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WHAT DETERMINES THE SPEED CLASS OF NOVAE?

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ABSTRACT

Recent theoretical hydrodynamic models show that novae of different speed classes can be obtained by varying the CNO enrichment and envelope mass. Recent observations seem to indicate that various degrees of CNO enrichment are found in the ejected shells of slow novae. We propose a unified picture for novae of different speed classes as a combination of CNO enrichment and envelope mass. Several consequences of our scheme are discussed. The observational and theoretical results are explained in the context of our unified picture.

Subject headings: stars: abundances — stars: interiors — stars: novae

I. INTRODUCTION

The presently widely accepted nova model is that of a white dwarf (WD) accreting hydrogen-rich material from a binary companion overflowing its Roche lobe. A thermonuclear runaway (TNR) occurs in the degenerate accreted envelope, leading to mass ejection and a very fast rise in luminosity as observed in classical novae. A recent theoretical and observational review of this subject has been published by Gallagher and Starrfield (1978).

The instability against TNR of a hydrogen-rich envelope on top of a cold WD has been demonstrated by Giannone and Weigert (1967), Rose (1968), Sparks (1969), and Rose and Smith (1972). Starrfield, Sparks, and Truran (1974) (hereafter SST 1974) included in the hydrodynamic calculations a detailed nuclear reactions scheme. SST (1974) assumed an envelope mass of $\sim 10^{-3}\ M_\odot$ and found that the only way to produce a fast nova was to assume *a priori* a high CNO abundance in the envelope. An initial parametric study on the effect of CNO enrichment on the class of the nova was carried out by SST (1974).

Many observational studies have indicated that nova ejecta are enriched with one or more CNO elements to various degrees (up to a factor of 100 over solar values has been claimed!). Pottasch (1959) found for five novae, on average, C had solar abundance, N was 45 times solar, and O had 5 times the solar value. (See Sparks, Starrfield, and Truran 1978) for a representative sample of more recent results, which generally confirm the above values, though Robbins and Sanyal 1978 found solar O values in HR Del.) These results gave rise to a general belief that nova speed class should be correlated with CNO enrichment (Sparks, Starrfield, and Truran 1978 [hereafter SST 1978]; Ferland and Shields 1978; Williams and Gallagher 1979). Despite the number of observers claiming CNO enhancements, two critical points must be remembered:

1) Most observers report enhancement measurements on only one or two (usually N and O) of the CNO nuclei. This is not at all sufficient to determine an initial CNO enrichment above the solar value. CNO material processed through the equilibrium CNO cycle should have a high abundance of N at the expense of C and O. As an example, the $Z = 0.03$ slow nova model of Prialnik, Shara, and Shaviv (1978) yielded a very large nitrogen enhancement ($N/N_\odot = 18$) and a moderate oxygen enhancement ($O/O_\odot = 1.8$) *by depleting the initial carbon down to* $C/C_\odot = 0.3$. *Only observations of all three nuclei seen simultaneously enhanced can be taken as serious evidence for* CNO *enhancements.*

We also mention the insensitivity of nova models with low or moderate Z ($\lesssim 0.10$) to enhanced helium abundances (at the expense of hydrogen). During a thermonuclear runaway, peak envelope temperatures reach $2\text{–}3 \times 10^8$ K before expansion and cooling starts. This is not enough to initiate He burning. The CNO cycle reactions saturate CNO nuclei with protons on a time scale short compared to the envelope expansion time scale. Because the nova runaway is controlled by the CNO cycle β-decays, a He overabundance by a factor of 2 or even 3 (relative to the Sun) has essentially no effect on the nova evolution. Though the He shows up in the nova spectrum, it has taken a "free ride" at the expense of the hydrogen.

