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THE NOVA OUTBURST

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Observational and Theoretical Studies of the Nova Outburst

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Abstract. A nova outburst is one consequence of the accretion of hydrogen rich material onto a white dwarf in a close binary system. The strong electron degeneracy of a massive white dwarf drives the temperatures in the nuclear burning region to values exceeding 10^8K under all circumstances. As a result, a major fraction of the CNO nuclei in the envelope are transformed into e^+ -decay nuclei, which constrains the nuclear energy generation and yields non-solar CNO isotopic abundance ratios. In addition, the observations demonstrate that white dwarf core material is dredged up into the accreted layers and these nuclei are the catalysts for producing peak rates of energy generation that can exceed $10^{16}\text{erg gm}^{-1}\text{s}^{-1}$. Observations show that there are two compositional classes of novae, one that occurs on a carbon-oxygen white dwarf and the other that occurs on an oxygen-neon-magnesium white dwarf. The best observed ONeMg nova is V1974 Cyg. Analysis of ROSAT data implies that the mass of the white dwarf is about $1.25M_{\odot}$ and we describe new hydrodynamic calculations of thermonuclear runaways on $1.25M_{\odot}$ ONeMg white dwarfs using an upgraded nuclear reaction network and the *OPAL* opacities. While the characteristics of these simulations are in reasonable agreement with the observations of V1974 Cyg, the amount of mass ejected is at least a factor of 10 less than observed. We suggest a solution for this discrepancy.

1. Introduction

The nova outburst occurs on the white dwarf (WD) component of a Cataclysmic Variable Binary star system. The fuel for the explosion comes from the hydrogen-rich secondary star that fills its Roche Lobe. Our theoretical understanding of these outbursts has shown that they are the largest hydrogen fueled explosions in the universe and, as a direct result of the explosion, material from the outer layers of the WD is blown out into space where it can be examined and analyzed by well-understood diagnostic techniques. The gas expanding away from the site of the explosion, in addition, provides an astrophysical laboratory for increasing our understanding of a variety of time-dependent phenomena. Some of these are the growth and evolution of stellar winds, forbidden emission lines, and dust grains. The analyses of these time-dependent processes requires observations in virtually every wavelength region using techniques ranging from γ -ray studies with COMPTON GRO to radio studies with the VLA.

Theoretical studies of the outburst show that the material accreted onto the WD grows in thickness until it reaches a temperature at its base that is sufficiently high for thermonuclear burning of hydrogen to begin. The further evolution of nuclear burning on the WD now depends on the mass and luminosity of the WD, the rate of mass accretion, and the chemical composition in the reacting layers (Starrfield 1989, 1990, 1993; Truran 1982; 1990; Gehrz et al. 1997; Starrfield et al. 1997b). The initial stages of the evolution to a thermonuclear runaway (TNR) are governed by nuclear generation from the proton-proton reaction chain. Since the rate of energy generation has a T^{4-6} dependence on the temperature and an X^2 dependence on the mass fraction of hydrogen, the rate can be extremely small and most of the nuclear and compressional energy will be transported to the surface and radiated. The WD spends most of the accretion time in this phase which determines the amount of material that is accreted prior to the TNR. A change in the physical conditions during this phase which, for example, increases the amount of heat trapped in these layers will reduce the evolution time to TNR and, thereby, the amount of accreted mass.

If the WD is massive and the bottom of the accreted layer is sufficiently degenerate when it reaches a temperature of 10^7 K, a TNR occurs, and the temperatures in the accreted envelope grow to values exceeding 10^8 K. During the early stages of the TNR, the CNO cycle proceeds in equilibrium because the lifetimes of the CNO nuclei against proton captures are much longer than the decay times for the e^+ -decay isotopes ^{13}N ($\tau_+ = 9.97$ min), ^{14}O ($\tau_+ = 70.5$ sec), ^{15}O ($\tau_+ = 122$ sec), ^{17}F ($\tau_+ = 64.5$ sec), and ^{18}F ($\tau_+ = 109.8$ min). As the temperatures increase in the shell source, the lifetimes of the CNO nuclei against proton captures decrease until, at temperatures of $\sim 10^8$ K, they become shorter than the e^+ -decay lifetimes. The e^+ -unstable isotopes now become the most abundant heavy nuclear species. In addition a convective region develops just prior to the explosion. It carries the radioactive nuclei produced by nuclear reactions deep in the interior to the surface on time-scales that are short compared to their half-lives.

