5. NOVAE AND ACCRETION DISKS

The Classical Nova Outburst*

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1. Introduction

In this review I will present and discuss both the nova outburst and the theoretical calculations related to its cause and evolution. I use the commonly accepted model for a nova: a close binary system with one member a white dwarf and the other member a larger, cooler star that fills its Roche lobe. Because it fills its lobe, any tendency for it to grow in size because of evolutionary processes or for the lobe to shrink because of angular momentum losses will cause a flow of gas through the inner Lagrangian point into the lobe of the white dwarf. The size of the white dwarf is small compared to the size of its lobe and the high angular momentum of the transferred material causes it to spiral into an accretion disk surrounding the white dwarf. Some viscous process, as yet unknown, acts to transfer mass inward and angular momentum outward through the disk so that a fraction of the material lost by the secondary ultimately ends up on the white dwarf. Over a long period of time, the accreted layer will grow in thickness until the bottom reaches a temperature that is high enough to initiate thermonuclear burning of hydrogen by the proton-proton reaction chain. The further evolution of thermonuclear burning on the white dwarf now depends upon the mass and luminosity of the white dwarf, the rate of mass accretion, and the chemical composition of the reacting layer.

Given the proper conditions, a thermonuclear runaway (hereafter: TNR) will occur, and the temperature in the accreted envelope will grow to values exceeding 10^8 K. At this time the positron decay nuclei become abundant which strongly affects the further evolution of the outburst. Theoretical calculations demonstrate that this evolution releases enough energy to eject material with expansion velocities that agree with observed values and that the predicted light curves produced by the expanding material can agree quite closely with the observations.

There are many reviews of the observed behavior of a nova in outburst. The classical references are those of PAYNE-GAPOSCHKIN [1] and MCGLAUGHLIN [2]. A more recent review is GALLAGHER and STARRFIELD [3]. A very recent review of the nova phenomena in general is treated in BODE and EVANS [72]. The existence of these reviews allows me to skip the basic observational data and concentrate on the observations that are directly related to the theory of the outburst.

†On leave from Arizona State University.

*Supported in part by National Science Foundation Grant AST83-14788 to Arizona State University, by the DOE, and by a sabbatical leave grant from the Association of Western Universities.

https://doi.org/10.1017/S0252921100086103 Published online by Cambridge University Press

2. Conditions which Produce an Outburst

Given that the outburst occurs as the result of accretion of hydrogen-rich material onto a white dwarf, it becomes possible to determine under what conditions an outburst will occur and produce the explosion that we call a nova. The calculations of MACDONALD [13] give us some insight into the physical processes that affect this evolution. He finds a dependence on white dwarf mass and, for a given $\dot{M}$, that the amount of accreted mass is fairly insensitive to the white dwarf luminosity as long as the luminosity is below some value. This is because for very low luminosities the nuclear energy generation comes mostly from the proton-proton chain which has a temperature dependence of only $\sim T^4$. This means that the secular evolution of the envelope, as a result of the p-p reaction chain, will be very slow since the nuclear burning time scale, τ_n, is:

$$\tau_n \cong \frac{C_pT}{\varepsilon_{nuc}} \tag{1}$$

where C_p is the specific heat at constant pressure and ε_{nuc} is the rate of nuclear energy generation in erg/gm/sec. As long as the nuclear burning time scale is much longer than the time scale to accrete the envelope, $\tau_A = M_e/\dot{M}$, the rate of evolution is determined by the rate of mass accretion. Once the initial luminosity of the white dwarf is high enough so that the nuclear energy comes from the CNO reactions, which have a T^{16} dependence, then the accreted envelope mass does depend on the luminosity of the white dwarf. For example, for a 1.00 $M_\odot$ white dwarf and $\dot{M} \sim 10^{-9}$ $M_\odot$/yr, the accreted envelope mass, M_e, equals 10^{-4} $M_\odot$ if the luminosity (L_{wd}) is 10^{-2} $L_\odot$ and $M_e = 5 \times 10^{-4}$ $M_\odot$ if $L_{wd} = 10^{-3}$ $L_\odot$.

The quantitative results change if we enhance the abundance of carbon in the envelope. As shall be discussed in more detail later, ε_{nuc} is directly proportional to the number of reacting nuclei in the envelope so that we can markedly decrease τ_n by enhancing the carbon nuclei in the envelope. The early stages of accretion are not noticeably affected since nuclear burning occurs only from the p-p reactions, but once the temperature reaches $\sim 10^7$ K, the TNR is accelerated so that peak temperature occurs earlier and less mass can be accreted. This becomes more important for both high luminosity and high mass white dwarfs where the shell source temperature exceeds 10^7 K at the beginning of the evolution.

MACDONALD [13] has also considered the effects of varying the mass accretion rate on M_e and finds that as the mass accretion rate increases the accreted envelope mass decreases. This was also found by PRIALNIK, et al. [10] in a hydrodynamic study of mass accreting onto a 1.25 $M_\odot$ white dwarf and by Starrfield, Sparks, and Truran in studies of accretion onto white dwarfs with masses of 1.38 $M_\odot$ and 1.25 $M_\odot$ [69, 70]. The explanation for this behavior is that the energy release from the gravitational compression of the accreting material produces enough energy to accelerate the TNR and, thereby, reduce the evolution time to peak temperature.

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It has also been found that if the white dwarf is too luminous and the shell source is not degenerate, a runaway will occur but no ejection will result. For the classical nova outburst, we require that the material in the shell source be degenerate in order that envelope expansion not halt the TNR too early in the evolution. The critical parameter for a degenerate runaway is most easily expressed in terms of the Fermi temperature, T_F, defined as

$$T_F = E_F/k \tag{2}$$

where E_F is the Fermi energy of the gas. Using standard formulae[20], we arrive at an expression for the critical Fermi temperature,

$$T_F = 3 \times 10^7 \left(\frac{\rho_3}{\mu_e}\right)^{2/3} K \tag{3}$$

where ρ_3 is the density in units of 10^3 gm/cm^3. The physical explanation of this expression is that the kinetic temperature of the gas must exceed the Fermi temperature of the electrons in order for the material to expand and slow or halt the TNR. However, if the shell source temperature is rising rapidly, then it can exceed T_F by a large amount before the envelope is sufficiently nondegenerate for expansion to begin and halt any further rise in temperature or ε_{nuc}. Equation (1) gives the nuclear burning time scale to be compared with the dynamical time scale, T_D, where

$$T_D = H_P/V_s \quad . \tag{4}$$

H_P is the pressure scale height and V_s is the local sound speed. We can express this in a slightly different form by making use of the definitions of these parameters, vis,

$$T_D = \left(\frac{P}{\rho}\right)^{½} \frac{1}{g} \tag{5}$$

For fast nova models with $P \sim 10^{20}$ dynes/cm^2, $g \sim 10^8$ cm/sec^2, and $\rho \sim 10^4$ gm/ cm^3; $T_D \sim 1$ sec. If the CNO nuclei are sufficiently enhanced, then ε_{nuc} can reach 10^{17} erg/gm/sec and $\tau_{nuc} << 1$ sec. Therefore, all of the proton captures will go to completion and halt the TNR. If, however, the CNO nuclei have a normal abundance, then the maximum rate of energy generation is $\sim 10^{14}$ erg/gm/sec and $\tau_{nuc} \sim 1$ sec. In this case the envelope expansion halts the TNR.

