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The Nova Outburst:
Thermonuclear Runaways on Degenerate Dwarfs

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Abstract

Observational and theoretical studies of the outbursts of classical novae have provided critical insights into a broad range of astrophysical phenomena. Thermonuclear runaways (TNRs) in accreted hydrogen-rich envelopes on the white dwarf (WD) components of close binary systems constitute not only the outburst mechanism for a classical nova explosion, but also for recurrent novae and a fraction of the symbiotic nova explosions. Studies of the general characteristics of these explosions, both in our own galaxy and in neighboring galaxies of varying metallicity, can teach us about binary stellar evolution, while studies of the evolution of nova binary systems can constrain models for the (as yet unidentified) progenitors of Type Ia supernovae. Further, the empirical relation between the peak luminosity of a nova and the rate of decline, which presents a challenge to theoretical models, allows novae to be utilized as standard candles for distance determinations out to the Virgo Cluster. Extensive studies of novae with IUE and the resulting abundance determinations have revealed the existence of oxygen-neon white dwarfs in some systems. The high levels of enrichment of novae ejecta in elements ranging from carbon to sulfur confirm that there is significant dredge-up of matter from the core of the underlying white dwarf and enable novae to contribute to the chemical enrichment of the interstellar medium. Observations of the epoch of dust formation in the expanding shells of novae allow important constraints to be placed on the dust formation process and confirm that graphite, SiC, and SiO2 grains are formed by the outburst. It is possible that grains from novae were injected into the pre-solar nebula and can be identified with some of the pre-solar grains or "stardust" found in meteorites. Finally, γ-ray observations during the first several years of their outburst, using the next generation of satellite observatories, could confirm the presence of decays from 7Be and 22Na.

1. Introduction

Classical novae participate in the cycle of Galactic chemical evolution in which grains and metal enriched gas in their ejecta, supplementing those of supernovae, AGB stars, and WR stars, are a source of heavy elements for the ISM. Once in the diffuse gas, this material is cycled through molecular clouds before being incorporated into young stars and planetary systems during star formation. Infrared observations have confirmed the presence of carbon, SiC, hydrocarbons, and oxygen-rich silicate grains in nova ejecta, suggesting that some fraction of the pre-solar grains recently identified in meteoritic material (Zinner 1

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1998) may come from novae (Gehrz et al. 1998, hereafter G98). The mean mass returned by a nova outburst to the ISM is $\sim 2 \times 10^{-4}$ M$_\odot$ (G98). Using the observed nova rate of 35±11 per year in our Galaxy (Shafter 1997), it follows that novae introduce $\sim 7 \times 10^{-5}$ M$_\odot$ yr$^{-1}$ of processed matter into the ISM. It is likely, however, that nova ejecta are more massive than believed, and this value is a lower limit (Saizar and Ferland 1994; G98). Finally, novae are expected to be the major source of $^{15}$N and $^{17}$O in the Galaxy and contribute to the abundances of other isotopes in this atomic mass range. Recent reviews can be found in Starrfield et al. (1997) and G98.

Many of the observational behaviors of the nova outburst are strongly dependent upon a complicated interplay of nuclear physics and convection during the final minutes of the TNR. While the proton-proton chain is important during the accretion phase of the outburst, when the amount of accreted mass is determined, it is the CN cycle reactions and, ultimately, the hot CNO sequences that power the final stages and the peak of the TNR. Moreover, the high temperatures ($2$ to $3 \times 10^6$ K) achieved in the TNR drive proton captures on the available CNO nuclei and form significant quantities of the radioactive isotopes $^{13}$N, $^{14}$O, $^{15}$O, and $^{17}$F. The $\beta^+$-decay lifetimes of these nuclei are short ($<10^3$ seconds) and limit nuclear energy generation on a hydrodynamic timescale ($\sim$ seconds). The high temperatures at the base of the envelope drive convection, which rapidly transports both energy and newly formed $\beta^+$-decay nuclei to the surface. The $\beta^+$-decay nuclei play an extremely important role at the peak of the outburst. (1) They provide significant heating in the surface layers (far removed from the thermonuclear burning regime) which drives expansion and ejection of these layers at high velocities. (2) They emit $\gamma$-rays at the surface which should be detectable from nearby novae, and when detected will provide a probe of the TNR. (3) Their decays yield stable isotopes of the CNO elements with nonsolar abundance patterns. Convection during this phase may also give rise to dredge up of matter from the underlying CO or ONeMg WD core. Such envelope enrichment not only is observed but is required to power the rapid early rise and super-Eddington luminosity phase of the light curves of the fastest classical novae.