The large abundances of the e^+ -decay nuclei, at the peak of the outburst plus convection, have the following consequences for the evolution of the outburst. (1) Since the energy production in the CNO cycle comes from proton captures interspersed by e^+ -decays, the rate at which energy is produced, at

temperatures exceeding 10^8K , depends only on the half-lives of the e^+ -unstable nuclei and the numbers of CNO/NeMg nuclei initially present in the envelope. (2) Since convection operates throughout the entire accreted envelope, it brings unburned CNO/NeMg nuclei into the shell source, when the temperature is rising very rapidly, and keeps the nuclear reactions operating 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 e^+ -unstable nuclei can reach the surface without decaying and the rate of energy generation at the surface can exceed 10^{13} to 10^{15} erg $\text{gm}^{-1} \text{s}^{-1}$ for a few minutes which contributes to the heating and ejection of the surface layers (Starrfield 1989; Starrfield et al. 1997a). (4) Finally, the e^+ -unstable 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 predicted from studies of equilibrium CNO/NeMg burning.

Novae are expected to be the major source of ^{15}N and ^{17}O in Galactic matter and to contribute to the abundances of other isotopes in this mass region. At peak temperatures in the TNR, nuclear reactions can also form interesting and potentially significant quantities of the longer lived, radioactive isotopes ^7Be , ^{22}Na , and ^{26}Al . The convective history of the envelope is characterized by a rapid early growth to the surface and a subsequent retreat in mass as the envelope relaxes from peak temperature in the TNR on a thermal timescale. This behavior suggests that there should be a considerable variation in the abundances through the envelope. In contrast, the composition of the material ejected at much later times, which comes from regions closer to the core-envelope boundary, should reflect equilibrium CNO cycle burning at high temperatures. Finally, the abundance determinations of nova ejecta suggest that there is efficient mixing of core material with the accreted matter (Starrfield et al. 1997a,b; Gehrz et al. 1997). Thus, *the chemical composition of the ejected material reflects a mixture of WD core plus accreted material*. This implies that the WDs in those novae that show the most extreme nuclear abundance enrichments in the ejecta may be decreasing in mass as a result of the outburst. These same abundance studies have also established that the underlying WDs are either carbon and oxygen (CO) or oxygen, neon, and magnesium (ONeMg) dwarfs.

Theoretical calculations 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 light curves produced by the expanding material are in reasonable agreement with the observations (Truran 1982; Starrfield 1989, 1995; Starrfield et al. 1992, 1997a; Politano et al. 1995). Our recent studies have shown that it is the outbursts that occur on ONeMg white dwarfs that produce the most interesting nucleosynthesis so we concentrate on that class of outburst in this review.

2. Oxygen-Neon-Magnesium Novae

The production of large amounts of ^{22}Na , ^{26}Al , and other intermediate mass nuclei in a nova outburst requires that the outburst occur on an ONeMg WD (Weiss and Truran 1990; Nofar, Shaviv, and Starrfield 1991). The first indication that they existed was the ultraviolet spectroscopic data obtained for V693 CrA

with the IUE satellite (Williams et al. 1985). It was clear just from inspection of the last set of spectra that neon was enriched in the ejecta. This was later confirmed by detailed analyses which showed that oxygen and magnesium were also enriched (Vanlandingham et al. 1997a, and references therein). Four years after the outburst of V693 CrA, Gehrz et al. (1985) reported that QU Vul showed enhanced neon. These results, in combination with the IUE spectra that also showed strong neon lines (Starrfield 1988), implied that the ejecta of QU Vul were enriched in neon and magnesium, as was again confirmed by detailed analyses (Saizar et al. 1992; Andreä et al. 1994; Austin et al. 1996). Truran and Livio (1986; see also Ritter et al. 1991 and Livio & Truran 1994) estimated that about one-third of all observed outbursts should be ONeMg novae.

Although there was strong circumstantial evidence that V838 Her was an ONeMg nova (Starrfield et al. 1993), confirmation came from analyses by Matheson et al. (1993) and Vanlandingham et al. (1996), who reported that both neon and sulfur were enriched in the ejecta. The abundances determined for V838 Her were in reasonable agreement with simulations of TNRs on massive ONeMg WDs (Starrfield et al. 1992; Politano et al. 1995).