The hydrostatic and hydrodynamic studies of accretion onto white dwarfs have identified those conditions which will result in TNR's. In order for a fast nova outburst to occur, it is necessary to accrete at a rate $\dot{M} \lesssim 10^{-9}$ $M_\odot$/yr onto a white dwarf with $M_{wd} > 1.1$ $M_\odot$ and a luminosity $L_{wd} \lesssim 10^{-2}$ $L_\odot$. In addition, it is also necessary to enhance the CNO nuclei in order to provide enough energy at the peak of the outburst to eject a shell of material with sufficient velocities to agree with the observations.

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3. Novae Abundances

As emphasized in the last section, the entire character of the outburst: light curve, ejection velocities, and speed class depend upon the amount of CNO nuclei initially present in the envelope. In addition, the fact that a fast nova outburst demands enhanced CNO abundances was one of the first and clearest predictions of the TNR theory of the nova outburst. I mention this point in order to emphasize the predictive nature of the TNR theory of the outburst. In fact, as late as 1977 (after the original papers on the TNR theory had appeared in print) a review was published which claimed that there was still no secure evidence for nonsolar abundances in novae [19].

Shortly thereafter, Williams and Gallagher and their collaborators began a series of investigations of nova shells from which the general conclusion was that not only were nova shells enhanced in CNO nuclei but that there was a correlation between degree of enhancement and nova speed class [5, 19-22]. In addition, studies of HR Del [23] and V1500 Cygni [24] have strengthened this correlation. A summary of the observed abundances for novae can be found in WEISCHER et al. [17]. The only counterexample to the CNO enhancement versus speed class relationship is DQ Her [20] which shows a very large enhancement of carbon although it was a slow nova. While its characteristics do test the theory, in fact, there are at least two simple explanations for this apparent paradox. The first is that the white dwarf is of considerably lower mass than found in typical nova systems [5, 25]; the second is that the mass transfer rate, $\dot{M}$, is considerably higher for DQ Her than for a fast nova [13]. The second hypothesis is suspect since some fast novae such as GK Per and V603 Aql are considerably brighter at minimum than DQ Her. The implication of this observation is that $\dot{M}$ is higher in these novae, not lower [26].

Studies of recent novae have led to some very interesting, if not perplexing, results. A most unusual recent outburst was that of the recurrent nova U Sco [27, 28], which at maximum showed strong H_β and HeII, but at minimum showed only lines of helium. The optical data imply that He/H in the ejecta was ~ 2 (by number). While the UV data imply nearly normal CNO abundances, they also imply that only $\sim 10^{-7}$ $M_\odot$ or less was ejected in the outburst, far lower than the canonical vaue of 10^{-4} $M_\odot$ to 10^{-5} $M_\odot$. U Sco was an extremely fast nova declining by more than eight magnitudes in one month and its ejection velocities may have exceeded 10^4 km/sec. Most surprising, spectra obtained at minimum suggest that either only helium is being transferred by the secondary or that this nova has found some way to hide the presence of hydrogen in an apparently normal (cool) accretion disc. Even if this nova were an accretion event, as has been suggested for the outburst of T CrB by WEBBINK [29], we are still faced with the problem that it is transferring helium and ejecting both helium and hydrogen. Note also that this object provides evidence for evolved secondaries in cataclysmic variables.

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It is also possible that some dwarf novae are transferring material enriched in helium [30, 31] which suggests that other elements may have abnormal abundances and that some of the enriched nuclei observed in the ejecta may come fron the secondary. In support of this possibility is a recent study of V603 Aql [32] that indicates that carbon is depleted and nitrogen is enhanced in the accretion disc; the implication being that the secondary is evolved. Unfortunately, the shell of V603 Aql has disappeared [33] and an abundance analysis of the ejected material is no longer possible.

Of great importance to our understanding of novae, have been the recent studies of novae using the International Ultraviolet Explorer Satellite. These include Nova Cygni 1978 which showed enhanced CNO [34] and the abundances were in agreement with the theoretical calculations of STARRFIELD, SPARKS, and TRURAN [35]; the studies of V603 Aql [32] and U Sco [28] mentioned already; Nova Corona Austrina 1981 [36, 70], and Nova Aquila 1982 [37, 71]. All of these novae showed very unusual abundances in the ejecta. The interpretation of Nova Corona Austrina is that it ejected core material from an oxygen, neon, magnesium white dwarf that had been processed through a hot hydrogen burning region by the nova outburst [70]. The most likely scenario suggests that the white dwarf had a main sequence mass of 8-12 $M_\odot$. Enhanced neon was also reported in V1500 Cygni [24]. These recent outbursts have very surprising implications and only underscore the need for continuing observations of novae in outburst.

The existence of enhanced nitrogen in the ejected shells of nova is strong evidence that a TNR has occurred in this material and because of the large enhancements of nitrogen found in novae it has been suggested that they are responsible for the production of nitrogen in the galaxy [38]. The observation that the $^{12}C/^{13}C$ isotopic ratio in DQ Her was also far from solar [39] supports the TNR theory as the cause of the outburst and indicates that the nuclear reactions have proceeded in a very non-equilibrium fashion as has been predicted for novae [35].

4. The Nuclear Physics of the Runaway

As has been shown in the theoretical papers on the nova outburst [6, 25, 35, 40-45, 68], the TNR theory is an application of nuclear physics to astrophysics. In our case, it is the operation of the CNO reactions at high temperatures and densities that not only imposes severe constraints on the energetics of the outburst but provides the kinetic energy for ejecting the shell and the luminous energy radiated during the outburst.

One of the most important results from these studies has been the identification of the role played by the β^+-unstable nuclei in the outburst. These four nuclei (^{13}N, ^{14}O, ^{15}O, ^{17}F) *influence the outburst in the following fashion:* during the early part of the evolution, the lifetimes of the CNO nuclei against proton captures are very much longer than the decay times for the β^+-unstable nuclei ($\tau(^{13}N)$ = 863s, $\tau(^{14}O)$ = 102s, $\tau(^{15}O)$ = 176s, $\tau(^{17}F)$ = 92 sec) so that these nuclei can decay and their daughters capture another proton in order to keep the reactions cycling. As the temperature increases in the shell source, the lifetime against proton capture continually decreases until, at temperatures of $\sim 10^8$ K, it competes favorably with the β^+-decay lifetimes. At this time the abundances of these nuclei increase to where they severely impact the nuclear energy generation in the envelope, since every proton capture must now be followed by a waiting period before the β^+-decay occurs and another proton capture can occur. I note also that all of the computer simulations show that during the evolution to peak temperature a convective region forms just above the shell source and gradually penetrates throughout virtually the entire accreted envelope. This means that at the peak of outburst the most abundant of the CNO nuclei in the envelope will be the β^+-unstable nuclei. This has a number of effects on the succeeding evolution. Since the energy production in the CNO cycle comes from a proton capture followed by a β^+-decay, at maximum temperature the rate at which energy is produced will depend only on the number of CNO nuclei initially present in the envelope. This is because the CNO reactions do not create new nuclei, but only redistribute them among the various CNO isotopes [40]. The rate of energy production at maximum can then be expressed as [15]:

$$\varepsilon_{cno} = 6 \times 10^{15}\, Z_{CNO} \text{ erg/gm/s} \quad . \tag{6}$$

This is called the β^+-limited CNO cycle and it is also important in calculations of the x-ray burst and transient sources [46]. The convective turnover time scale, τ_{con}, for the envelope is

$$\tau_{con} = \frac{\Delta r_s}{V_{con}} \tag{7}$$

where Δr_s is the shell thickness, and V_{con} is the velocity of the convective elements. τ_{con} is $\sim 10^2$ sec near the peak of the TNR so that a significant fraction of the β^+-decay nuclei can reach the surface without decaying. Therefore, the rate of energy generation at the surface can reach 10^{12} to 10^{13} erg/gm/sec as has been found in the numerical calculations [25]. Because of the presence of convection in the envelope during the evolution to the peak of the outburst, which brings fresh unburned CNO nuclei into the shell source and because the temperature is rising very rapidly, the nuclear reactions operate far from equilibrium and the resulting energy generation is not reproduced by equilibrium burning formulae (or calculations) at any fixed temperature.

