

V445 PUPPIS: HELIUM NOVA ON A MASSIVE WHITE DWARF

MARIKO KATO

Department of Astronomy, Keio University, Hiyoshi, Yokohama 223-8521, Japan; mariko@educ.cc.keio.ac.jp

AND

IZUMI HACHISU

Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, Komaba,
Meguro-ku, Tokyo 153-8902, Japan; hachisu@chianti.c.u-tokyo.ac.jp

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ABSTRACT

The 2000 outburst of V445 Puppis shows unique properties, such as the absence of hydrogen, the enrichment of helium and carbon, and the slow development of the light curve with a small amplitude that does not resemble any classical novae. This object has been suggested to be the first example of a helium nova. We calculate theoretical light curves of helium novae and reproduce the observational light curve of V445 Pup. Modeling indicates a very massive white dwarf (WD), more massive than $1.3 M_{\odot}$. The companion star is possibly either a helium star or a helium-rich main-sequence star. We estimate the ignition mass as several times $10^{-5} M_{\odot}$, the corresponding helium accretion rate as several times $10^{-7} M_{\odot} \text{ yr}^{-1}$, and the recurrence period as several tens of years. These values suggest that the WD is growing in mass and ends up either a Type Ia supernova or an accretion-induced collapse to a neutron star.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (V445 Puppis) — white dwarfs

1. INTRODUCTION

The outburst of V445 Puppis was discovered on 2000 December 30 by K. Kanatsu (Kato & Kanatsu 2000). The spectrum shows an absence of hydrogen and enrichments of helium and carbon. The optical spectrum is not yet published, but near-infrared spectra confirm the absence of Paschen and Brackett hydrogen lines (Ashok & Banerjee 2003 and references therein). Light curves reported to VSNET¹ show the small amplitude of the outburst ($\Delta m_v \sim 6$) and the shape of the light curve, which do not resemble those of classical novae, recurrent novae, or other cataclysmic variables. From these unique properties, this object is suggested to be a helium nova (Ashok & Banerjee 2003).

Infrared observations suggest dust formation. During the outburst, infrared spectra consistent with dust emission are observed on 2001 January 2, JD 2,451,912 (Ashok & Banerjee 2003), and on 2001 January 31, JD 2,451,941 (Lynch, Russell, & Sitko 2001). Ashok & Banerjee (2003) argued that the thermal emission comes from dust formed during the 2000 outburst, while Lynch et al. (2001) claimed that it comes from a pre-existing dust shell of a previous outburst. Henden, Wagner, & Starrfield (2001) reported that V445 Pup was fainter than $V \sim 20$ on 2001 October 4, JD 2,452,187, with a remark that the object is evidently shrouded by a thick and dense carbon dust shell. Ashok & Banerjee (2003) reached the same conclusion based on the *JHK* observation on 2001 November 1, JD 2,452,215. To summarize, an optically thin dust shell exists on the outburst phase, and a thick dust shell is formed 80 days after the star fades away.

Helium novae have been theoretically predicted by Kato, Saio, & Hachisu (1989) as a nova outburst phenomenon caused by helium shell flash on a white dwarf (WD). They considered two cases of helium accretion: a helium accretor from the companion helium star or a hydrogen-rich matter accretion from a normal companion with a high accretion rate. In the latter case,

a part of the hydrogen-rich matter accreted is processed into helium, and it accumulates on the WD. When the mass of the helium layer reaches a critical mass, an unstable weak helium shell flash occurs. This is the helium nova. In a helium nova, mass loss owing to optically thick wind is relatively weak, and most of the helium envelope burns into carbon and oxygen and accumulates on the WD (Kato & Hachisu 1999). Through many periodic helium shell flashes, the WD gradually grows in mass and ends up an accretion-induced collapse to a neutron star or explodes as a Type Ia supernova (Nomoto, Thielemann, & Yokoi 1984).

In this Letter, we present light-curve modeling of V445 Pup and show that this object is indeed a helium nova on a massive WD. We also estimate the helium accretion rate and the recurrence period of outbursts.