V1974 Cyg was the brightest nova seen in outburst since V1500 Cyg and it was observed from γ -ray to radio wavelengths. Important data were obtained by ROSAT (Krautter et al. 1996; Balman et al. 1997) and IUE (Hauschildt et al. 1994a; Shore et al. 1993, 1994a, 1996; 1997 Austin et al. 1996). Austin et al. (1996) and Hayward et al. (1996) analyzed the ejecta of V1974 Cyg and showed that the distribution was consistent with the outburst occurring on an ONeMg WD. Finally, both Shore et al. (1993) and Austin et al. (1996) obtained values for the ejected mass of $\sim 5 \times 10^{-5} M_{\odot}$. V1974 Cyg was also observed by ROSAT on 18 occasions from 22 April 1992 until 3 Dec. 1993 when it rose from 0.3 cts s^{-1} to a peak of 76 cts s^{-1} in July 1993 (making it the brightest Super Soft X-ray Source) before declining to 0.2 cts s^{-1} in Dec. 1993. We analyzed the soft component, which we attributed to the signature of ongoing nuclear burning in the accreted layers on the WD (Krautter et al. 1996; Shore et al. 1997; Balman et al. 1997). We used the total nuclear burning time, ~ 18 months, to arrive at a mass estimate for the WD of $\sim 1.25 M_{\odot}$, and the time scale for the decline to estimate that $\sim 10^{-5} M_{\odot}$ of material remained on the WD at the end of the constant bolometric luminosity phase.

3. Elemental Abundances: Emission Line Studies.

In a series of papers, we have presented our analyses of the ejecta abundances for virtually all recent, bright, well-observed novae. This work is driven by the recognition that the abundances that we are determining are a measure of the core composition of WDs with different masses. While this gas has been processed through accretion, mixing, and hot hydrogen burning, it is possible to iterate values for the initial abundances through evolutionary simulations and determine the actual core composition. In addition, the study of novae ejecta is central to the understanding of the nature of the outburst. Gaseous shells having a range in mass from $M_{ej} \sim 10^{-7}$ to $10^{-3} M_{\odot}$ are ejected with velocities of 4×10^2 to 10^4 km s^{-1} from each outburst, and this material may be an important nucleosynthesis source for certain elements and/or isotopes in

the ISM such as ${}^7\text{Li}$, ${}^{13}\text{C}$, ${}^{15}\text{N}$, ${}^{17}\text{O}$, and ${}^{26}\text{Al}$. The fact that some novae form considerable quantities of dust soon after outburst (Gehrz 1988; Shore et al. 1994a; Gehrz et al. 1997) may have consequences for the dust content of the Galactic disk and the interpretation of some of the observed anomalies in the pre-solar grains found in meteorites (Anders and Zinner 1993).

When observed immediately after discovery, nova ejecta are typically optically thick and must be studied with stellar atmospheres. As the nova ejecta expand, however, their density drops, continuum emission becomes less important, and forbidden lines from highly ionized species become progressively more pronounced in the spectrum. Although for many years it was thought that this phase could be treated by the standard techniques devised for HII regions or planetary nebulae, it now seems clear that more sophistication is needed. There are a number of reasons. First, the densities in the ejecta are high, $> 10^7 \text{ cm}^{-3}$, which is above the critical densities of the forbidden lines of many important ions (Osterbrock 1989). Second, there is a hot photoionizing source that governs the ionization and excitation of the important elements. Third, the expanding material is generally not spatially resolved so that a given spectrum effectively integrates over regions with widely different electron densities and temperatures.

Fourth, another problem is including the evolution of the central star. Although it is possible to follow the evolution of nuclear burning on the WD in X-rays (Krautter et al. 1996; Balman et al. 1997) and the UV (Shore et al. 1997), this is not as easy in other wavelength regions. The observations of the evolution of both GQ Mus (Shanley et al. 1995) and V1974 Cyg (Krautter et al. 1996; Balman et al. 1997) show that the length of the nuclear burning stage is quite variable, and ROSAT observations of 55 recent novae in outburst indicate that nuclear burning lasts less than 10 years (Orio 1997). Once nuclear burning ceases and the X-rays stop maintaining the ionization, the ejecta begin to recombine. The ionization of the ejecta initially increases as the X-ray emission increases; it then decreases because of the onset of recombination. The continuing expansion, however, causes a drop in recombination since the density continues to decrease, and the competition between these two effects eventually leads to a freeze-out of the ionization fractions of the ejecta. The continuing decrease in density causes the emission lines to steadily weaken because of the drop in the emission measure but the relative ion contribution to the abundances remains roughly constant (Krautter et al. 1996, Shore et al. 1997).

