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Theoretical Studies of Accretion of Matter onto White Dwarfs and the Single Degenerate Scenario for Supernovae of Type Ia

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Abstract. We review our current knowledge about the thermonuclear processing that occurs during the evolution of accretion onto white dwarfs both with and without the mixing of core with accreted material. We present a brief summary of the Single Degenerate Scenario for the progenitors of Type Ia Supernovae in which it is assumed that a low mass carbon-oxygen white dwarf is growing in mass as a result of accretion from a secondary star in a close binary system. The growth in mass requires that more material remain on a white dwarf after a thermonuclear runaway than is ejected by the explosion. Recent hydrodynamic simulations of accretion of solar material onto white dwarfs *without mixing* always produce a thermonuclear runaway and "steady burning" does not occur. For a broad range in WD mass (0.4 $M_\odot$ to 1.35 $M_\odot$), the maximum ejected material occurs for the 1.25$M_\odot$ sequences and then decreases as the white dwarf mass decreases. Therefore, the white dwarfs are growing in mass as a consequence of the accretion of solar material and as long as there is no mixing of accreted material with core material. In contrast, a thermonuclear runaway in the accreted hydrogen-rich layers on the *low* luminosity WDs in close binary systems where mixing of core matter with accreted material has occurred is the outburst mechanism for Classical, Recurrent, and Symbiotic novae. The differences in characteristics of

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these systems is likely the WD mass and mass accretion rate. The high levels of enrichment of CN ejecta in elements ranging from carbon to sulfur confirm that there is dredge-up of matter from the core of the WD and enable them to contribute to the chemical enrichment of the interstellar medium. Therefore, studies of CNe can lead to an improved understanding of Galactic nucleosynthesis, some sources of pre-solar grains, and the Extragalactic distance scale. The characteristics of the outburst depend on the white dwarf mass, luminosity, mass accretion rate, and the chemical composition of both the accreting material and WD material. The properties of the outburst also depends on when, how, and if the accreted layers are mixed with the WD core and the mixing mechanism is still unknown.

1. Introduction

We take, as given, the model for Cataclysmic Variables (CVs) that has been developed over the past 50 years (Crawford & Kraft 1956): accretion occurs onto the white dwarf (WD) component in a close binary system. While the compact object is a WD, the secondary is a larger, cooler star that typically fills its Roche Lobe (in the Restricted Three-Body Problem). In some Symbiotic systems, which include the Symbiotic Novae such as RS Oph, V407 Cyg, and T CrB, the orbital period is so long that the secondary may not fill its Roche Lobe but mass transfer onto the WD must be occurring in order for an explosion to occur. We note, in addition, that larger only refers to the radius of the secondary. In many cases, the secondary is less massive than the WD. Because the secondary fills its Roche Lobe, any tendency for it to grow in size because of evolutionary processes or for the Roche Lobe to shrink because of angular momentum losses will cause a flow of gas through the inner Lagrangian point into the Roche Lobe surrounding the WD. The size of the WD is small compared to the size of its Lobe and the angular momentum of the transferred material causes it to spiral into an accretion disc surrounding the WD. Some viscous process acts to transfer material inward and angular momentum outward so that some fraction of the material lost by the secondary ultimately ends up on the WD while some material must be ejected from the accretion disk.

The accreting material gradually forms a layer of fuel on the WD and the bottom of this layer is compressed by the strong gravity of the WD and the continuously infalling material. The accreted layer is heated both by compression and by the flow of heat from the interior. Over a period of time, the accreted layer on the WD grows in mass until the bottom reaches temperatures that are sufficiently high to initiate thermonuclear burning of hydrogen by the proton-proton chain of reactions. In addition, by this time the bottom of the layer has become electron degenerate. Because the material is degenerate, the energy release does not result in expansion and cooling of the accreted layers. Therefore, once nuclear burning in the bottom of the layer reaches thermonuclear runaway (TNR) conditions, the temperatures in the nuclear burning region will exceed 10^8K for low mass WDs ($M_{WD}<1.0$ $M_\odot$). For higher mass WDs ($M_{WD}>1.2$ $M_\odot$) these temper-

atures can exceed 2×10^8K even if there has been no mixing of core material with the accreted material. Hydrodynamic studies show that the further evolution of the thermonuclear burning and its evolution to a TNR on the WD now depends upon the mass and luminosity of the WD, the rate of mass accretion, and the chemical composition of the nuclear burning layer. This last condition implies that the evolution of the resulting TNR will differ depending on whether or not mixing of core with accreted material has taken place. As we will discuss, whether or not mixing has taken place has important consequences on the secular evolution of the WD. Therefore, in this review we distinguish between those systems in which the accreted material does not mix with core material and those that do mix with core material. We will also discuss the effects of the other parameters.

Recent reviews of the properties and evolution of CVs can be found in Warner (1995); Knigge et al. (2011); Knigge (2011a,b). Recent reviews of the Classical Nova phenomena can be found in Gehrz et al. (1998, hereafter, G98), Warner (1995), Hernanz & José (2002, and references therein), Hernanz & Jose (2008), and Starrfield et al. (2008, hereafter, S08). In the next section, we present the basic physics of a thermonuclear runaway and the importance of the β^+-unstable nuclei. We follow that with sections on: the initial conditions, the Single Degenerate (SD) scenario for the progenitors of Supernovae of Type Ia, the Classical Nova Outburst, a discussion of future work, and end with a Summary and Conclusions.

2.   The Basic Physics of a Thermonuclear Runaway

Hydrodynamic simulations show that the consequences of accretion from the secondary is a growing layer of hydrogen-rich gas on the WD. When the deepest layers of the accreted material have become both hot and electron degenerate, a TNR occurs near the base of the accreted layers. For the physical conditions of temperature and density that occur in this environment, nuclear processing proceeds by hydrogen burning, first from the proton-proton chain and, subsequently, via the carbon, nitrogen, and oxygen (CNO) cycles. If there are heavier nuclei present in the nuclear burning shell, then they will contribute significantly to the energy production and the resulting nucleosynthesis. Simulations of this evolution for the classical nova (CN) outburst, designed to fit the observed properties of the ONe nova V1974 Cyg found that changes in the nuclear reaction library and opacities caused important changes in the results (Starrfield et al. 2000, and references therein). More recently, Starrfield et al. (2009, hereafter, S09) redid some of those calculations with the Iliadis (2005, priv. comm.) reaction library and the Hix & Thielemann (1999a) network solver and found that all previous work had neglected the *pep* reaction ($p + e^- + p \rightarrow d + \nu$: (Schatzman 1958; Bahcall & May 1969)) which, when included, changed the ejecta abundance predictions (S09). This reaction has a density squared dependence and, while not important for energy production in the Sun, in the outer layers of a WD the density can reach to 10^4 gm cm^{-3} which significantly increases the energy production at a given temperature and density. The increased energy production causes the temperature to increase faster for a given mass accretion rate and the TNR occurs earlier with less mass accreted. A smaller amount of accreted mass implies a lower peak temperature and, thus, the nucleosynthesis predictions change just based on the inclusion of this one nuclear reaction rate.

Nevertheless, while the proton-proton chain is important during the accretion phase of the outburst (before the rise to the TNR), during which time the amount of accreted mass is determined, it is the CNONe cycle reactions and, ultimately, the hot CNO sequences that power the final stages and the evolution to the peak of the TNR. Energy production and nucleosynthesis associated with the CNO hydrogen burning reaction sequences impose interesting constraints on the energetics of the runaway. In particular, the rate of nuclear energy generation at high temperatures ($T > 10^8$K) is limited by the timescales of the slower and temperature insensitive positron decays, particularly ^{13}N ($\tau_{1/2} = 600$s), ^{14}O ($\tau_{1/2} = 102$s), and ^{15}O ($\tau_{1/2} = 176$s). The behavior of the positron decay nuclei holds important implications not only for the nature and consequences of CN outbursts where the accreted and core material are mixed but also for the simulations where there is no mixing. For example, significant enhancements of envelope CNO concentrations are required to insure high levels of energy release on a hydrodynamic timescale (seconds for WDs) and thus produce a violent outburst (Starrfield 1989; Starrfield et al. 1998, hereafter, S98; S09).

The large abundances of the positron decay nuclei, at the peak of the TNR, have important and exciting consequences for the further evolution of the TNR. (1) Since the energy production in the CNO cycle comes from proton captures, interspersed by β^+-decays, the rate at which energy is produced, at temperatures exceeding 10^8K, depends only on the half-lives of the positron decay nuclei and the numbers of CNO nuclei initially present in the envelope. (2) Since near peak temperature in the TNR convection operates throughout the entire accreted envelope, unburned CNONeMg nuclei are carried into the nuclear burning region, when the temperature is near maximum, and the nuclear reactions operate far from equilibrium. (3) Since the convective turn-over time scale is $\sim 10^2$ sec near the peak of the TNR, a significant fraction of the positron decay nuclei are able to reach the surface without decaying and the rate of energy generation at the surface can exceed 10^{13} to 10^{15} erg gm^{-1} s^{-1} (depending upon the enrichment). (4) These same nuclei decay when the temperatures in the envelope have declined to values that are too low for any further proton captures to occur, yielding isotopic ratios in the ejected material that are distinctly different from those ratios predicted from studies of equilibrium CNONeMg burning. (5) Finally, the decays of these nuclei provide an intense heat source throughout the envelope that helps eject the material from off the WD. Theoretical studies of this mechanism show that sufficient energy is produced, during the evolution described above, to eject material with expansion velocities that agree with observed values and that the predicted bolometric light curves for the early stages are in reasonable agreement with the observations (S89; S98; S08). Finally, the β^+-decay heating of the outermost regions of the WD envelope reduces the temperature gradient and, in turn, curtails convection in the surface layers. The growth of convection from the burning region to the surface and its subsequent retreat in mass, as the envelope relaxes from the peak of the runaway on a thermal timescale, implies that there should exist variations in the elemental and isotopic abundances in the ejected gases.

