

Comparing Thermonuclear Runaway Conditions in Recurrent and Classical Novae

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Abstract. The thermonuclear runaway model for recurrent novae (RNe) may invoke three ingredients to reproduce the short recurrence time of these events: (1) a white dwarf (WD) close to the Chandrasekhar limit (2) that the WD be hot and (3) a high accretion rate, $\dot{M}$. The relative importance of each of these is discussed by evaluating how each modifies the thermal structure of the accreting layer of the WD. This comparison shows that, in terms of the runaway ignition mechanism, RNe form a relatively continuous extension of Classical Novae (CNe) in short-period binaries accreting due to Roche Lobe overflow. While the WD core temperature is an essential element in setting the conditions of the runaway in those low- $\dot{M}$ systems, it is found to be relatively unimportant at the extremely high $\dot{M}$ characteristic of RNe. By contrast, both the mass and $\dot{M}$ are found to be essential to achieve the short recurrence times observed in RNe such as RS Oph.

1. Introduction

A Nova outburst is the result of a thermonuclear runaway in the hydrogen-rich accreted layers on a white dwarf (WD) accreting mass from a companion in a binary (see Shara 1989 for a review). For purposes of comparison to Recurrent Novae (RNe), we will consider Classical Novae (CNe) as those which occur in the short-period Cataclysmic variables (CVs; Warner 1995) which consist of a WD primary accreting mass from a normal low-mass star that is filling its Roche lobe. These spend most of their life accreting at rates $\dot{M} \approx 10^{-9}$ – $10^{-11} M_{\odot} \text{ yr}^{-1}$ (see Howell et al. 2001, for example evolutionary calculations). CVs are formed when the companion to a WD (made during a common envelope event) comes into contact with its Roche lobe as a result of angular momentum losses. CVs typically begin mass transfer with orbital periods of 3-8 hours and evolve toward shorter orbital periods as the binary loses angular momentum. Due to the requirement for high $\dot{M}$, RNe generally occur in binaries with giant donors, although there are also short orbital period RNe (e.g. T Pyx, see also Anupama, these proceedings). After some initial uncertainty (Truran et al. 1988), thermonuclear runaway mechanisms won out over alternatives for explaining the RN outbursts (e.g. Starrfield et al. 1988; Kato 1990; Hachisu & Kato 2000).

The properties of CNe are closely tied to the mass transfer properties of the binary both directly via $\dot{M}$ and the ability of $\dot{M}$ to change the interior temperature of the WD (Townsley & Bildsten 2004). This has a noticeable impact on the

nova rate and the type of conditions under which most novae occur, specifically the level of degeneracy of the ignition site (Townsend & Bildsten 2005).

2. Nova Ignition Conditions

The thermonuclear runaway in a Nova system occurs when the density and temperature at the base of the accreted layer become high enough that the energy released by nuclear burning cannot be effectively transported away. The thermal structure of the outer layer of the WD determines how much mass needs to be accreted to reach these conditions. This structure was discussed in detail by Townsend & Bildsten (2004; hereafter TB04), some results of which we will summarize briefly here. Generally the thermal structure depends on three characteristics of the accreting WD: its mass, M , interior temperature, T_c , and the accretion rate, $\dot{M}$. Much like cooling WDs (e.g. Salaris et al. 2000), the outer layer of accreting WDs forms a radiative layer overlying a conductive, and therefore thermally well-connected, constant temperature core.

The energy liberated as material comes to rest on the WD surface is deposited in the very outermost layers and does not penetrate deeply due to the steep temperature gradient in the radiative layer (Townsend & Gänsicke 2008). The temperature in the radiative layer is set by the flux which must be carried out from near the base of the accreted layer. During the accretion phase between nova outbursts, entropy advected into the star as material is piled atop the accreted layer is liberated by the compression of that material. The settling of this material in the gravitational potential is the energy source, and most of the energy liberated escapes through the surface of the WD. As the runaway draws near, a small but significant amount of energy is released due to a low level of nuclear “simmering” prior to the unstable runaway.

