Quiet Novae with Flat Maximum – No Optically Thick Winds

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Abstract

I will explain why most novae show a sharp optical peak in the light curve, whereas a small number of novae, such as PU Vul, shows a long-lasting flat optical maximum. Re-examination of occurrence condition of optically thick winds clarifies that hydrostatic evolutions, in which optically thick winds are suppressed, are realized during nova outbursts on low mass white dwarfs (WDs) (less than \( \sim 0.7 \ M_\odot \)). In such a case, a nova outburst evolves very slowly, because of no strong mass-ejection, and stays at low temperature stage a long time, which results in a long-lasting flat optical peak. This explains outburst nature of symbiotic nova PU Vul, that shows flat optical maximum lasted as long as eight years with no spectral indication of wind mass-loss. On the other hand, in ordinary nova outbursts, strong optically thick winds inevitably occur that carry out most of the envelope matter very quickly. Thus the light curve decays immediately after the optical peak, which results in a sharp peak of optical light curve.

1. Introduction

Nova is a thermonuclear runaway event on an accreting WD. After a shell flash sets in the envelope of the WD expands to a giant size. Strong optically thick winds occur that blow off a large part of the envelope. The photospheric temperature rises with time that causes the optical magnitude decrease while the total luminosity is almost constant. Figure 1 shows the HR diagram for the decay phase of nova outburst of solar composition (see [7] for HR diagram of CO nova). The optically thick winds widely occur and continue until the small open circles in Figure 1 (in green region).

In the decay phase the envelope settles down into a thermal equilibrium in which nuclear energy generation is balanced with radiative loss. The star moves leftward as the envelope mass decreases due to wind mass-loss and nuclear burning. Finally hydrogen nuclear burning stops and the star cools down.

The decay timescale depends strongly on the WD mass. A very massive WD crosses HR diagram in a few month. For example, recurrent nova RS Oph (\( M_{\text{WD}} \sim 1.35M_\odot \)) shows the total decay time as short as 80 days as shown in Figure 2. Much longer timescales are obtained for less massive WDs, e.g., 7 yr for 1.0\( M_\odot \), 80 yr for 0.6\( M_\odot \), 270 yr for 0.5\( M_\odot \).

Figure 1 distinguishes the regions where the optically thick wind occurs or not. The wind does not occur in the high temperature region of each WD and also in the less massive WDs. As the optically thick wind is accelerated deep inside the photosphere where the OPAL opacity has a prominent peak at log \( T(K) \)\( \sim 5.2 \), no wind is accelerated when the photospheric temperature is higher than this peak temperature. This is the reason of no wind in the left side of the small dot in Figure 1. On the other hand, in less massive WDs (\( \leq 0.5M_\odot \)), optically thick wind does not occur because the luminosity is always smaller than the local Eddington luminosity (described later) and the radiation-pressure-gradient is insufficient to accelerate the wind.

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The occurrence of optically thick winds in low mass WDs (~ 0.6 $M_\odot$) has not been fully clarified yet. Kato and Hachisu (2009) examined the boundary condition of occurrence of the wind and found that there are two kind of solutions with/without winds, both of which can be realized in nova outbursts on low mass WDs as shown in Figure 1, and that the occurrence of the winds depends on the ignition mass of a shell flash. As the optically thick winds essentially determine a nova evolution because of its large mass-loss rate, it is important to know when it occurs (when it does not) and how different the light curves are.

This short report aims to explain how and why the difference arises between the sharp peak such as in RS Oph (Figure 2) and other many classical nova and the long-lasted flat peak in PU Vul (Figure 3). This report is mainly based on the results of [8]. In Section 2, we introduce our simplified model to follow evolution of nova outbursts. Internal structure and evolution of nova envelopes are explained in Section 3. Section 4 presents the occurrence condition of optically thick winds for various WD masses that closely relate with the flat peak light curve. Conclusions follow.

2. Simplified Model

We can approximate nova evolution with a sequence of solutions that consists of steady-wind and static solutions because evolution timescale is much larger than hydrodynamical timescale except very early phase of shell flash [10, 7, 11]. When the optically thick wind occurs we solve the equations of motion, mass continuity, radiative diffusion, and conservation of energy, from the bottom of the hydrogen-rich envelope through the photosphere assuming steady-state. When the optically thick wind does not occur, we solve equation of hydrostatic balance instead of equation of motion. The occurrence of optically thick winds is detected by the conditions (1) the photospheric luminosity approaches the Eddington limit.
and (2) at the same time the thermal energy at the photosphere is comparable to the gravitational energy as described in Kato (1985) [6].

