 2). These WD masses, 0.57 $M_\odot$ and 0.6 $M_\odot$, are not much different, because they are in the middle of the permitted range of the WD mass, 0.53–0.65 $M_\odot$, as explained below to avoid extremely small and large mass-loss rates. The 0.57 and 0.6 $M_\odot$ models correspond respectively to the left and upper sides to the “wind region” (a triangle region in Figure 10 of Kato & Hachisu 2009) for the corresponding composition.

During the outburst, the photospheric temperature gradually rises and the photospheric radius decreases with an almost constant photospheric luminosity. Figure 5 shows the developments of the temperature and radius of Models 1 and 2 as well as observational estimates taken from the literature. Vogel & Nussbaumer (1992) suggested that the temperature was as low

| Subject | Model 1 | Model 2 | Units |
|---------|---------|---------|-------|
| $X$     | 0.5     | 0.5     |       |
| $Y$     | 0.494   | 0.494   |       |
| $Z$     | 0.006   | 0.006   |       |
| WD mass | 0.57    | 0.6     | $M_\odot$ |
| Distance from UV fit$^a$ | 3.7 | 3.9 | kpc |
| $M_{\text{V, peak}}^b$ | -5.49 | -5.58 | mag |
| $t_{\text{peak}}^b$ | 5.2 | 5.7 | $10^7$ erg s$^{-1}$ |
| H-burning rate$^c$ | 2.7 | 3.0 | $10^{-7} M_\odot$ yr$^{-1}$ |
| Maximum radius | 62 | 63 | $R_\odot$ |
| Initial envelope mass$^d$ | 5.8 | 4.6 | $10^{-5} M_\odot$ |
| Assumed wind mass-loss rate ($log T_{\text{ph}} < 5$)$^e$ | 5.0 | 3.0 | $10^{-5} M_\odot$ yr$^{-1}$ |
| Assumed wind mass-loss rate ($log T_{\text{ph}} > 5$)$^f$ | 1.0 | 1.0 | $10^{-5} M_\odot$ yr$^{-1}$ |
| Mass lost by the wind ($log T_{\text{ph}} < 5$)$^e$ | 0.60 | 0.34 | $10^{-5} M_\odot$ |
| Mass lost by the wind ($log T_{\text{ph}} > 5$)$^f$ | 0.61 | 0.44 | $10^{-5} M_\odot$ |

Notes.

$^a$ With $E(B-V) = 0.43$.

$^b$ Values at log $T_{\text{ph}}$(K) = 3.9.

$^c$ Values at log $T_{\text{ph}}$(K) = 4.5.

$^d$ The mass at the rising phase.

$^e$ Optically thin wind from log $T_{\text{ph}}$(K) = 4 to 5.05.

$^f$ Optically thin wind at log $T_{\text{ph}}$(K) > 5.05.
of their slower evolutions. The minimum WD mass may be
obtained for the largest wind mass-loss rate that we adopt,
1 \times 10^{-6} M_\odot yr^{-1} from Equation (2). With plausible values
of the optically thin wind mass-loss rate, which may be a few to
several \times 10^{-7} M_\odot yr^{-1}, we may conclude that the WD is about
0.6 M_\odot.

### 4.2. Optical Light Curve

Figure 6 shows optical light curves of Models 1 and 2, of
which characteristic values are summarized in Table 2. These
two models are selected from fitting with the UV light curves,
but also reproduce well the optical light curve in the flat maximum
as well as the subsequent decline until 1989, except for the first
eclipse in 1980 which is not taken into account in our model.

After 1989 the theoretical light curve largely deviates from
observed optical magnitudes. In this stage, spectra are emission-
line dominated and the continuum is very weak (Yoo 2007).
These emission lines come from optically thin plasma outside
the photosphere which is not included in our model. Therefore,
our theoretical models give much lower magnitudes than that of
observational data.

In our theoretical models, the flat peak corresponds to the
era of low photospheric temperature (7000–9000 K) as shown
in Figure 5. The temperature gradually rises with time and
reaches 10,000 K which is indicated by the cross in Figure 6,
where we assume the optically thin mass loss begins. After that
the nova entered the coronal phase and many emission lines
appeared (Kanamitsu et al. 1991b; Nussbaumer & Vogel 1996).

Our model temperature is consistent with these observational
properties.

### 4.3. Internal Structure of the Envelope at the Flat Peak

Figure 7 shows internal structures of the envelopes of Models
1 and 2 with photospheric temperature log T_{ph} (K) \sim 3.9. Here,
the local Eddington luminosity is defined as

\[ L_{\text{Edd}} \equiv \frac{4\pi c G M_{\text{WD}}}{\kappa}, \]

where \( \kappa \) is the opacity in which we use the OPAL opacity. Since the opacity \( \kappa \) is a function of temperature and density, the Eddington luminosity is also a local variable. This Eddington luminosity has the deepest local minimum at \( \log R \) (cm) = 10.4–11.2 that corresponds to the Fe peak of OPAL opacity. There appears a large density-inversion layer at \( \log r \) (cm) \~{} 10.2–11.2 corresponding to the super-Eddington region \( (L_{\text{Edd}} < L_r) \). This density-inversion arises in order to keep hydrostatic balance in the super-Eddington region. Such a structure is very different from ordinary nova wind solutions, in which the density monotonically decreases as \( r^{-2} \) (Kato & Hachisu 1994, 2009), but similar to that of red giants.