2. INPUT PHYSICS

The decay phase of helium nova outbursts can be followed by using an optically thick wind theory (Kato & Hachisu 1994). The structure of the WD envelope is calculated by solving the equations of motion, continuity, energy transport, and energy conservation. The details of computation have been already presented in Kato & Hachisu (1999) for helium shell flashes on a $1.3 M_{\odot}$ WD. Here other various WD masses are examined that are 1.1, 1.2, 1.3, 1.33, 1.35, and $1.377 M_{\odot}$. For the 1.1 and $1.2 M_{\odot}$ WDs, we assume the Chandrasekhar radius, and for the $1.3 M_{\odot}$ WD, we adopt the radius of the helium-burning zone, $\log R_{\text{WD}} = 8.513$, in Kato et al. (1989). For more massive WDs, we adopt the radius of accreting WDs (Nomoto et al. 1984). The $1.377 M_{\odot}$ WD is a limiting case of mass-accreting WDs just before a central carbon ignition (Nomoto et al. 1984). The composition of the envelope is assumed to be uniform with $(X, Y, C + O, Z) = (0.0, 0.48, 0.5, 0.02)$ for $\leq 1.3 M_{\odot}$, which is taken from Kato & Hachisu (1999), and $(0.0, 0.38, 0.6, 0.02)$ for $\geq 1.33 M_{\odot}$. Changing the ratio of carbon to oxygen with the total mass ratio constant ($C + O = \text{const}$) hardly changes the result. OPAL opacity is used.

¹ See <http://vsnet.kusastro.kyoto-u.ac.jp/vsnet/index-j.html>.

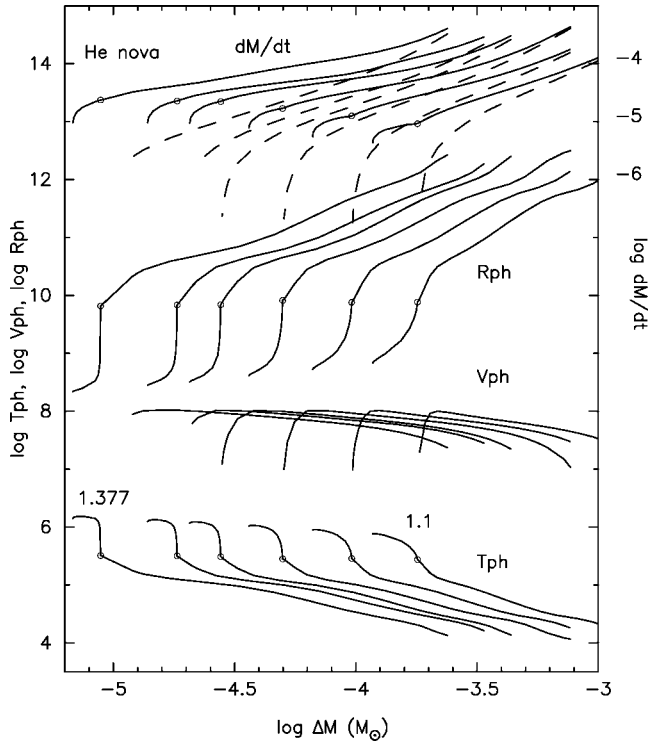


FIG. 1.—*Top*: Total envelope mass-decreasing rate (nuclear burning+wind mass loss; *solid curve*) and wind mass-loss rate (*dashed curve*) in units of solar masses per year. *Second from top*: Photospheric radius R_{ph} (in units of centimeters). *Third from top*: Wind velocity V_{ph} (in units of centimeters per second). *Bottom*: Temperature T_{ph} (in units of kelvins) against the envelope mass (ΔM) in units of solar masses. Time runs from right to left because the envelope mass is decreasing in time. The wind mass loss stops at the point marked by a small open circle. The WD mass is 1.1, 1.2, 1.3, 1.33, 1.35, and 1.377 M_{\odot} , from right to left.

3. LIGHT-CURVE MODELING

Figure 1 shows the photospheric temperature T_{ph} , the photospheric wind velocity V_{ph} , the photospheric radius R_{ph} , the wind mass-loss rate, and the total mass-decreasing rate of the envelope (the wind mass-loss rate plus the nuclear burning rate). At the maximum expansion, the star reaches somewhere on the curve depending on the envelope mass and moves leftward in time. The wind mass loss stops at the point marked by the small open circles. After that, the star moves further leftward owing to nuclear burning. The solution of 1.3 M_{\odot} is already presented in Kato & Hachisu (1999).