The envelope becomes unstable and must evolve dynamically when the nuclear heating outruns the local cooling. This can be expressed by the instability condition

$$\frac{\partial \epsilon_{\text{nuc}}}{\partial T} > \frac{\partial \epsilon_{\text{cool}}}{\partial T} , \quad (1)$$

where ϵ_{nuc} is the nuclear heating per mass and it is convenient to use a one-zone approximation to define $\epsilon_{\text{cool}} = 4acT^4/\kappa y^2$ where a is the radiation density constant, c is the speed of light, κ is the radiative opacity and y is the column depth from the surface. TB04 found that this one-zone condition was insufficient to describe nova ignition below $\dot{M} \sim 10^{-10} M_{\odot} \text{ yr}^{-1}$ due to a combination of the ignition region moving into the conductive layer and the low temperature leading to the dominance of $p + p$ burning, which is much less temperature sensitive. Both the higher $\dot{M}$ CNe (in CVs above the period gap) and RNe are expected to have ignitions which are well predicted by the one-zone instability condition, creating a remarkable continuity between these two kinds of runaways. Assuming a Kramer’s opacity, and that cooling is limited by the radiative regime, the above ignition condition can be translated into more physical units. When ignition is by proton capture on ^{12}C , this gives

$$T_{7,\text{ign}} = 1.1 \frac{g_8^{1/7.5}}{\rho_3^{0.27} (X X_{12})^{1/15}} , \quad (2)$$

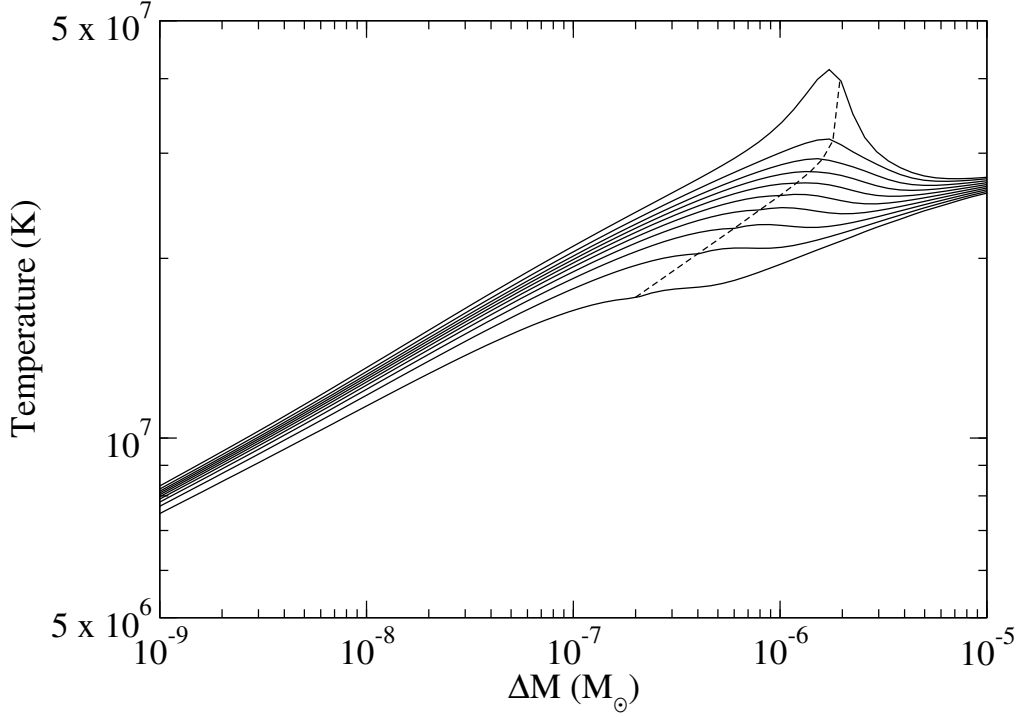


Figure 1. Thermal profile in a white dwarf during buildup to a recurrent nova runaway. This WD is $1.35M_{\odot}$ and has $\dot{M} = 10^{-7}M_{\odot} \text{ yr}^{-1}$. Profiles (solid) are shown every 2 years beginning from 2 years after onset of accretion ending at 19.5 years when a convection zone is formed. The evolution of the base of the accreted layer is shown by a dashed line.

where T_7 and g_8 and ρ_3 are temperature, surface gravity and density at the base of the accreted layer in units of 10^7 K, 10^8 cm s^{-1} and 10^3 g cm^{-3} respectively, X is the mass fraction of hydrogen and X_{12} is the mass fraction of carbon.