These two solutions are representative of those in the long-lasting flat peak in the optical light curve (Figure 6), i.e., the envelope is extended to 50–60 \( R_\odot \) and the temperature is as low as \( \log T_{\text{ph}} \) (K) \~{} 3.9–4.0. The convection, which

![Figure 6. Optical and UV light curves of PU Vul. Optical data are taken from IAU Circular (for dip: 3421, 3477, 3494, 3589, 3604, 3610, and 3655), Wenzel (1979), Yamashita et al. (1982), Belyakina et al. (1982b), Chochol et al. (1981), Purgathofer & Schnell (1982), Kolotilov (1983), Purgathofer & Schnell (1983), Iijima & Ortolani (1984), Iijima (1989), Kanamitsu et al. (1991b), Klein et al. (1994), Kolotilov et al. (1995), Yoon & Honeycutt (2000), and AAVSO (after JD 2,452,000). Large red open circles denote the flux of \( \text{IUE} \) UV 1455 Å band. Calculated light curves are also shown for Model 1 (thin solid line) and Model 2 (dashed line). The scale in the right-hand-side axis denotes that for observational data. Scale for the theoretical UV flux is \((0, 6.25)\) for Model 1 and \((0, 7.0)\) for Model 2 in units of \(10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}\) for the distance of 10 pc. The cross/small dot indicate starting/end point of the assumed optically thin wind mass loss. See the text for more details.

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

Table 3

| Composition | Minimum Massa | Maximum Massb |
|-------------|---------------|---------------|
| \( X = 0.5, Y = 0.294, Z = 0.006 \) | 0.53 \( M_\odot \) | 0.65 \( M_\odot \) |
| \( X = 0.5, Y = 0.29, Z = 0.01 \) | 0.5 \( M_\odot \) | 0.62 \( M_\odot \) |
| \( X = 0.7, Y = 0.28, Z = 0.02 \) | 0.5 \( M_\odot \) | 0.67 \( M_\odot \) |
| \( X = 0.7, Y = 0.29, Z = 0.01 \) | 0.52 \( M_\odot \) | 0.72 \( M_\odot \) |

Notes.

a In case of a very large mass-loss rate of \( 1 \times 10^{-6} \text{ M}_\odot \text{ yr}^{-1} \).
b Extreme case of no wind mass loss.
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6.0 × 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ as in Figure 6. From these values we obtain the distance of } d = 3.7 \text{ kpc with the absorption } A_v = 8.3 \times E(B - V) \text{ for } \lambda = 1455 \text{ Å (Seaton 1979); here we use } E(B - V) = 0.43 \text{ (obtained in Section 2.1). If we use the upper and lower limits of } E(B - V) = 0.43 \pm 0.05, \text{ we get the distance of } d = 3.7^{+0.7}_{-0.6} \text{ kpc. The error coming from the UV flux fitting is much smaller and up to \pm 0.15 kpc. In the same way, we obtain } d = 3.9^{+0.7}_{-0.6} \text{ for Model 2. If we adopt a different set of chemical composition, the resultant distance is also changed. For the } 0.6 M_\odot \text{ WD we obtain } 3.8 \text{ kpc for } (X, Z) = (0.5, 0.01), 3.3 \text{ kpc for } (0.7, 0.02), \text{ and } 3.5 \text{ kpc for } (0.7, 0.01). \text{ Taking into account that } Z = 0.02 \text{ is a bit larger than the recent estimate of solar value } (Z = 0.0128; Grevesse 2008), 3.3 \text{ kpc may be a smaller limit. Thus, we may summarize our distance estimates as } d = 3.8 \pm 0.7 \text{ kpc. The error includes ambiguities of the } E(B - V), \text{ WD mass, and chemical composition.}

5. DISCUSSION

As described in Section 3, a nova becomes a supersoft X-ray source in the later phase of the outburst. In PU Vul, however, the maximum temperature is not high enough compared with a typical classical nova because of the less massive WD (\sim 0.6 M_\odot). Our theoretical model predicts that the outburst of PU Vul is still ongoing and the temperature is continuously rising. The temperature will finally reach the maximum temperature of \sim 3 \times 10^5 \text{ K just before hydrogen burning stops (X-ray turnoff), while the flux is almost constant at } (2-3) \times 10^{37} \text{ erg s}^{-1}. \text{ Therefore, we may expect supersoft X-ray from PU Vul in the future, but it is very difficult to predict this epoch, because it strongly depends on the model parameters, such as the optically thin wind mass-loss rate and the chemical composition of the envelope.}

No X-ray observations of PU Vul have been made since 1992 November. The detected X-ray flux was attributed to a shock origin of colliding winds (Hoard et al. 1996; Mürset et al. 1997). PU Vul is a symbiotic nova in which the M-giant companion blows a massive cool wind that may preferentially distribute in the orbital plane. This cool wind may prevent a clear detection of supersoft X-rays from the hot WD. Therefore, the probability of detecting supersoft X-rays would be higher when the WD is in front of the cool wind of the giant (around 2014) and would be very low near the eclipse (2020–2021).

