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A COMPOSITE LIGHT CURVE MODEL OF THE SYMBIOTIC NOVA PU VUL (1979)

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Abstract. PU Vul (1979) is a symbiotic nova that shows a long-lasting flat optical peak followed by a slow decline. We made a quasi-evolution model for outbursts on a 0.6 $M_\odot$ white dwarf consisting of a series of static solutions with optically-thin winds. Our theoretical models reproduce well the observed visual/UV light curves as well as the new estimates of the temperature and radius of the hot component. We also modeled the light curve of the 1980 and 1994 eclipses as the total eclipse occulted by a pulsating M-giant companion star. In the second eclipse, the visual magnitude is dominated by nebular emission which is possibly ejected from the hot component between 1990 to 2000. We have quantitatively estimated three components of emission, i.e., the white dwarf, companion and nebular, and made a composite light curve that represents well the evolution of the PU Vul outburst.

Key words: stats: symbiotic, novae, cataclysmic variables, white dwarfs, individual (PU Vul)

1. INTRODUCTION

PU Vul (Nova Vulpeculae 1979) is a symbiotic nova that consists of a white dwarf (WD) and a red giant (RG). The outburst is a thermonuclear runaway phenomenon. PU Vul is also an eclipsing binary with a period of 13.4 yr, and during the eclipse, different emission components are occulted differently, which provides us clues to the nature of each component. Kato et al. (2011) presented a light curve model of PU Vul that reproduces the long-lasting flat optical peak, but not the following decline phase, because their work did not include emissions from the RG and nebulae. Here, we assume that these three components, the WD, RG and nebulae, contribute to the light curve, and make a composite light curve model of PU Vul based on the analysis of two eclipses.

2. NOVA OUTBURST MODEL

A nova outburst is a thermonuclear runaway event on the WD surface. After the hydrogen shell flash sets in, the envelope on the WD expands to a giant size.

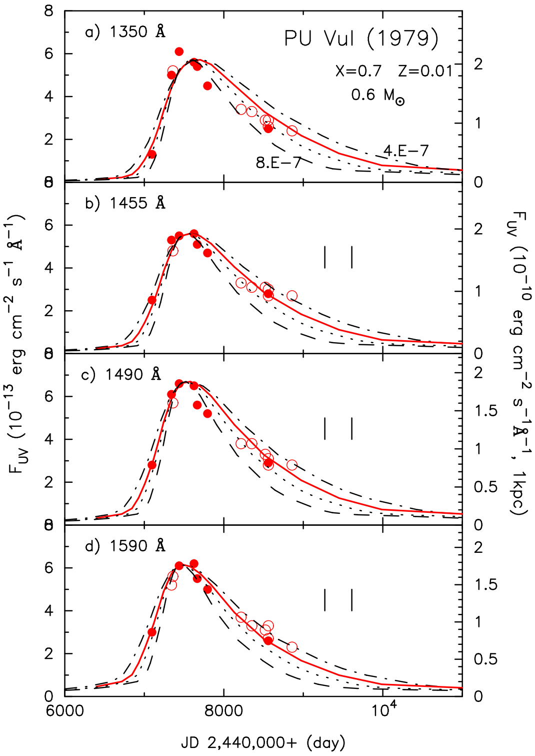

Fig. 1. UV light curves for the four continuum bands: (a) 1350 Å, (b) 1455 Å, (c) 1490 Å and (d) 1590 Å. Theoretical light curves are also shown for an assumed distance of 1 kpc (with right-side axis); They are for a 0.6 $M_\odot$ WD with chemical composition of the envelope $X = 0.7$ and $Z = 0.01$ and four different optically-thin wind mass-loss rates. Dash-dotted curves: $4\times10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, red solid curves: $5\times10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, dotted curves: $6\times10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ and dashed curves: $8\times10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. Short vertical lines in panels (b), (c) and (d) show the period of the second eclipse at the optical V band between JD 2 449 270 and 2 449 610. Among the observational data, the open circles denote those which have low accuracy because they were observed with short exposures (< 1000 s) or were obtained from very noisy spectra.