It is significant that the $\beta^+$-decay heating of the outermost regions of the nova envelope reduces the temperature gradient and, in turn, curtails convection in the surface layers. The growth of convection from the burning region to the surface and its subsequent retreat in mass, as the envelope relaxes from the peak of the runaway, implies that there may well exist considerable variations in the elemental and isotopic abundances through the envelope. Observations that provide data on abundance gradients in nova ejecta can improve our knowledge of the history of convection during the TNR.

2. Emission Line Studies.

The studies of novae ejecta are central to the understanding of the nature of the outburst. Gaseous shells having a range in mass from $\sim 10^{-7}$M$_\odot$ to $10^{-3}$M$_\odot$ are ejected with velocities of $4 \times 10^4$ to $10^5$ km s$^{-1}$, and this material may be an important source of certain isotopes in the ISM such as $^7$Li, $^{13}$C, $^{18}$N, $^{17}$O, and $^{26}$Al. Some novae form considerable quantities of dust soon after outburst (G98) which may have consequences for the dust content of the CNO elements with nonsolar abundance patterns. Convection during the peak of the runaway, implies that there may well exist considerable variations in the elemental and isotopic abundances through the envelope. Observations that provide data on abundance gradients in nova ejecta can improve our knowledge of the history of convection during the TNR.

We have recently developed and used new methods to determine the ejecta abundances for recent, bright, well-observed novae (G98; Starrfield et al. 1998, hereafter S98; and references therein). Our motivation is that the abundances that we have determined are a measure of the core composition of WDs with different masses. The method that we are using involves a photoionization code (CLOUDY: Ferland 1996), in combination with an optimisation technique which allows us to obtain a solution for all elements simultaneously. The code is run a number of times (with different initial conditions) both for data obtained on the same date, and for data obtained on different dates, in order to determine the abundances and estimates both of the errors in the abundances and the uniqueness of the solution.
Since the CLOUDY integration provides the radial dependence of the density, one can also determine the ejected gas mass. We have now done this for V838 Her (Vanlandingham et al. 1996), V693 CrA (Vanlandingham et al. 1997), PW Vul (Schwarz et al. 1997b), and LMC 1990#1 (Vanlandingham et al. 1998). The results obtained for V838 Her confirmed a high sulfur abundance in the ejecta that was predicted by our earlier studies of TNRs on 1.35M$_\odot$ WDs (Starrfield et al. 1992; Politano et al. 1995). We are currently analyzing LMC 1991 and V1974 Cyg.


The early UV spectra obtained for most novae show a continuum rising to the red with features characteristic of an expanding optically thick “iron curtain.” The iron curtain is caused by overlapping absorption lines from low ionization stages of the iron group elements (Hauschildt et al. 1992, 1995, 1996, 1997). An accurate treatment of the spectrum at this time requires the use of a spherical, expanding, Non-LTE, model atmosphere code. Our current studies are being done with PHOENIX (Hauschildt et al. 1996, 1997, and references therein). Hauschildt et al. (1994a) used PHOENIX to study the evolution of V1974 Cyg and they found, from spectral syntheses, that V1974 Cyg was caught in the “fireball” stage (Gehrz 1988). We also found that the fits of the synthetic spectra to the observed spectra were improved if the CNO abundances were enhanced by a factor of ~ 10. This abundance determination was supported by a later determination of the nebular abundances (Austin et al. 1996; Hayward et al. 1996). The later spectra, obtained after the initial recovery from ultraviolet minimum, were also well reproduced and Hauschildt et al. (1994a) again found it necessary to increase the CNO abundances by about a factor of 10 over solar values. Since enhanced metal abundances were also required to fit the “fireball” spectrum, this implied that the envelope was thoroughly mixed during the earliest stages of the outburst. Hauschildt et al. (1994b) analyzed optical and IUE spectra of the slow, dust forming, CO nova, V705 Cas and found that radiation pressure was sufficient to eject the material. Similar analyses have now been carried out for OS And (Schwarz et al. 1997a), LMC 1988 #1 (Schwarz et al. 1998), and LMC 1991 (Schwarz et al. 1999, in prep.).