As a fiducial recurrent nova system, we take parameters close to those found by Hachisu & Kato (2000) to form a good match for RS Oph. We use a WD with $M = 1.35M_{\odot}$, accreting at $\dot{M} = 10^{-7}M_{\odot} \text{ yr}^{-1}$. This combination leads to an ignition mass of approximately $2 \times 10^{-6}M_{\odot}$ and thus a recurrence time of about 20 years. We find an actual recurrence time of 19.5 years. Profiles of the accreted layer during the buildup to runaway, up to the onset of convection, are shown in Figure 1. The simulation is begun with a cooling WD structure with $T_c = 3 \times 10^7$ K and an accreted layer mass of $M_{\text{acc}} = 4 \times 10^{-9}M_{\odot}$. Profiles are evenly spaced in time every 2 years, with the lowest corresponding to 2 years after onset of accretion. A dashed line indicates the evolution of the base of the accreted layer.

It is apparent from the figure that this T_c is likely close to, and perhaps a bit above, the equilibrium T_c for this $\dot{M}$. The profiles initially show that the core layers just below the accreted layer are cooling, and that later they are heated, in a similar manner to that discussed for low accretion rate objects in TB04. It is possible that there would be time for an object like RS Oph to

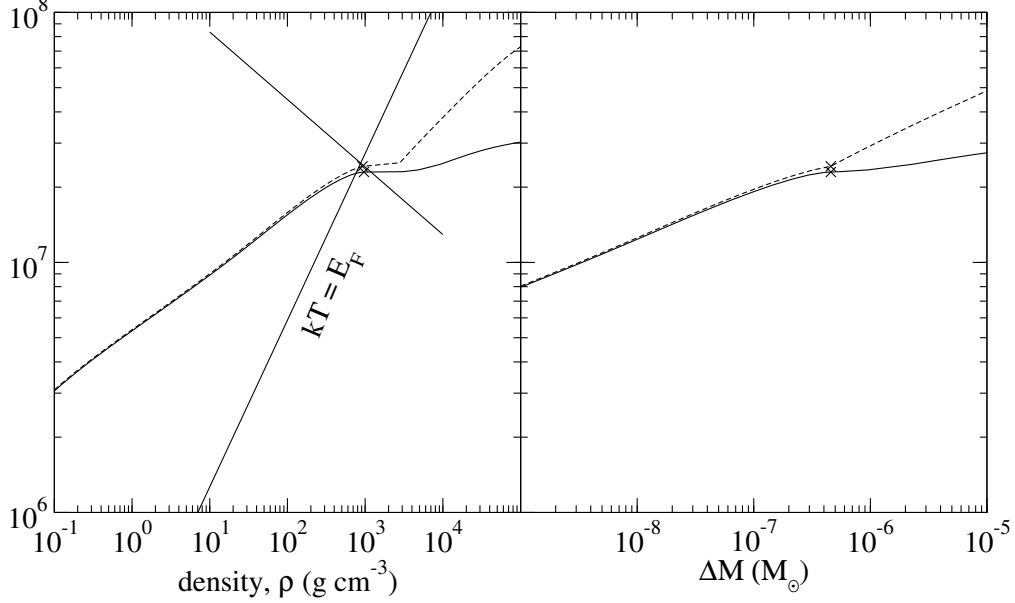


Figure 2. Temperature structure curves for a WD in density, ρ , and mass coordinate measured in from the surface, ΔM , with two different core temperatures T_c , 3×10^7 K (solid) and 10^8 K (dashed). Both curves have $M = 1.35 M_\odot$ and $\dot{M} = 10^{-7} M_\odot \text{ yr}^{-1}$. The base of the accreted layer is marked with an $\times$ on both curves, and the one-zone ignition condition, equation 2, is shown by the downward-sloping solid line. Even this significant change in T_c has fairly little effect on the T and ρ at the base of the accreted layer.

bring its WD to the equilibrium T_c . The surface luminosity, which is mostly due to heat liberated by compression in the accreted layers, is about $16 L_\odot$ when $M_{\text{acc}} = 0.25 M_{\text{ign}}$. If a similar luminosity is available for heating the WD core during buildup to nova when T_c is much lower than the equilibrium temperature, then this implies a core thermal time of just over 10^5 years. This would be even shorter if a significant amount of hot helium ashes are left on the surface of the WD after the runaway. We will see below that the ignition conditions are not very sensitive to the WD T_c .

