A NEW ESTIMATION OF MASS ACCUMULATION EFFICIENCY IN HELIUM SHELL FLASHERS TOWARD TYPE Ia SUPERNOVA EXPLOSIONS

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ABSTRACT

We have calculated the mass accumulation efficiency during helium shell flashes to examine whether or not a carbon-oxygen white dwarf (C+O WD) grows up to the Chandrasekhar mass limit to ignite a Type Ia supernova (SN Ia) explosion. It has been frequently argued that luminous supersoft X-ray sources (SSSs) and symbiotic stars are progenitors of SNe Ia. In such systems, a C+O WD accretes hydrogen-rich matter from a companion and burns hydrogen steadily on its surface. The WD expands a hydrogen-rich envelope and undergoes periodic helium shell flashes. Using the OPAL opacity, we have reanalyzed a full cycle of a helium shell flash on a 1.3 M⊙ C+O WD and confirmed that the helium envelope of the WD expands to blow a strong wind. A part of the accumulated matter is lost by the wind. The mass accumulation efficiency during helium shell flashes is estimated as ηHe = −0.175(log M + 5.35)² + 1.05 for −7.3 < log M < −5.9 and ηHe = 1 for −5.9 ≤ log M ≤ −5.0, where the mass accretion rate M is in units of M⊙ yr⁻¹. In relatively high mass accretion rates, as expected in recent SN Ia progenitor models, the mass accumulation efficiency is large enough for C+O WDs to grow to the Chandrasekhar mass, i.e., ηHe = 0.9 for log M = −6.3 and ηHe = 0.57 for log M = −7.0. The wind velocity (~1000 km s⁻¹) is much faster than the orbital velocity of the binary (~300 km s⁻¹), and therefore the wind cannot be accelerated further by the companion’s motion. We suggest observational counterparts of helium shell flashes in relation to long-term variations in supersoft X-ray fluxes of SSSs and symbiotic stars.

Subject headings: binaries: close — novae, cataclysmic variables — stars: mass loss — supernovae: general — white dwarfs

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are widely believed to be a thermonuclear explosion event of a white dwarf (WD), although the immediate progenitors have not been identified yet. Among many evolutionary paths toward SNe Ia proposed so far, arguments are now focused on the Chandrasekhar (Ch) mass model versus the sub-Chandrasekhar (sub-Ch) mass model and the single degenerate (SD) model versus the double degenerate model (see, e.g., Branch et al. 1995 for a review of SN Ia progenitors). Of these models, the SD/Ch model is the most promising one both from the observational and theoretical points of view (e.g., Nomoto et al. 1994 for a review; Kobayashi et al. 1998).

One example of the SD/Ch model is a luminous supersoft X-ray source (SSS) in which the WD accretes hydrogen-rich material at relatively high rates (M ≳ 1 × 10⁻⁷ M⊙ yr⁻¹; van den Heuvel et al. 1992). The WD accretes almost pure helium (Y = 0.98) as a result of stable hydrogen-shell burning, and it experiences helium shell flashes. In a strong flash, the envelope expands greatly (e.g., Iben 1982) and may suffer wind mass loss or a Roche lobe overflow (e.g., Kato, Saio, & Hachisu 1989, hereafter KSH89). If a large part of the helium layer will be lost by the wind, the WD hardly grows in mass to the Chandrasekhar mass (Cassisi, Iben, & Tornambé 1998, hereafter CIT98). Thus, it is essentially important to estimate the efficiency of the net mass accumulation onto the C+O core. KSH89 has first estimated the mass accumulation efficiency in helium shell flashes. They used the old opacity, however, and it should be recalculated with the new opacity.

A new evolutionary path of the SD/Ch scenario, in which a WD accretes hydrogen-rich matter from a lobe-filling red giant (WD+RG system), has been proposed by Hachisu, Kato, & Nomoto (1996, hereafter HKN96). In this model, optically thick winds blow from WDs, which stabilize the mass transfer even if the donor has a deep convective envelope. The WD steadily accretes hydrogen-rich matter from the companion. Its mass eventually reaches the Chandrasekhar mass limit, and the WD explodes as an SN Ia. Hachisu, Kato, & Nomoto (1999a) show that this WD+RG system is one of the main channels to SNe Ia. Li & van den Heuvel (1997) extended HKN96’s model to another type of binary system consisting of a mass-accreting WD and a lobe-filling, more massive, evolved main-sequence star (WD+MS system). Hachisu & Kato (1999) further proposed an evolutionary path to binaries consisting of a WD and a somewhat evolved MS star characterized by helium-rich accretion as observed in U Sco. This is another main channel to SNe Ia, as shown by Hachisu et al. (1999a).