Finally, it is not clear that a given abundance solution, obtained only from ratios of lines, is unique. Therefore, a new optimization method has been developed to address these problems (Vanlandingham et al. 1996, 1997a,b and references therein). It requires an initial estimate of the abundances, ejecta radii, filling factor, and covering factor (Vanlandingham et al. 1996, 1997a,b). In addition, it uses a density gradient that comes from hydrodynamic modeling of the outburst. These parameters are then used as input for a CLOUDY (Ferland 1996) integration through a model of the ejected shell which results in a prediction of the strengths of a number of emission lines. These predicted line strengths are then compared to the observed line strengths, and a value of χ^2 is determined which measures the accuracy of the fit of the model to the observations. At this point, new initial parameters are chosen and another integration of CLOUDY is performed. The new parameters are chosen using the Davidson-Fletcher-Powell

variable metric algorithm (Press et al. 1992) as provided in the MINUIT program from CERNLIB (James and Roos 1993). This algorithm uses the value of the function with respect to each parameter, as well as the derivative, to find the steepest slope in parameter space. MINUIT (with CLOUDY as a subroutine) rapidly drives the value of χ^2 to low values. Once a solution is found, the input parameters are varied one by one so that the errors associated with each parameter are determined. This method has now been used for V838 Her (Vanlandingham et al. 1996), V693 CrA (Vanlandingham et al. 1997a), and PW Vul (Schwarz et al. 1997a). Studies of LMC 1990 #1 (Vanlandingham et al. 1997b) and LMC 1988 #1 (Schwarz et al. 1997c) are in progress.

4. Spherical, Expanding, Non-LTE Atmosphere Studies:

The first UV spectra obtained for many novae show a continuum rising to the red with features characteristic of an expanding optically thick "iron curtain", caused by overlapping absorption lines from low ionization stages of the iron group elements. An accurate treatment of the spectrum at this time requires the use of a spherical, expanding, model atmosphere code. Our current studies have been done with PHOENIX, which was developed by Hauschildt et al. (1992; 1994a; 1994b; 1995; 1997). Using this code spectral syntheses were performed for the first few UV and optical spectra of V1974 Cyg by Hauschildt et al. (1994a). They found that V1974 Cyg was caught in the stage when the rapidly expanding, adiabatically cooling shell had not yet reached optical maximum (the "fireball" stage: Gehrz 1988). Hauschildt et al. also reported that the fits of the synthetic spectra to the observed spectra were improved if they used CNO abundances enhanced by a factor of ≈ 10 . This result was supported by later studies of the nebular abundances (Austin et al. 1996; Hayward et al. 1996).

Combined IUE and optical spectra, obtained after the initial recovery from UV minimum, were well reproduced by the models and Hauschildt et al. (1994a) again found it necessary to increase the C, N, and O abundances by about a factor of 10 over solar values. The enhanced abundances were strong evidence for significant hydrogen depletion in the ejected shell as expected in a nova explosion since metal rich WD core material is mixed into the shell during the TNR, and hydrogen fusion reactions power the outburst. *Since enhanced metal abundances were also required to fit the "fireball" spectrum, this implies that the envelope was thoroughly mixed during the earliest stages of the outburst.* These results demonstrate the power of spectral syntheses techniques.

The next bright nova that we studied was the slow, dust forming, CO nova, V705 Cas (Shore et al. 1994b; Hauschildt et al. 1994b). Hauschildt et al. analyzed optical and IUE spectra and found that radiation pressure was sufficient to eject the material even in a slow, low luminosity nova such as V705 Cas. Recently, Hauschildt et al. (1996, 1997) have used operator-splitting techniques (Hauschildt 1992; 1993), to add numerous elements in Non-LTE. Using the updated code, Schwarz et al. (1997a) examined the early UV spectra of the CO nova OS And and found that the inclusion of Fe II in Non-LTE improved the fits of the atmospheres to observed spectra. The earliest spectra showed the typical "iron curtain" pseudo-continuum. These spectra could be fitted with a solar metallicity composition. The spectra obtained later in the evolution, when the

temperatures had increased and the densities had dropped, again showed a solar composition. We point this out because analyzing spectroscopic time sequences provides important constraints on both the method and the evolution of the nova. Finally, Schwarz et al. (1997c) are now analyzing the UV and optical spectra of LMC 1988 # 1, which was the first Extragalactic nova to be observed with the IUE satellite. They find that fits to the observed spectra are improved by treating the Fe I to Fe III line formation in NLTE, that the CNO abundances are about 10 times solar, and that the other elements have the LMC metallicity (about 1/3 solar).