These nuclei also have the effect of "storing" energy for release on very long time scales compared to the dynamical time scale of the envelope. Once peak temperature is reached and the envelope begins to expand, one would expect the rate of energy generation to drop precipitously which is just what happens in those calculations which utilize an equilibrium formula for ε_{nuc} [45]. However, in more realistic

https://doi.org/10.1017/S0252921100086103 Published online by Cambridge University Press

calculations, which include a detailed calculation of the abundance changes with time of the nuclei, the rate of energy generation declines only as the abundances of the β^+-unstable nuclei decline since their decay is neither temperature nor density dependent. In fact, the numerical calculations done with enhanced CNO [25] show that more than 10^{47} erg is released into the envelope after its expansion has begun. The envelope reaches radii of more than 10^{10} cm before all of the ^{13}N has disappeared. Therefore, the decay of the β^+-unstable nuclei provides a delayed source of energy which is ultimately responsible for both ejecting the shell and producing the luminous output of the outburst. Finally, since these nuclei decay when the temperatures in the envelope have declined to values that are too low for any further proton captures to occur, the final isotopic ratios in the ejected material will not agree with those ratios predicted from studies of equilibrium CNO burning.

The discussion up to this point has not required the assumption of enhanced CNO nuclei but is based on the hypothesis that in order for an outburst to occur the shell source will be degenerate enough so that the peak temperature exceeds 10^8 K. If this occurs, the effects of the β^+-unstable nuclei become inevitable. However, the observational fact that the CNO nuclei are enhanced in the ejecta also requires them to be enhanced in the nuclear burning region. All of our arguments about the effects of the β^+-unstable nuclei are only strengthened if the CNO nuclei are enhanced. Peak energy generation is increased, more energy is stored for release at late times in the outburst, and the resulting isotopic and elemental ratios in the ejecta will be very unusual. We have found that it is enhanced CNO nuclei that are required to power a fast nova outburst and, in fact, no calculation at a mass of 1.3 $M_\odot$ or less, based on a solar mixture, has been successful in reproducing a realistic fast nova [5].

5. A Theoretical Nova Outburst

a) The rise to bolometric maximum

The initial phase of the rise to maximum of the outburst occurs very rapidly and is determined by the convective turnover time scale in the envelope. For most of the evolution, nuclear burning is proceeding by the proton-proton chain and the temperature in the shell source changes very slowly. In the last part of the evolution, the CNO reactions become important, and since they have a T^{16-18} temperature dependence, the progress to the peak accelerates rapidly. The calculations show that once the shell source temperature reaches $\sim 2 \times 10^7$ K, a convective region forms just above the shell source and gradually grows toward the surface as the shell source temperature continues to increase. Up to this point, no sign of the impending explosion has reached the surface. However, when the temperature in the shell source passes $\sim 10^8$ K, the convective region finally reaches to the surface and the energy produced in the deep interior can now increase the surface luminosity. In addition, since the convective turnover time scale is $\sim 10^2$ sec, a reasonable fraction of the β^+-unstable nuclei are carried to the surface where they decay and so the rate of energy genera-

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tion at the surface can exceed 10^{12} to 10^{13} erg/gm/sec within 10^3 sec or so after peak temperature. Since the surface layers are very thin (10^{-8} $M_\odot$ or less), the luminosity can reach or exceed 10^5 $L_\odot$. At this time the envelope is expanding at velocities of 1 to 10 km/sec and cannot have expanded very far so that its radius is still small and the effective temperature is ~ 5×10^5 K. Therefore, novae at bolometric maximum will be very luminous EUV or soft x-ray sources (Fig. 1).

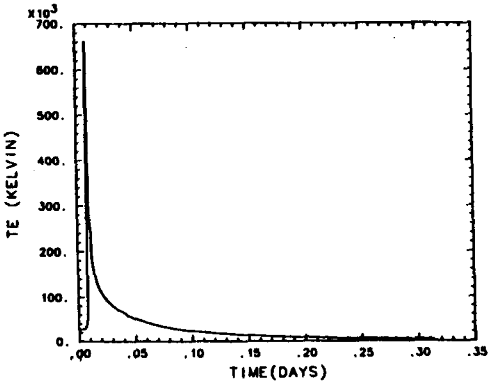

Figure 1. The effective temperature as a function of time for a 1.25 $M_\odot$ model accreting at a rate of 1.6×10^{-10} $M_\odot$/yr.

b) Rise to visual maximum

Once the outburst has reached its peak, both in nuclear energy production and in shell source temperature, the envelope begins to expand. It is also likely for fast novae that the surface luminosity exceeds the Eddington luminosity hastening the change from hydrostatic equilibrium to hydrodynamic expansion. In addition, some envelopes have such high CNO enhancements that the rapid rise to peak temperature in the shell source causes a shock wave to form which also accelerates the envelope and causes hydrodynamic expansion [48, 25]. Only under rare conditions (extreme CNO enhancements and large envelope masses), however, does this shock eject any material. All studies of the nova phenomena which assume only hydrostatic motion break down at this point.

Peak visual luminosity occurs when the luminous, expanding shell reaches its maximum effective radius; ~ 10^{12} cm to 10^{13} cm. This radius is determined by the expanding gas cooling until a temperature ~ 7-9 $\times 10^3$ K is reached. At this point hydrogen recombines and the opacity drops rapidly so that the photosphere then begins to move inward with respect to mass fraction [3, 49, 50]. The time from peak temperature in the shell source to peak visual luminosity depends on the rate of expansion of the envelope. The observational data imply that there is in general an inverse correlation between speed class and time to maximum in that the faster novae expand more rapidly and reach visual maximum faster than do the slower novae. DQ Her violated this correlation because it rose to maximum very rapidly, unlike other slow novae.