After it reaches the optical peak, the envelope expansion settles down into a steady-state. The optical magnitude decays as the envelope mass decreases while the photospheric temperature rises with time. In low mass WDs, no optically thick winds occur, so the decay phase of nova evolution can be followed by a quasi-hydrostatic sequence. 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 evolution of novae is followed by connecting these solutions along the envelope mass-decreasing sequence. The evolution time is calculated from the mass decreasing rate which is the sum of the two rates, the hydrogen nuclear burning and the mass loss by optically-thin wind. We assume that an optically-thin wind begins when the photospheric temperature rises to $\log T_\mathrm{ph}(\mathrm{K}) \sim 4.0$. The wind mass-loss rate is a parameter that is determined from fitting with observational data. We used OPAL opacities. The mixing-length

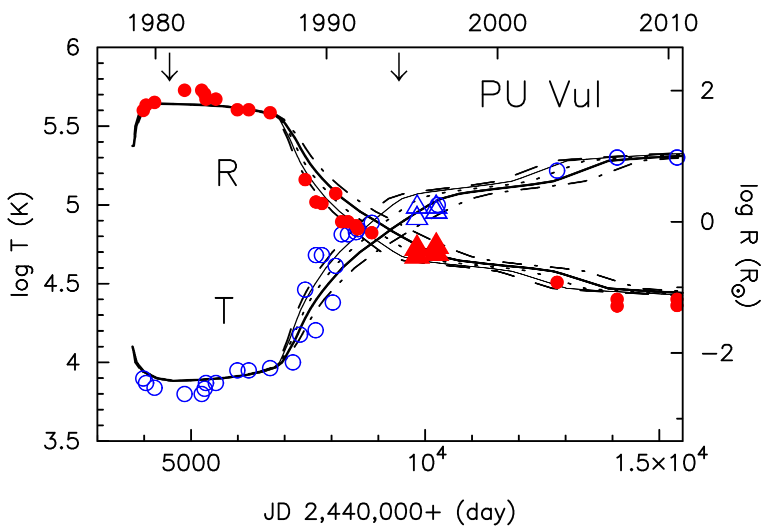

Fig. 2. Development of the temperature (open symbols and the left ordinates) and radius (filled symbols and the right ordinates) of the hot component of PU Vul. Lines denote the blackbody temperatures and radii of the 0.6 $M_\odot$ WD photosphere with $X = 0.7$ and $Z = 0.01$ for five different wind mass-loss rates. Dash-dotted lines: $4 \times 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$, thick solid lines: $5 \times 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$, dotted lines: $6 \times 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$, thin solid lines: $7 \times 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$ and dashed lines: $8 \times 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$. Two downward arrows indicate the central times of two eclipses.

parameter of convection is assumed to be $\alpha = 1.5$. We calculate optical and UV light curves from the blackbody spectrum of photospheric temperature, T_{ph}. The mass and radius (i.e., the bottom of the hydrogen shell-burning) of the WD are assumed to be 0.6 $M_\odot$ and the Chandrasekhar radius, respectively. The chemical composition of the envelope is assumed to be uniform with (X, Y, Z)= (0.7, 0.29, 0.01) by weight for hydrogen, helium and heavy elements. This method and numerical techniques are essentially the same as those in Kato et al. (2011).

3. LIGHT CURVE MODEL OF THE HOT COMPONENT

During the outburst, the photospheric temperature gradually rises and the photospheric radius shrinks while the bolometric luminosity is almost constant. The main emitting wavelength region shifts from optical to UV and then to the supersoft X-rays. Figure 1 shows UV light curves of four narrow wavelength bands around 1350, 1455, 1490 and 1590 Å extracted from the IUE data archive (http://sdc.laeff.inta.es/ines). A shorter wavelength band light curve reaches its peak value in a later phase, indicating that the temperature rises with time.