3.   Initial Conditions for the Outburst

A short description of the history of the development of the TNR hypothesis for the outburst is given in Starrfield (1989) and will not be repeated here. One of the important developments since

that review have been the calculations of the amount of hydrogen-rich material that can be accreted before the TNR is triggered. In the 1980's there were both analytic (Fujimoto 1982a,b) and semi-analytic (MacDonald 1983) calculations to determine the amount of material that could be accreted onto a WD before the TNR occurred. Since that time, there have been a number of studies of accretion onto WDs using Lagrangian hydrostatic or hydrodynamic computer codes which follow the evolution of the material as it gradually accretes onto the WD. These calculations show that the amount of material accreted onto the WD is a function of the WD mass, luminosity, the composition of the accreted matter, and the mass accretion rate ($\dot{M}$). If the mixing of the accreted material with the core occurs during the accretion process, then the core nuclei added to the accreted layers will affect the amount of material accreted prior to the TNR by increasing the opacity and trapping the heat from the nuclear burning regime in those layers where the heat is produced (S98). Although there have been a number of multi-dimensional studies investigating mixing during the nova outburst (Glasner et al. 1997; Kercek et al. 1998; Glasner et al. 2007; Casanova et al. 2010, 2011a,b, and references therein), they are limited by CPU time considerations to following the evolution only near the peak of the outburst. If mixing actually occurs much earlier or much later in the evolution, then we still need one-dimensional calculations to suggest the answer.

Hydrodynamic studies show that most of the time to the TNR is spent and most of the mass is accreted during the phase when the principle nuclear burning process is the proton-proton chain (S89; S98; Yaron et al. 2005, S08). Therefore, there is a competition between the radiative diffusion time to the surface (convection does not start until just before the peak of the TNR) and the energy production which depends both on the temperature ($\sim T^{4-6}$) and the hydrogen mass fraction ($\epsilon \sim X^2$). In addition, because these layers are degenerate, electron conductivity can transport some of the energy into the interior. Nevertheless, it was the original hydrodynamic studies that showed as long as the radiative opacity was "small", most of the energy produced in the nuclear burning regime at the bottom of the accreted layers was transported to the surface and radiated. Therefore, the temperature in the nuclear burning region increased slowly during the proton-proton phase of accretion. Thus, the hydrodynamic studies showed that the amount of mass accreted during the proton-proton phase depended on the opacity (metallicity) of the material (S09).

If we assume that no mixing has occurred between the core and accreted layers during the proton-proton phase, then increasing the metallicity of the infalling matter results in an increase in its opacity. The increased opacity traps more of the heat (produced by compression and nuclear burning in the deeper layers of the accreted material) in the region where it is produced and thus the temperature increases faster per unit accreted mass then for material with a lower opacity (metallicity). In contrast, lowering the metallicity by accreting material representative of the LMC (one-third Solar metallicity or less), reduces the opacity and increases the rate of heat transport out of the nuclear burning layers. As a result, the temperature increases more slowly and more material is accreted. A more massive accreted layer causes a higher density at the bottom and the explosion becomes more violent (Starrfield et al. 1999; José et al. 2007). This result is in agreement with the observations of novae in the LMC (della Valle et al. 1992, 1994).

If, however, the accreting material mixes with core material during this phase, either by shear mixing (Sparks & Kutter 1987; Kutter & Sparks 1987; Rosner et al. 2001; Alexakis et al. 2004) or by elemental diffusion (Prialnik & Kovetz 1984; Kovetz & Prialnik 1985), the addition of heavy nuclei to the accreted layers will increase their opacity. The opacity increase will reduce the amount of material accreted before the onset of the TNR and, thereby, the amount of material ejected during the outburst. Given that the theoretical predictions of the amount of material ejected during the outburst are already far lower then the observations (S08), increasing the metals in the accreted layers by early mixing exacerbates this disagreement.

There is an interesting corollary to this point. The OPAL opacities (Rogers & Iglesias 1994) and Iglesias & Rogers (1996) were improved over previous opacities by increasing the number of atomic energy levels and improving the treatment of line broadening. This had the effect of increasing the opacities for the same densities and temperatures even without changing the abundances. In order to study this effect, we included the latest OPAL opacities (Rogers & Iglesias 1992, 1994; Iglesias & Rogers 1996) in NOVA (S98 and references therein) and calculated new evolutionary sequences in order to simulate the outburst of V1974 Cyg (Nova Cyg 1992). The increased opacities had profound effects on the simulations. Because the new opacities were larger than those we had been using (the Iben (1975) fit to the Cox & Stewart (1970a,b) opacities), we found that the heat from the nuclear reactions was trapped more effectively in the layers where it was produced. Our simulations ejected a factor of ten less mass than was inferred from observations (S98). This discrepancy was also found in a study of accretion onto CO and ONe WDs (José & Hernanz 1998; José et al. 1999). One possible solution to this problem involves mixing of the accreted hydrogen-rich material into a residual helium-rich shell which is the remnant of previous outbursts and subsequent quiescent hydrogen burning (Krautter et al. 1996). The increased mass fraction of helium will reduce the opacity and allow a larger fraction of the energy produced in these layers to be transported to the surface and radiated away. Simulations with increased helium are in progress (Starrfield et al. 2012, in prep.)

Prialnik et al. (1982) were the first to show that there was a strong effect of the rate of mass accretion on the ignition mass. They found that increasing the rate of mass accretion increased compressional heating and, thereby, caused the temperatures in the accreted layers to rise more rapidly (per given amount of accreted mass) than for lower mass accretion rates. The observed mass accretion rates of $\sim 10^{-9}$ $M_\odot$ yr^{-1} (Townsley & Bildsten 2002, 2004) resulted in much smaller amounts of material being accreted when compared to simulations where the rate of mass accretion was a factor of 10 to 100 times smaller. While it has also been suggested that increasing the mass accretion rate much above $10^{-8}M_\odot$ yr^{-1}, on low luminosity WDs, would cause extremely weak flashes, new simulations of accretion (with no mixing of accreted with core material) find that even mass accretion rates as high as $2 \times 10^{-6}M_\odot$ yr^{-1} still result in TNRs and the expansion of the outermost layers to 10^{12}cm or larger (Starrfield et al. 2012). Starrfield et al. (2012) also report that TNRs occurred on WDs with masses as low as 0.4$M_\odot$.

Next we turn to the idea that there exists a "steady burning" regime where the infalling material burns at exactly the same rate as it is accreted (Paczynski & Zytkow 1978; Sion et al. 1979; Iben 1982; Fujimoto 1982a,b; Yoon et al. 2004). The steady burning assumption is that

only a WD accreting at a specific $\dot{M}$ can grow in mass. Otherwise, it either suffers nova explosions (lower $\dot{M}$) or rapidly expands, fills its Roche Lobe, and shuts off accretion (higher $\dot{M}$). The assumption of steady burning is relevant to the the existence of the Supersoft X-ray Binary Sources (SSS) discovered by ROSAT (Trümper et al. 1991). The SSS sources have luminosities of $L_* \sim 10^{37-38}$erg sec^{-1} and effective temperatures ranging from $3 - 7 \times 10^5$K. van den Heuvel et al. (1992, hereafter, V92) first suggested that they could be SN Ia progenitors because their luminosities implied that they were in the steady burning regime and that it was possible that the mass of the WD could be growing toward the Chandrasekhar limit (see also Branch et al. 1995; Kahabka & van den Heuvel 1997). Nevertheless, except for the pioneering work of Sion et al. (1979) (see also Iben (1982); Cassisi et al. (1998); Yoon et al. (2004)), no stellar evolution calculations had been done for massive WDs ($M_* > 1.3$M$_\odot$) accreting at high mass accretion rates for the sufficiently long times required to test the steady burning hypothesis. Calculations had been done for lower mass CO WDs ($M_* \sim 0.8$M$_\odot$) by Iben (1982) and Sion & Starrfield (1994), but the luminosities and effective temperatures of their simulations were too low to agree with the observations of SSS such as CAL 83 or CAL 87 and it was not clear that the WDs that they studied would reach the Chandrasekhar Limit. In a hydrodynamic study using NOVA (Starrfield et al. 2004, hereafter S04), we reported that accretion of Solar material onto hot (2.3×10^5K), luminous (30L$_\odot$), 1.25M$_\odot$ and 1.35M$_\odot$ CO WDs, using a large range in mass accretion rates, caused the accreted material to burn quiescently in the surface layers and the WD grew in mass toward the Chandrasekhar Limit. This work was criticized by Nomoto et al. (2007) and Shen & Bildsten (2007) because they could not reproduce our results using *static* stellar models. In addition, Nomoto et al. (2007) claimed that the surface mass zones were too large. Calculations of solar mass accretion onto low luminosity WDs has now been done by Starrfield et al. (2012) and they find that steady burning as described above does not exist (see also Idan et al. 2012). We discuss this result later in this review.