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We attribute the fact that such a correlation exists at all to the physical fact that the rate of expansion must depend on the ratio of the nuclear energy release per gram during the final stages of the TNR to the binding energy per gram of the envelope. TRURAN [5] computes this energy release by considering that only one or two protons will be captured on a CNO nucleus in the last few minutes of the TNR and finds that

$$\varepsilon_{TNR} \sim 2.7 \times 10^{15} \left(\frac{\eta_{CNO}}{\eta^{\theta}_{CNO}}\right) \text{ erg/gm} \quad (8)$$

where η_{CNO} and $\eta^{\theta}{}_{CNO}$ are the fraction by number of the CNO nuclei in the envelope and sun [51] respectively. This is to be compared with the binding energy per gram for the envelope.

$$\frac{GM}{R} \cong 1.3 \times 10^{18} \, M_{\theta} \, R_8^{-1} \text{ erg/gm} \quad (9)$$

where R_8 is the stellar radius in units of 10^8 cm. It is clear that in the last stages of the outburst the envelope cannot produce a significant amount of nuclear energy (per gram), as compared to the gravitational binding energy (per gram), unless the CNO nuclei are enhanced. However, if they are not, then we must consider the total nuclear energy release on a long time scale and compare this to the total binding energy of the envelope. On a long time scale there is more than enough nuclear energy available, 6×10^{18} erg/gm times 10^{-5} $M_{\theta} \sim 10^{47}$ ergs, to eject the entire shell but the envelope expands much more slowly than for a fast nova.

c) The constant bolometric luminosity phase

This phase was first discovered by GALLAGHER and CODE [52] and extended to other novae by GALLAGHER AND STARRFIELD [53]. It is one of the most important predictions of the TNR theory for the classical nova outburst [3-6, 25]. What was predicted and what the UV [34, 36, 54] and IR observations [55, 57] show is that the bolometric light curve of a typical nova is uncorrelated with the visual light curve. In the observational studies one finds that a typical nova energy distribution hardens as the visual magnitude declines resulting in a large fraction of the energy being emitted outside the optical region of the spectrum. At late stages, if grains form in the ejecta, then the nova becomes extremely bright in the IR as the grains reradiate the UV output of the nova. The total luminosity remains constant or declines only slightly, while the visual light curve declines by large factors. Thus, the visual light curve is a poor indicator of the total energy emitted during the nova outburst.

The physical cause of this phenomena, as predicted by the numerical calculations, is as follows: only 10% to 50% of the accreted material is ejected in the initial outburst. Once the shell has been ejected, the remaining material, which was

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initially expanding at large velocities, slows and returns to hydrostatic equilibrium. The remnant gas is hot and has a radius of $\sim 10^{10}$ cm to $\sim 10^{12}$ cm depending upon the mass of the remnant envelope. The larger the amount of accreted mass remaining on the white dwarf the larger the radius of the remnant envelope. Over a few days, this extended envelope slowly shrinks and its effective temperature increases as it becomes completely convective. Its structure at this time is analogous to that of an asymptotic giant branch star with one exception: the white dwarf core is cold, not hot. Once it returns to hydrostatic equilibrium, the temperature of the shell source is $\sim 5 \times 10^7$ K. The remnant is now radiating energy at close to the Eddington limit. The calculations show, again as one would expect for asymptotic giant branch stars, that the luminosity depends on the core mass and that the radius (or effective temperature) depends on the envelope mass.

The decline in visual magnitude can then be understood as a shift of the peak energy into the UV and then the EUV. Once the effective temperature exceeds $\sim 7 \times 10^4$ K, we can calculate the bolometric correction by assuming that the visual magnitude is the Rayleigh-Jeans tail of a black-body energy distribution. In this case [5, 58]:

$$\text{B.C.} \propto 7.5 \log_{10} \frac{T_{ef}}{T_{ei}} \tag{10}$$

Where T_{ei} and T_{ef} are the initial and final effective temperatures. We see, therefore, that the decline in visual magnitude of the typical nova can be attributed to the increasing effective temperature of the remnant. If we identify the luminosity from this phase of the outburst with the plateau luminosity as discussed by IBEN [12], then it becomes possible to estimate the white dwarf mass based on a determination of the total energy output at this time [13].

However, it is also the case that some fast novae exceed not only this luminosity, but also the Eddington luminosity during the early stages of the outburst. One such case was Nova V1500 Cygni 1975 whose luminosity at maximum exceeded 7×10^5 $L_\odot$ [54]. Its photospheric radius, shortly after maximum, was estimated to be $\sim 2 \times 10^{13}$ cm, which is consistent with an expansion velocity of $\sim 1.2 \times 10^3$ km/sec [59]. The amount of matter required to define a photosphere at this point exceeded 10^{-6} $M_\odot$; so that the rate of mass loss up to this time must have exceeded 10^{22} gm/sec in agreement with calculations of BATH [49, 50]. From this rate one can obtain a mass loss energy requirement of,

$$\frac{GM}{R} \dot{M} \sim 2 \times 10^6 \, L_\odot \tag{11}$$

which is more than a factor of 10 larger than the peak radiative luminosity. A value of this magnitude emphasizes the requirements for overabundances of the CNO nuclei in this outburst [53]. A similar analysis shows that Nova V1668 Cygni 1978 must have also exhibited a super-Eddington phase [13].

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This early super-Eddington phase is very short lived since it drives such a large rate of mass loss. In fact, the luminosity had declined for V1500 Cygni by the time of the ANS observations in December 1975, about three months after the peak [54]. Once the luminosity of the nova has dropped to the plateau luminosity, then its further evolution is somewhat slower. The evolution back to minimum will take about 1 to 10 years after the cessation of nuclear burning [60-62]. Note, however, that the time scale to burn all of the remaining envelope, τ_n, is very long compared to the observed time scale of the outburst of about 1 to 2 years; vis [5]:

$$\tau_n = 400 \left(\frac{M_e}{10^{-4} M_\Theta}\right) \left(\frac{L}{2\times10^2 L_\Theta}\right)^{-1} \text{yr} \qquad (12)$$

This time scale is obtained from the numerical calculations which assume no other processes are acting to shut off the outburst.

d) The turn-off phase

It is this phase which is, as yet, the least studied and the least understood. The reasons for this are quite clear, in an outburst lasting about a year, it becomes easy for an observational astronomer to turn to other problems when the object of interest has become quite faint and measurable changes are occurring very slowly. Unfortunately, it is just at this time that the white dwarf rids itself of enough material to halt nuclear burning in the shell and the remaining material collapses back onto the white dwarf. It is also during this time that the accretion disc must reestablish itself so that the system can begin evolving to another outburst in 10^4 to 10^5 years [63]. As was discussed in the last section, the numerical calculations predict a very long evolution time for the remnant. This prediction is in apparent disagreement with the observations. Therefore, there must be some physical processes, not presently included in the calculations, which act to strip the remnant of the accreted envelope on a rapid time scale. One such mechanism is stellar wind type mass loss [61, 64], which could drive mass loss rates as high as 10^{-6} to 10^{-7} M_Θ/yr for our luminous remnants. This rate could be increased if carbon, nitrogen, and oxygen are enhanced in the envelope since the rate depends on the number of strong lines present in the UV.

Another process, considered in detail by MACDONALD [65], see also [4, 25, 73], is that the radius of the white dwarf plus the nuclear burning envelope exceeds the radius of the binary system during the early stages of the outburst. Dynamical friction, caused by the secondary orbiting within the outer radius of the remnant, will then drive mass loss [65, MACDONALD 1985 preprint]. This process continues until the equilibrium radius of the remnant shrinks within the roche lobe of the white dwarf. At this time tidal forces from the secondary could possibly act to drive some additional mass loss.

