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The fate of a WD accreting H-rich material at high rates

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Abstract. We study a white dwarf (WD) accreting solar-composition material at high accretion rates. We find that after many cycles of Hydrogen flashes, several large Helium burning flashes expel the accreted envelope, leaving no net mass accumulation. Thus, the WD will not reach the Chandrasekhar mass nor ignite carbon before the donor stops the accretion process.

Key words. Stars: Novae – Stars: Supernovae

1. Introduction

The standard SN type Ia progenitor is a WD accreting at very high rates, having a net accumulation of mass. One can distinguish two cases, accretion of H-rich and accretion of He-rich material. Equally important is the initial mass of the accreting WD. Although a small mass WD can in principle grow in mass at high accretion rates, if a massive WD does not grow as well, no eventual explosion will ensue. For a detailed review of progenitor scenarios for SN Type Ia (see Podsiadlowski et al. 2008).

Here we wish to address the specific case of high rate H-accretion. We know from the work of (Prialnik & Kovetz 1995), that if one is to capture the long term secular behavior of the WD, a relatively large number of cycles is required. For this reason, we should be prepared to simulate several thousands of cycles. We begin by describing the model, continue with the results and end with a short discussion about the important energy budget in the system.

2. Model description

The initial model includes a $1 M_{\odot}$ C/O WD. The central core temperature was 6×10^{7}K. No rotation was included. We assumed that the dissipation of the rotational energy in the boundary layer is complete and radiated away.

Special attention was paid to have a fine mass division, mainly near the surface of the WD and on the outer part of the accreted envelope. The cyclic phenomenon demands very fine division during mass loss and peak burning. Therefore, the minimal mass shell chosen was $10^{-7} M_{\odot}$. The program determines automatically the mass shells and their distribution according to the specified accuracy. At the peak, over 4000 mass shells were required in the dynamic model. We included all relevant nuclear reactions up to A=40 and used the intermediate electrostatic screening correction.

Three basic models were calculated, one with a WD mass of $1 M_{\odot}$, one with $1.25 M_{\odot}$ and one with $1.35 M_{\odot}$ despite the recent finding by Weidemann (2000) that this mass is too high for a C/O WD. In all models the accretion rate was $10^{-6} M_{\odot}/yr$. According to Nomoto (1982), this accretion rate is high enough to puff the accreting system into a red giant-like star burning at steady state and evolving on a timescale determined by the nuclear burning.

A crucial issue is the treatment of the mass loss. At each time step, we check whether an optically thick wind can exist (Kovetz 1998) and assume that if it can exist, it does. A solution for a thick wind is then found and used to calculate the expected mass loss rate. The mass of the outermost shell is then corrected for the mass-loss. When the ratio between two adjacent mass shells exceeds a prescribed condition, a new mass division is established in which the ratio between two successive mass shells does not exceed a prescribed value.

The parameters are chosen in such a way that the readjustments due to the mass loss and the merger of shells does not induce unacceptable fluctuations and is effectively smooth. If the procedure is artificially inhibited, the mass which had to be removed expands to infinity, and reduces the time step to unacceptably small values due to shells at very large radii. We stress that in no case did the removal of the mass give rise to additional mass loss, namely, no rarefaction wave was created. The possibility of an optically thin wind was not checked in this calculation.

As for the initial conditions, most calculations assume a bare WD with an unperturbed temperature and density distributions. But in reality, since many flashes can take place on the WD surface, mass can be ejected and heat can flow into the WD. The aforementioned initial conditions are thus inappropriate. As we shall see, even high accretion rates lead to flashes, which are not very powerful but might cause some mass loss. As a consequence, the cumulative effect of successive flashes, whether small or large, cause a secular change in the structure of the WD and dramatically affect the long term outcome. The tacit assumption is that any initial conditions will converge to a unique dynamic behavior after a sufficiently large number of cycles.

In view of the above basic questions, we calculated a series of models in which the above limitations were lifted and pose the following questions: Does the mass of the WD increase? And if the answer is yes, how far can it increase and can it reach the Chandrasekhar mass? Is a WD accreting at a high rate a viable model for the progenitor of a SN of any kind?

3. Results

In contrast to Fujimoto (1982), we find that the hydrogen does not burn steadily, but does so in flashes. Hydrostatic calculations do not properly describe the problem.