4. New Evolutionary Sequences for TNRs on White Dwarfs.

In order to simulate the new observational results, we have updated and improved our 1D, hydrodynamic, evolution code (NOVA) using the most recent opacities (OPAL: Iglesias and Rogers 1993; Rogers et al. 1996) and nuclear reaction rates. We calculated new evolutionary sequences for 1.25M$_\odot$ WDs, to simulate the outburst of V1974 Cyg and found that the addition of the OPAL opacities had profound effects on the results (S98). Because the new opacities were larger than those we had been using, we found that the energy from the nuclear reactions was trapped more effectively in the layers where it was produced, causing the temperatures to rise more rapidly for a given amount of accreted mass. Thus, the TNR occurred earlier in the accretion phase with less material required to initiate the TNR. The new simulations ejected a factor of ten less mass than inferred from observations of the outburst of V1974 Cyg (Starrfield et al. 1997; S98). This result further increases the discrepancy between theory and observation with respect to the masses of nova ejecta (S98; José and Hernans 1998). In S98, it was predicted that mixing of the accreted hydrogen-rich material into a helium-rich layer (a remnant of the previous outburst) would reduce the opacity and allow more mass to be accreted. This has now been verified (Starrfield et al. 1999, in preparation).
5. Multidimensional Studies of Mixing During the Thermonuclear Runaway

A critical problem in nova studies is the growth and development of the convective region in response to the TNR. This problem may also be closely connected to another problem: how and when are WD core nuclei dredged up into the accreted matter? The transport of heat and $\beta^+$-decay nuclei to the surface by convection, as the TNR rises to its peak, influences a number of observable features of novae that can be used both to guide and to constrain the simulations. Two of these features are: (1) The early evolution of the visual light curves of fast novae on which the use of novae as “standard candles” is based. During this phase the bolometric luminosity of a nova can remain more than an order of magnitude above the Eddington luminosity for several days (confirmed for LMC 1991 by Schwars et al. 1999, in prep.). (2) The composition of matter ejected by a nova as a function of time. Both of these features depend on the amount and composition of the material dredged up from the underlying CO or ONeMg WD core.

Recently, due to advances in computing power, it has become possible to treat convection at or near the peak of the TNR in both 2D and 3D. This has been made tractable for nova studies since the relevant timescales are all on the order of seconds. For example, the dynamical timescale $\tau_{\text{dyn}}$, at a density $\sim 10^4$ g cm$^{-3}$ is of order seconds. The nuclear burning timescale decreases from years to seconds, once the temperature rises above $10^6$ K, until constrained by the $\beta^+$-decay lifetimes. Finally, the convective timescale is of order seconds near the peak of the runaway (S98).

Glasner et al. (1997a,b) explored thermonuclear ignition and explosive hydrogen burning in novae with a 2D code. They followed the evolution of a convective hydrogen-rich envelope accreted onto a CO WD at a time close to the peak of the TNR and found convective motions which dredged up sufficient material from the core to explain the observed levels of heavy element enrichment in nova ejecta ($\sim 30\%$ to $40\%$ by mass: G98). The redistribution of nuclear energy generation over the envelope, caused by the outward transport of short lived $\beta^+$-decay nuclei, was also found to play a significant role in the outburst. In a complementary study, Kercek et al. (1998a) examined the early stages of the evolution, using the same initial model as Glasner et al. While their simulations confirmed the finding of Glasner et al., mixing was not as strong and occurred over a longer timescale. Finally, preliminary results obtained from 3D calculations, using the same input physics, a similar resolution, and the same code as before, display less overshoot mixing and a completely different flow structure (Kercek et al. 1998b).

Given the differences in these calculations, the general inferences that can be drawn from the existing multidimensional calculations are: (1) the amount of convective mixing occurring prior to the TNR is negligible; (2) the amount of convective mixing occurring during the early stages of the TNR is a sensitive function of the degree of degeneracy; and (3) convective overshoot mixing, which dredges-up CO- or ONeMg-rich matter from the underlying WD core, may be sufficient to produce the observed enrichments of nova ejecta. Since the heavy element enrichment of the envelope via this mechanism does not occur until late in the evolution to the TNR and if there is no other mixing during accretion, then the envelope composition will be that of the material being transferred by the secondary. This keeps core material out of the accreted layers until the peak of the TNR and, in turn, the opacity stays low and the amount of accreted material is increased (S98).