Another important parameter, for a given WD mass and mass accretion rate, is the luminosity of the underlying WD. It has been found that as the luminosity of the WD declines, the amount of accreted material increases (S98). This is because the energy radiated by the underlying WD also heats the accreted layers. In fact, it is this heating plus compressional heating as accretion progresses that causes the deepest accreted layers to finally reach nuclear burning temperatures. As the luminosity decreases, this heat source becomes less important, the accreting layers stay cool for a longer period of time, and more mass is accreted.

The final parameter that affects the amount of material that is accreted prior to the TNR is the mass of the WD. All other parameters held constant, the accreted mass is inversely proportional to the mass of the WD (MacDonald et al. 1985, and references therein) and numbers showing this are given in S89. Equation 1 illustrates how the ignition mass can be estimated.

$$P_{\text{crit}} = \frac{GM_{\text{WD}}M_{\text{ig}}}{4\pi R_{\text{WD}}^4} \tag{1}$$

P_{crit} is assumed to be $\sim 10^{20}$ dyne cm^{-2} and a mass-radius relation for WDs gives the ignition

mass, M_{ig}. Equation (1) is obtained by realizing that a critical pressure must be achieved at the bottom of the accreted layers before a TNR can occur (Fujimoto 1982a,b, G98). Note, however, that the actual value of the critical pressure is also a function of WD composition and rate of accretion (S89). If one assumes the above value for the pressure, then the amount of accreted mass can range from less than $10^{-5}M_\odot$ for WDs near the Chandrasekhar Limit to values exceeding $10^{-3}M_\odot$ for 0.4 $M_\odot$ WDs. In addition, because the surface gravity of a low mass WD is smaller than that of a massive WD, the bottom of the accreted layers is considerably less degenerate at the time the TNR occurs. Therefore, the peak temperature, for a TNR on a low mass WD, may not even reach 10^8K so that no interesting nucleosynthesis occurs.

4.   The Single Degenerate Scenario for Supernova Ia progenitors

The relationship between accretion onto WDs, via accretion from a non-degenerate secondary, and Supernova Ia (SN Ia) explosions is designated the single degenerate scenario (SD). It is one of the two major suggestions for the objects that explode as a SN Ia, the other being the double degenerate (DD) scenario. In the standard paradigm SD scenario, a WD in a close binary system accretes material from its companion and grows to the Chandrasekhar Limit. As it nears the Limit, it first convectively "simmers" in the core and then an explosion occurs. In contrast, the double degenerate scenario (DD) requires the merger or collision of two WDs to produce the observed explosion. While for many years the SD scenario was the more prominent, a number of concerns led to major efforts to better understand the DD scenario. However, the SD scenario is capable of explaining most of the observed properties of the SN Ia explosion via the delayed detonation model (Khokhlov 1991; Kasen et al. 2009; Woosley & Kasen 2011; Howell et al. 2009, and references therein). Reviews of the various proposals for SN Ia progenitors (Branch et al. 1995), producing a SN Ia, and the implications of their explosions can be found in Hillebrandt & Niemeyer (2000), Leibundgut (2000, 2001), Nomoto et al. (2003), and Howell (2011).

Recently, the well studied outburst of SN 2011fe in M101 showed that the star that exploded was likely a carbon-oxygen (CO) WD (Nugent et al. 2011) with a companion that was probably a main sequence star (Li et al. 2011; Bloom et al. 2012) although EVLA (Chomiuk et al. 2012) and optical (Bloom et al. 2012) observations have ruled out most types of CVs. In addition, Schaefer & Pagnotta (2012) find no star at the "center" of a SN Ia remnant in the LMC but Edwards et al. (2012) find a large number of stars near the "center" of a second LMC SN Ia remnant and they state that they cannot rule out a CV as the progenitor. Nevertheless, Schaefer & Pagnotta (2012) claim that they rule out the SD scenario or, as is more likely, the secondary in their LMC remnant was fainter than their detection limit. Even more recently, Dilday et al. (2012) claim that PTF 11kx was a Symbiotic system that exploded as a SN Ia implying strongly that there are multiple SN Ia channels. Further support for the SD scenario, comes from observations of V445 Pup (Nova Pup 2000) which imply that it was a helium nova (helium accretion onto a WD) because there were no signs of hydrogen in the spectrum at any time during the outburst but there were strong lines of carbon, helium, and other elements (Woudt & Steeghs 2005; Woudt et al. 2009, and references therein). Because it was extremely luminous before the outburst, the secondary is

thought to be a hydrogen deficient carbon star (Woudt et al. 2009, and references therein). Since one of the defining characteristics of a SN Ia explosion is the absence of hydrogen or helium in the spectrum at any time during the outburst or decline, the existence of V445 Pup implies that mass transferring binaries exist in which hydrogen is absent at the time of the explosion.

Therefore, in order to study the SD scenario, we used our one-dimensional (1-D), implicit, hydrodynamic, computer code (NOVA) to study the accretion of Solar composition material (Lodders 2003) onto WD masses of $0.4M_\odot$, $0.7M_\odot$, $1.0M_\odot$, $1.25M_\odot$, and $1.35M_\odot$. We used two initial WD luminosities (4×10^{-3} $L_\odot$ and $10^{-2}L_\odot$) and seven mass accretion rates ranging from $2 \times 10^{-11}M_\odot$ yr^{-1} to $2 \times 10^{-6}M_\odot$ yr^{-1}. We used an updated version of NOVA (S09, and references therein) that includes a nuclear reaction network that has now been extended to 187 nuclei (up to ^{64}Ge). NOVA also uses the OPAL opacities (Iglesias & Rogers 1996, and references therein), the Iliadis (2005, priv. comm.) nuclear reaction rates, recent equations of state (Timmes & Arnett 1999; Timmes & Swesty 2000), and new nuclear reaction network solvers (Hix & Thielemann 1999b; Timmes 1999). NOVA can now follow CN explosions past the first outburst on the WD (Starrfield et al. 2004) and uses more mass zones in the calculations. It also includes the new Arnett et al. (2010) algorithm for mixing-length convection and the Potekhin electron conductivities described in Cassisi et al. (2007, and references therein). These improvements have had the effect of changing the initial structures of the WDs so that they have smaller radii and larger surface gravities which produce quantitative but not qualitative changes in our CN simulations (Starrfield et al. 2012, in prep.).

Fig. 1 shows the results for all 70 simulations that we have done (each data point represents the two initial luminosities). In all cases we obtain a TNR which, for some simulations, ejects some material, and after some evolutionary time may cause the WD radius to grow to $\sim 10^{12}$cm. These fully implicit, time-dependent, calculations show that the sequences exhibit the Schwarzschild & Härm (1965) thin shell instability which implies that steady burning does not occur. An expanded study of the stability of thin shells can be found in Yoon et al. (2004) who investigated (among other studies) the accretion of hydrogen-rich material onto a WD. Using their results, we find that our sequences begin in a stable region (see their Fig. 8 and Fig. 11) but with continued accretion evolve into instability. We also find that low mass WDs do not eject any mass while the high mass WDs do eject a small fraction of the accreted material (a maximum of $\sim 4\%$ for the $1.25M_\odot$ sequences but ranging down to $\sim 0.1\%$ for the $0.7M_\odot$ sequences). Therefore, the WDs are growing in mass as a result of the accretion of Solar material and assuming no mixing with core material. (This is not the case for CNe which show sufficient core and accreted material in their ejecta that the WD must be losing mass as a result of the outburst.) We identify these accreting systems with those CVs (Dwarf, Recurrent, Symbiotic novae) that show no core material either on the surface of the WD or in their ejecta. Our results could explain the findings of Zorotovic et al. (2011) who report that the WDs in CVs are growing in mass. In addition, the best studied Dwarf Novae have WD masses larger than the canonical value of $\sim 0.6M_\odot$. These are U Gem ($1.2M_\odot$: Echevarría et al. 2007), SS Cyg ($0.8M_\odot$: Sion et al. 2010), IP Peg ($1.16M_\odot$: Copperwheat et al. 2010), and Z Cam ($0.99M_\odot$: Shafter 1983). Therefore, it is possible that some Dwarf Novae could be SN Ia progenitors.
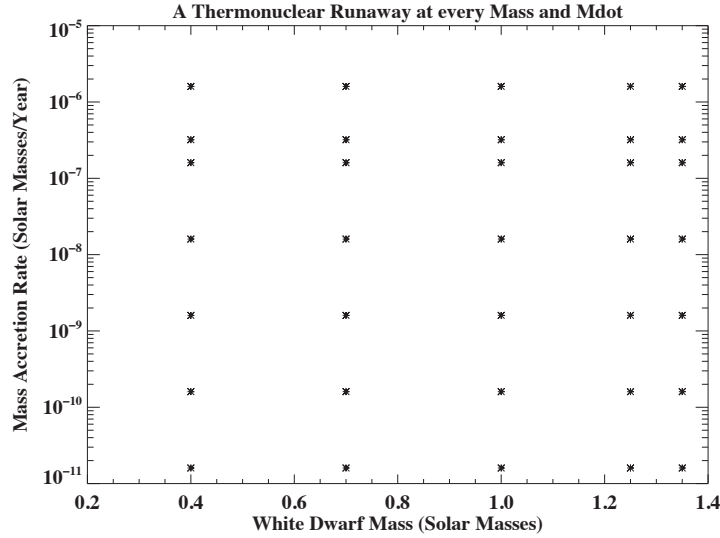
A Thermonuclear Runaway at every Mass and Mdot

Figure 1 WD mass vs. Log $\dot{M}$ for each of the evolutionary sequences that we calculated. Since each point represents the two initial luminosities we used, there are 70 sequences shown here. Each of these exhibited a TNR. In no case did "steady burning" occur.