The amount of material which remains on the white dwarf after an outburst also impacts the discussion of the secular evolution of the white dwarf. Since the outburst of fast novae require that 10% to 30% of the accreted envelope must be CNO nuclei, probably mixed up from the carbon-oxygen or oxygen-neon-magnesium core, and that each outburst ejects a significant fraction of the envelope plus core material, then we are forced to the conclusion that the long time evolution of the fast nova is to slowly whittle away the core. One interesting sidelight to this point, is that as the accreting matter penetrates deeper into the core material, each succeeding outburst will sample a different phase of the history of the evolution of the white dwarf. We can imagine the abundance of this material slowly changing from pure carbon to carbon plus oxygen and possibly even oxygen, neon, and magnesium. However, the above is true only for fast novae. For slow novae, which do not show enhanced abundances and probably eject only by a wind plus dynamical friction [42, 65], it is possible that there is no mass lost from the white dwarf and that the secular evolution of the system produces a thick helium layer on the white dwarf. This question is still open.

At the same time that we are discussing mass loss mechanisms, it is also appropriate to point out a possible mass gaining mechanism. The energy radiated from the primary will be sufficient to provide an intense source of heat in the outer layers of the secondary [25]. This can drive the envelope of the secondary out of thermal equilibrium and additional mass will be lost from the secondary into the lobe of the primary during the active stages of the outburst. Without detailed numerical calculations it is not possible to predict the fate of this material.

The last point to be discussed is the final evolution of the remnant material once it is too thin to sustain any further nuclear burning. Just prior to turn-off the remnant will be at its hottest point in the outburst since bolometric maximum. Estimates of its temperature are very difficult since we do not, as yet, know how much mass will be left on the white dwarf. However, it seems likely that very high effective temperatures can be attained, possibly as large as 5×10^5 K. This means that this state will be unobservable except in the EUV. Once this stage is reached, then the further evolution will be very rapid and the nova will decline in a few weeks to months [75]. It seems clear that the nova must turn off before the evolution to the new outburst begins. Otherwise, if the envelope is still burning and still convective, the addition of material will cause the remnant radius to expand and resume mass ejection as has been shown in the studies of accretion onto high luminosity white dwarfs with steady burning [7, 8, 12, 74]. Note that the white dwarf luminosities used in these calculations are much too large to agree with observations of old novae.

6. Numerical Calculations of a Nova Outburst

The most detailed calculations of the TNR theory for the nova outburst are found in a series of papers by STARRFIELD, SPARKS, and TRURAN [25, 42, 68, 69, 75]. Here we present some actual simulations of an outburst. The initial model for the first study had the envelope in place and in both thermal and hydrostatic equilibrium. The difference between this approach and the "accretion" approach, where hydrogen rich material is gradually added to the surface layers, is discussed in detail in STARRFIELD et al. [46]. In essence, the thermal structure of the envelope is determined by the assumed initial luminosity of the white dwarf, the time history of the nuclear reactions, and the equations of stellar structure. In the accretion studies [11], the envelope mass is defined by the numerical procedure, and the thermal structure at any time is determined by the same conditions plus the compressional heating and an assumption about the internal energy of the accreted material when it is placed on the star. In both cases, the thermal structure is eventually determined by the nuclear reactions so that the difference between these two procedures is the neglect of compressional heating in the studies with the envelope in place. In fact, the main effect of this difference is on the time scale to outburst. The envelope masses found in the "in place" studies are quite comparable to those of the "accretion" studies. In fact, we have used various envelope masses in our computations. A more serious problem with the published "accretion" studies is that most of them have used equilibrium CNO reaction rates which is an unrealistic assumption for the most important stages of the outburst.

In the first study, the white dwarf was assumed to have a mass of 1.00 $M_\odot$ although this value is larger than the commonly accepted value of 0.6 $M_\odot$ for single white dwarfs [66]. This is because the white dwarfs in close binaries appear to have masses $\geq$ 1.0 $M_\odot$ [13]. We varied the envelope mass (M_e) in this study [25] (hereafter STS) from 10^{-4} $M_\odot$ to 10^{-3} $M_\odot$. The latter stellar envelope had a pressure of 10^{20} dynes/cm^2 at the CEI [9, 13]. The model with the lowest envelope mass has almost half the envelope material in the form of ^{12}C. The initial luminosity of the white dwarf was 2×10^{-2} $L_\odot$, chosen so that the time scale to runaway would be ~ 10^3 years. While the above enhancement of carbon may seem extreme, the observed carbon abundance for DQ Her exceeded this value and for V1500 Cygni it was found to be ~ 30% by mass.

The initial density and temperature at the CEI (the model with $M_e = 10^{-4}$ $M_\odot$) was 2.4×10^3 gm/cm^3 and 1.2×10^7 K, respectively. The Fermi temperature at this density was ~ 8×10^7 K and the pressure was 3×10^{18} dynes/cm^2. The model with $M_e = 10^{-3}$ $M_\odot$ had a density and temperature at the CEI of 1.4×10^4 gm/cm^3 and 1.7×10^7 K, respectively. The Fermi temperature for this density was 2.4×10^8 K and the pressure at the CEI was 10^{20} dynes/cm^2. As we shall see, both models produce a fast nova outburst.

I shall describe only the $M_e = 10^{-4}$ $M_\odot$ evolutionary sequence in any detail. It took ~ 10^3 years to reach the peak of the TNR. During this time a convective region formed just above the shell source (it first appeared when the shell source temperature reached 2.5×10^7 K) and grew slowly toward the surface (1 month). It reached to the surface just when the shell source temperature passed 6×10^7 K. The energy

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release from the β^+-unstable nuclei caused the rate of energy production at the surface to reach 10^{13} erg/gm/sec and this heating accelerated the surface layers to expansion velocities of 8 km/sec.

Once the shell source temperature reached ~ 10^8 K, it took only 50 sec to reach a peak temperature of 1.46×10^8 K. The peak rate of energy generation was 4×10^{15} erg/gm/sec. The mass fraction of ^{14}O grew to ~ 10^{-3} (by mass) at the peak of the thermonuclear runaway. The growing temperature in the shell source passed the Fermi temperature 100 to 200 seconds before peak temperature was reached so that the envelope had time to begin expanding. This caused the temperature turnover and decline from maximum. The sequence with $M_e = 10^{-3}$ $M_\odot$ evolved much more rapidly since the degree of electron degeneracy was higher and the star could not react to the TNR on a nuclear burning time scale. It took this sequence only 36 seconds to reach a peak of 2.52×10^8 K and it was within 1 sec of peak temperature when it exceeded the Fermi temperature. Peak energy generation was 2×10^{17} erg/gm/sec so that the nuclear burning time scale at this time was only a fraction of a second. This was much shorter than the dynamical time scale, ~ 1 sec, and the maximum rate of energy generation was reached when all of the CNO nuclei in the envelope became β^+-unstable nuclei. At the same time, the rapid rise in temperature caused an over pressure to develop in the shell source and a shock wave formed which moved through the envelope in 1.04 sec but ejected no material.

The lower envelope mass sequence, $M_e = 10^{-4}$ $M_\odot$, ejected 3.5×10^{-5} $M_\odot$ moving with speeds from 350 km/sec to 3200 km/sec; a kinetic energy of 6×10^{44} ergs. The ejected mass amounted to 32% of the initial envelope. Peak bolometric magnitude was $-11^m.4$ while peak visual magnitude was $-7^m.5$. [25] The light curve is published in [25]. These values fall well within those observed for normal fast novae.