We show in fig. 1 the general behavior of the total luminosity as a function of time, for a $1 M_{\odot}$ WD. The H burning is unstable, and exhibits cyclic behavior with a period of 7-8 years. Over the cycle, the luminosity changes by over a factor of 10, while the changes from cycle to cycle are quite small. The flashes are characterized by a very sharp rise and a much slower decline. A refined picture is shown fig. 2, where we see that the system becomes super-Eddington for a couple of years during which the rate of decline in luminosity is relatively low, but towards about three quarters of the cycle, the rate of decline increases. The minimum state is very short.

Despite the fact that the luminosity during the flash is above the Eddington luminosity, no mass loss developed. This is because the luminosity was used to expand the thin hydrogen shell, without allowing the velocity to reach the escape speed.

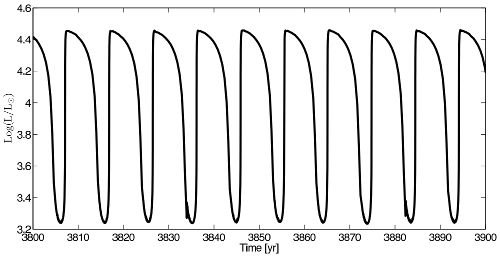

Fig. 1. The secular sequence of flashes for a $1 M_{\odot}$ WD.

The burnt H accumulates as He. It is important to note that H is left only in the new accreted outer envelope. The composition of the system is that of the original heavy elements, surrounded by a thick layer of He

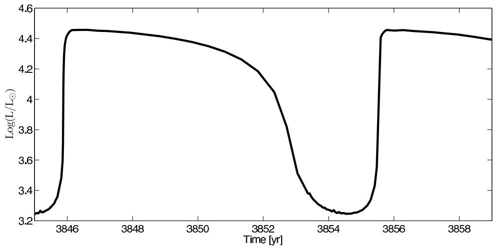

Fig. 2. The secular sequence of flashes.

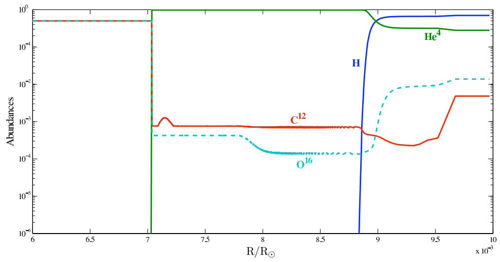

Fig. 3. The abundances as function of radius after 3000 cycels.

(nearly $0.01M_{\odot}$) as shown in fig. 3. At this phase, the system appears as a perfect recurrent object which accretes the ashes onto the original WD. Hardly any secular changes are noticeable during the first few thousand cycles.

The small outbursts cause a heat wave to propagate into the base of the He and into the C-O core (see fig. 4). It is interesting to compare the temperature profiles between this calculation of high accretion rate ($10^{-6}M_{\odot}$), and an accretion rate typical to a classical nova (e.g., $10^{-9}M_{\odot}$). In fig. 5 we present these two profiles for the same initial condition. In the scenario of the low accretion rate the WD is eroded in mass and therefore no secular heat wave formes. While in the case of the high accretion rate, there is no mass ejecta, the radius of the WD oscillates and part of the energy released in the outburst flows inwards. The temperate in the base of the He layer can reach temperatures of over 10^8K, namely, He ignition may occure.

The surprise appeared after 4153 cycles, once the accreted mass accumulated to $10^{-2}M_{\odot}$. The temperature inside the He layer reached 1.2×10^8K (cf. fig. 4), while $T_{\rm core}$ increased during these 10,000 years of accretion by 3% (from 6×10^7K to 6.2×10^7K). At that point, He ignited in a strong flash (cf. fig. 6). The peak nuclear energy generation reached 10^{12}erg/s and the maximum temperature reached 7×10^8K. Note that the peak nuclear luminosity, which is contributed solely by the H burning, hardly changes in the H flashes that precede the strong He flash, on the other hand, the minimum luminosity rises. This is due to the slow rise in He burning.

