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TITLE A THEORETICAL AND OBSERVATIONAL REVIEW OF RESULTS ON NOVA EXPLOSIONS OCCURRING ON ONeMg WHITE DWARFS

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A THEORETICAL AND OBSERVATIONAL REVIEW OF RESULTS ON NOVA EXPLOSIONS OCCURRING ON ONeMg WHITE DWARFS*

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ABSTRACT

The nova outburst is the second most violent explosion that occurs in a galaxy. In this review I present the recent observational and theoretical studies that have demonstrated that there exist two classes of nova outburst. One type of nova occurs on a CO white dwarf and the other type of nova occurs on an ONeMg white dwarf. The second class of outbursts are much more violent and occur much more frequently then the first class of outbursts. Hydrodynamic simulations of both kinds of outbursts are in excellent agreement with the observations.

1 Introduction

In this review I present and discuss new theoretical calculations related to the cause and evolution of the nova outburst. I assume that the model for a cataclysmic variable also holds for the nova: a close binary system with one member a white dwarf and the other member a 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 a disc surrounding the white dwarf. Some viscous process, as yet unknown, acts to transfer material inward and angular momentum outward so that a fraction of the material lost by the secondary ultimately ends up on the white dwarf. The accreted layer grows in thickness until the bottom reaches thermonuclear burning temperatures. The further evolution of the white dwarf now depends upon its mass and luminosity, the rate of mass accretion, and the chemical composition of the reacting layer. Given the proper conditions, a thermonuclear runaway (hereafter: TNR) occurs, driving the temperatures in the accreted envelope to values exceeding 10^8K. 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 curve produced by the expanding material can agree quite closely with the observations.

Published reviews of the classical nova outburst [1-9] summarize the work up to 1985, here I will concentrate on more recent work and describe the studies done with the International Ultraviolet Explorer Satellite that have demonstrated the existence of ONeMg white dwarfs in nova systems. Recent reviews of novae can be found in Bode and Evans [5], Bode [9], and Starrfield [4,6,7,8].

2 Initial Conditions for the Outburst

It is now possible to estimate the amount of material that can be accreted by a white dwarf of a given mass and luminosity as a function of mass accretion rate and composition [4]. The strength of the outburst is determined by a "proper" pressure at the core-envelope interface (hereafter: CEI). In order to produce a fast nova, one requires a proper pressure of 10^{20} dynes/cm^2. Given this value, it becomes possible to compute the envelope mass as a function only of white dwarf mass since there exists a mass-radius relation for white dwarfs [16,17]. Note that since the radius of a white dwarf is inversely proportional to its mass, the envelope mass decreases as the white dwarf mass increases and, therefore, the energy necessary to eject the entire envelope decreases as the white dwarf mass increases. This implies that it becomes easier to produce a nova outburst, and especially a fast nova outburst, as the white dwarf mass increases.

This is, of course, not the whole story since the white dwarf luminosity, the mass accretion rate, and the chemical composition all strongly affect the evolution to the outburst. The calculations of MacDonald [14] give us some insight into the physical processes that determine this evolution. He finds the dependence on white dwarf mass as described in the last paragraph. In addition, he finds that, for a given 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 $\sim T^4$. If the initial luminosity of the white dwarf is high enough so that 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 $M \sim 10^{-9} M_\odot \, yr^{-1}$, 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. ε_{nuc} is directly proportional to the number of reacting nuclei in the envelope so that we can markedly decrease the accretion time by large enhancements of carbon or oxygen nuclei (as long as the shell source temperature exceeds $\sim 10^7$K where these reactions become important). The early stages of accretion are not noticeably affected since nuclear burning is occurring 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.

MacDonald [14] 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._ [12] 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 $1.25 M_\odot$ [46,47]. 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 reduce the evolution time to peak temperature.

Given that enough mass has been accreted at some rate, $\dot{M}$, and that the temperature in the shell source has reached a point where the TNR has begun, what are the conditions that determine the resulting evolution of the runaway? It turns out that it is the degree of degeneracy at the CEI that determines this evolution. If the white dwarf is too luminous and the shell source is not degenerate, a runaway but no ejection may occur as has been proposed for some of the "Symbiotic Novae" [10,11,13,15]. In order for a classical nova outburst to occur, we require that the material in the shell source be degenerate enough so that envelope expansion will not halt the TNR too early in the evolution [4].