2.1. Core Temperature

We begin by gauging the impact of varying the core temperature of the WD, T_c , on the thermal profile and therefore the ignition. Figure 2 shows two cases with $T_c = 3 \times 10^7$ and 10^8 K. The structure curve is shown in temperature-density space (left panel) in order to allow comparison of the position of the base of the accreted layer with the ignition curve described by equation 2. The right panel shows the structure in mass coordinate from the surface ΔM . These structures are evaluated using the quasi-static method from TB04, with $M_{\text{acc}} = 5 \times 10^{-7} M_\odot$ which is approximately $0.25 M_{\text{ign}}$ for our fiducial model. By comparing to Figure 1 we see that the static approximation provides a very good representation of the envelope state when M_{acc} is a small or modest fraction of the total M_{ign} .

We find that the T - ρ position of the base of the accreted layer is relatively insensitive to T_c for these values of T_c . Higher values of T_c are unlikely. The luminosity escaping the core at $T_c = 10^8$ K is just over $1 L_\odot$, such that the cooling time even in the presence of accretion is approximately 10^7 years. It is very unlikely that less time than this passed between the time the WD was formed and the second star in the binary ascended the giant branch. Lower T_c also has little impact on the position of the base of the accumulated layer because its temperature is set by that necessary to allow the heat being released by compression to escape the surface of the star.

This demonstrates the first important difference between RNe and short-period CNe. For low $\dot{M}$, T_c can be an important factor in setting the state at the base of the accumulated layer, and therefore the point of ignition. This is especially true in the pp -dominated regime where the base of the envelope is degenerate, and therefore very close to T_c when the runaway begins. A similar effect to that seen here is observed in the higher $\dot{M}$ cases $\sim 10^{-9} M_\odot \text{ yr}^{-1}$, where M_{ign} is not strongly sensitive to T_c due to the significant compressional energy release and the weak coupling to the core. However, since the $T_{c,\text{eq}}$ is lower in those cases, $\sim 10^7$ K, there is a greater possibility that an elevated T_c due to a young WD might effect the ignition.