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2) Most observations of nova spectra are taken in the bright nebular stage. As Williams *et al.* (1978), Collin-Souffrin (1977) and others have recently pointed out, these spectra are a mixture of the stellar remnant, accretion disk, and ejection shell. Severe inhomogeneities in the ejecta and confusion of emission from the different system members make interpretation of the nebular spectra very difficult. The very large differences in abundances claimed by different observers for a given element in a given nova make most of the abundance determinations suspect. Even more suspect are the grossly simplifying assumptions made by most observers in reducing their spectra (details are given by Collin-Souffrin 1977).

Only in the last year have spectroscopic analyses of two old nova *shells*, uncontaminated by disk or WD emission, been published. Williams *et al.* (1978) concluded that the CNO nuclei were enhanced by a factor of 10–100 in the cold shell around nova DQ Herculis 1934. However, the same type of analysis (Williams and Gallagher 1979) showed that the CNO abundances were essentially solar in the filaments of Nova RR Pictoris 1925. *Moreover, both these objects were slow novae* (Payne-Gaposhkin 1957). These abundance analyses, the most dependable to date, confuse the claimed correlation between CNO enrichment and nova speed class (SST 1978).

Prialnik, Shara, and Shaviv (1978) (hereafter PSS 1978) showed that a slow nova TNR can be obtained with solar CNO abundances and with sufficiently low envelope mass. Later Prialnik, Shara, and Shaviv (1979) (hereafter PSS 1979) showed that, by varying the envelope mass, novae of different speed classes can be obtained. Some of these results have been confirmed by SST (1978) and by Nariai, Nomoto, and Sugimoto (1979) (hereafter NNS).

As SST (1974) have emphasized, the white dwarf luminosity L_{WD} affects only the time scale τ_{TNR} leading up to a TNR. The violence of the TNR is not affected. This is because for a given envelope M_{envel} sufficient to trigger a TNR, complete degeneracy at the envelope base occurs for all $L_{\mathrm{WD}} \lesssim 10^{-1.5}\, L_{\odot}$. Decreasing L_{WD} decreases the envelope base temperature T_b and increases τ_{TNR}. *Once a TNR starts, however,* L_{WD} *and* T_b *are greatly surpassed by the envelope base luminosity and temperature. Thereafter,* L_{WD} *and* T_b *play no role in the TNR.*

We show in the next section how all these results can be understood using envelope mass M_{envel} (and hence accretion rate $\dot{m}$) and enrichment Z together as input parameters to the problem. We do not discuss in any detail the possible sources of CNO enrichment or other abundance peculiarities (high He, Ne, Fe in several novae probably present before the TNR). We note also that rotation, magnetic fields, and details of the accretion process have not been considered in most of the models we discuss below (except NNS's 1979 accretion model). Nevertheless, a remarkable range of theoretical and observational results can be understood in terms of the parameters M_{envel} and Z.

II. THE CNO ENRICHMENT–M_{envel} PLANE

The body of calculations performed by SST (1974, 1978) and later by PSS (1978, 1979) and NNS (1979) indicate that many parameters are involved in the nova problem. In the limit of low L_{WD}, the two dominant parameters which most affect the nova explosion are the CNO enrichment and M_{envel}. We delay discussion of what parameters determine M_{envel} to a later section. We assume for now that M_{envel} can vary, depending on the mass accretion rate $\dot{m}$ and the total mass M_{WD} of the WD.

a) The Variation of M_{envel} *at Constant* Z $(Z \sim Z_{\odot})$

Consider a given fixed (for the moment) M_{WD} and assume that all envelopes have

$$Z = [\mathrm{CNO}]/[\mathrm{CNO}]_{\odot} = 1\,,$$

i.e., solar CNO abundance. When M_{envel} is very low (cf. Fig. 1), no TNR occurs. The density at the envelope base is too low to ignite hydrogen via pycnonuclear reactions. If L_{WD} is low enough, so is T_b and so *p-p* chain reactions are negligible. We have a DA white dwarf with a hydrogen-rich envelope which is no different from all single WDs. We call this configuration a dud as the material present is insufficient to initiate a TNR.