The sequence with a larger envelope mass ejected ~ 10^{-4} $M_\odot$ moving with speeds from 350 to 2800 km/sec; a kinetic energy of ~ 9×10^{44} erg. This was only 10% of the accreted envelope and 90% was left on the white dwarf to be ejected during the constant luminosity phase. In the first sequence the remnant material reached an outer radius of 3×10^{10} cm before slowly collapsing to ~ 8×10^9 cm. The more massive envelope sequence had a larger remnant mass and it reached 6×10^{11} cm before collapsing to 7×10^{10} cm. During the collapse period, the effective temperature of the remnant reached ~ 3×10^5 K and the luminosity declined to the plateau luminosity but our calculations did not predict that any further mass loss occurred.

Nevertheless, as discussed in the last section, the remnant envelope must be lost for this star to return to minimum. I shall not repeat that discussion here. It is necessary to point out, however, that the radius of the remnant (for the large envelope mass sequence) exceeded the Roche lobe radius of many of the old nova systems and dynamical friction must play an important part in the further evolution of this object [65]. The material ejected at this late time in the outburst will have a low density and high velocity so that when it impacts the denser, slower moving, principal ejecta it will be Rayleigh-Taylor unstable. This is probably the physical cause for the very clumpy nature of novae ejecta.

We have also considered models with a different degree of CNO enhancement. In fact, in all of our studies we have determined the minimum degree of enhancement necessary to produce an outburst and eject material with a nova type light curve. We find that for a given white dwarf mass and envelope mass, that the strength of the outburst is strongly correlated with the degree of CNO enhancement. As we increase the enhancement, the peak shell source temperature, the amount of ejected material, and the ejection velocities all increase.

In another study we investigated the effects of no CNO enhancement as a proposed model for the slow nova outburst [42]. We followed the evolution of a 1.25 $M_\odot$ white dwarf with an envelope mass of 1.25×10^{-4} $M_\odot$ and assumed only a solar mixture (Z = .015). The entire evolution occurred on a much longer time scale than for the fast novae. One of the most exciting features of this study was that we achieved mass ejection from radiation pressure and that the theoretical light curve agreed quite closely with the observed light curve of Nova HR Del 1967. The simulation took about 10^6 sec to evolve to high luminosities and reached the plateau luminosity (L_p) as discussed by IBEN [12]. Similar behavior was found in other studies of slow novae [43, 45, 65]. However, as pointed out by MACDONALD [65], these calculations neglect the dynamical friction which occurs as the close binary revolved within the newly rekindled envelope. Since the extended envelope of the slow nova sequence [42] exceeded $\sim 10^{12}$ cm, this will certainly be an important effect in any slow nova studies. Nevertheless, this sequence did eject material and the theoretical calculations did resemble a very slow nova outburst.

We have also evolved TNR's on massive white dwarfs (1.38 $M_\odot$) in a successful attempt to produce outbursts which resemble those of the recurrent nova U Sco [68]. We used the spherical accretion code of KUTTER and SPARKS [16] to accrete solar composition material at a variety of rates onto white dwarfs with various luminosities. Our results produced sequences that took less than 40 years to reach the peak of the outburst and then ejected material by radiation pressure. The amount of material ejected is in good agreement with the observations. A light curve for one such sequence is published in STARRFIELD, SPARKS, and TRURAN [68].

For our most recent studies, we have developed a new accretion code which is very fast and accurate. We have now used it to study accretion and the resulting thermonuclear runways on 1.25 $M_\odot$ white dwarfs. We have used a variety of white dwarf luminosities and rates of mass accretion onto the white dwarf and have also utilized four different compositions for the accreting material: (1) a solar mixture of the CNO elements, (2) half of the accreting material solar composition and half carbon and oxygen, (3) half solar and half carbon, and (4) half solar and half oxygen. The last mixture was used to simulate accretion of material onto an O-N_e-Mg white dwarf.

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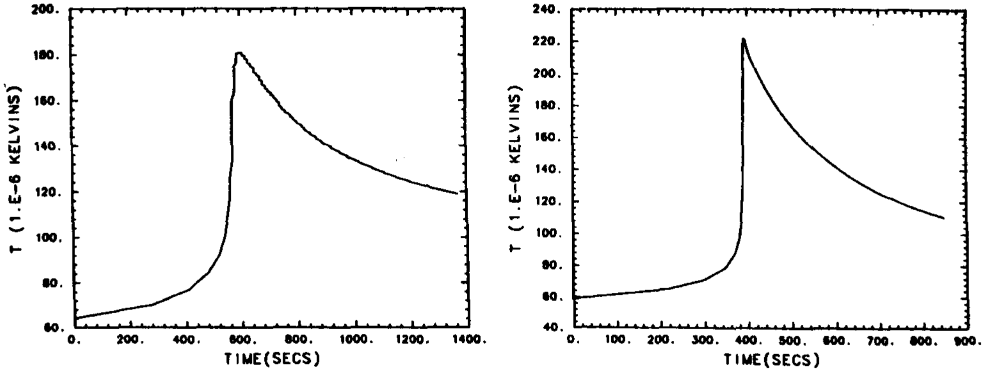

Fig. 2a, b. The peak temperature in the shell source for two models. Figure 2a (on left) is from a 1.00 $M_\odot$ white dwarf accreting at a rate $\dot{m} = 10^{16}$ gm/sec and with both carbon and oxygen enhanced. Figure 2b (on right) is for a 1.25 $M_\odot$ white dwarf accreting at $\dot{m} = 10^{16}$ gm/sec and with only carbon enhanced.

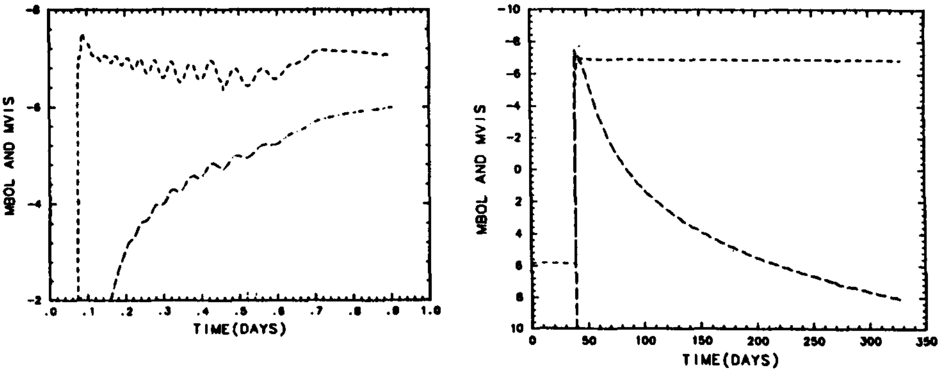

Fig. 3a, b. The bolometric (upper curve) and visual light curve for an evolutionary sequence with a 1.25 $M_\odot$ white dwarf accreting at 5 × 10^{17} gm/sec and with only oxygen enhanced. Figure 3a shows the early part of the light curve while Fig. 3b shows nearly the entire outburst.

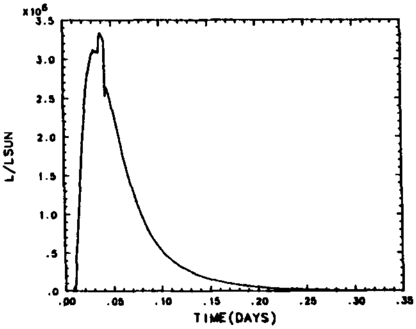

Fig. 4. The luminosity versus time for a 1.25 $M_\odot$ white dwarf accreting carbon enhanced material at a rate of 10^{16} gm/sec. At maximum this sequence is radiating at more than ten times L_{ED}.