All of these WD models will experience helium shell flashes followed by optically thick winds on their way to an SN Ia. If most of the helium matter is blown off in the wind, the WD cannot grow to the Chandrasekhar mass (MCh). Therefore, once again it is essentially important to evaluate the efficiency of mass accumulation during the wind phase of helium shell flashes in order to reach the definite conclusion of SN Ia progenitors.

CIT98 criticized HKN96’s model and concluded that the white dwarf mass hardly increases to MCh because of heavy mass loss owing to a Roche lobe overflow during helium shell flashes. However, once the optically thick wind occurs during helium shell flashes, the wind velocity is as fast as ~1000

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km s$^{-1}$, much faster than the orbital velocity ($\leq$300 km s$^{-1}$), so that the companion motion hardly affects the mass ejection. The wind matter quickly goes away from the system without any interaction to the orbital motion. Therefore, their argument has no physical meaning when a strong wind occurs.

In this Letter, we have followed a full cycle of helium shell flashes including the mass loss owing to optically thick winds in order to obtain the mass accumulation efficiency of accreting WDs. We have used the same techniques as in KSH98 but adopted OPAL opacity that has a strong peak around $\log T (K) \sim 5.2$, which drives a strong wind as shown by Kato & Hachisu (1994). In § 2, we describe our methods, assumptions, and main results of helium shell flashes on a 1.3 $M_\odot$ WD. Discussions follow in § 3.

2. MASS LOSS DURING HELIUM SHELL FLASHES

KSH98 adopted two different approaches for following a full cycle of helium shell flashes: time-dependent hydrostatic calculation and mimicking time-dependent behavior by a sequence of steady state wind solutions. They combined these two methods because the time-dependent Henyey code failed when the envelope expands greatly, while the steady state approach works well. We have used the same basic approaches as in KSH98 to follow a full cycle of helium shell flashes on a 1.3 $M_\odot$ WD. The main difference is in the wind solutions, which we replaced by the new solutions recalculated with the updated OPAL opacity (Iglesias & Rogers 1996).

The ignition models are unchanged because the OPAL opacity gives essentially the same values as the old opacity does at higher temperatures of $\log T (K) > 6$. We have assumed the same white dwarf radius of 1.3 $M_\odot$, i.e., $\log R$ (cm) = 8.513, and the envelope chemical composition of $Y = 0.48$, C + O = 0.5, and $Z = 0.02$ for helium, carbon plus oxygen, and heavy elements (including C+O in solar ratio) by weight, respectively. Such a small helium content is expected as follows: in the early stage of a shell flash, the convection spreads over the entire envelope, then descends and disappears before the photosphere reaches the maximum expansion. The ashes of helium burning, i.e., carbon and oxygen, are mixed into the entire envelope to reduce the helium content by about a half, on average, from the initial value of $Y = 0.98$. Thus, we have assumed the uniform composition with $Y = 0.48$ in quasi-evolutionary sequence. The convective energy transport is included in both the static and the wind solutions by the mixing-length theory with the mixing-length parameter of 1.5. The convection is, however, inefficient in the wind solutions because a wind is too fast (supersonic) compared with the convective motion (subsonic) (see Kato & Hachisu 1994 for details).

Figure 1 depicts evolutionary tracks of one cycle of helium shell flashes. After the onset of a shell flash, the helium layer expands to reach the maximum expansion of the photosphere, the radius of which depends on the ignition mass $\Delta M_g$ of the helium layer. We call this the rising phase. In the rising phase, the optically thick wind occurs when the photospheric temperature decreases to $\log T_{ph} \sim 5.45$. After the maximum expansion, the photospheric radius decreases with the envelope mass and the star moves blueward in the HR diagram. After the wind stops, the envelope mass further decreases owing to nuclear burning and the star moves downward to come back to the original position. We call this the decay phase.