Figure 2 shows theoretical light curves corresponding to the models in Figure 1. A more massive WD shows a more rapid decline because of a smaller helium envelope mass, as shown in Figure 1. Difference in the chemical composition, for example, $(Y, C + O) = (0.38, 0.6)$ and $(0.48, 0.5)$ on the 1.3 M_{\odot} WD, hardly changes the theoretical light curves as shown in Figure 2 (see the difference between the dotted curve and the solid curve).

After the onset of a helium shell flash, the star brightens up and reaches somewhere on the theoretical curve and moves rightward on the curve in time (Fig. 2). Note that the $t = 0$ in these template light curves is not the onset of ignition of a particular object. The first point is determined by the ignition mass, i.e., the envelope mass at helium ignition for an individual object. If it is more massive, it first appears much farther left on the light curve, and the outburst lasts for a longer time.

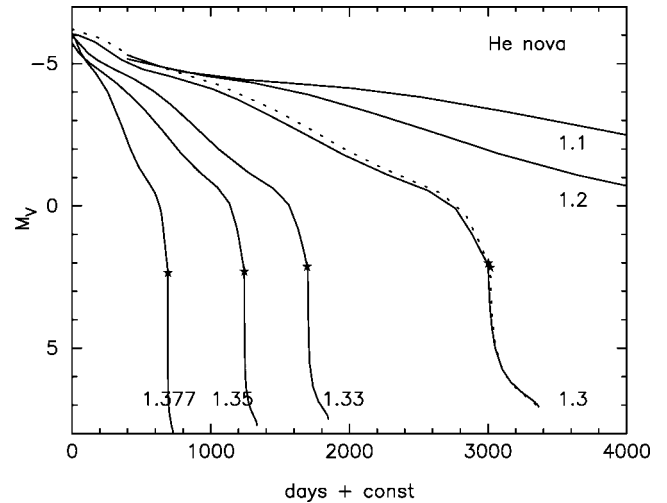


FIG. 2.—Template of our theoretical light curves for helium novae. WD masses are attached to each light curve in units of solar masses. The dotted curve denotes a 1.3 M_{\odot} model with different composition $(X, Y, C + O, Z) = (0.0, 0.38, 0.6, 0.02)$. The wind mass loss stops at the asterisk on each curve.

The V magnitude decreases slowly in the early stage and goes down quickly in the later stage. Especially after the wind stops at the point denoted by the asterisk, the star quickly fades away. The helium burning stops at the last point of each curve.

Observational data of V445 Pup taken from VSNET is shown in Figure 3. The mean decreasing rate of V445 Pup is about 1.8/200 (mag day $^{-1}$). The light curves of the 1.1 and 1.2 M_{\odot} WDs decline too slowly to be compatible with the observation even if we choose any parts of their light curves. On the other hand, we are able to fit a part of our theoretical light curves for WDs more massive than 1.3 M_{\odot} to the ob-