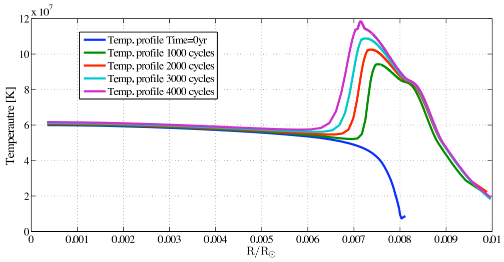

Fig. 4. Temperature profiles as function of the cycle number—the formation of a heat wave penetrating into the base of the He envelope and the CO WD.

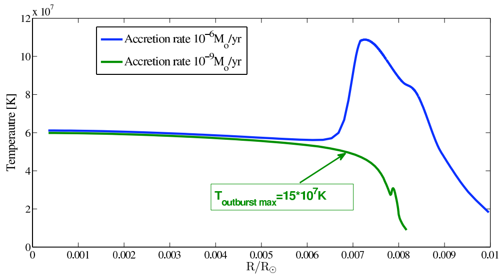

Fig. 5. Temperature profiles for a $1M_{\odot}$ WD having $T_{\rm core} = 10^6$K and $\dot{m}_{\rm acc} = 10^{-9}M_{\odot}yr^{-1}$ (green) and $10^{-6}M_{\odot}yr^{-1}$ (blue), after 3000 cycles of outbursts.

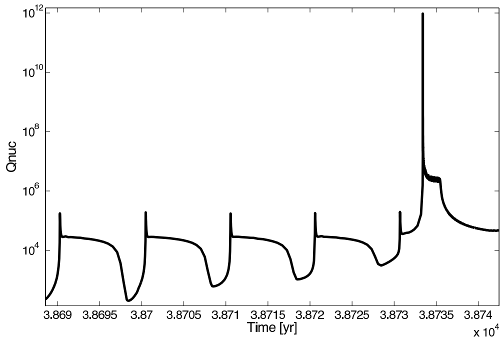

Fig. 6. The approach to the giant flash which ejected 1/3 of the accreted envelope.

The very strong He flash caused a temperature wave which propagated to the H burning at the top of the pure He layer, raised its temper-

Table 1. The total accumulated mass as function of WD mass for $\dot{M} = 10^{-6} M_{\odot} yr^{-1}$

WD Mass $[M_{\odot}]$	Final accreted mass $[M_{\odot}]$
1.0	9.9×10^{-3}
1.25	7.5×10^{-4}
1.35	1.1×10^{-4}

ature significantly, accelerated the burning accordingly, and caused an ejection of about 1/3 of the accreted He layer. This repeated twice more, and the entire He layer was ejected.

Table 1 summarizes the total accumulated mass obtained with $\dot{m}_{\rm acc} = 10^{-6} M_{\odot} yr^{-1}$, as function of the WD mass. In all three calculations, the last stage was nearly the same—once the temperature in the base of the He envelope was high enough, the He ignites and the entire accreted envelope was ejected.

4. Energetics: how come?

As is well known, the energy released in He burning per unit mass is insufficient to eject it from the (original) surface of the WD. According to the simple classical estimate, the gravitational binding energy of the envelope is given by $E_{grav} = G M_{WD} m_{env} / R_{WD}$, while the available energy is $E_{nuc} = Q m_{env}$. As the envelope is very small and compact, the radius which enters the binding energy calculation is essentially the radius of the white dwarf. Under these conditions, one finds that $E_{nuc,He} < E_{grav}$ and no mass can be ejected through helium burning.

The present results imply that one of the assumptions in the simplest calculation breaks down. Indeed, as the mass accumulated over more than 4000 cycles, a very small but continuous and steady change builds up in the accreted envelope. As a consequence, the envelope heats to a large extent through adiabatic compression of the accreted material.

When the small fraction of the luminosity from the stellar boundary layer was artificially omitted, the final result hardly changed. The envelope heated and consequently expanded mostly through adiabatic compression of the accreted material and in this way an envelope with a large radial extent was created. The WD attempted to become a red giant. Thus, most of the energy needed for the ejection of the envelope was supplied to it during the accretion process and not during the eruption. Once the envelope became bloated, the mass ejection became possible and indeed took place.

The theory of super-Eddington luminosities predicts a decrease in the effective radiation absorption coefficient (Shaviv 1998) which results from instabilities which lead to inhomogeneities. We rerun the problem with the proper correction to the effective radiative absorption coefficient (which is part of the corrections required by the theory) and found practically the same result: There is no net mass accreted by the WD in the long run. The next correction by the theory requires a change in the mass loss and we believe that its introduction will probably not change the final outcome, namely the mass of the WD will not change, however, the details (peak power, duration etc) will change significantly.