We have performed simulations for the detectability of supersoft X-ray with the assumed values of \( E(B - V) = 0.43 \) and \( d = 3.8 \text{ kpc. It will be possible to detect PU Vul at 0.007 counts s}^{-1} \text{ with the EPIC-pn camera on board XMM-Newton when the temperature is } T(K) \sim 5.3 \text{ and the luminosity is } \sim 5 \times 10^{37} \text{ erg s}^{-1} \text{ (probably in 2010–2020) and at about 1 count s}^{-1} \text{ near the X-ray turnoff time, i.e., } \log T(K) \sim 5.5 \text{ and } \sim 2 \times 10^{37} \text{ erg s}^{-1} \text{ (probably in 2006–2090). However, these estimates are based on our Models 1 and 2 only, and there is a large ambiguity due to the uncertainty of the model parameters and assumptions. Specifically, the above estimated year depends strongly on the assumed wind mass-loss rate after the photospheric temperature of the WD envelope rises to } \log T(K) = 5.05. \text{ If the wind mass loss will weaken much, the X-ray turnoff time is much later than the above estimates.}

We expect that a large part of the envelope will remain on the WD after the outburst of PU Vul, because no optically thick wind occurs. From the initial envelope mass and the matter lost by the optically thin wind as in Table 2, we estimate the envelope mass that will remain after the outburst. Highly dependent on the assumed mass-loss rate as well as on the other parameters, it is dominant in energy transport in the rising phase of nova outbursts (Prialnik 1986), has retreated and is ineffective in and after the flat peak. The convection occurs where the opacity decreases outward, i.e., the local Eddington luminosity increases outward. The largest convective region is at log \( r \) (cm) = 10.5–11.4, corresponding to the super-Eddington region (see Figure 7). In all convective regions, convection is ineffective in energy transport due to low density, and is unable to carry all of the energy flux. Therefore, the structure is super-adiabatic, i.e., entropy decreases outward. This situation is different from the convective core of intermediate-mass main-sequence stars or the inner convective envelope of low-mass red giant stars, where the convective energy transport is effective and the temperature gradient is very close to the adiabatic gradient (Hayashi et al. 1962; Iben 1965).

The Eddington luminosity with electron scattering opacity \( L_{\text{Edd,el}} = 4\pi c G M /[0.2(1 + X)] \) is often used as an easy estimate of the WD luminosity. We note, however, that the photospheric luminosity is only 54% of \( L_{\text{Edd,el}} \) for Model 1 (0.57 \( M_\odot \) WD) and 57% for Model 2 (0.6 \( M_\odot \) WD).

4.4. Distance

The distance to PU Vul is obtained from the comparison of the 1455 Å band flux with the corresponding model fluxes (Hachisu & Kato 2006; Kato & Hachisu 2005, 2007). The flux of Model 1 is \( F_{\lambda}^{\text{mod}} = 2.2 \times 10^{-6}\epsilon(d/10 \text{ pc})^2 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \) at the peak. The corresponding observed flux is \( F_{\lambda}^{\text{obs}} = \)}
estimated to be about 70%–90% of the initial envelope mass for reliable model parameters. Mass-accreting WDs are, in general, potential candidates of progenitors of Type Ia supernovae (SNe Ia). However, low-mass WDs (∼0.9 M_⊙) such as in PU Vul have not been considered as candidates of SNe Ia, because it is difficult for them to reach the Chandrasekhar mass limit (e.g. Hachisu et al. 1999a, 1999b; Kato 2010).

6. CONCLUSIONS

Our main results are summarized as follows.

1. Based on the idea of Kato & Hachisu (2009) that a long-lasting flat peak of optical light curves can be reproduced by a sequence of wind-suppressed static solutions, we have succeeded in reproducing the long-lasting optical flat peak of PU Vul as well as the UV 1455 Å continuum light curve. Our model is consistent with spectral features with no indication of strong winds in the flat peak of PU Vul.

2. An analysis of the IUE spectra of PU Vul indicates $E(B - V) = 0.43 ± 0.05$.

3. We obtain a mass range of the WD between 0.55 and 0.65 M_⊙ by comparing our theoretical light curves with the UV light curve.

4. We obtain the distance of $d = 3.8 ± 0.7$ kpc with $E(B - V) = 0.43 ± 0.05$.

5. We may conclude that the outburst of PU Vul is still ongoing, and has already entered the supersoft X-ray phase. We encourage X-ray observations in the UV light curve.

We thank Joanna Mikolajewska for valuable discussion on observational features of PU Vul. We are also grateful to the anonymous referee for useful comments that helped to improve the manuscript. We also thank the American Association of Variable Star Observers (AAVSO) for the visual data of PU Vul. This research has been supported in part by the Grant-in-Aid for Scientific Research (20540227, 22540254) of the Japan Society for the Promotion of Science.

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