2.2. White Dwarf Mass

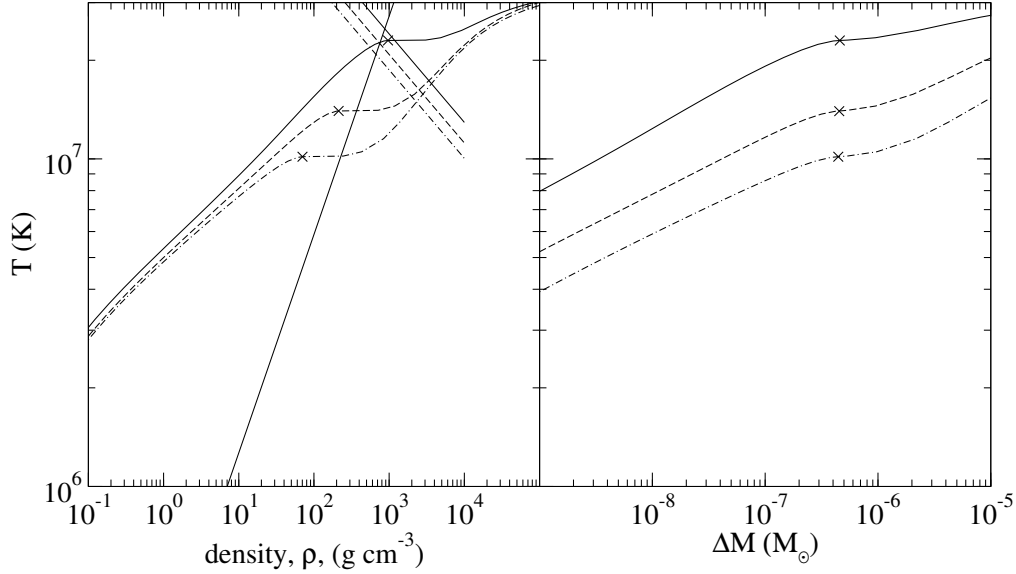


Figure 3. Temperature structure curves for a WD in density, ρ , and mass coordinate measured in from the surface, ΔM , with three different WD masses M , 1.35 (solid), 1.2 (dashed) and $1.0 M_\odot$ (dash-dot). All have $T_c = 3 \times 10^7$ K and $\dot{M} = 10^{-7} M_\odot \text{ yr}^{-1}$. The base of the accreted layer is marked with an $\times$, and the one-zone ignition condition, which is different for each mass, is shown by the downward-sloping lines. The density at the base of the accreted layer is strongly reduced with decreasing mass, leading to an increase of M_{ign} , and therefore recurrence time, of orders of magnitude.

In order to test the dependence on WD mass, M , we reduce it from our fiducial value of $1.35 M_\odot$ to 1.2 and $1.0 M_\odot$, keeping $\dot{M}$ and T_c fixed. As shown in Figure 3 this results in a strong reduction in the density at the base of the accreted layer and a reduction in the overall temperature of the radiative envelope at a given depth. The luminosity released due to compression is similar in all these cases, given approximately by $L \simeq \dot{M} k_B T_b / \mu m_p$ (TB04) where k_B is Boltzmann's constant, T_b is the temperature at the base of the accreted layer, μ is the mean molecular weight of the accreted material and m_p is the proton mass. The overall flux is reduced due to the larger radii in the lower mass cases, lowering the temperature of the accreted layer at a given ΔM . Note that the level of degeneracy at ignition does not appear strongly affected by the reduced M , although the recurrence time is much longer.

2.3. Variation with Accretion Rate

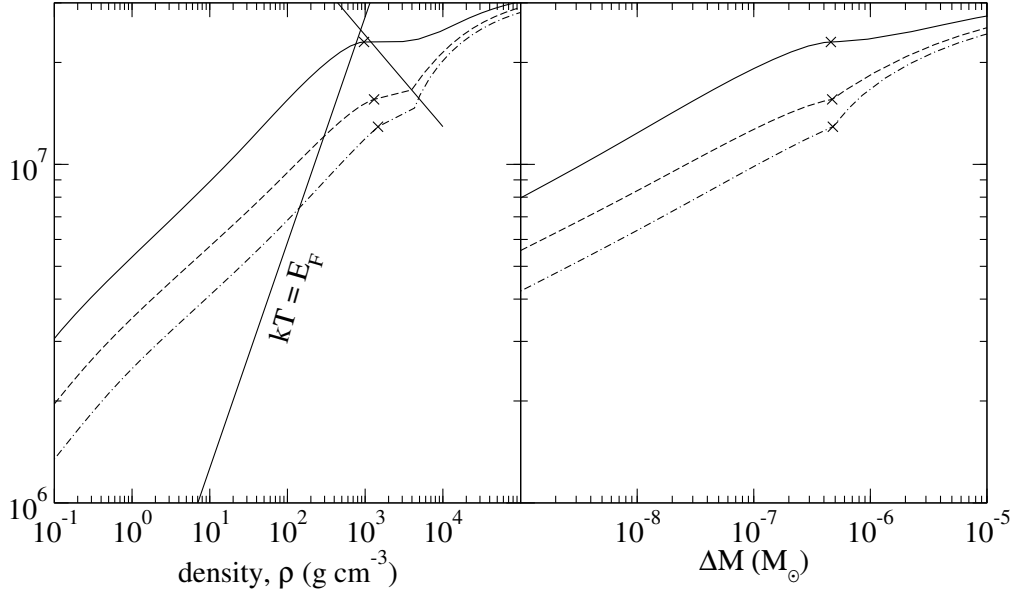


Figure 4. Temperature structure curves for a WD in density, ρ , and mass coordinate measured in from the surface, ΔM , with three different accretion rates $\dot{M} = 10^{-7}$ (solid), 10^{-8} (dashed), and $10^{-9} M_\odot \text{ yr}^{-1}$ (dot-dashed). All have $T_c = 3 \times 10^7$ K and $M = 1.35 M_\odot$. The base of the accreted layer is marked with an $\times$, and the one-zone ignition condition is shown by the downward-sloping line. While the density at the base increases with decreasing $\dot{M}$, the thermal state of the envelope is much lower, delaying ignition of burning. Note also the degeneracy will be much stronger for ignitions at lower $\dot{M}$.