We also show the accretion time to TNR for all our sequences (Fig. 3). Clearly, as the WD mass increases, the accretion time decreases for the same $\dot{M}$. This is because higher mass WDs initiate the TNR with a smaller amount of accreted mass. Given the existence of Recurrent Novae and Symbiotic Novae with recurrence times ranging from a few years (U Sco) to about 20 years (RS Oph) or longer (T Pyx, V407 Cyg, and T CrB), Fig. 3 shows that it is possible for Recurrent Novae to occur on WDs with masses as low as $0.7 M_\odot$. Therefore, although it is often claimed that only the most massive WDs have recurrence times short enough to agree with the observations of Recurrent Novae, this plot shows that this is not the case and basing WD mass determinations of Recurrent Novae on short recurrence times is incorrect. We also note that it is possible for a Recurrent Nova outburst to occur on a high mass WD for an extremely broad range of $\dot{M}$.

Finally, in Fig. 4 and Fig. 5 we show the light curves for two of our simulations. The WD mass is 0.4 $M_\odot$ in Fig. 4 and 1.35 $M_\odot$ in Fig. 5. The mass accretion rate we used for Fig 4. is $2 \times 10^{-9} M_\odot yr^{-1}$ and for Fig. 5 we used $3 \times 10^{-7} M_\odot yr^{-1}$. We chose the latter value because it is in the center of the steady burning mass accretion regime. The evolution of the bolometric magnitude is the solid line in each plot and the V magnitude is shown as the dashed line. We stop the plot when the outer radius reaches $\sim 10^{12}$cm and the expanding material has become optically thin. The lower mass WD takes years to evolve while the higher mass WD takes only days. We find that as the mass of the WD increases, the time scale to the TNR decreases.
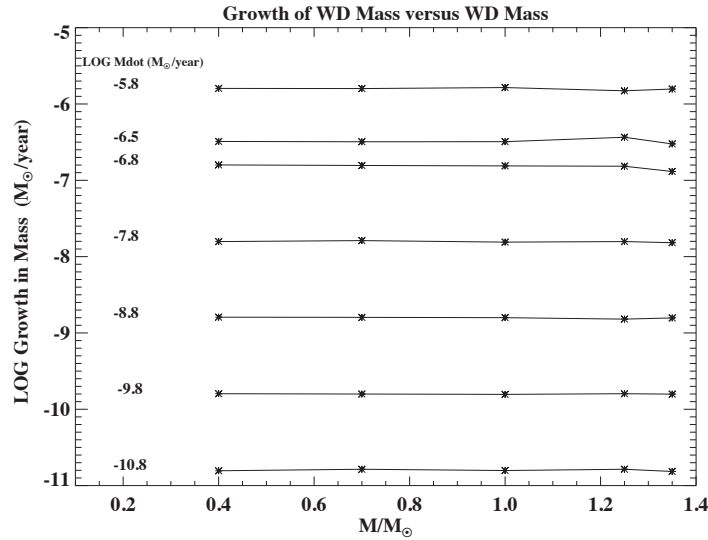
Figure 2 The log of the difference between the mass accreted and the mass lost. We display the log of the growth in mass (in units of $M_\odot$ yr^{-1}) as a function of WD mass for each of our simulations. Each point is the amount of accreted (less ejected) mass divided by the time to reach the TNR for the given simulation. The lines connect the points for the same $\dot{M}$ and we give the log of $\dot{M}$ along a column on the left of the figure.

The initial decline before the final rise in Fig. 4 is caused by the conversion of some of the internal energy, produced by ongoing nuclear burning near the surface, being transformed into the potential energy necessary for the material to climb out of the deep gravitational well of the WD. The most extreme result is for the 0.4 $M_\odot$ WD for which it takes more than one year for the expanding material to recover and begin to become more luminous and hotter. Such an effect, combined with the interaction with the accretion disk (and possibly the secondary) might be responsible for some of the pre-maximum halts seen in some classical novae (Hounsell et al. 2010).

5.   The Classical Nova Outburst

In previous sections we discussed the results for accretion onto WDs in which no mixing with WD core material had taken place. If such mixing occurs, and sufficient core material is mixed up into the accreted layers, then a CN outburst occurs and typically ejects material at high speeds. In fact, the importance of continued studies, both theoretical and observational, is that observations of the CN outburst show that a nova ejects metal enriched gas and grains during its outburst and this material is a source of heavy elements for the Interstellar Medium (ISM). The observed
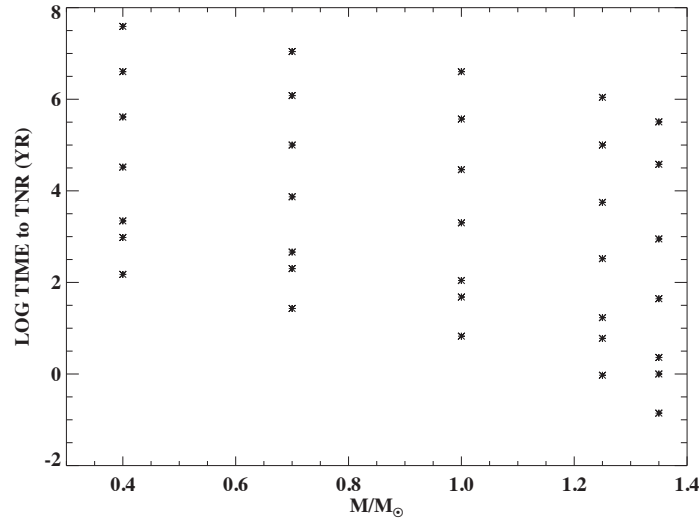
Figure 3 The log of the accretion time to the TNR as a function of WD mass. Each of the data points is for a different $\dot{M}$ and the value of $\dot{M}$ increases downward for each WD mass. The value of $\dot{M}$ is given in Figure 1. The accretion time, for a given $\dot{M}$ decreases with WD mass because it takes less mass to initiate the TNR as the WD mass increases.

enrichment demands that mixing of the accreted material with core material must have taken place at some time during the evolution to the outburst. The ejection velocities measured for CN ejecta can exceed, in many cases, 10^3 km s^{-1} so that this material is rapidly mixed into the diffuse gas where it is then incorporated into molecular clouds before being formed into young stars and planetary systems during star formation. Therefore, CNe must be included in studies of Galactic chemical evolution as they are predicted to be the major source of ^{15}N and ^{17}O in the Galaxy and contribute to the abundances of other isotopes in this atomic mass range.

Infrared observations have confirmed the formation of carbon, SiC, hydrocarbons, and oxygen-rich silicate grains in nova ejecta, suggesting that some fraction of the pre-solar grains identified in meteoritic material (Zinner 1998; Amari et al. 2001a,b; José et al. 2004; Gehrz 2008; Pepin et al. 2011) may come from CNe. The mean mass ejected during a CN outburst is $\sim 2 \times 10^{-4}$ M$_\odot$ (G98) Using the observed nova rate of 35±11 per year in our Galaxy (Shafter 1997), it follows that CNe introduce $\sim 7 \times 10^{-3}$ M$_\odot$ yr^{-1} of processed matter into the ISM. There is probably more material ejected than presently believed, however, and this value is a lower limit (Saizar & Ferland 1994, G98).

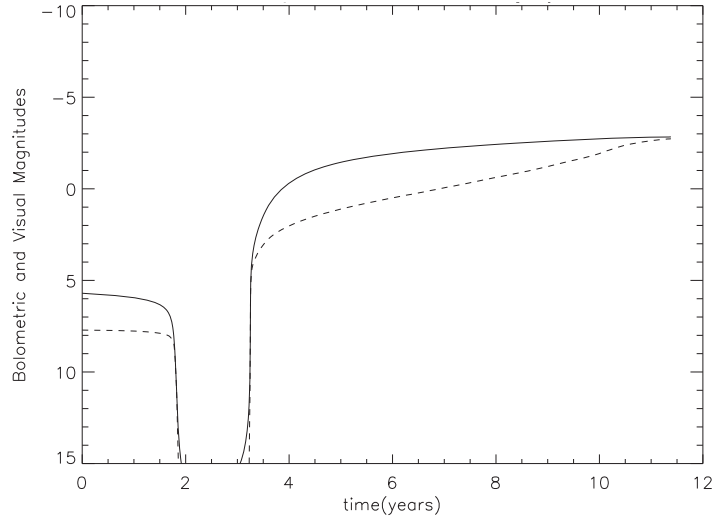CNe are frequent and varied and observations of their outbursts provide an extensive dataset

Figure 4 The light curve for one of our sequences. The solid line is the Bolometric Magnitude and the dashed line is the Visual Magnitude. This sequence had a WD mass of $0.4M_\odot$ and $\dot{M}$ of $2 \times 10^{-9}M_\odot$ yr^{-1}. Note that it takes nearly 5 years to reach maximum light in the visual The calculation is stopped when the outer radii reach 10^{12}cm but no material has been ejected.

to test theories of their explosions and their evolution. For example, the composition of matter ejected in a CN outburst must depend on both the amount and composition of the material mixed up from the underlying CO or ONe WD core plus the phase of the TNR at which this mixing occurs. Moreover, the envelope composition, the amount of mixing from the nuclear burning region to the surface, and the amount of material ejected into the ISM affects the contribution of CNe to Galactic chemical evolution. In addition, since core material must be mixed with accreted material during the evolution to explosion and then ejected into space after being processed through hot, hydrogen burning, we have a nearly unique opportunity to determine the core abundances of WDs of various masses and evolutionary histories. Finally, we also note that CNe and Recurrent Nova outbursts are the only stellar explosions for which the nuclear physics input at present is mainly based on the direct results of laboratory experiments and no extrapolation to lower energies is necessary.