For the rising phase, evolutionary tracks are approximated by a sequence of static solutions with a constant envelope mass until the optically thick wind occurs (see KSH98 for details). Three tracks have been calculated with (a) $\Delta M_g = 4.8 \times 10^{-5} M_\odot$, (b) $\Delta M_g = 8.7 \times 10^{-5} M_\odot$, and (c) $\Delta M_g = 3.5 \times 10^{-4} M_\odot$. These ignition masses are realized for the helium accretion rates of (a) $M_{acc} = 1.7 \times 10^{-6} M_\odot$ yr$^{-1}$, (b) $M_{acc} = 6.7 \times 10^{-7} M_\odot$ yr$^{-1}$, and (c) $M_{acc} = 1 \times 10^{-5} M_\odot$ yr$^{-1}$, respectively. The helium accretion rates of (a) and (b) correspond to the largest rates of hydrogen steady shell burning, $M_{acc} \sim L_{eddy}/Xe_{ph}$ in the envelope with $X = 0.35$ and $X = 0.7$, respectively, where $L_{eddy} \propto 1/(1+X)$ is the Eddington luminosity for electron scattering and $e_{ph}$ is the nuclear energy release of hydrogen burning per unit mass. Thus $M_{acc}$ is proportional to $1/X(1+X)$ for the hydrogen content $X$. Such a low hydrogen content of $X = 0.35$ (or $Y = 0.63$) is expected in the helium-rich matter accretion in the recurrent nova U Sco (Hachisu & Kato 1999).

The evolutionary track for (a) $\Delta M_g = 4.8 \times 10^{-5} M_\odot$ is very close to the curve for the decay phase (thick curve) and is omitted in Figure 1. No optically thick winds occur in this case because the photospheric temperature does not decrease to $\log T_{ph} \sim 5.45$. At the maximum expansion, the photospheric temperature reaches $\log T_{ph} = 5.83$ (indicated by arrow a) and the radius $R_{ph} = 0.022 R_\odot$.

In the case of (b) $\Delta M_g = 8.7 \times 10^{-5} M_\odot$, the wind mass loss begins at $\log T_{ph} = 5.45$. The maximum expansion is reached at $R_{ph} \leq 0.70 R_\odot$ and $\log T_{ph} \leq 5.05$ (indicated by arrow b), where the equality stands when we neglect the wind mass loss in the rising phase. The star moves blueward along the thick curve in the decay phase. The envelope mass is decreasing owing to wind and nuclear burning. The optically thick wind ceases at $\log T_{ph} = 5.45$. In the third case of (c) $\Delta M_g = 3.5 \times 10^{-4} M_\odot$, the wind mass loss begins at $\log T_{ph} = 5.44$ and the star reaches the maximum expansion at $R_{ph} \leq 9.1 R_\odot$ and $\log T_{ph} \geq 4.45$ (indicated by arrow c).

These tracks for three different envelope masses merge into
one track after the maximum expansion because the envelope reaches a thermal equilibrium in the decay phase. The more massive the ignition mass is, the more redward the star moves in the H-R diagram, that is, the star is traveling a longer track to a lower temperature. If the ignition mass is as large as \( \Delta M_{\text{ig}} \sim 7.7 \times 10^{-4} M_\odot \), the star reaches \( T_{\text{ph}} \geq 4.07 \). This envelope mass, \( \Delta M_{\text{ig}} = 7.7 \times 10^{-4} M_\odot \), corresponds to the ignition mass at \( M_{\text{acc}} = 4.5 \times 10^{-8} M_\odot \text{ yr}^{-1} \).

Figure 2 shows the photospheric temperature \( T_{\text{ph}} \), the photospheric radius \( R_{\text{ph}} \), and the photospheric wind velocity \( V_{\text{ph}} \) in the decay phase of helium shell flashes. The arrows indicate the same three ignition masses as in Figure 1. At the maximum expansion, the star reaches this position and then moves blueward as the envelope mass decreases owing to wind mass loss and nuclear burning. The wind mass loss stops at \( \Delta M = 5.0 \times 10^{-5} M_\odot \), marked by a filled circle. The photospheric velocity is as large as \( \sim 1000 \text{ km s}^{-1} \), which is much faster than the previous results (\( \sim 300 \text{ km s}^{-1} \) in KSH98) because of a strong acceleration driven by the large peak of the OPAL opacity.

The newly obtained wind velocities are much faster than the orbital velocities of SN Ia progenitors of the WD+MS or WD+RG systems (\( \sim 300 \text{ km s}^{-1} \)). Therefore, we can neglect effects of the binary motion on the mass ejection during the common envelope phase, since the envelope matter quickly goes away with little interaction with the orbital motion. This implies that neither a Roche lobe overflow nor a common envelope action plays an important role on mass ejection.