In the rising phase of nova outburst, I integrated energy conservation equation without energy generation term due to nuclear burning and later estimated energy generation using the temperature and density obtained. In the decay phase I set the condition that the energy generation is balanced with radiative energy loss because the envelope settles down into a thermal equilibrium [11]. Convective energy transport is calculated in static solutions using the mixing length theory with $\alpha = 1.5$. The OPAL opacity [3] is used. The chemical composition of the envelope is assumed to be uniform throughout the envelope with the solar composition $X = 0.7$ and $Z = 0.02$. These equations and method of calculations are already published in [7, 8].

3. Internal Structures

Figures 4 and 5 show the distribution of the diffusive luminosity and the local Eddington luminosity against the temperature for solutions along the rising phase. Here, the local Eddington luminosity is defined as

$$L_{\text{Edd}} \equiv \frac{4\pi cGM}{\kappa},$$

where $\kappa$ is the OPAL opacity. Since the opacity $\kappa$ is a function of the temperature and density, the Eddington luminosity is also a local variable. This Eddington luminosity has a local minimum at $\log T (K) = 5.25$ corresponding to the opacity peak as shown in e.g., Figures 4f and 5f.

As the shell flash goes on, the diffusive luminosity increases with time and approaches the Eddington luminosity near the photosphere (Figures 4a,b, and c). When the photospheric temperature decreases to $\log T (K) \sim 5.2$, matter is

Fig. 2. Three ($y$, $V$, and $I_c$) bands light curves for the 2006 outburst of recurrent nova RS Oph. Theoretical model [2] indicates that the WD of RS Oph is very massive, $1.35 \, M_\odot$. Figure taken from [2].

Fig. 3. Optical and UV light curves of PU Vul. Large open circles denote the continuum flux of IUE UV 1455 Å band. The scale in the right-hand-side denotes that for observational data. No optically thick wind occurs. Solid and dashed lines denote theoretical nova model of 0.57 and 0.6 $M_\odot$ WD. The downward arrow indicates the epoch of eclipse. Taken from [9].
Fig. 4. Evolutionary change of the diffusive and Eddington luminosities in the rising phase of a nova. The envelope mass is $4.2 \times 10^{-5} M_\odot$. $l$ denotes the ratio of the luminosity to the Eddington luminosity at the photosphere. The optically thick winds occur in (d)-(f). The small dot denotes the critical point.

Fig. 5. Same as Figure 4, but for the envelope mass $7.0 \times 10^{-5} M_\odot$. Optically thick winds are not accelerated and all the solutions are static solution. (Taken from [8]) Note that the super Eddington region at $\log T \sim 5.2$ is narrow in this diagram, but very wide in Figure 6.

Accelerated and optically thick steady wind begins (Figure 4d). After that, the envelope continuously expands to reach the maximum expansion, where the optical magnitude reaches the maximum. A narrow super-Eddington region appears corresponding to the opacity peak at $\log T (K) \sim 5.2$.

Figure 5 shows a rising phase similar to those in Figure 4, but for the case of massive envelope of $\Delta M_{\text{ig}} = 7.0 \times 10^{-5} M_\odot$. In this case no winds are accelerated when the envelope expands beyond the opacity peak of $\log T (K) \sim 5.2$ (Figure 5d) and the envelope continuously expands without optically thick winds (Figure 5e and 5f).

Note that the structure of the static solution just before the wind occurs (Figure 4c) is very similar to that of the adjacent wind solution (Figure 4d) as pointed out by [6] for the old opacity, which means that the optically thick winds occur very quietly. Moreover, the two solutions, Figure 4c and Figure 5c are also very similar. In later stages, however, the two sequences develop very different envelope structures.