The hydrodynamic studies show that at least three of the observational behaviors of the CN outburst are strongly dependent upon the complicated interplay of nuclear physics and convection that occurs during the final minutes of the TNR. These are: (1) the early evolution of the observed light curves on which their use as "standard candles" is based. (2) The observed peak luminosity of fast CNe which is typically super-Eddington. In some cases for as long as two weeks (Schwarz et al. 2001). (3) The composition of matter ejected by a CN which depends on the amount and composition of the material dredged up from the underlying CO or ONe WD core. Moreover, the amount of core nuclei in the ejecta implies that the WD in a CN system is losing mass as a result of continued outbursts and, therefore, a CN cannot be a SN Ia progen-
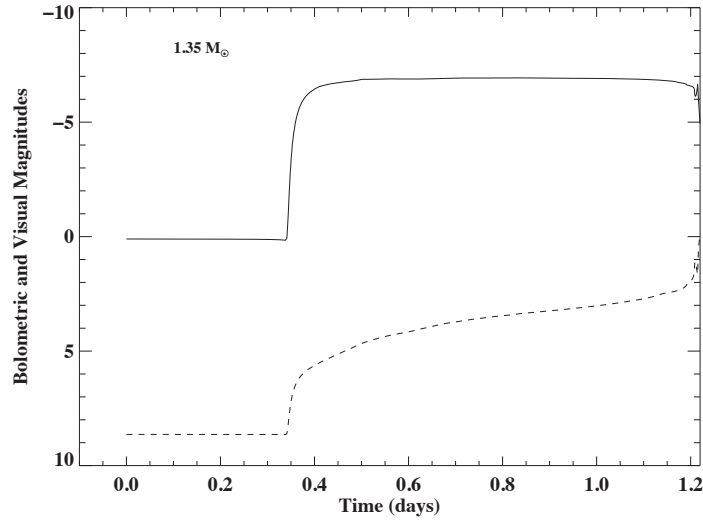
Figure 5 This figure shows the light curve for a sequence with a mass of 1.35$M_{\odot}$ and an $\dot{M}$ of $3 \times 10^{-7} M_{\odot}$ yr^{-1}. We chose this rate to show that choosing an $\dot{M}$ in the middle of the "steady burning" regime still results in a TNR. Note that on this WD it takes less than one day to reach maximum. A small amount of material was ejected.

itor (MacDonald 1983; Starrfield et al. 2000). Theoretical studies of the CN outburst have been recently reviewed by S08 and Hernanz & Jose (2008) and here we only briefly review the latest work with the *pep* reaction included (S09).

In S09 we evolved a series of evolutionary sequences on both 1.25$M_{\odot}$ and 1.35$M_{\odot}$ WDs and compared those results with evolutionary sequences done with the *pep* reaction not included. We used four different nuclear reaction rate libraries in order to determine the effects on CN simulations of nearly 15 years of improvements in the nuclear reaction rates. The most up-to-date library at that time was that of Iliadis (2005, priv. comm.). Fig. 6 is taken from S09 and shows the variation of temperature with time for the zone where peak conditions in the TNR occurred in the 1.35$M_{\odot}$ evolutionary sequences. Here we plot four simulations done with the *pep* reaction included and the Anders & Grevesse (1989) Solar abundances mixed with a half Solar and half ONe mixture (see S09). The initial conditions for all 4 sequences are the same and listed in S09. The nuclear reaction rate library used for each sequence is identified on the plot and in the caption. The reference to the library used for that calculation is given in the caption. The time coordinate is arbitrary and chosen to clearly show each evolutionary sequence. There are clearly differences between the four simulations. Peak temperature drops from $\sim 4.1 \times 10^{8}$ K to $\sim 3.9 \times 10^{8}$ K and peak nuclear energy generation drops by about a factor of 2 from the oldest

library to the newest library (8.4×10^{17}erg gm^{-1}s^{-1} to 4.4×10^{17}erg gm^{-1}s^{-1}). The temperature declines more rapidly for the sequence computed with the oldest reaction library (Politano et al. 1995) because it exhibited a larger release of nuclear energy throughout the evolution. This causes the overlying zones to expand more rapidly and the nuclear burning region to cool more rapidly. In contrast, the newest library, with the smallest expansion velocities, cools more slowly. As expected for the increased WD mass and gravity, the simulations at $1.35M_\odot$ evolve more rapidly near the peak in the TNR than those at $1.25M_\odot$.

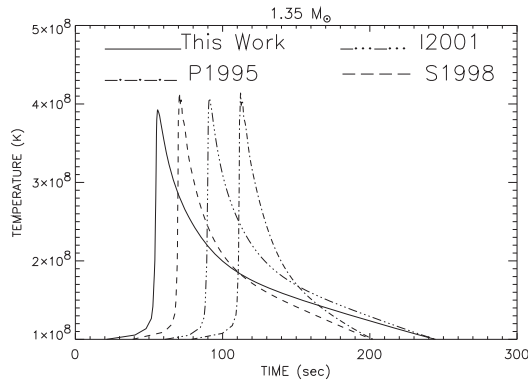

Figure 6 The variation with time of the temperature in the zone in which the TNR occurs around the time of peak temperature This zone is usually one zone above the core-envelope interface. We have plotted the results for four different simulations on a $1.35M_\odot$ WD. The identification with calculations done with a specific nuclear reaction rate library is given on the plot. S1998 refers to Starrfield et al. (1998), P1995 refers to Politano et al. (1995), I2001 refers to Iliadis et al. (2001), and This Work refers to the calculations done with the August 2005 Iliadis nuclear reaction rate library and reported in S09. (The details of the August 2005 library are given in S09.) The curve for each sequence has been shifted slightly in time to improve its visibility.

In order to more clearly show which nuclei are produced by CNe explosions, in Fig. 7 we plot the stable, ejected nuclei compared to the Anders and Grevesse (1989) Solar abundances (Timmes et al. 1995). The x-axis is the atomic mass number. The y-axis is the logarithmic ratio of the ejecta abundance divided by the Solar abundance of the same nucleus. The most abundant isotope of a given element is marked by an asterisk and isotopes of the same element are connected by solid lines and labelled by the given element. These plots are patterned after similar plots in Timmes et al. (1995). They show for the $1.35M_\odot$ simulation done with the latest reaction rate library that ^{15}N, ^{17}O, and ^{31}P are significantly overproduced in CN ejecta. Other nuclei are overproduced by factors of a thousand and could be important for CN nucleosynthesis.

All abundances given in the following discussion are in mass fraction. The initial abundance of ^{1}H is 0.365 (half Anders and Grevesse [1989] and half ONe and is the same abundance used in Politano et al. (1995, P1995) and Starrfield et al. (1998, S1998) and its abundance declines to ~0.31 in all 5 sequences. This decline of 0.05 in mass fraction results in energy production from proton captures of ~ 2×10^{46} erg which agrees with the values typically quoted for CN
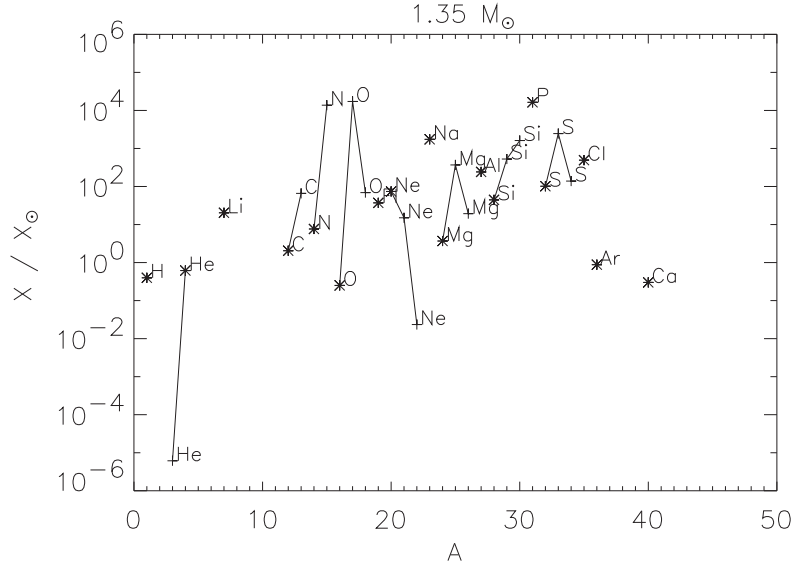
Figure 7 The abundances (mass fraction) of the stable isotopes from hydrogen to calcium in the ejected material for the $1.35 M_\odot$ sequence calculated with the August 2005 reaction rate library of Iliadis. The x-axis is the atomic mass and the y-axis is the logarithmic ratio of the abundance divided by the corresponding Anders & Grevesse (1989) Solar abundance. As in Timmes et al. (1995), the most abundant isotope of a given element is designated by an "$*$" and all isotopes of a given element are connected by solid lines. Any isotope above 1.0 is overproduced in the ejecta and a number of isotopes are significantly enriched in the ejecta.

