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 super-Eddington accretion rates. We find that after many cycles of hydrogen ignition and burning, several large Helium burning flashes expel the accreted envelope, leaving no net mass accumulation. This implies that such a system will not undergo accretion induced collapse.

1. Introduction
The standard progenitor for SN type Ia is that of 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 and 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 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 $10^7$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 size of the mass shells and their number according to the specified accuracy. At the peak, over 4000 mass shells were used in the dynamic model. We included all relevant nuclear reactions up to $A=40$ and used the intermediate electrostatic screening correction.

Two basic models were calculated, one with a WD mass of 1$M_\odot$, and one with 1.2$M_\odot$ despite the recent finding by Weidemann (2000) that this is too high. In both 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 lead into a situation in which the model evolves 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 such a wind 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 the masses of the last two outermost 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 inhibited artificially, the mass which had to be removed expands to infinity, and reduces the time step to unacceptably small values once the shell reaches many solar radii. We stress that in no case did the removal of the mass found to induce additional mass removal, namely no rarefaction wave was created leading to endless mass loss. The possibility of an optically thin wind was not checked in this calculation.

Next comes the question of 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 surface of the WD, mass can be ejected and heat can flow into the WD, the aforementioned initial conditions are obviously inappropriate. As we shall see, even high accretion rates lead to flashes, which are not very powerful but still 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 long time.

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 with Fujimoto (1982), we find that the hydrogen does not burn steadily, but does so in flashes instead. 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. The hydrogen 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.

The burnt hydrogen accumulates as helium. It is important to note that the burning is complete, no hydrogen is left and the composition of the envelope is that of the original heavy elements, surrounded by a thick layer of He. 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 cycles.

The surprise appeared after 4153 cycles, once the accreted mass accumulated to $10^{-2}M_\odot$. The temperature inside the helium layer reached $1.2 \times 10^8 K$ (see fig. 3), while the WD core
temperature increased during these 10,000 years of accretion by 3% (from $6 \times 10^7$K to $6.2 \times 10^7$K). At that point, helium ignited in a strong flash (see fig. 4). The peak nuclear energy generation reached $10^{42}$erg/sec and the maximum temperature reached a peak of $7 \times 10^8$K. Note that the peak nuclear luminosity, which is contributed solely by the hydrogen burning, hardly changes in the hydrogen flashes that precede the strong helium flash, on the other hand, the minimum luminosity rises. This is due to the slow rise in helium burning.

The very strong He flash caused a temperature wave which propagated to the hydrogen burning at the top of the pure helium layer, raised it to a high temperature, accelerated the burning accordingly, and caused an ejection of about 1/3 of the helium layer accreted. This phenomenon repeated two more times with the outcome that the entire accreted helium layer was ejected.

4. Energetics: How come?
As is well known, the energy released in helium 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 $E_{grav} = GM_{WD}m_{env}/R_{WD}$, while the available energy is $E_{nuc} = Qm_{env}$. 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 $E_{nuc,Helium} < E_{grav}$ and no mass can be ejected through helium burning.

The present results implies 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.
When the small fraction of the luminosity from the stellar boundary layer was artificially omitted, the final result hardly changed. The envelope expanded mostly through adiabatic compression and 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 not change the outcome.

5. Conclusions
The general belief until now was that the high accretion rate prevents degeneracy, thereby giving rise to quiet burning. We find that this is not the case. The 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 completely and the ejecta therefore contain no hydrogen. This implies that the non existence of hydrogen in 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 guess 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.

This research has been supported by the Israel Science Foundation, grant 1589/10.

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