As the mass of the envelope increases, so does the degeneracy at the bottom of the hydrogen-rich envelope; a mild TNR occurs without any mass ejection (Shara, Prialnik, and Shaviv 1977). The white dwarf appears as a very hot blue object radiating mostly in the far-UV. We call this an EUV (extreme UV) nova. When the mass of the envelope is further increased, the runaway becomes more violent as the density and degeneracy at the bottom of the hydrogen-rich envelope increases. This leads to a moderately fast nova, as shown by PSS (1979).

The speed class of a classical nova is observationally determined (i.e., defined) *by the rate of decline of the apparent brightness after maximum, rather than by the total nova energetics.* Because of the uncertainties in measuring M_{envel}, the total kinetic energy E_{kin} of the ejecta is somewhat uncertain. Because of the bolometric corrections, large suspected UV and IR fluxes, and uncertainties in nova distances, the total radiated flux E_{rad} is somewhat uncertain. Because of uncertainties in M_{WD} and M_{envel}, the total energy E_{pot} required to lift the envelope out of the WD potential well is also somewhat uncertain. Gallagher and Starrfield (1976) have argued that $E_{\mathrm{rad}} + E_{\mathrm{kin}}$ is approximately constant for all novae, and that speed class is determined by the maximum energy generation rate during the TNR. In fact, E_{pot} is always greater (and usually much greater) than $E_{\mathrm{rad}} + E_{\mathrm{kin}}$. Thus most ($>80\%$) of the nova's energy budget is spent on E_{pot}, and this must be one of the fundamental factors defining a nova's speed class.

PSS (1978) have shown that the "shutoff" mechanism of novae with $Z \sim Z_{\odot}$ is fuel exhaustion, i.e., expulsion of most of the hydrogen-rich envelope by means of an optically thick wind. All other things being equal, *lower mass envelopes should be ejected in less time than high mass envelopes, leading to faster novae.* Fast novae are also *observationally* characterized by higher ejection velocities, leading again to more rapid depletion of the envelope and "shutoff." When the mass of the envelope is low (for the reasons discussed below), the energy released by the TNR accelerates the envelope to higher velocites. Conversely, as M_{envel} is increased in Figure 1, we enter the domain of the slow nova. Here the envelope is too massive to suffer large accelerations. Generally speaking, as M_{envel} increases from zero to some critical number, the violence of the nova (in terms of ejecta kinetic energy) increases. Beyond that maximum the observed velocities decrease, until only a distended giant results.

During a TNR in the degenerate hydrogen-rich envelope of a WD temperatures of over 1.5×10^8 K are encountered. Thus the CNO cycle nuclear reactions become β-decay limited (SST 1974) and the energy generation rate is independent of temperature and density. For this reason, still higher envelope masses for $Z \lesssim Z_\odot$ do not produce more violent TNRs, instead, the TNR is smothered. By "smothered" we mean that no mass ejection occurs, though the WD envelope puffs up and the star becomes a luminous giant (SST 1974). If the giant swallows its WD companion, a very high luminosity by drag dissipation results. The possible fates of such objects have been discussed by Ostriker (1976), Paczyński (1976), Sparks and Stecher (1974), and Livio, Shara, and Shaviv (1979).

b) *The Variation of Z at Constant M_{envel}*

i) *Low M_{envel}*

Let us now consider what happens when the CNO abundance is raised progressively with M_{envel} held fixed. As shown qualitatively in Figure 1, low values of M_{envel} gives rise to the sequence dud-EUV-fast-super-moderate-EUV-dud. Progressive enrichment with CNO favors the TNR speed and violence. When the number of CNO nuclei equals that of the number of protons ($\tilde{Z} = \tilde{Z}_c$, where $\tilde{Z} =$ stellar CNO abundance/solar CNO abundance), the TNR speed is maximized. Up to $\sim 5 \times 10^{17}$ ergs g^{-1} can be released in seconds. This is energy enough to eject matter at $\sim 7 \times 10^8$ cm s^{-1} from a WD. If only the deepest envelope layers are so enriched, and the rest of the envelope has $Z \sim 2Z_\odot$ (Starrfield, Truran, and Sparks 1975), a "super" nova is produced. Ejection velocities of 10^{10} cm s^{-1} are attained. Hence the region $Z \sim 0.9$ gives rise to very fast novae. Somewhat lower values of Z give rise to even more energetic novae as two or more protons can be captured sequentially by a CNO nucleus. The TNR then proceeds for a longer period of time but releases more energy. The only precondition for this to happen is a sufficiently large M_{envel} to avoid a dud. For $\tilde{Z} > \tilde{Z}_c$, progressively larger M_{envel} are required to speed up the *p-p* chain and ignite the CNO reactions.