5. Theoretical Studies of Novae

We have, earlier, studied accretion of hydrogen-rich material onto ONeMg WDs with masses of $1.0M_{\odot}$, $1.25M_{\odot}$, and $1.35M_{\odot}$ using a large nuclear reaction network (Politano et al. 1995). However, the recent analysis of the X-ray light curve of V1974 Cyg suggests that the mass of the WD is $\sim 1.25M_{\odot}$ (Krautter et al. 1996). Therefore, in order to better understand the evolution of V1974 Cyg, in Starrfield et al. (1997a) we concentrated on WDs with a mass of $1.25M_{\odot}$. There were three major differences between the sequences in Politano et al. (1995) and those in Starrfield et al. (1997a). The latter study used the *carbon-rich* OPAL opacities (Iglesias and Rogers 1993), updated nuclear reaction rates (Van Wormer et al. 1994; Herndl et al. 1995), and more efficient convection. These changes had major effects on the evolution (Starrfield et al. 1997a). The most important change was caused by the fact that the OPAL opacities are larger than those used in Politano et al. Therefore, heat was trapped more effectively in the layers where nuclear fusion was occurring, the temperatures in these layers rose faster, and it took less time to reach the TNR. For equal mass accretion rates, the sequence with the OPAL opacities accreted less material.

The new reaction rates are larger around mass 26 than those used previously and the amount of ^{26}Al produced during the evolution is smaller than found in our previous studies. Another study of mass accretion onto ONe WD's has found similar results (Josè, et al. 1997). They used a different core composition than Starrfield et al. but updated reaction rates and report that a smaller amount of ^{26}Al is produced in a given TNR. However, the large amount of mass ejected in the outburst of QU Vul still argues for a contribution by novae to Galactic ^{26}Al .

One problem, characteristic of nova simulations, that has become worse as a result of our new calculations is that the amount of ejected mass has decreased. Since the opacities are larger than before, an increased fraction of the nuclear energy is trapped in the nuclear burning region during the proton-proton phase of evolution. This reduces the amount of accreted (and ejected) mass which is to be compared to the results of Shore et al. (1993), Austin et al. (1996), and Hayward et al. (1996) who obtained values for the ejected mass of V1974 Cyg ranging from $\sim 5 \times 10^{-5}M_{\odot}$ to nearly $\sim 5 \times 10^{-4}M_{\odot}$. Our predictions for the amount of mass ejected during the early phase of the nova outburst is more than a factor of 10 less than observed. This alone is not too significant a problem since mass loss induced by common envelope interactions (MacDonald et al. 1986; Truran & Glasner 1995) and by radiation pressure driven winds, acting in combination, can increase the *total* mass ejected. It is of far greater concern

that our simulations did not accrete as much mass (prior to runaway) as was observed to be ejected. It would appear that improving the input physics in our simulations has worsened the conflict between our results and the observations, with respect to estimates of the total envelope mass.

We emphasize that this is not a problem unique to V1974 Cyg. Observations of other ONeMg novae indicate that they are ejecting more material than theoretical considerations predict can normally be accreted. For example, the observations of V838 Her suggest that the outburst occurred on a WD with a mass $\sim 1.35 M_{\odot}$. Theoretical predictions imply that such a WD will accrete $\sim 4 \times 10^{-6} M_{\odot}$ before the TNR occurs (Starrfield 1989; Gehrz et al. 1997). Observations of the outburst, however, indicate that somewhere between $10^{-4} M_{\odot}$ and $6 \times 10^{-4} M_{\odot}$ were ejected during the outburst (Woodward et al. 1992, Vandelandingham et al. 1996). For another example, we refer to the outburst of QU Vul. Its outburst was very slow, for an ONeMg outburst, and we suggest that the explosion occurred on a $1.0 M_{\odot}$ WD. Such a WD should be able to accrete about $1.3 \times 10^{-4} M_{\odot}$ before the bottom reaches a pressure of $\sim 10^{20}$ dynes cm^{-2} (Starrfield 1989; Gehrz et al. 1997). The observations of QU Vul, however, imply that nearly $10^{-3} M_{\odot}$ was ejected (Saizar and Ferland 1994; Shin et al. 1997).