5. Accretion rate of $10^{-7} M_{\odot} yr^{-1}$

After eliminating the option of achieving the Chandrasekhar limit with an accretion rate of $10^{-6} M_{\odot} yr^{-1}$, and based on the results by Yaron et al. (2005), showing that the WDs erode for accretion rates of $10^{-8} M_{\odot} yr^{-1}$ and below, we followed several WD's with different masses all accreting at a rate of $10^{-7} M_{\odot} yr^{-1}$. Table 2 lists the results of our thousands of cycles calculations for $\dot{M} = 10^{-7} M_{\odot} yr^{-1}$. The properties given in table 2 are the mass of the WD, the core temperature, the accreted, ejected, and residual mass, and the interval between outbursts. WDs with different core temperatures will slightly change the masses.

We actually confirmed the results by Yaron et al. (2005). For an accretion rate of $10^{-7} M_{\odot} yr^{-1}$, the WD mass increases but the residual mass is so small that over a few hundred thousand cycles are needed.

6. Conclusions

The general belief until now was that the high accretion rate prevents degeneracy, thereby giving rise to quiet burning with the consequence that the WD increases its mass secu-

Table 2. Characteristics of the nova envelope for an accretion rate of $10^{-7} M_{\odot} yr^{-1}$

$M_{wd}[M_{\odot}]$	Core Temp. $[10^6 K]$	Accreted Mass $[M_{\odot}]$	Ejected Mass $[M_{\odot}]$	Residue Mass Per Cycle $[M_{\odot}]$	Recurrence Time [yr]
1.00	60.	9×10^{-6}	$8. \times 10^{-6}$	1×10^{-6}	100.
1.25	50.	1.5×10^{-6}	1.2×10^{-6}	3×10^{-7}	16.
1.35	50	3.5×10^{-7}	2.6×10^{-7}	9×10^{-8}	3.7
1.40	60.	5×10^{-8}	4×10^{-8}	1×10^{-8}	0.5

larly. We find that the standard theory of nuclear runaways on C/O WD's negates this possibility. The high accretion process is accompanied by thermonuclear pulses having luminosity increases of more than a factor of ten.

We also find that all the accreted hydrogen burns out nearly completely and the ejecta therefore contain almost no hydrogen. This implies that the non-existence of hydrogen in the observed ejecta does not imply that the accreted matter did not contain any hydrogen as well. Recall that the lack of hydrogen in the ejecta is considered as one of the strongest observational evidences for the idea of helium accretion.

Last, the high accretion rate does not lead in this case to a secular increase in the mass of the white dwarf. On the contrary, the WD is even eroded through the giant eruptions.

We have good reasons to suppose that a more massive WD behaves in the same way. The cycles will be shorter but we expect the higher mass WDs to have a similar ratio between secular changes and the cycle length, and therefore give rise to essentially the same result. This point is now under investigation.

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7. Discussion

MARGARITA HERNANZ: Are you finding sensitivity to the WD properties?

IRIT IDAN: Yes the WD structure is important. We checked for example two WD core temperature 60 and 10 million degrees—the results remained almost the same.

CHRISTIAN KNIGGE: So, you are getting outbursts (unstable burning) even in the so-called steady-burning regime? Is this consistent with other people's work (how does it explain the observational existence of supersoft sources).

IRIT IDAN: Yes we are getting outbursts in the so called "steady burning" zone for accretion rates of 10^{-7} and $10^{-6} M_{\odot} yr^{-1}$. The study of the "steady burning" zone was carried out until now only in a hydrostatic calculation, ignoring the dynamical effects of the problem and the long term evolution. The main goal of my talk was to demonstrate that it is important to follow the calculations for a long period of time—few cycles are not enough to reach meaningful conclusions about the long term behavior of the system. As for the super soft sources, could it be that their progenitors are He accretors?

MIKHAIL REVNIVTSEV: How important are the limitation of 1D calculations for your model? Can 2D or 3D cases be completely different?

IRIT IDAN: A 2D or 3D calculation could change the final results. But one has to remember that such calculations didn't change the results by much for lower accretion rates. In any case it is crucial to follow any calculation for a long period of time, few cycles usually don't tell the entire story.

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