Figure 3 shows the total mass decreasing rate of the envelope \( \log \left[ d(\Delta M)/dt \right] \), which is the sum of the wind mass loss rate \( \dot{M}_{\text{wind}} \) and the mass decreasing rate owing to nuclear burning \( \dot{M}_{\text{nuc}} \) against the envelope mass log \( \Delta M \) for the decay phase of helium shell flashes. The processed matter accumulates at a rate higher than the mass ejection rate for the region of \( \log \Delta M < -3.74 \), and then a large part of the envelope matter accumulates on the white dwarf. These results are very different from the case of nova outbursts, in which most envelope mass is blown off. It is because of the difference in the nuclear energy release per unit mass between hydrogen burning and helium burning: hydrogen burning produces energy 10 times larger than that of helium burning, i.e., only 1/10 of the hydrogen-rich envelope mass is enough to blow the entire envelope off.

Figure 4 shows the accumulation efficiency defined by the ratio of the processed matter remaining after one cycle of helium shell flash to the ignition mass. The amount of matter lost by the wind in the decay phase is calculated from the rate of wind mass loss and nuclear burning in Figure 3. This accumulation ratio is well fitted by the solid curve expressed by

\[
\eta_{\text{nuc}} = \begin{cases} 
1, & -5.9 \leq \log M \leq -5 \\
-0.175 (\log M + 5.35)^2 + 1.05, & -7.3 < \log M < -5.9 
\end{cases}
\]

where \( M \) is in units of \( M_\odot \text{ yr}^{-1} \).

3. Discussion

CIT98 have followed the evolution of hydrogen-accreting white dwarfs. These WDs are undergoing many cycles of hydrogen shell flashes until a strong helium shell flash develops to expand the envelope to a red giant dimension. Based on these calculations with the old opacity, they concluded that a hydrogen-accreting white dwarf will not become an SN Ia because almost all of the helium envelope is lost from the system by a Roche lobe overflow or a common envelope ejection. CIT98 further denied the possibility of HKN96’s scenario.

In what follows, we criticize CIT98’s argument and support the growth of C+O WDs as expected in HKN96’s and Li & van den Heuvel’s (1997) models. CIT98 calculated only much less massive white dwarfs of 0.516 and 0.8 \( M_\odot \) to criticize the \( \sim 1.3 M_\odot \) model of HKN96. The trends of the envelope expansion and the mass accumulation depend on the WD mass because of the large difference in the surface gravity; nuclear
energy release in helium burning is comparable to the gravitational potential energy for massive WDs, i.e., the ratio of nuclear energy release to gravitational potential energy is ~1.0 for a 1.3 $M_\odot$ WD, whereas it is as large as 3.9 for a 0.8 $M_\odot$ WD and 8.9 for a 0.5 $M_\odot$ WD. For massive WDs, therefore, a large part of helium is consumed to produce nuclear energy before the envelope expands against the gravity. It reduces the helium content of the envelope. This low helium content in the envelope increases the burning speed in mass coordinates as understood from $\dot{M}_{\text{nuc}} \approx \frac{L_{\text{ultr}}}{Y_{\text{He}}}$, where $e_{\text{He}}$ is the nuclear energy release per unit mass for helium burning. Thus, CIT98’s criticism is inappropriate in the sense that their results for less massive WDs cannot be directly applied to very massive WDs.

Once the optically thick wind occurs, a Roche lobe overflow or a common envelope ejection discussed in CIT98 becomes physically meaningless because the wind velocity of ~1000 km s$^{-1}$ is much faster than the orbital velocity of the companion ($\leq 300$ km s$^{-1}$) of typical SN Ia progenitors (WD+MS or WD+RG model). The wind goes away quickly without any effective acceleration by the companion. After the wind stops, the photospheric radius ($\leq 0.1 R_\odot$) is much smaller than the Roche lobe ($\geq 1 R_\odot$). Therefore, neither a Roche lobe overflow nor a common envelope ejection works in our binary system.

We have ignored the hydrogen-rich envelope above the helium layer. An accreting 1.3 $M_\odot$ WD has a hydrogen-rich envelope of $\sim 10^3$ $M_\odot$ above the helium layer, depending on the mass transfer rate, chemical composition, and the other details of binary models. This is much smaller ($\leq 0.01$) than the mass of the helium layer at ignition, and we have neglected its contribution to the mass accumulation efficiency. The hydrogen-rich envelope will be quickly blown off at a very early stage of helium shell flashes.

Helium shell flashes may be observed as transient SSSs. For high mass accretion rates, as expected in SN Ia progenitors, shell flashes are so weak that the surface temperature never decreases to less than $\sim 1 \times 10^5$ K. Therefore, it will be a bright supersoft X-ray phenomenon with a faint optical counterpart. For a 1.3 $M_\odot$ WD, the bright SSS stage lasts $\sim 1$–3 yr with a recurrence period of a few tens to several tens of years. For more massive WDs just before SN Ia explosions, it lasts several months with a recurrence period of several years.

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