Abundance determinations for nova ejecta have confirmed the levels of enrichment required by the theoretical studies to reproduce the dynamical features of nova outbursts and, in addition, have established that both CO and ONeMg WDs occur in nova binary systems (G98, S98). Further, the significant enhancements of heavy elements in nova ejecta, taken together with the observational determinations of the masses of nova ejecta, confirm that novae make important contributions to the abundances of some of the CNO isotopes in the Galaxy. Novae are expected to emit $\gamma$-rays and/or hard X-rays early in the
outburst, from the decays of the $\beta^+$-unstable isotopes, although such emission has yet to be detected by COMPTON (Diehl and Timmes 1998). Similarly, novae have been predicted to produce significant amounts of $^7\text{Be}$ and $^{22}\text{Na}$, although no $\gamma$-rays from their decays have been observed by COMPTON late in the outburst (Shrader et al. 1994; Iyudin et al. 1995). Finally, while the compositions of novae ejecta are predicted to be quite distinctive, to exhibit abundance variations as a function of time, and to be incorporated into grains, no unambiguous signature of nova processing has yet been identified in the pre-solar grains found in meteorites (Starrfield et al. 1997; Zinner 1998).

Because both CO and ONeMg WDs are found in nova systems, it is crucial for our understanding of the outburst to calculate evolutionary sequences for consistent choices of WD mass, envelope mass, and composition (CO or ONeMg) that can be compared directly to data for individual nova systems. We have, therefore, evolved models designed to fit the observed properties of the ONeMg nova V1974 Cyg (S98). These simulations predicted sufficient $^{22}\text{Na}$ production by this nova so that its $\gamma$-ray emission should have been detected by COMPTON - but it wasn't detected (Shrader et al. 1994). Another discrepancy was the comparison of the abundance predictions with observations, suggesting that our simulations were over-producing nuclei in the mass region past magnesium. The source of these discrepancies appears to be that we used the post carbon burning abundances of Arnett & Truran (1969) for the core abundances. In contrast, the recent study of carbon burning nucleosynthesis by Ritossa et al. (1996) predicts lower abundances for Mg and Si. If their distribution is implemented, however, we expect a lower level of $^{26}\text{Al}$ production from novae (José and Hernans 1998). Improved rate data for nuclei in the vicinity of silicon and sulfur are now becoming available (Iliadis et al. 1998, preprint) and new calculations will improve predictions of the amount of intermediate mass elements in nova ejecta.

We have also recently calculated improved evolutionary sequences for CO WDs. These novae are known to produce the largest amounts of dust (Starrfield et al. 1997; G98). One important motivation for this study is that the isotopic abundance patterns predicted for CO nova ejecta show similarities to some of those found in pre-solar SiC grains in meteorites (Anders & Zinner 1993; Zinner 1998). Laboratory studies of these grains are providing new information and significant constraints on stellar evolution, convective mixing, and Galactic chemical evolution (Zinner 1998). Although most of these grains were probably formed in supernovae and AGB stars, there exists a subgroup which may carry a nova signature (Anders & Zinner 1993). In support of the suggestion of Anders & Zinner, infrared observations (G98) have confirmed the formation of interesting grains (graphite, SiC, hydrocarbons, and silicates) in nova ejecta. However, the compositions determined for the ejected shells of novae from optical and UV studies typically show O/C > 1 (G98; S98). Since grains of carbon, SiC, and hydrocarbons were identified early in the outburst and oxygen-rich silicate grains later in the outburst for both QV Vul and V705 Cas (G98), it implies that distinct regions with O/C > 1 and O/C < 1 can occur in the ejecta of the same nova.

7. Further Work

In view of the purpose of this meeting, to honor Brian Warner and his contributions to Cataclysmic Variables, we end this review not with a summary of what has been learned about the nova outburst but, rather, what needs to be learned for a better understanding of novae and their contributions to astrophysics. We are working on these problems and hope to report significant progress at Brian's 70th birthday party.

- We do not know how, or when, core material is mixed into the accreted envelope (convective dredge-up and diffusion are two likely candidates), nor do we understand how the outward mixing of radioactive species influences the dynamics of the nova explosion. We, therefore, feel that it is necessary to carry out more multidimensional hydrodynamic simulations of convection plus nuclear burning near the peak of the TNR.
The nova outburst ejects core material from a WD into space, where it can be studied and analyzed. We feel that much is to be learned by further analyses of both the early, optically thick spectra and the later emission line spectra of novae. These data will provide compositions, ejected masses, and the energetics of the ejecta.

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