explosions (G98; S08). Interestingly, the abundance of ^{4}He decreases slightly as the reaction rate library is improved so that the smallest increase in ^{4}He occurs in the calculations done with the latest library. These results show, as emphasized in Krautter et al. (1996, see also S1998 and S08), that the large amounts of helium observed in CN ejecta (G98) implies first, that most of the observed helium was mixed up from the outer layers of the WD by the TNR; and second, that it was actually produced in previous CN outbursts on the WD. This speculation is also relevant for the large enrichments of nitrogen observed in CN ejecta (S08). The observed nitrogen is probably ^{15}N produced in previous outbursts, mixed into the accreted material from the WD outer layers, and then ejected by the CN outburst. Examining the behavior of the individual abundances, ^{12}C and ^{13}C are virtually unchanged by the updated reaction rates. In contrast, the abundance of ^{14}N nearly doubles and that of ^{15}N decreases by a factor of two going from the first to the latest reaction rate library. ^{16}O also doubles in abundance while ^{17}O grows by a factor of 60 and becomes the most abundant of the CNO nuclei in the ejecta. For this WD mass, the C/O ratio is 0.12. The abundance of ^{18}O declines by nearly a factor of 5 and the abundances of ^{18}F and ^{19}F also decline by large factors.

The initial abundance of ^{20}Ne in all four sequences is 0.25 and it is depleted by a smaller amount in the calculations done with the latest library. The abundance of ^{22}Na decreases with the

library update and ^{24}Mg is severely depleted by the TNR. In fact, all the Mg isotopes are depleted in the calculations done with the latest library. In contrast, ^{26}Al is unchanged by the changes in the reaction rates while the abundance of ^{27}Al drops by a factor of two. This result implies that TNRs on more massive WDs eject about the same fraction of ^{26}Al as ^{27}Al. Contrary to a conclusion in Politano et al. (1995), S09 finds that the amount of ^{26}Al ejected is virtually independent of WD mass. All the Si isotopes (^{28}Si, ^{29}Si, and ^{30}Si) are enriched in the calculations done with the latest library and because of the higher temperatures reached in the simulations ^{29}Si, and ^{30}Si are more abundant in the $1.35M_\odot$ simulations than in the $1.25M_\odot$ simulations. Other nuclei whose abundance is largest in the calculations done with the latest library are ^{31}P and ^{32}S. These nuclei are also more abundant at the higher WD mass because of the higher temperatures reached in the simulations on more massive WDs. In addition, while the abundance of ^{33}S is hardly dependent on the reaction rate library, it is nearly 30 times more abundant in the calculations done with the more massive WD. Finally, we note that while the ejecta abundances of ^{34}S, ^{35}Cl, ^{36}Ar, and ^{40}Ca have all declined as the reaction rate library has been improved, they are all produced in the nova TNR since their final abundances exceed the initial abundances.

6. Where do we go from here?

The calculations that we have reported above show that we get observed behaviors both with and without mixing of accreted material with core material. With mixing we get CNe and the observations imply that because of the explosion enough mass is lost from the WD that it cannot be growing toward a SN Ia explosion. In contrast, if no mixing occurs, then we get TNRs that occur on timescales in agreement with Recurrent and Symbiotic Novae but as is observed almost no mass is ejected. Thus, we predict that these systems and Dwarf Nova systems that contain WDs that are growing in mass could reach the Chandrasekhar Limit and explode as a SN Ia. The question then becomes: why do some systems mix and some do not. Although there have recently been a number of multi-dimensional studies investigating mixing during the nova outburst (Casanova et al. 2010, 2011a,b, and references therein), as already mentioned they are limited to following the evolution only near the peak of the outburst. Mixing may actually occur much earlier or much later in the evolution thus further one-dimensional calculations are necessary. Finally, as noted earlier, observations of V445 Pup (Nova Pup 2000) showed no signs of hydrogen in the spectrum at any time during the outburst (Woudt & Steeghs 2005; Woudt et al. 2009, and references therein) and continued studies of accretion of helium-rich material are necessary.

Because of these uncertainties and new discoveries, new simulations of accretion both with mixing and without mixing using a variety of compositions are required to better understand the secular evolution of these systems. The simulations done by our group will continue but with two major changes. First, we will use MESA, as described below, and second we will switch to a new reaction rate library currently being constructed called STARLIB (Longland et al. 2010; Iliadis et al. 2010a,b,c). In the next few paragraphs we discuss why these changes are necessary.

Thermonuclear reaction rates are an essential ingredient for any stellar model. A library of experimental thermonuclear reaction rates, based on nuclear physics input gathered from labor-

atory measurements, was first published by Fowler and collaborators more than 40 years ago (Fowler et al. 1975; Caughlan & Fowler 1988, and references therein). The incorporation of Fowler's rates into stellar evolution calculations represented a paradigm shift for the field of stellar structure and evolution. Subsequent work (Angulo et al. 1999; Iliadis et al. 2001) incorporated newly measured nuclear cross sections, but the reaction rates were still computed using techniques developed prior to 1988. One problem with these, and most other, published thermonuclear reaction rates was that either a recommended value was reported without any estimate of its uncertainty, or recommended values were published together with "upper limits" and "lower limits" that had no statistically rigorous foundation. A solution to this problem was devised by Longland et al. (2010) and Iliadis et al. (2010a,b,c).

Suppose laboratory measurements of all necessary nuclear physics quantities have been performed. Using the probability density function for each nuclear physics input, one can randomly sample over each distribution and calculate a thermonuclear reaction rate according to the usual formalism (e.g., Iliadis 2007). Repeating the sampling many times provides the Monte Carlo reaction rate probability density. Its associated cumulative distribution is then used to derive reaction rates with a precise statistical meaning. An example is shown in Fig. 8 for a single resonance in a hypothetical reaction. Randomly sampling over the measured energy and strength of this resonance yields the reaction rate probability density distribution, shown in red (top). Note that the reaction rate is well approximated by a lognormal function (black line). The lower panel displays the corresponding cumulative distribution that can be used to derive reaction rates as quantiles. For example, the 0.16, 0.50, and 0.84 quantiles correspond to a "low rate", "recommended rate", and "high rate", respectively, for a coverage probability of 68%. Other values for the quantiles can be chosen. The important point is that any reaction rate derived from the rate probability density has a precisely defined coverage probability. Therefore, for the first time, we can provide statistically meaningful thermonuclear reaction rates and use them to perform realistic stellar evolution and nucleosynthesis simulations.

Experimental Monte Carlo reaction rates are now available for 66 reactions involving stable and radioactive target nuclei in the A=14-40 range, including many of the key reactions for stellar hydrogen through oxygen burning (Iliadis et al. 2010a). Based on these rates, Iliadis et al. have constructed a comprehensive, next-generation nuclear reaction rate library for stellar modeling, called STARLIB. It has a tabular format and lists, for 60 temperature grid points between 10^6 K and 10^9 K, the recommended (best) rate and an additional parameter (the spread parameter of the lognormal rate distribution). With the tabulated information the reaction rate probability density function can be calculated at each temperature grid point; see Longland et al. (2010) for details. To the experimental Monte Carlo rates Iliadis et al. have added: (i) other experimental reaction rates from the literature for which Monte Carlo rates are not yet available; (ii) the latest experimental and theoretical weak interaction decay rates; (iii) the latest theoretical Hauser-Feshbach rates calculated using the code TALYS (Goriely et al. 2008); and (iv) experimental rates for neutron-induced reactions based on the KADoNIS v0.3 evaluation[1]. For all reaction or decay rates based on theory a factor of 10 uncertainty is adopted. The STARLIB library is publicly
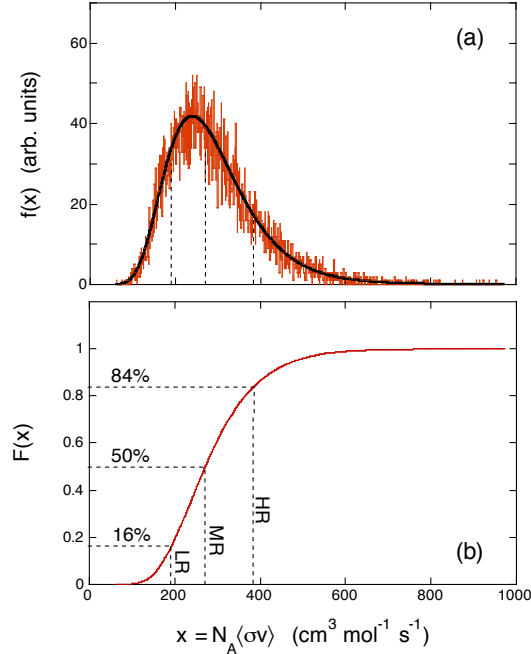
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[1]See: `http://www.kadonis.org`.