The accretion rate, $\dot{M}$, appears to be the most important parameter for setting a short recurrence time. While the range of possible T_c and M is fairly limited, and not very different between CNe and RNe, orders of magnitude in $\dot{M}$ are possible. Also, $\dot{M}$ affects both M_{ign} and the accumulation rate, magnifying its impact on the recurrence time. To evaluate the impact of lower $\dot{M}$, Figure 4

shows, in addition to our fiducial case with $\dot{M} = 10^{-7} M_{\odot} \text{ yr}^{-1}$, also $\dot{M} = 10^{-8}$ and $10^{-9} M_{\odot} \text{ yr}^{-1}$. The T_c and M are again held fixed at the fiducial values of $3 \times 10^7 \text{ K}$ and $1.35 M_{\odot}$. These latter $\dot{M}$ s are actually normal for many CNe, such that this is a direct comparison of the most massive CNe to RNe. It is evident that the base of the accreted layer is significantly more degenerate in the case of $\dot{M}$ appropriate for CNe. Also we see that the equilibrium core temperature should be a bit lower for CNe, more like 10^7 K (TB04). In fact the temperature curves shown in Figure 4 for the lower $\dot{M}$ values are significantly elevated due to the high T_c assumed. Approximately half of the surface luminosity in the case of $\dot{M} = 10^{-9} M_{\odot} \text{ yr}^{-1}$ is coming from cooling of the WD core.

By comparing Figures 3 and 4 we observe that producing a recurrent nova of the high frequency of RS Oph and a similar level of degeneracy with a lower mass WD is difficult. A lower M and thus surface gravity would require a higher $\dot{M}$ such that the base of the accreted layer would not be degenerate at the time of ignition. While such a configuration is still unstable due to being a thin shell, the mass ejection episode is likely to be much less strong.

3. Conclusions

By comparing thermal profiles of accreting WDs at different T_c , M and $\dot{M}$ against nova ignition conditions, we have shown that RNe form a relatively continuous extension of CNe in lower $\dot{M}$ systems. At the high $\dot{M}$ relevant to RNe, realizable values of T_c show that it is not an important determining factor in the time of the ignition. A combination of high mass and high $\dot{M}$ is necessary to display the short recurrence times characteristic of RNe and maintain the degeneracy of the ignition layer. The mass must be near the highest possible for a WD, otherwise ignition would not take place under degenerate conditions, although a runaway is still inevitable.

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Discussion

Sion: Just a comment in reference to a point raised by Herwig. Both the thin shell and degenerate flash were delineated by Giannone and Weigert (1967, ZA, 67, 41). Both of these types of runaways occurred in the same TNR. This TNR was triggered by compressional heating.

Towneley: My evaluation of $\frac{\partial \epsilon_{\text{nuc}}}{\partial T} > \frac{\partial \epsilon_{\text{cool}}}{\partial T}$ is a version of the thin shell instability condition.

Kato: Do you have an ignition mass for a massive WD?

Towneley: For a $1.35M_{\odot}$ WD, $M_{\text{ig}} = 2 \times 10^{-6}M_{\odot}$.

Kato: This is consistent with my calculations. It is difficult to calculate the ignition mass for a massive WD. There are some in the literature, but some of them assumed polytropic envelopes and some use the old opacities or some approximation. There seem to be no reliable ignition masses except yours.

Gehrz: In the systems that we call true “classical” novae with long recurrence times and low accretion rates, a long standing problem has been that TNR models do not give large enough ejected masses, which are observed to be as large as $1 - 5 \times 10^{-4}M_{\odot}$. Do your new models solve this problem in any way?

Towneley: Our models are able to reproduce these large masses as ignition masses, which gives an effective approximate maximum ejected mass. The large mass is from low accretion rate objects. The currently outstanding question is how many of the objects with large measured ejected masses can be explained with low mass accretion rates. They should be either $P_{\text{orb}} < 2.5$ hr or magnetic.