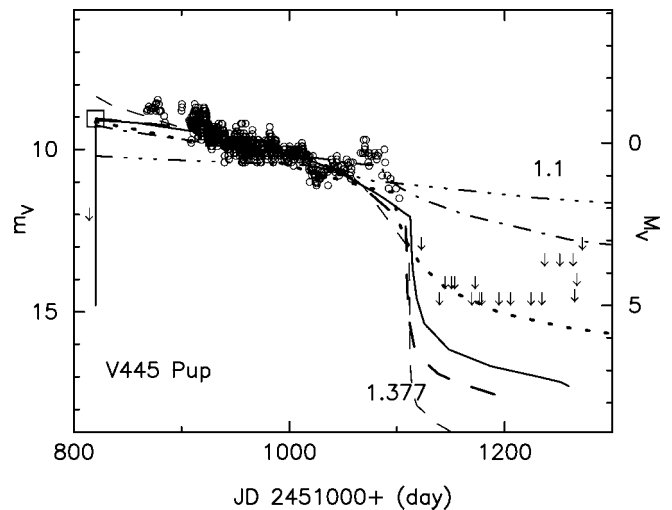


FIG. 3.—Light-curve modeling of V445 Pup. Only a later part of the theoretical curve in Fig. 2 is realized in V445 Pup. Values are 1.1 M_{\odot} (*triple-dot-dashed line*), 1.2 M_{\odot} (*dash-dotted line*), 1.3 M_{\odot} (*dotted line*), 1.33 M_{\odot} (*solid line*), 1.35 M_{\odot} (*thick dashed line*), and 1.377 M_{\odot} (*thin dashed line*). The theoretical curves except 1.33 M_{\odot} are shifted in the vertical direction (magnitude scale is on the right-hand side): 1.5, 1.5, and 0.5 mag upward for 1.1, 1.2, and 1.3 M_{\odot} and 0.2 and 0.9 mag downward for 1.35 and 1.377 M_{\odot} , respectively. The open circles and arrows represent observational data taken from VSNET (magnitude scale is on the left-hand side). The large open square indicates the assumed visual peak of our theoretical light curve for 1.377 M_{\odot} .

servational data. Thus, we may conclude that V445 Pup has a WD more massive than $1.3 M_{\odot}$.

To fit the vertical axis of the light curves, we obtain an apparent distance modulus of $(m - M)_V = 9.8$ as shown in Figure 3. The horizontal axis (time) is also shifted to fit the data. Here we adopt the middle part of our theoretical light curves around $M_V \sim 1$ that has a decline rate of $\sim 1.8/200$ (mag day $^{-1}$).

A slow decline lasts longer than 200 days, and the brightness suddenly drops. This point corresponds to the cease point of the optically thick wind. After the wind mass loss stops, the photosphere shrinks very rapidly. This feature is also shown in theoretical light curves for classical novae (Kato 1997) and recurrent novae (Kato 1999) of very massive WDs. This also appears in theoretical light curves of helium novae.

All the theoretical curves of 1.2 – $1.377 M_{\odot}$ are similar until JD 2,452,100 and deviate from each other after that day. The light curve of $1.1 M_{\odot}$ is too slow to decline and it should be excluded in the following discussion. We also think that the 1.2 and $1.3 M_{\odot}$ WDs do not meet the upper limit (arrows) of the observational data after JD 2,452,100. Finally, we adopt the conclusion that V445 Pup has a massive ($\geq 1.33 M_{\odot}$) WD.

4. DISCUSSION AND CONCLUSIONS

V445 Pup shows a quick decrease in the light curve from JD 2,452,100 in Figure 3. One may attribute this quick decrease to a thick dust shell formation in carbon-rich ejecta. If a dust shell is quickly formed and becomes optically thick to block the stellar light, we may expect a quick decrease in the light curve. In this case, the star moves along the theoretical curve in Figure 3 for a while and then drops down earlier than the theoretical fadeaway. Even if a blackout by dust occurs in this system, the light-curve modeling during the slow decline phase hardly changes. For a WD less massive than $1.2 M_{\odot}$, any part of the light curve cannot fit the data and is also excluded. For the $1.3 M_{\odot}$ WD (and barely the $1.2 M_{\odot}$ WD), it is required that a thick dust shell formation effectively occurs just near the theoretical fadeaway to meet the observational data (the upper limits, arrows in Fig. 3). For WDs more massive than $1.3 M_{\odot}$, we can shift the theoretical light curve rightward, but it is as large as by about 100 days from the limit of the decline rate, $\sim 1.8/200$ (mag day $^{-1}$). Therefore, we safely conclude that the WD of V445 Pup is still as massive as $1.3 M_{\odot}$ or more.