This figure also shows model light curves of the 0.6 $M_\odot$ WD with chemical composition of $X = 0.7$, $Y = 0.29$ and $Z = 0.01$. Each band light curve is made from the blackbody temperature of our evolution model. Here we assume four optically-thin wind mass-loss rates of (4–8) $\times 10^{-7}$ $M_\odot$ yr^{-1}. For a higher mass-loss rate, the evolution is faster and the UV light curve is narrower. All these light curves more or less well reproduce observational UV light curves in each wavelength band. Comparing these theoretical light curves with the observational

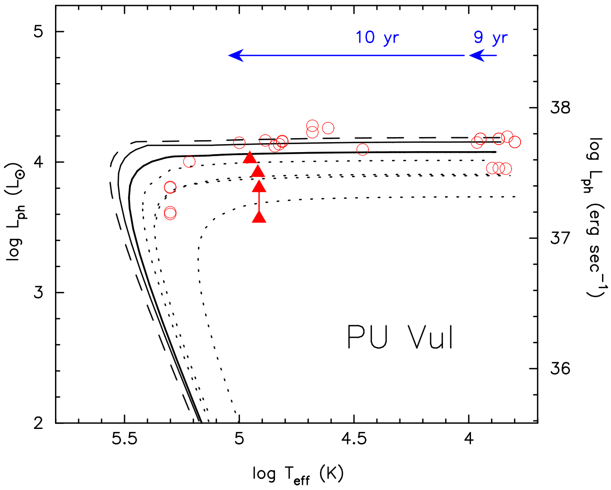

Fig. 3. Evolution of PU Vul in the HR diagram. Circles and triangles are our observational estimates. Lines denote theoretical models. Two solid lines indicate the models of 0.6 $M_\odot$ WD with different composition: $X = 0.5$ and $Z = 0.01$ (the upper solid line) and with $X = 0.7$ and $Z = 0.01$ (the lower solid line). Dashed line denotes a 0.7 $M_\odot$ WD with $X = 0.7$ and $Z = 0.01$. Four dotted lines denote 0.5 $M_\odot$ WD models with different chemical compositions and radii: the upper is for $X = 0.5$ and $Z = 0.02$, the two next almost overlapping lines are for $X = 0.7$ and $Z = 0.01$ (upper) and $X = 0.7$ and $Z = 0.02$ (lower), and the lowest line is for a WD with $X = 0.7$ and $Z = 0.02$ and a larger radius. The arrows indicate evolution time scales of 0.6 $M_\odot$ WD with $X = 0.7$ and $Z = 0.01$ – from the beginning of the flat peak to $\log T$ (K) = 4.0, and from $\log T$ (K) = 4.0 to 5.05.

data, we derive the distance to PU Vul to be 5.3 ± 1.0 kpc. This value is in good agreement with $d = 4.7 \pm 0.6$ kpc resulting from analysis of the pulsating giant component of PU Vul. In the rest of our study, we use $d = 4.7$ kpc.

We have deduced the temperature, radius and total luminosity of the hot component (WD) of PU Vul using information available in the literature. Figure 2 shows the temperature and radius changes with time. This figure also shows theoretical curves for the 0.6 $M_\odot$ WD with different optically-thin wind mass-loss rates, 4, 5, 6, 7 and 8 $\times 10^{-7}\ M_\odot$ yr^{-1}. The higher the mass-loss rate, the faster is the evolution. These models show a good agreement with observational estimates.

Figure 3 shows our estimates of the temperature and luminosity in the HR diagram. Here we assumed $d = 4.7$ kpc and $E_{B-V} = 0.30$ to obtain the luminosity. Filled triangles are deduced from the IUE data taken in 1995/96, some of which give a lower value of the luminosity. The connected upper values are another estimate obtained from the optical V magnitude of the hot component, using the method proposed by Mürset & Nussbaumer (1994).