Finally, our theoretical studies of the turn-off of a nova after the explosive phase suggest that most of the accreted hydrogen is burned to helium prior to the return to quiescence. Thus, we argue that the material remaining on the WD is mostly helium. This result, in combination with the most recent ejecta abundance determinations which show large enrichments of helium (Starrfield et al. 1997a), suggests that the helium observed in the current outburst was actually produced in previous outbursts.

6. Where is the "Missing" Mass?

As discussed in the last section, our evolutionary sequences neither accrete nor eject sufficient material to agree with the observations and improving both the nuclear reactions and the opacities used in our evolutionary calculations has worsened the agreement. While improvements in the nuclear reaction rates made only slight changes, including the OPAL opacities had substantial effects. In fact, Starrfield et al. (1997a) lowered both the initial WD luminosity and the rate of accretion in order to approach the amount of mass ejected by the simulations of Starrfield et al. (1992) and Politano et al. (1995).

It is clear why this must be the case. Improving the opacities implies that more levels and lines are included, more detailed broadening mechanisms are included, and the level populations are treated in a more realistic fashion (Rogers et al. 1996, and references therein). Virtually all of these changes act to increase the opacity at a given temperature and density when compared to older generations of opacity tables. In nova studies, increasing the opacity during the accretion phase, makes it easier to trap the heat produced by the nuclear reactions and the temperatures rise more rapidly per unit accreted mass. This implies, in turn, that the accretion time is shorter and the amount of accreted mass lower than found in earlier studies. The results of these changes are only

exacerbated when we realize that the mixture of core material into the envelope, which enriches the heavy element mass fractions, also increases the opacity.

Clearly, the effect of an increased opacity on the TNR depends on precisely when and how the enriched material is mixed into the accreted material. Four mechanisms have been proposed and they are discussed in detail in Sparks et al. (1990) and Livio (1994). Two result in mixing during the entire accretion process: diffusion (Prialnik and Kovetz 1984; Kovetz and Prialnik 1985, 1994; Iben et al. 1991, 1992a, b; Iben 1992) and accretion-driven shear mixing (Kutter and Sparks 1987; Sparks and Kutter 1987). Diffusion can produce large enrichments if the accretion rate is low: $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$ (or lower). The observed rates of mass accretion in classical novae, however, are about one to two orders of magnitude higher (Livio 1994, and references therein). The other two occur when convection is important. One is convective overshooting via flame propagation during the peak of the TNR (Woosley 1986) and the other is convection-driven shear mixing (Kutter and Sparks 1989). Although Woosley (1986) refers to the process as convective overshooting, in fact the physical process involves the penetration of convective elements below the lower boundary of the convective region. Therefore, we prefer to call this "undershooting" in order to distinguish it from the motion of the elements above the convective region. Recent 2-dimensional studies imply that undershooting is an important physical process in the nova outburst (Glasner and Livne 1995; Glasner et al. 1997; Kercek et al. 1997).

The phase which determines the *total* amount of material that can be accreted prior to TNR is the proton-proton burning phase. This phase occurs first because it proceeds at the lowest temperatures. Because the temperature dependance of the proton-proton reaction sequence is low, $\epsilon_{\text{nuc}} \sim T^{4-6}$, a major fraction of the nuclear energy produced by this sequence is radiated (along with the compressional energy produced by the accreting material). Therefore, the increase in temperature per unit accreted material is very small and the WD spends a major fraction of the accretion time in this phase. Once the temperatures have risen to about 10 million degrees, the CNO cycle reactions, $\epsilon_{\text{nuc}} \sim T^{16-18}$, become important and the TNR quickly (compared to the time spent in the proton-proton phase) evolves to peak conditions.

The material being transferred by the donor star is assumed to have a solar mixture of elements. The assumption commonly made is that this mixture is immediately enriched by core material (either by diffusion or shear mixing). The core nuclei act to increase the opacity and, thereby, reduce the amount of accreted material in the given simulation. If one requires that the opacity be kept small, then these mechanisms either cannot be occurring or they cannot be mixing core material to the surface. These mechanisms, however, have been well studied both in nova simulations (Kovetz and Prialnik 1994; Iben et al. 1992) and in other areas of astrophysics and we cannot assume, for some unknown reason, that they are not working in the case of accretion onto WDs.