Figure 8 Results of Monte Carlo calculations for a single resonance in a hypothetical reaction at a temperature of T=0.5 GK. The resonance parameters are $E_r = 300 \pm 15$ keV and $\omega\gamma = 4.1 \pm 0.2$ eV. The reaction rate is sampled 10,000 times; (top) reaction rate probability density function, shown in red; the black solid line represents a lognormal approximation (see text); (bottom) cumulative reaction rate distribution; the vertical dotted lines represent the low, median and high Monte Carlo reaction rates, obtained from the 0.16, 0.50 and 0.84 quantiles, respectively.

available and also provides the Monte Carlo reaction rate code to the astrophysics community [2]. The importance of using STARLIB in new simulations is that it will contain the latest rates in a form that is easily incorporated into stellar evolution simulations. There are numerous rates that still need new measurements and our studies will help to identify those rates that strongly affect the nucleosynthesis. Finally, we emphasize that using this reaction rate library now allows us to do stellar evolution with "error bars" in the sense that we can easily vary the rates in STARLIB using the spread parameter, and determine the robustness of our results.

We will combine the rates from STARLIB with MESA. MESA[3] (Paxton et al. 2011), is a set of modules for computational stellar astrophysics. It includes open source libraries for a wide range of simulations in stellar astrophysics. Among these are one-dimensional hydrodynamics, the latest opacities and equations of state, a number of nuclear reaction rate libraries (including STARLIB), adaptive mesh refinement, element diffusion, rotation, and pulsation. Although it is

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[2] The website is `http://starlib.physics.unc.edu/index.html`; username: starlib; password: bil.rats.
[3] See: `http://mesa.sourceforge.net/` and `http://mesastar.org/`.

a relatively new code, it is now being used by a large number of researchers on a broad variety of problems. The large number of people working to improve it and maintain it suggests that it is time to move away from NOVA.

We are now using MESA + STARLIB to study the accretion of both hydrogen- and helium-rich material onto WDs using a broad range in both WD properties (mass, initial luminosity, mass accretion rate, and composition) and composition of the accreting material. Our initial conditions have been chosen to mimic those observed for CVs (Dwarf, Classical, Recurrent, and Symbiotic Novae). We have compared the initial studies done with MESA to those already done with NOVA (Starrfield et al. 2004, 2009, 2012, and references therein) using both codes to verify and validate the results. Using MESA produces quantitative but not qualitative changes in our accretion simulations (Newsham, et al 2012, in prep). In addition, while simulations with NOVA can be done with up to 400 Lagrangian zones, we are using more than 3000 zones in our studies with MESA. We will also include chemical diffusion and rotation in our studies which we cannot do with the current version of NOVA. Including diffusion will make the results more dependent on $\dot{M}$ since the lower the $\dot{M}$ the longer the time to explosion and the more time for chemical diffusion to become important (Prialnik & Kovetz 1984; Kovetz et al. 1984; Iben 1991, and references therein).

Our work in this area will, therefore, involve four major changes to our previous calculations: (i) use MESA with STARLIB, (ii) improve the treatment of convection and include rotation and diffusion, (iii) increase the number of mass zones used in the simulations, and (iv) vary the composition of the accreting material. We are studying: **1.** The effects of using the new Monte Carlo reaction rates on our simulations of Dwarf, Classical, Recurrent, and Symbiotic Novae (accretion onto low luminosity WDs), and the Super Soft X-ray binary sources (accretion onto high luminosity WDs). **2.** The consequences of accreting either a pure helium mixture or a hydrogen deficient helium enriched mixture onto WDs varying the WD mass, luminosity, and prior history. **3.** A new set of studies of TNRs for both CO and ONe WDs where we include the various mechanisms that can cause mixing of accreted with core material. **4.** A Monte Carlo post-processing study of CN nucleosynthesis using temperature-density-time trajectories from our evolutionary calculations.

7.   Conclusions

We have reviewed our current knowledge about the thermonuclear processing that occurs during the evolution of the accretion onto WDs both with and without the mixing of core with accreted material. If the SD scenario for the progenitors of SN Ia is valid, then we require the growth of a CO WD to the Chandrasekhar Limit. This, in turn, requires that more material remain on a WD after a TNR than is ejected by the TNR. Hydrodynamic simulations and observations of the CN outburst, where mixing must have occurred, show that more mass is lost than accreted by the WD and a CN cannot be a SN Ia progenitor. In contrast, our hydrodynamic simulations of accretion of solar material onto WDs *without mixing* always produce a TNR and "steady burning" does not occur. We have studied a broad range in WD mass (0.4 M$_\odot$ to 1.35 M$_\odot$) and find that

the maximum ejected material ($\sim 4\%$) occurs for the $1.25M_\odot$ sequences and then decreases to $\sim 0.1\%$ for the $0.7M_\odot$ sequences. Therefore, the WDs are growing in mass as a consequence of the accretion of solar material, and as long as there is no mixing of accreted material with core material. Finally, the time to runaway is sufficiently short for accretion onto most of the WD masses that we studied that Recurrent Novae could occur on a much broader range of WD mass than heretofore believed.

In contrast, a TNR in the accreted hydrogen-rich layers on the *low* luminosity WDs in CV binary systems, where mixing of core matter with accreted material occurs, is the outburst mechanism for Classical, Recurrent, and Symbiotic novae. The differences in characteristics of these systems is likely the WD mass and mass accretion rate. The importance of studying the large numbers of CNe that are discovered each year is that the interaction between the hydrodynamic evolution and nuclear physics lies at the basis of our understanding of how the TNR is initiated, evolves, and grows to the peak of the explosion. The high levels of enrichment of CN ejecta in elements ranging from carbon to sulfur confirm that there is dredge-up of matter from the core of the WD and enable them to contribute to the chemical enrichment of the interstellar medium. Therefore, studies of CNe can lead to an improved understanding of Galactic nucleosynthesis, some sources of pre-solar grains, and the Extragalactic distance scale.

It is recognized that the characteristics of the CN explosion are strongly dependent upon a complicated interplay between nuclear physics, the β^+ limited CNO reactions, and convection during the final stages of the TNR. The light curves, the peak luminosities (which can exceed the Eddington luminosity), the levels of envelope enrichment, and the composition of CN ejecta are all strongly dependent upon the extent and timescale of convective mixing during the explosion. The characteristics of the outburst depend on the white dwarf mass, luminosity, mass accretion rate, and the chemical composition of both the accreting material and WD material. The evolution of the outburst also depends on when, how, and if the accreted layers are mixed with the WD core which is still unknown. The importance of nuclear physics to our understanding of the progress of the outburst can be seen when we compared a series of evolutionary sequences in which the only change was the nuclear reaction rate library.

Finally, we described the STARLIB reaction rate library and how we will use it with MESA to improve our understanding of accretion of material onto WDs.

Acknowledgements

References

Alexakis, A., Calder, A. C., Heger, A., et al. 2004, ApJ, 602, 931

Amari, S., Gao, X., Nittler, L. R., et al. 2001a, ApJ, 551, 1065

Amari, S., Zinner, E., José, J., & Hernanz, M. 2001b, Nuclear Physics A, 688, 430

Anders, E., & Grevesse, N. 1989, Geochemica & Cosmica Acta, 53, 197

Angulo, C., et al. 1999, Nucl. Phys. A, 656, 183

Arnett, D., Meakin, C., & Young, P. A. 2010, ApJ, 710, 1619

Bahcall, J. N., & May, R. M. 1969, ApJ, 155, 501

Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, ApJL, 744, L17

Branch, D., Livio, M., Yungelson, L. R., Boffi, F. R., & Baron, E. 1995, PASP, 107, 1019

Casanova, J., José, J., García-Berro, E., Calder, A., & Shore, S. N. 2010, A&A, 513, L5

—. 2011a, A&A, 527, A5

Casanova, J., José, J., García-Berro, E., Shore, S. N., & Calder, A. C. 2011b, Nature, 478, 490

Cassisi, S., Iben, I. J., & Tornambe, A. 1998, ApJ, 496, 376

Cassisi, S., Potekhin, A. Y., Pietrinferni, A., Catelan, M., & Salaris, M. 2007, ApJ, 661, 1094

Caughlan, G. R., & Fowler, W. A. 1988, Atomic Data and Nuclear Data Tables, 40, 283

Chomiuk, L., Soderberg, A. M., Moe, M., et al. 2012, ApJ, 750, 164

Copperwheat, C. M., Marsh, T. R., Dhillon, V. S., et al. 2010, MNRAS, 402, 1824

Cox, A. N., & Stewart, J. N. 1970a, ApJSupp, 19, 243

—. 1970b, ApJSupp, 19, 261

Crawford, J. A., & Kraft, R. P. 1956, ApJ, 123, 44

della Valle, M., Bianchini, A., Livio, M., & Orio, M. 1992, A&A, 266, 232

della Valle, M., Rosino, L., Bianchini, A., & Livio, M. 1994, A&A, 287, 403

Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, ArXiv e-prints, 1207-1306

Echevarría, J., de la Fuente, E., & Costero, R. 2007, AJ, 134, 262

Edwards, Z. I., Pagnotta, A., & Schaefer, B. E. 2012, ApJL, 747, L19

Fowler, W. A., Caughlan, G. R., & Zimmerman, B. A. 1975, ARAA, 13, 69

Fujimoto, M. Y. 1982a, ApJ, 257, 767

—. 1982b, ApJ, 257, 752

Gehrz, R. D. 2008, Classical Novae, 2nd edn., ed. M. F. Bode & A. Evans (Cambridge: University Press), 167–193