Figure 3 also shows the theoretical HR tracks of WDs with masses of 0.5, 0.6 and 0.7 $M_\odot$ for various chemical compositions of the envelope. The 0.5 $M_\odot$ WD models are depicted by four dotted lines. The top line is for cold WDs (the Chandrasekhar radius) with the chemical composition $X = 0.5$ and $Z = 0.02$ (lower). The middle two lines are a cold WD with $X = 0.7$ and $Z = 0.01$ (upper) and with $X = 0.7$ and $Z = 0.02$. These lines almost overlap, because the photospheric luminosity hardly depends on the heavy element contents. The lowest dotted curve denotes a hot WD with $X = 0.7$ and $Z = 0.02$, which we

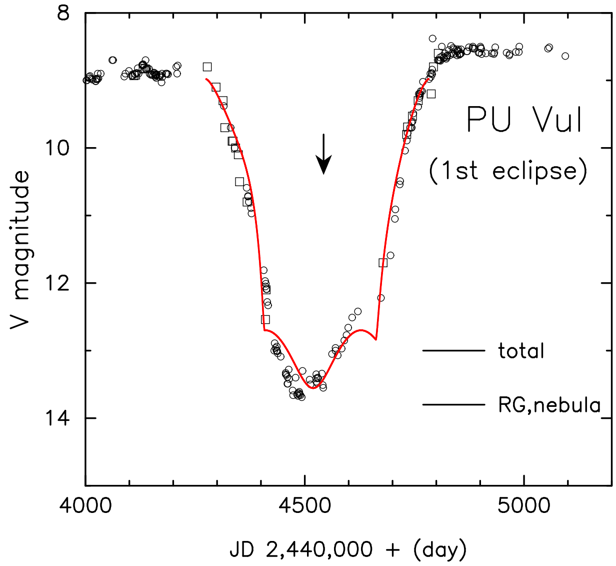

Fig. 4. A close-up view of the first eclipse. Optical data are the same as in Kato et al. (2011). The red solid line indicates the eclipse light curve model in which the WD is occulted by the pulsating RG with amplitude of 75 % around its equilibrium luminosity corresponding to $m_V = 13.8$. We also assume the additional nebular component of $m_V = 13.8$. The total mean magnitude of the bottom of the eclipse is $m_V = 13.0$. The downward arrow indicates the date of mid-eclipse, JD 2 444 532. See text for more details.

assume a larger WD radius for steady-state accretion. The luminosity is smaller in the hot WDs because a weaker gravity balances a lower temperature at the nuclear burning region, resulting in a smaller luminosity. All of these models show a lower luminosity than the observational estimates of the hot component of PU Vul. Therefore, we conclude that the WD in PU Vul is more massive than 0.5 $M_\odot$.

On the other hand, the 0.7 $M_\odot$ WD with $X = 0.7$ and $Z = 0.02$ (dashed line) shows the luminosity consistent with observations. But in this case, the evolution is too fast and inconsistent with the evolution of UV light curve. More massive WDs ($> 0.7\ M_\odot$) are excluded because of too fast evolution (see Kato et al. 2011). Therefore, we may conclude that the WD in PU Vul is likely to be about 0.6 $M_\odot$ (in the range 0.5 $M_\odot < M_{\rm WD} < 0.7\ M_\odot$).

The two solid lines indicate the model of 0.6 $M_\odot$ with different hydrogen content, $X = 0.7$ and 0.5, with $Z = 0.01$. Their HR tracks are consistent with the observational estimates.

4. THE ECLIPSE LIGHT CURVE MODEL

We made light curve models of the first (1980) and the second (1994) eclipses, assuming spherical shapes of both stars with the inclination angle of the orbit, $i = 90°$. As will be shown later, the RG is radially pulsating with a period of 218 days, and we assume that the luminosity changes in a sinusoidal shape around the equilibrium magnitude $m_V = 13.8$, and the radius changes in a sinusoidal anti-phase. During the eclipses, the WD is totally occulted by the pulsating RG, but we assumed additional nebular emission, which was not occulted in the first