Figure 6 compares internal structures of two types of solutions, with/without optically thick winds. These envelopes are for the same WD mass, chemical composition, and photospheric temperature. We see a remarkable difference in the
density distribution. The optically thick wind solution (thin line) shows monotonically decreasing density as $r^{-2}$ in the outer envelope ($\log r (\text{cm}) \gtrsim 10.3$), while the static solution develops a large density-inversion region at $\log r (\text{cm}) \sim 10 - 11.3$ corresponding to a super Eddington region. This density-inversion arises in order to keep hydrostatic balance in the super-Eddington region ($L_{\text{Edd}} < L_r$) as expected from the equation of hydrostatic balance. Inefficient convections occur in the region of $L_{\text{Edd}} < L_r$, but are unable to carry all of the diffusive energy flux, thus the structure is super-adiabatic.

In 0.4 and 0.5 $M_\odot$ WD, the envelope structure is more or less like that of the static solution of 0.6 $M_\odot$, i.e., with a wide density-inversion. However, in such less massive WDs, optically thick winds are not accelerated at all; No wind solutions exist.

4. Occurrence of Winds and Sharp/Flat Optical Maximum

As we have seen in the previous sections, the optically thick wind occurs in a smaller envelope mass ($\Delta M_{\text{ig}} = 4.2 \times 10^{-5} M_\odot$), but suppressed in a larger envelope mass ($7.0 \times 10^{-5} M_\odot$) for 0.6 $M_\odot$ WD. In other words, for a given WD mass ($> 0.5 M_\odot$), winds occur during a shell flash for a limited range of the ignition mass.

Figure 7 shows the region of the wind mass-loss in the diagram of the WD mass
- ignition mass. When the ignition mass is smaller than $\Delta M_{\text{wind}}$ the envelope cannot expand much and the photospheric temperature does not decrease to the opacity peak of $\log T (K) \sim 5.2$ (see Figures 4a-c and 5a-c). Therefore, no optically thick winds occur (“no expansion”). On the other hand, when the ignition mass is larger than $\Delta M_{\text{exp}}$, winds are suppressed in a way that density-inversion balances to radiation-pressure gradient in a super-adiabatic region (the region “expansion” which is an abbreviation of “quasi-static expansion”). In this case the envelope expands quietly because of no winds. Therefore, optically thick winds occur only for $\Delta M_{\text{wind}} < \Delta M_{\text{ig}} < \Delta M_{\text{exp}}$.

The upper part of Figure 7, however, is not realized in actual mass-accreting WDs. Numerical calculations of shell flash showed that the ignition mass is up to $6 \times 10^{-7} M_\odot$ for 1.4 $M_\odot$, $8 \times 10^{-5} M_\odot$ for a 1.0 $M_\odot$ WD, and $3 \times 10^{-4} M_\odot$ for a 0.65 $M_\odot$ WD [12] for various accretion rates. Therefore, “expansion” solutions are realistic only in less massive WDs, $\sim 0.5 - 0.7 M_\odot$. When the ignition mass is larger than $\Delta M_{\text{exp}}$, the shell flash develops in a quasi-static manner. When the ignition mass is smaller, the shell flash evolves as a usual nova outburst. A small difference in ignition mass causes large difference in the envelope structure as well as the evolution timescale, because the strong wind mass-loss governs nova evolution once it occurs.

Kato et al. (2010) [9] show that such a “static expansion” is realized in symbiotic nova, PU Vul, which showed no indication of strong wind mass-loss in its spectrum during the flat peak. Figure 3 shows the theoretical models calculated by Kato et al. for $\sim 0.6M_\odot$ WDs. As no optically thick winds occur, the evolution timescale is as long as a decade, thus the envelope keeps low surface temperatures several years. This is the reason why PU Vul shows a long-lasted flat optical maximum. This is a remarkable contrast with a majority of novae that shows a sharp peak like RS Oph (Figure 2), in which strong optically thick winds blow off a large part of the envelope in a very short timescale.

5. Conclusion

Once the optically thick wind occurs, it blows off a large part of the envelope mass, thus the light curve quickly decreases immediately after the optical maximum, making a sharp optical peak. When the winds does not occur, the light curve shows a long-lasted flat peak. Such a flat peak will be observed only in less massive WDs ($< 0.7 M_\odot$), because wind-suppressed solutions are realized only in less massive WDs with a relatively massive ignition mass. PU Vul is a good example of such a wind-suppressed evolution.

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