Gehrz, R. D., Truran, J. W., Williams, R. E., & Starrfield, S. 1998, PASP, 110, 3

Glasner, S. A., Livne, E., & Truran, J. W. 1997, ApJ, 475, 754

—. 2007, ApJ, 665, 1321

Goriely, S., Hilaire, S., & Koning, A. J. 2008, A&A, 487, 767

Hernanz, M., & José, J., eds. 2002, American Institute of Physics Conference Series, Vol. 637, Classical Nova Explosions

Hernanz, M., & Jose, J. 2008, ArXiv e-prints, 0809.3914

Hillebrandt, W., & Niemeyer, J. C. 2000, ARAA, 38, 191

Hix, W. R., & Thielemann, F.-K. 1999a, Journal of Computational and Applied Mathematics,

109, 321

—. 1999b, ApJ, 511, 862

Hounsell, R., Bode, M. F., Hick, P. P., et al. 2010, ApJ, 724, 480

Howell, D. A. 2011, Nature Communications, 2

Howell, D. A., Conley, A., Della Valle, M., et al. 2009, ArXiv e-prints, 0903.1086

Iben, Jr., I. 1975, ApJ, 196, 525

—. 1982, ApJ, 259, 244

—. 1991, ApJSupp, 76, 55

Idan, I., Shaviv, N. J., & Shaviv, G. 2012, Journal of Physics Conference Series, 337, 012051

Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943

Iliadis, C. 2007, Nuclear Physics of Stars (Wiley-VCH)

Iliadis, C., D'Auria, J. M., Starrfield, S., Thompson, W. J., & Wiescher, M. 2001, ApJSupp, 134, 151

Iliadis, C., et al. 2010a, Nucl. Phys. A, 841, 31

—. 2010b, Nucl. Phys. A, 841, 251

—. 2010c, Nucl. Phys. A, 841, 323

José, J., Coc, A., & Hernanz, M. 1999, ApJ, 520, 347

José, J., García-Berro, E., Hernanz, M., & Gil-Pons, P. 2007, ApJL, 662, L103

José, J., & Hernanz, M. 1998, ApJ, 494, 680

José, J., Hernanz, M., Amari, S., Lodders, K., & Zinner, E. 2004, ApJ, 612, 414

Kahabka, P., & van den Heuvel, E. P. J. 1997, ARAA, 35, 69

Kasen, D., Röpke, F. K., & Woosley, S. E. 2009, Nature, 460, 869

Kercek, A., Hillebrandt, W., & Truran, J. W. 1998, A&A, 337, 379

Khokhlov, A. M. 1991, A&A, 245, 114

Knigge, C. 2011a, ArXiv e-prints, 1101.2011

Knigge, C. 2011b, in Astronomical Society of the Pacific Conference Series, Vol. 447, Evolution of Compact Binaries, ed. L. Schmidtobreick, M. R. Schreiber, & C. Tappert, 3

Knigge, C., Baraffe, I., & Patterson, J. 2011, ApJSupp, 194, 28

Kovetz, A., & Prialnik, D. 1985, ApJ, 291, 812

Kovetz, A., Prialnik, D., & Shaviv, G. 1984, ApJ, 282, 584

Krautter, J., Oegelman, H., Starrfield, S., Wichmann, R., & Pfeffermann, E. 1996, ApJ, 456, 788

Kutter, G. S., & Sparks, W. M. 1987, ApJ, 321, 386

Leibundgut, B. 2000, A&A Reviews, 10, 179

—. 2001, ARAA, 39, 67

Li, W., Bloom, J. S., Podsiadlowski, P., et al. 2011, Nature, 480, 348

Longland, R., et al. 2010, Nucl. Phys. A, 841, 1

MacDonald, J. 1983, ApJ, 267, 732

MacDonald, J., Fujimoto, M. Y., & Truran, J. W. 1985, ApJ, 294, 263

Nomoto, K., Saio, H., Kato, M., & Hachisu, I. 2007, ApJ, 663, 1269

Nomoto, K., Uenishi, T., Kobayashi, C., et al. 2003, in From Twilight to Highlight: The Physics of Supernovae, ed. W. Hillebrandt & B. Leibundgut, 115

Nugent, P. E., Sullivan, M., Cenko, S. B., et al. 2011, Nature, 480, 344

Paczynski, B., & Zytkow, A. N. 1978, ApJ, 222, 604

Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJSupp, 192, 3

Pepin, R. O., Palma, R. L., Gehrz, R. D., & Starrfield, S. 2011, ApJ, 742, 86

Politano, M., Starrfield, S., Truran, J. W., Weiss, A., & Sparks, W. M. 1995, ApJ, 448, 807

Prialnik, D., & Kovetz, A. 1984, ApJ, 281, 367

Prialnik, D., Livio, M., Shaviv, G., & Kovetz, A. 1982, ApJ, 257, 312

Rogers, F. J., & Iglesias, C. A. 1992, ApJ, 401, 361

—. 1994, Science, 263, 50

Rosner, R., Alexakis, A., Young, Y.-N., Truran, J. W., & Hillebrandt, W. 2001, ApJL, 562, L177

Saizar, P., & Ferland, G. J. 1994, ApJ, 425, 755

Schaefer, B. E., & Pagnotta, A. 2012, Nature, 481, 164

Schatzman, E. L. 1958, White Dwarfs (Amsterdam, North-Holland Pub. Co.; New York, Interscience Publishers)

Schwarz, G. J., Shore, S. N., Starrfield, S., et al. 2001, MNRAS, 320, 103

Schwarzschild, M., & Härm, R. 1965, ApJ, 142, 855

Shafter, A. W. 1983, PhD thesis, California Univ., Los Angeles.

—. 1997, ApJ, 487, 226

Shen, K. J., & Bildsten, L. 2007, ApJ, 660, 1444

Sion, E. M., Acierno, M. J., & Tomczyk, S. 1979, ApJ, 230, 832

Sion, E. M., Godon, P., Myzcka, J., & Blair, W. P. 2010, ApJL, 716, L157

Sion, E. M., & Starrfield, S. G. 1994, ApJ, 421, 261

Sparks, W. M., & Kutter, G. S. 1987, ApJ, 321, 394

Starrfield, S. 1989, in Classical Novae, ed. M. F. Bode & A. Evans, 39–60

Starrfield, S., Iliadis, C., Hix, W. R., Timmes, F. X., & Sparks, W. M. 2009, ApJ, 692, 1532

Starrfield, S., Illiadis, C., & Hix, W. R. 2008, Classical Novae, 2nd edn., ed. M. F. Bode & A. Evans (Cambridge: University Press), 77–101

Starrfield, S., Schwarz, G. J., Truran, J. W., & Sparks, W. M. 1999, in Bulletin of the American Astronomical Society, Vol. 31, American Astronomical Society Meeting Abstracts #194, 977

Starrfield, S., Sparks, W. M., Truran, J. W., & Wiescher, M. C. 2000, ApJSupp, 127, 485

Starrfield, S., Timmes, F. X., Hix, W. R., et al. 2004, ApJL, 612, L53

Starrfield, S., Timmes, F. X., Iliadis, C., et al. 2012, Baltic Astronomy, 21, 76

Starrfield, S., Truran, J. W., Wiescher, M. C., & Sparks, W. M. 1998, MNRAS, 296, 502

Timmes, F. X. 1999, ApJSupp, 124, 241

Timmes, F. X., & Arnett, D. 1999, ApJSupp, 125, 277

Timmes, F. X., & Swesty, F. D. 2000, ApJSupp, 126, 501

Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJSupp, 98, 617

Townsley, D. M., & Bildsten, L. 2002, in Astronomical Society of the Pacific Conference Series, Vol. 261, The Physics of Cataclysmic Variables and Related Objects, ed. B. T. Gänsicke, K. Beuermann, & K. Reinsch, 31

Townsley, D. M., & Bildsten, L. 2004, ApJ, 600, 390

Trümper, J., Hasinger, G., Aschenbach, B., et al. 1991, Nature, 349, 579

van den Heuvel, E. P. J., Bhattacharya, D., Nomoto, K., & Rappaport, S. A. 1992, A&A, 262, 97

Warner, B. 1995, Cataclysmic variable stars, Vol. 28 (Cambridge: University Press)

Woosley, S. E., & Kasen, D. 2011, ApJ, 734, 38

Woudt, P. A., & Steeghs, D. 2005, in American Institute of Physics Conference Series, Vol. 797, Interacting Binaries: Accretion, Evolution, and Outcomes, ed. L. Burderi, L. A. Antonelli,

F. D'Antona, T. di Salvo, G. L. Israel, L. Piersanti, A. Tornambè, & O. Straniero, 647–650

Woudt, P. A., Steeghs, D., Karovska, M., et al. 2009, ApJ, 706, 738

Yaron, O., Prialnik, D., Shara, M. M., & Kovetz, A. 2005, ApJ, 623, 398

Yoon, S.-C., Langer, N., & van der Sluys, M. 2004, A&A, 425, 207

Zinner, E. 1998, Annual Review of Earth and Planetary Sciences, 26, 147

Zorotovic, M., Schreiber, M. R., & Gänsicke, B. T. 2011, A&A, 536, A42