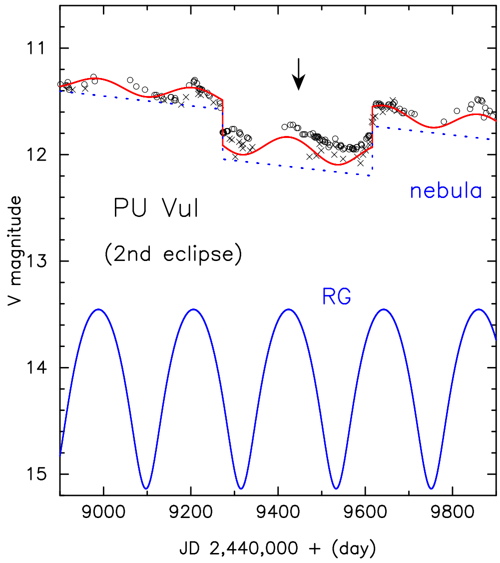

Fig. 5. A close-up view of the second eclipse. Observational data are taken from Kolotilov et al. (1995) (crosses) and Yoon & Honeycutt (2000) (open circles). The upper solid line (red) indicates the composite light curve which is the sum of the pulsating RG (lower solid line, blue) and of the nebula emission (dotted line). The RG pulsates with the amplitude of 65 % around its equilibrium luminosity corresponding to $m_V = 13.8$. The downward arrow indicates the date of mid-eclipse, JD 2 449 447.

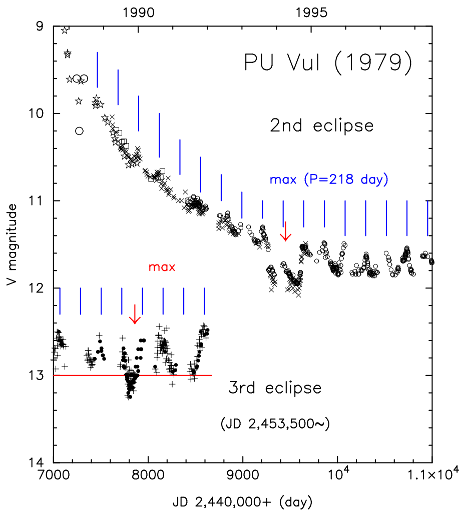

Fig. 6. A close-up view of the light curve of PU Vul for the period from JD 2 447 000 to 2 451 000 (upper curve) and from JD 2 453 500 to 2 457 500 (lower curve). The horizontal line indicates the magnitude $m_V = 13.0$. Downward arrows indicate the central time of the eclipses, JD 2 449 447 and 2 454 362. Short vertical lines indicate epochs of the maximum magnitudes of pulsation of the M giant with a period of 218 days.

eclipse but was partially occulted in the second eclipse.

Figure 4 shows our model light curve for the first eclipse. We obtain the total duration of the eclipse $D = 508$ days, the totality at $d = 254$ days and $R_c/a = (D + d)/(2\pi P_{orb}) = 0.24$, where a is the separation of the two stars, $P_{orb} = 4915$ days is the orbital period. The equilibrium radius of the pulsating RG is $R_c = 0.25\,a$. The amplitude of the RG luminosity is 75 % in the linear scale $\Delta L/L$, and the amplitude of the radius is 5 %. Here, we assume the nebular emission of $m_V = 13.8$ in addition to the RG component of $m_V = 13.8$, so the mean value of the bottom is $m_V = 13.0$.

In the second eclipse, the WD is dark in optical wavelengths, and the main contribution is the nebular emission. We modeled the eclipse light curve as in Figure 5. Here, the amplitude of RG luminosity is 65 % and the amplitude of the radius is 3 %. The total duration of the eclipse is $D = 345$ days and the totality $d = 343$ days. The equilibrium radius of the pulsating RG is $R_c = 0.22\,a$. We find that 35 % occultation of the nebula emission yields a good fitting.

The radius of the hot component is found to be $R_h/a = 0.07$ for the first eclipse, that corresponds to $R_h \sim 85$–$130\ R_\odot$. In the second eclipse, the steep decline/increase of ingress/egress suggests $R_h/a < 0.001$ which corresponds to $R_h < 1$–$2\ R_\odot$. Thus, the radius of the hot component reduced by a factor of 100 from the 1st to the 2nd eclipse. This is consistent with the theoretical estimates in Figure 2.

Figure 6 shows a periodic modulation of magnitudes, which becomes prominent in the later phase of the outburst where the WD component becomes dark. This modulation is due to the RG pulsation, and one of the minima accidentally coincides with the time expected for the "third eclipse" in 2007 indicated by an arrow. This dip is too narrow to be a total eclipse so we regard that this is a pulsation minimum of the M-giant.