In summary, the hydrostatic and hydrodynamic studies of accretion onto white dwarfs have identified those conditions which will result in a TNR. In order for a fast nova to occur, it is necessary to accrete at a rate $\dot{M} < 10^{-8}$ $M_\odot$ yr^{-1} onto a white dwarf with $M_{wd} > 1.1$ $M_\odot$ and a luminosity $L_{wd} \sim 10^{-2}$ $L_\odot$. 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 at sufficient velocities to agree with the observations.

3 Nova Abundances from Ultraviolet Studies

The entire character of the outburst: light curve, ejection velocities, and speed class depends 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 emphasize this point because of the predictive nature of the TNR theory for the outburst. In fact, as late as 1977 (after the original papers on the TNR theory appeared in print) a review was published which claimed that there was still no secure evidence for non-solar abundances in novae [18].

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 are nova shells enhanced in CNO nuclei but that there is a correlation (with a few exceptions) between degree of enhancement and nova speed class [3,18-21]. A summary of the observed abundances for novae can be found in Truran and Livio [51].

Studies of recent novae have led to some very interesting results. A most unusual recent outburst was that of the recurrent nova U Sco [24,25] which at maximum showed strong Hβ and HeII 4686 but at minimum showed only lines of helium. The optical data imply that He/H in the ejecta was ~ 2, while the UV data imply nearly normal CNO abundances. The data also imply that only $\sim 10^{-7}$ $M_\odot$ or less was ejected in the outburst, far lower than the canonical value 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. Finally, I note that in a recent study of V603 Aql [26], it was found that carbon is deplated and nitrogen is enhanced in the accretion disc; the implication is that the secondary is evolved. However, they also found that the CNO abundances were close to solar implying that the enhanced CNO in the ejected material comes from the core of the white dwarf.

Of great importance to our understanding of classical novae have been the recent studies using the International Ultraviolet Explorer Satellite. These include Nova Cygni 1978 which showed enhanced CNO [27], in agreement with the theoretical calculations of Starrfield, Sparks, and Truran [28]; the studies of V603 Aql [24] and U Sco [25] mentioned already; Nova Corona Austrina 1981 [29,47,48], and Nova Aquila 1982 [30,48,49]. The interpretation of Nova Corona Austrina, Nova Aql 1982 and Nova Vul 1984 #2 is that they all ejected material from an oxygen, neon, magnesium white dwarf that had been processed through a hot hydrogen burning region by the nova outburst [47,48]. The most likely scenario suggests that the white dwarf had a main sequence mass of 8-12$M_\odot$ and must now have a mass of $\sim$1.1$M_\odot$ to have survived nondegenerate carbon burning . Enhanced neon was also reported in V1500 Cygni [22]. These recent outbursts have very surprising implications with respect to stellar evolution and underscore the need for continuing observations of novae in outburst.

The existence of enhanced nitrogen in the ejected shells of novae is 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 [31]. The observations that the $^{12}C/^{13}C$ isotopic ratio in DQ Her was far from solar [32] supports the TNR theory as the cause of the outburst and indicates that the nuclear reactions have proceeded in a very nonequilibrium fashion as predicted for novae [28].

4 Hydrodynamic Calculations of the Nova Outburst

The most detailed calculations of the TNR theory for the nova outburst are found in a series of papers by the author, Warren Sparks, and James Truran [23,28,33,34,35,39,46,47]. Here I summarize these papers. The initial model for our first studies 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. [39]. 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 "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 more recent studies, we have included spherical accretion by a very fast rezoning technique.

The white dwarf was usually assumed to have a mass exceeding 1.00 $M_\odot$ although this value is larger than the quoted value of 0.6 $M_\odot$ for single white dwarfs [42]. This is because the white dwarfs in close binaries appear to have masses ≥ 1.0 $M_\odot$ [14]. I shall describe only the $M_e = 10^{-4}$ $M_\odot$ evolutionary sequence in any detail. It took $\sim 10^3$ 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 2.5×10^7K) and grew slowly toward the surface (1 month). It reached to the surface just when the shell source temperature passed 6×10^7K. The energy 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 $\sim 10^8$K, it took only 50 sec to reach a peak temperature of 1.46×10^8K. 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 which caused the temperature turn-over 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 2.52×10^8K 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 overpressure to develope in the shell source and a shock wave formed which moved through the envelope in 1.04 sec but ejected no material. This sequence ultimately 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 $-7^m.5$. These values fall well within those observed for normal fast novae.