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All of the solar accretion evolutionary sequences resulted in a thermonuclear runaway and a rapid rise in luminosity. However, the sequences which utilized very luminous white dwarfs: $L > 0.1\ L_\odot$ did not eject any material and the accreted envelope quickly burned to pure helium. Therefore, accretion onto luminous, i.e., young white dwarfs will produce a growing layer of helium on the surface of the white dwarf. Accretion onto low luminosity white dwarfs for $\dot{M} < 10^{-8}\ M_\odot\ yr^{-1}$ produced ejection but a significant fraction of the accreted envelope remained on the white dwarf and again resulted in a growing layer of helium on the surface.

The evolutionary studies done with the envelope consisting of half solar material and half carbon and oxygen or solar material and half carbon produced very similar results. Accretion onto luminous white dwarfs produced an outburst, but no mass was lost and a major fraction of the outburst luminosity was radiated in the EUV. Because carbon is so highly reactive, the runaway occurred before the envelope had accreted sufficient material to become degenerate and only a "weak" outburst occurred. At low white dwarf luminosities and small mass accretion rates, an outburst occurred and a major fraction of the envelope was ejected. The results of this study are given in Figures 1 to 4.

The evolutionary sequences done with a solar composition plus half oxygen were equivalent to the other studies of accretion onto high luminosity white dwarfs. However, on low luminosity dwarfs for the same $\dot{M}$, the outbursts were much more violent and a much larger fraction of the accreted envelope was ejected. All of these results are currently being prepared for publication.

7. Predictions of the Abundances in the Ejecta

An important prediction of the theoretical studies of the nova outburst is that the abundances in the ejecta will be very nonsolar. This is true not only for the fast nova where we require very enhanced CNO nuclei in order to produce an explosive outburst but also for the slow nova where the very long time scale of the outburst is sufficient to convert a great deal of the hydrogen in the envelope to helium. The sequences that were presented in the last section are among those that were used to obtain these predictions.

We find that the 1.0 $M_\odot$ low envelope mass simulation [25] ejects 36% carbon (by mass), 12% nitrogen, and 0.7% oxygen. The rest of the ejected envelope is hydrogen and helium. The isotopic ratios are $X(^{12}C)/X(^{13}C) = 0.56$; $X(^{14}N)/X(^{15}N) = 122$, and $X(^{16}O)/X(^{17}O) = 120$. Since this simulation developed a peak temperature of only 1.5×10^8 K, very little of the ^{16}O was processed during the outburst. On the other hand, we enhanced only the ^{12}C in this sequence and it was converted to ^{13}C by the $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C$ reaction sequence. The temperature was too low for a significant number of $^{13}N(p,\gamma)^{14}O$ or $^{13}C(p,\gamma)^{14}N$ reactions to occur and so little ^{14}N was produced [77]. This is the explanation of the large amount of ^{13}C present in the ejecta. Such a large abundance of ^{13}C may have been confirmed by a study of CN which appeared in spectra taken of DQ Her near maximum [39].

For the study with the high mass envelope ($M_e = 10^{-3}$ $M_\odot$), the elemental isotopic predictions are quite different. First, because the CNO nuclei make up a much smaller fraction of the envelope, and second, because at maximum the temperatures are high enough for a large number of $^{13}N(p,\gamma)^{14}O$ reactions to occur and feed ^{14}N. The elemental abundances in the ejecta are 1.3% (by mass) carbon, 7.6% nitrogen and 2.4% oxygen. The isotopic ratios are very interesting: $X(^{12}C)/X(^{13}C) = 1.3$, $X(^{14}N)/X(^{15}N) = 0.7$, and $X(^{16}O)/X(^{17}O) = 0.5$. For two of the three elements, the odd isotope has a greater abundance than the even! It would have been the same for ^{13}C but ^{13}N is destroyed by a proton capture to ^{14}O. An interesting sidelight is that the CNO abundances observed in V1668 Cygni [34] agree closely with this last study.

One point about the low envelope mass evolution is that since the shell source never gets hot enough to burn ^{16}O, the observed abundance of C+N to O will give us the initial C/O ratio in the enriching material. If we are steadily exposing deeper and deeper material in the carbon-oxygen core, then we should observe a range of C+N/O in fast novae.

Up to now we have only considered the CNO nuclei, but it has also been shown that lithium should be enhanced in the ejecta [67]. We have found in all of the fast nova calculations that a significant fraction of the ^3He initially present in the envelope is processed to ^7Be and ^7Li is then produced through the $^7Be(e^-,\nu)^7Li$ capture. All of the fast nova evolutionary sequences produced ^7Li with a production ratio of 200 times solar and ^7Li should be overabundant in novae ejecta.

The composition predictions for the slow nova differ greatly from those of the fast nova. Because we do not enhance the CNO nuclei in the envelope we do not expect to find them enhanced in the ejecta, although nitrogen should be enhanced relative to carbon, and this is born out by the studies of HR Del. In addition, once the peak of the outburst has passed, the reactions are proceeding in equilibrium at a high temperature. Because of the long time scale of the outburst, all of the reactions have time to go to completion and because the envelope is completely convective throughout the outburst, all of the envelope is processed through the shell source. This means that we cannot expect to produce any ^7Li enhancement in the ejecta. The observed N/C ratio should show signs of nuclear burning but the isotopic ratios should not be unusual. Finally, because of the long time scale for the outburst we expect a very nonsolar H/He abundance ratio as is observed [5].

8. Summary and Discussion

In this review I have presented both the theoretical and observational evidence that leads to the inescapable conclusion that the classical nova outburst is the direct result of a TNR in the accreted hydrogen rich envelope of the white dwarf. The most important evidence in favor of this theory has been the predictions and confirmation both of enhanced CNO nuclei in the ejecta and of a constant luminosity phase in the outburst. Observational support has also come from the discovery of a strong (but not total) correlation between speed class and CNO enhancement. In addition,

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calculations of the light curves for slow novae and most fast novae show excellent agreement with observed light curves with some exceptions. The theoretical simulations show that given a white dwarf with a specific envelope mass and elemental enhancement it is possible to eject shells of material and that this material has velocities and kinetic energies in the range of observed values.

One of the most interesting features of the TNR theory for the nova outburst has been the identification of the importance to the outburst of the positron decay nuclei (^{13}N, ^{14}O, ^{15}O, ^{17}F) whose half-lives, all on the order of minutes, determine the character of the outburst at maximum. Because the bottom of the accreted envelope is degenerate, with Fermi temperatures exceeding 8×10^7 K, peak temperatures during the outburst will exceed 10^8 K at which point the lifetimes against proton capture for the CNO nuclei become smaller than the positron decay half-lives. From this point on, the positron decay nuclei limit the energy production rate since any further proton captures must wait for a positron unstable nucleus to decay (these decay rates are neither temperature nor density dependent for the conditions in a white dwarf envelope). On the other hand, the positron unstable nuclei have stored a great deal of energy for release at late times during the outburst and because convection has operated during the evolution to the peak, these nuclei have been spread throughout the envelope providing a long period of steady energy release which ejects the shell and produces the radiated output of the nova. The calculations show that the amount of ejected material and its velocities are strongly correlated with the degree of CNO enhancement. Finally, because these nuclei decay at late times in the outburst, their daughter nuclei will be overabundant compared to the equivalent amount of solar material. In fact, in some simulations the amount of ^{13}C ejected exceeded that of ^{12}C and ^{15}N exceeded ^{14}N.