The recurrence period of helium novae is estimated as follows: The ignition mass, i.e., the envelope mass at the onset of the helium shell flash, is approximated by the mass of our wind solution at the optical peak. As the beginning time of eruption is not certain, we assume that it begins at JD 2,451,820 in Figure 3, i.e., shortly after the latest upper limit observation at JD 2,451,814. The schematic light curve is shown by the vertical line in Figure 3. Then the ignition mass is approximated by the mass of the wind solution marked by the square, which is $4.9 \times 10^{-5} M_{\odot}$ for a $1.33 M_{\odot}$ WD. A model of helium shell flashes predicts a relation between the mass accretion rate and the ignition mass. According to Saio's numerical calculation of steady helium accretion (H. Saio 2003, private communication), the corresponding mass accretion rate is $7.1 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. The recurrence period of helium novae is simply estimated, from the ignition mass divided by the accretion rate, as 69 yr. If we take the beginning of the outburst as the date

of discovery, JD 2,451,868, these values slightly changed to be $4.6 \times 10^{-5} M_{\odot}$, $7.6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, and 61 yr, respectively. For the case of a $1.35 M_{\odot}$ WD at JD 2,451,820, they are $4.2 \times 10^{-5} M_{\odot}$, $5.0 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, and 84 yr.

The distance to the star has been poorly known. We have estimated it from the comparison of the absolute magnitude of theoretical light curves and the apparent magnitude of observed data to be about 640 pc for $1.33 M_{\odot}$ and 700 pc for $1.35 M_{\odot}$ with an assumed extinction $A_V = 0.78$ (Ashok & Banerjee 2003). This value is consistent with an upper limit of 3 kpc based on the strength of an interstellar absorption given by R. M. Wagner.²

We have estimated the helium mass accretion rate to be several times $10^{-7} M_{\odot} \text{ yr}^{-1}$. In such a high accretion rate, the helium flash is very weak, and only a part of the envelope is blown in the wind while the rest of it accumulates on the WD (Kato & Hachisu 1999). Therefore, the WD will grow in mass after many cycles of helium shell flashes. The fate of the WD is either a Type Ia supernova or an accretion-induced collapse to a neutron star, depending on its initial WD mass (Nomoto & Kondo 1991).

The nature of the companion star is also interesting. The companion could be a helium star or a helium WD, from which the WD accretes helium matter directly. Another possibility of the companion is a helium-rich main-sequence star as suggested in the companion star of U Sco. With such high accretion rates, hydrogen shell flashes are very weak or the shell burning is almost stable. For example, hydrogen shell burning is steady for a mass accretion rate higher than $3.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ for $X = 0.7$ and $6.2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ for $X = 0.5$ for a $1.35 M_{\odot}$ WD. These values depend very weakly on the WD mass. This means that for the mass accretion rate we have estimated for V445 Pup, hydrogen burning is stable for $X = 0.7$, but unstable shell flashes repeat for $X = 0.5$. For a $1.33 M_{\odot}$ WD, hydrogen burning is stable for $X \geq 0.5$ but unstable for $X = 0.35$. In the case of steady hydrogen burning, the brightness of the WD is estimated to be $M_V = 7.8$ for $1.35 M_{\odot}$ and 7.6 for $1.33 M_{\odot}$ WDs, respectively. These values are below the upper limit of observation. Before the outburst, V445 Pup shows a constant brightness of ~ 14.5 mag. This luminosity may be a contribution from the accretion disk, not included in our theoretical light curves.

To summarize our results: We calculate light curves of helium novae and reproduce observational data for V445 Pup. From light-curve modeling, we conclude that the WD mass is more massive than $1.3 M_{\odot}$, the envelope mass at ignition is several times $10^{-5} M_{\odot}$, the mass accretion rate from the companion is several times $10^{-7} M_{\odot} \text{ yr}^{-1}$, and the recurrence period of helium nova outbursts is several tens of years. Distance to the star is estimated to be 640–700 pc with $A_V = 0.78$. Because the wind is weak, the WD is growing in mass and, therefore, V445 Pup is a candidate of Type Ia supernova progenitors.

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² See <http://vela.as.arizona.edu/~rmw/v445pup.html>.

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Note added in proof.—In a very recent paper, Ashok & Banerjee (2003) discuss the possibility of soft X-ray detection in V445 Pup. In our model, massive wind may absorb soft X-rays, and we do not expect soft X-ray fluxes during the wind phase. After the wind stops, soft X-rays may be observed, i.e., after the visual magnitude quickly drops and until the nuclear burning is extinguished.