To resolve this problem, therefore, we again refer to the analysis of the ROSAT observations of V1974 Cyg and GQ Mus which showed that there must be a layer of helium-rich material which remains on the surface of the WD after the outburst (Krautter et al. 1996; Starrfield et al. 1996a). We emphasize, in addition, that the large enrichments of helium in the ejecta of most novae imply that a helium layer must be present on most of the WDs in nova systems.

Although this layer will contain a significant fraction of heavy nuclei immediately after the end of an outburst, the long accretion times required to reach accreted masses of $5 \times 10^{-5} M_{\odot}$, or larger, should provide sufficient time for these nuclei to gravitationally settle into the outer layers of the core. Given the existence of this helium layer, therefore, we claim that diffusion and shear mixing do occur but they do not mix accreted material into core material, they mix accreted material into the *remnant helium layer* on the WD.

One consequence of mixing helium with the accreted material is that this also *reduces* the opacity in the surface layers (as long as the heavier nuclei have settled out of this layer) and will, therefore, lengthen the time to runaway and increase the amount of accreted material. A second and *more* important consequence of enriching helium is that this will have a major effect on the rate of nuclear energy production from the proton-proton reaction sequence. This is because the rate of the first reaction in the sequence, ${}^1\text{H}(p, \beta^+ \nu){}^2\text{H}$, depends on X^2 . Reducing the hydrogen mass fraction will reduce the rate of energy generation and slow the evolution to the peak of the TNR. We have verified the effects of an enriched helium layer on the time to TNR (Starrfield et al. 1998, in preparation).

Nevertheless, given the existence and effects of the helium layer, we are still faced with the problem of enriching the accreted material with core material. We emphasize that the results from the abundance determinations demand that core material be brought up into the accreted layers so that the mixture can be processed through hot, hydrogen burning and ejected into space. Our proposed solution to the mixing problem is based on the existence and the properties of convection during the outburst. It is during this stage that multidimensional studies find that "flames" develop and spread by small scale turbulence (Fryxell and Woosley 1982; Shankar et al. 1992; Shankar and Arnett 1994).

Therefore, Glasner et al. (1997) and Kercek et al. (1997) have used two different 2-dimensional, hydrodynamic codes to investigate the role of convection during the *peak* stages of the TNR. They both find that convective undershooting at the core-envelope interface dredges core matter up into the accreted material which can be enriched to more than 30%. This is an important result since not only does it provide for a reasonable enrichment of the envelope, it indicates that this enrichment does not occur until the TNR is close to peak conditions, and when the increased opacity (produced by the enriched nuclei) can no longer act to reduce the amount of accreted material. In addition, since the accreted gas has already been mixed with the helium layer by either diffusion or accretion-driven shear mixing, undershooting does not have to first penetrate some fraction of the helium layer before reaching core material. It is our claim, therefore, that all of the mechanisms proposed to mix accreted material with core material operate at some time during the accretion process.

7. Discussion

If it is undershooting at the peak of the TNR that is responsible for the envelope enrichment, then this has important and far-reaching implications for the current state of nova calculations. First, it allows us to accrete a mixture that consists of solar plus helium material (or possibly less than solar: Schwarz et al. 1997a),

which results in a smaller opacity and a larger amount of accreted material. Second, because it is the composition of the accreting material that determines the opacity, we expect differences in accretion times and nova characteristics for novae with different metallicities. If metallicity of the accreted material is important, for example, then we should expect differences between Halo and Disk novae as is observed (Della Valle et al. 1992). In addition, LMC novae should be brighter and eject more material than Galactic novae of the same type since the LMC metallicity is about one-third that of the Galaxy. This is also observed (Della Valle et al. 1994). One caveat, however, is that previous outbursts should have polluted the secondary with high Z ejecta which would then be transferred onto the primary reducing the metallicity effects (Marks et al. 1997). That this may not be taking place suggests that hydrodynamic studies of the interaction between the WD secondary and the expanding high- Z ejecta should be done.