5. COMPOSITE LIGHT CURVE

Figure 7 shows the optical light curve from the beginning of the outburst. It also shows the theoretical light curves of $0.6\ M_\odot$ model with chemical composition of $X = 0.7$, $Y = 0.29$ and $Z = 0.01$. In this model, no optically thick winds take place, but we assume the optically thin wind of $5.0 \times 10^{-7}\ M_\odot\,\mathrm{yr}^{-1}$ that begins at $\log T_{ph} = 4.0$ (a large open square) until $\log T_{ph} = 5.05$, and $1.0 \times 10^{-7}\ M_\odot\,\mathrm{yr}^{-1}$ after that.

This model reproduces well the observed UV light curve and also the optical light curve up to 1989. After 1989 PU Vul entered the nebular phase and emission-lines dominated the spectra. Our model light curve does not include emission lines, and it quickly decays as the photospheric temperature rises with time. As a result, the optical brightness decays much faster than the observed one.

We have constructed a composite light curve which is a sum of the three components, i.e., emissions from the WD photosphere, RG and nebula. For the RG component, we adopt a mean magnitude of $m_V = 13.8$ as indicated by the horizontal line in Figure 7. For the nebular contribution, we assume a form depicted by the dash-three-dotted line, in order to reproduce a good fitting with the observed one, that shows enhancement in the nebular phase between $\log T\,(\mathrm{K}) = 4.0$ (the open square) and $\log T\ (\mathrm{K}) = 5.09$ (JD=2 451 100) consistent with our assumption of optically-thin winds.

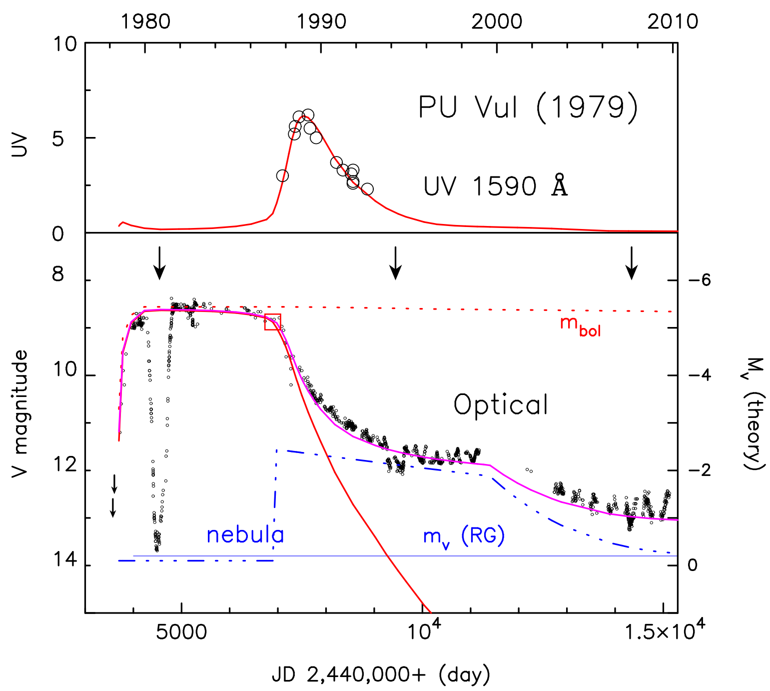

Fig. 7. A composite light curve model of PU Vul. The magenta solid line in the lower panel indicates a composite light curve of three components of emission from the WD photosphere (red thick solid line), RG mean luminosity (horizontal thin solid line at $m_{\rm v} = 13.8$), and nebula emission (dash-three-dotted line). The 0.6 $M_\odot$ WD model is depicted by the solid lines for UV 1590 Å band in units of 10^{-13} erg cm^{-2}s^{-1}Å^{-1} (above: the same figure as in Figure 1d), for the V band (lower figure: the red thick solid line) and by the horizontal dotted curve for bolometric magnitude. Optical data are the same as in Kato et al. (2011). This trial V-band light curve gives a little bit smaller luminosity, so the curves are shifted upward by 0.26 mag. The downward arrows indicate the central time of eclipse.

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