Given the properties of the nuclear reactions and the predicted abundances as a function of nova speed class, we turned to the observational evidence for confirmation or denial of the predictions. In fact, the recent studies of nova shells and the UV observations of novae in outburst demonstrate that such a correlation exists with one notable exception: DQ Her. This object was a slow nova with the largest amount of carbon in the ejecta of any well studied nova. In addition, analysis of its spectrum near maximum indicated nonsolar $^{12}C/^{13}C$ and $^{14}N/^{15}N$ isotopic ratios; the strongest evidence for the operation of a TNR in the nova outburst. The existence of this object underscores the wide variety of initial conditions that are possible in a prenova object. The theoretical studies have shown that even a massive enhancement of carbon in the accreted envelope of a low mass white dwarf ($M \leq 0.9\ M_{\odot}$) can only produce a slow nova. Further observational studies of novae show that carbon, nitrogen, and oxygen are definitely enhanced in novae (although some of the carbon appears as nitrogen), and that neon and helium are enhanced in some novae. Finally, there has been a prediction that ^7Li should be enhanced in novae ejecta but confirmation of that prediction must wait until new detection schemes are devised.

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The theoretical calculations that were presented in this chapter illustrate all of the physical processes that have been identified as relevant to the outburst. The calculations demonstrate that the cause of the constant UV luminosity from novae is that fraction of the accreted envelope not ejected during the burst stage of the outburst. This material is hot ($T_e = 10^5$ K), luminous ($L \sim L_{ed}$), and evolving on a nuclear time scale. In order for the outburst to end, this material must be ejected and it is one of the remaining problems in the studies of the nova outburst to identify the physical processes that are responsible for the ejection of the remaining material and the return to quiescence of the nova. Once we have understood this phase of the outburst, then we shall have a means of predicting the secular evolution of the white dwarf in nova binaries and, thereby, determining whether it is losing or gaining mass as a result of the outburst.

One final point, yet to be answered about the nova phenomena is the source of the enhanced nuclei in the accreted envelope. It does not seem likely that these nuclei are produced in the secondary, and numerical studies of shear instabilities have not produced a nova outburst. It may be possible that the enhancement is the result of combined hydrogen-helium runaways in the accreted envelopes, but the defining conditions for such runaways have yet to be identified.

This review has greatly benefitted from discussions (and arguments) with Jim Truran, Warren Sparks, Jay Gallagher, and Bob Williams. I would also like to thank Drs. M. Bode, F. Cordova, A. N. Cox, R. Gehrz, J. MacDonald, E. Sion, E. Ney and H. Van Horn for valuable discussions. Support both from the National Science Foundation through grant AST83-14788 to ASU and from the Association of Western Universities is gratefully acknowledged. I would also like to thank Drs. George Bell, Stirling Colgate, and Michael Henderson for the hospitality of the Los Alamos National Laboratory.

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Discussion

Owocki: I have several questions regarding the wind type mass loss from the post outburst extended envelope: 1) What is the characteristic size of the envelope? 2) Is the wind intrinsically time varying or can it be modeled as a quasi steady state flow? 3) What drives such a wind? 4) What is the role of the wind in controlling the overall outburst?

Starrfield: 1) The size of the remnant, hydrostatic envelope is a function of the mass remaining on the white dwarf and ranges from $\sim 10^{10}$ cm (low mass) to $\sim 10^{12}$ cm (large mass). 2) It has been modeled by Bath and others as a quasi steady state flow. 3) The high luminosity, $L \sim L_{ED}$, which drives the flow is produced in the shell source which has not turned off and will not turn off until all of the remaining mass is lost. 4) The wind sets the time scale to the end of the outburst and the beginning of the evolution to a new outburst.

Ogelman: How does the 5 to 10 year turn off time scale come about if the nuclear burning time scales are so much larger.

Starrfield: We postulate that an optically thick radiation pressure driven wind removes this mass on a very rapid time scale: $\sim 10^{-6}$ $M_\odot$/yr or higher.

Shull: You mentioned an overproduction of ^{26}Al in the Neon-rich novae and yet these are just a subclass of novae. Do you produce enough ^{26}Al to account for the ISM x-ray line recently detected and attributed to novae?

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Starrfield: Four of the last 10 outbursts have been Neon (and presumably ^{26}Al) rich. They have high ejection velocities so that this material will be well mixed through the ISM. We must do the hydrodynamic calculations with an extensive nuclear reaction network in order to determine how much ^{26}Al is ejected per outburst.

Icke: It seems that most nova shells are elliptical. I have tried to reproduce this by using Leon Lucy's particle hydrodynamic code to see if the revolution of the binary could produce this, but have found this effect to be insufficient. Could the asymmetry be intrinsic to the white dwarf? And what would it say about the explosion mechanism?

Starrfield: A number of us have tried to model this behavior but not with any convincing results. Tom Jones of Minnesota proposed that it was caused by the rotation of the white dwarf. If this is the case it should not affect the explosion. An interesting sidelight is that the ejecta from the 1985 outburst of RS Oph seems to be in two jets.

Bath: Could you comment on the distinguishing characteristics of nuclear runaway classical nova explosions versus supercritical accretion events?

Starrfield: Gladly. We have performed simulations of supercritical accretion onto white dwarfs as has Livio. We both find that no mass is ejected and that the visual light curve drops much more rapidly than observed.

Blandford: How confident are you that mass accreted equatorially in a disk or along polar field lines will be able to spread horizontally around the surface of the star. This would seem to be a prerequisite of a quasispherical outburst.

Starrfield: Calculations of diffusion time scales on white dwarfs show that they are very short because of the high gravity. If we assume that material is spread horizontally by a similar random walk process, then these time scales, $\sim 10^4$ yrs or less, are smaller than the accretion time scales. In addition, once the outburst begins it will become highly convective which should act to entrain material at the edges. Therefore, even if it starts out highly localized it should eventually mix the entire surface.

Blandford: Can you produce an overabundance of ^{22}Ne in the outburst?

Starrfield: You are referring to the Ne-E anomaly. We are currently redoing our nuclear reaction network in order to determine how much neon and aluminum are made in an outburst on a ne-O-mg white dwarf.

McCray: 1) Regarding the model for rapidly recurrent novae. I estimate that the accretion luminosity of the prenova star must be $\sim 10^2$ to 10^3 $L_\odot$. Is this observed? 2) Did I understand correctly that the disk spectrum of U Sco was pure helium, while the nova model included hydrogen?

Starrfield: 1) You are correct, but it could be very hot and emitting in the EUV. 2) We used a solar mixture and a significant fraction was burned to helium. We also used much smaller amounts of hydrogen and still obtained an outburst. Nevertheless, you are only emphasizing the point I tried to make in my talk: Where does the hydrogen come from?

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Kriz: Nova TCrB consists of a giant and a component of two solar masses. Is it a real nova or does it belong to another class of objects?

Starrfield: Kenyon has recently reobserved TCrB and finds that the mass of the compact component may be less than 1.5 $M_{\odot}$ and, therefore, in the correct mass range for a white dwarf. Nevertheless, Webbink has proposed that its outburst is caused by supercritical accretion and so it may not be related to other kinds of novae.

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