In another study we investigated the effects of no CNO enhancement as a proposed model for the slow nova outburst [35]. We followed the evolution of a 1.25 $M_\odot$ white dwarf with an envelope mass of 5×10^{-5} $M_\odot$ 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 [13]. Similar behavior was found in other studies of slow novae [36-38]. However, as pointed out by MacDonald [41], these calculations neglect dynamical friction which occurs as the close binary revolves within the newly rekindled envelope. Since the extended envelope of the slow nova sequence [35] exceeded 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.

In our most recent studies [46,47], we have evolved TNR s on massive white dwarfs ($1.38M_\odot$ and $1.25M_\odot$) in successful attempts both to produce outbursts which resemble those of recurrent novae such as U Sco and also outbursts which resemble those that occur on ONeMg white dwarfs [47]. We used a spherical accretion code [47] 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 a small amount of material by radiation pressure. This is in good agreement with the observations.

Finally, we have developed a new accretion code that is very fast and accurate. We have used it to study accretion onto $1.25M_\odot$ white dwarfs with a range of luminosities and rates of mass accretion. We have utilized a variety of chemical compositions in order to simulate both ONeMg and CO white dwarfs. All of the solar accretion studies resulted in a TNR and a rapid rise in luminosity. Accretion onto luminous (young) white dwarfs did not produce a classical nova outburst. Accretion onto low luminosity white dwarfs did produce ejection but a significant fraction of the accreted layer remained on the white dwarf. This produced a layer of helium and the mass of the white dwarf increased as a result of the nova outburst.

The evolutionary studies done with the envelope consisting of half solar material plus half carbon and oxygen or half solar material plus half carbon produced very different 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, an outburst occurred and a major fraction of the envelope was ejected. The evolutionary sequences done with half solar and half oxygen were very violent and a very large fraction of the accreted envelope was ejected [48]. This composition is not so far-fetched as it seems since both theoretical and observational analyses of PG1159-035 (a pulsating variable star) suggest that it is very rich in oxygen near the surface [44,50]. We identify this calculation with the recently discovered outbursts occurring on ONeMg white dwarfs.

5 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 low envelope mass simulation [23] 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. 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 [32]. It should also be noted that the $^{13}N(p,\gamma)^{14}O$ reaction rate has been reduced in the most recent compilation of the Caltech group [40] which could change these early predictions.

For studies with the high mass envelopes ($M_e = 10^{-3} M_\odot$), 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 [28]! 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 [27] 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 [45]. We have found in all of the fast nova calculations that a significant fraction of the ^{3}He initially present in the envelope is processed to ^{7}Be and ^{7}Li is then produced through the ^{7}Be(e-,ν)^{7}Li capture. All of the fast nova evolutionary sequences produced ^{7}Li with a production ratio of 200 times solar and ^{7}Li should be over abundant 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 proceed in equilibrium at high temperatures. 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 ^{7}Li 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 non-solar H/He abundance ratio as is observed for all novae [3,51].

6 Summary and Discussion

In this review I have presented both 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 a 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, calculations of the light curves for slow novae and most fast novae show excellent agreement with observed light curves. 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 x 10^7K, peak temperatures during the outburst will exceed 10^8K 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. Finally, because these nuclei decay at late times in the outburst, their daughter nuclei will be overabundant compared to an equivalent amount of solar material. In fact, in some simulations the amount of ^{13}C ejected exceeded that of ^{12}C.

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 novae shells and the UV observations of novae in outburst demonstrate that such a correlation exists with two notable exceptions: DQ Her and Nova Vul 1984 #2. DQ Her 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 non-solar ^{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 pre-nova object. The theoretical studies have shown that even a massive enhancement of carbon in the accreted envelope of a low mass white dwarf ($M \sim 0.9\ M_\odot$) can only produce a slow nova. Further studies of novae show that carbon, nitrogen, and oxygen are definitely enhanced in novae, (although some of the carbon appears as nitrogen) and helium is enhanced in all novae. Finally, there has been a prediction that ^{7}Li should be enhanced in novae ejecta but confirmation of that prediction must wait until new detection schemes are devised.

The theoretical calculations that were presented in this review 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 by either a strong stellar wind or by dynamical friction.

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.

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