Third, we have identified two compositional classes of novae, those that occur on CO WDs and those that occur on ONeMg WDs (Starrfield et al. 1986). If ONeMg novae come from a younger population, so that the secondaries are transferring material with a higher metallicity, then we can expect differences in the characteristics of the explosions between these two classes in addition to the ejecta abundances. Fourth, if the WDs in these systems are rotating, then the amount of undershooting should vary on cylindrical shells and, unless there is a large amount of horizontal mixing at the peak of the outburst, there should be abundance differences from equator to poles. This could then manifest itself in observable abundance differences in the resolved nebulae. In addition, the latitudinal abundance differences should result in large differences in the rates of energy generation, peak temperature, and energetics of the outburst from the equator to the poles. This variation, in turn, could be responsible for the non-spherical ejection observed in virtually all novae. Fifth, the amount of undershooting should depend on the composition of the accreting material and the mass, luminosity, and rate of rotation of the WD. Therefore, the "strength" of the outburst (usually attributed to the amount of core material mixed into the accreted layers) will depend, in some as yet undetermined way, on all these parameters. This implies the need for a new set of studies with large variations in these parameters plus the thickness of the helium shell.

Sixth, the results of Glasner et al. (1997) and Kercek et al. (1997), in combination with the results reported in this paper, also have strong implications with respect to our understanding of the outbursts of recurrent novae (RNe). We note that both observations and theory imply that the RNe outbursts occur on massive WDs and require large mass accretion rates (Starrfield et al. 1985; Starrfield et al. 1988; Shore et al. 1991; Krautter et al. 1996). In addition, these same studies imply that only a small fraction of the accreted envelope is ejected and most of the material is burned to helium and remains as a thick layer on the WD. This is in contrast to what was found for V1974 Cyg where only a fraction of the accreted layers remained on the WD (Krautter et al. 1996). If the time scales are too short for either accretion-driven shear mixing or diffusion to penetrate the helium layer, then it may also be the case that undershooting is unable to penetrate through the helium buffer layer and down into the core so that the ejected abundances will only be enriched in helium as is observed (Shore et al. 1991).

Finally, if the accretion rate is low, then the classical nova outburst will occur above the core-envelope interface, and undershooting will not be able to mix down through the helium layer and dredge-up core material. This could explain why some slow novae, such as PW Vul (Saizar et al. 1991; Andreä et al. 1994; Schwarz et al. 1997b) eject material enriched only in helium. We emphasize that our explanation for the cause of too little mass being ejected in ONeMg nova outbursts is based on both recent observational and theoretical studies. The major differences between our proposed mechanism and the calculations that have been done previously is the existence of a helium buffer layer between the newly accreted material and the core (implied by recent X-ray studies of novae by Krautter et al. [1996] and Shanley et al. [1995]) plus the 2-dimensional calculations that indicate that mixing occurs by undershooting during the peak of the TNR (Glasner et al. 1997; Kercek et al. 1997).

8. Summary

In this review we presented calculations of TNRs in the accreted hydrogen-rich envelopes of ONeMg white dwarfs. These results, in combination with one-zone nucleosynthesis studies have demonstrated that novae produce ^{22}Na , ^{26}Al , and other intermediate mass nuclei in astrophysically interesting amounts. Specifically: 1) hot hydrogen burning on ONeMg white dwarfs can produce as much as 2% of the ejected material as ^{26}Al and 3% as ^{22}Na . 2) The largest amount of ^{26}Al is produced in the lowest mass white dwarfs, which according to our evolutionary calculations, should eject the largest amount of material. The observations of QU Vul, a slow ONeMg nova, indicate that it has ejected about $10^{-3}M_{\odot}$. It must be emphasized, however, that such a large amount of ejected mass is inconsistent with the amount predicted to be accreted onto a typical ONeMg WD whose mass is expected to exceed $1.25M_{\odot}$. 3) The largest amount of ^{22}Na is produced by the highest mass ONeMg WDs. These novae are predicted to be among the fastest and most luminous of all novae.

Finally, (1) convective efficiency has a strong effect on the progress of the outburst. Increasing the convective efficiency, increases the "strength" of the outburst. (2) The opacity of the accreted material has a strong effect on the total accreted mass prior to the TNR. The opacity determines the rate at which energy is transported away from the region where nuclear burning is occurring and increasing the opacity reduces the amount of material accreted before the TNR. (3) Recent improvements in the nuclear reaction rates have not significantly changed the energetics of the outburst. They have, however, changed the nucleosynthesis predictions. (4) The observed ejecta abundances, in combination with the energetics, show that a significant fraction of the helium ejected during the outburst was produced in a prior outburst. The presence of this helium layer influences the evolution to the peak of the TNR by reducing the hydrogen mass fraction and the rate of energy generation by the proton-proton reaction sequence. Increasing the helium abundance lengthens the time to TNR, and increases the accreted envelope mass.

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