Increasing $\tilde{Z}$ beyond $\tilde{Z}_c$ leads to a hydrogen-poor envelope. It is progressively harder to get a fast nova as $\tilde{Z}$ is increased, and at the extreme right-hand side of Figure 1 only duds exist.

ii) *Higher M_{envel}*

Higher values of M_{envel} yield the sequence giant-slow-moderate-fast-"super"-fast-moderate-giant-dud. The existence of a giant in the top (left, right) (low, high $\tilde{Z}$, large M_{envel}) of Figure 1 is again due to the nature of the CNO reactions. At low $\tilde{Z}$, energy generation in a massive envelope is insufficient (without CNO catalysts) to eject mass (SST 1974). The giant evolves on the *nuclear* time scale of the puffed-up envelope.

At high $\tilde{Z}$ ($\tilde{Z} \rightarrow 50$ is the same as $Z = 1$, a pure C/O WD) all the hydrogen initially present burns during the TNR, puffing up the envelope. The envelope cools on a *thermal* time scale back to a WD configuration.

c) *Speed Class and $\tilde{Z}$*

Assume for the moment that the probability of finding a WD with M_{envel} in the range $[M_{\text{envel}}, M_{\text{envel}} + dM_{\text{envel}}]$ and with a CNO abundance in the range $[\tilde{Z}, \tilde{Z} + d\tilde{Z}]$ does not depend on M_{envel} and $\tilde{Z}$. Then the probability of finding a nova of given speed class with $\tilde{Z}$ in the range $[\tilde{Z}, \tilde{Z} + d\tilde{Z}]$ depends only on the appropriate relative area (for the given speed class) in the $(M_{\text{envel}}, \tilde{Z})$-plane of Figure 1. For example, fast novae can appear in the areas bounded by ABCDE (area 1) or FGHI (area 2) in Figure 1. Consider the range $[\tilde{Z}, \tilde{Z} + d\tilde{Z}]$ which may fall in either area 1 or area 2. The probability of finding a fast nova with $\tilde{Z}$ in the range $[\tilde{Z}, \tilde{Z} + d\tilde{Z}]$ is the area in Figure 1 bounded by $[\tilde{Z}, \tilde{Z} + d\tilde{Z}]$ and either area 1 or area 2, divided by the sum of areas 1 and 2. We predict, therefore, that most but not all fast novae have high $\tilde{Z}$. *A wide range in $\tilde{Z}$ should be observed for fast novae.* Similarly, slow novae should have a very wide range of $\tilde{Z}$, in agreement with the observations of Williams *et al.* (1978) and Williams and Gallagher (1979).

In fact, the calculation is somewhat more complicated. Since novae are apparently a recurrent phenomenon (Ford 1978), we must take into account, in the probability of discovery of a given nova, the recurrence rate which is not well known. The discovery probability must be divided by the period of recurrence. An exact calculation of this type cannot at present be carried out. However, this correction will probably strengthen the previous conclusion.

Figure 1 summarizes all the arguments given above. Simulation results are plotted beside the authors' initials. The figure assumed a given M_{WD} and a given (low) L_{WD}. In fact the calculations (Table 1) have been done for a range of M_{WD}. For every M_{WD} $(0.8 \lesssim M_{\text{WD}} \lesssim 1.4\ M_\odot)$ a similar figure exists. The boundaries of the regions in Figure 1 shift somewhat as

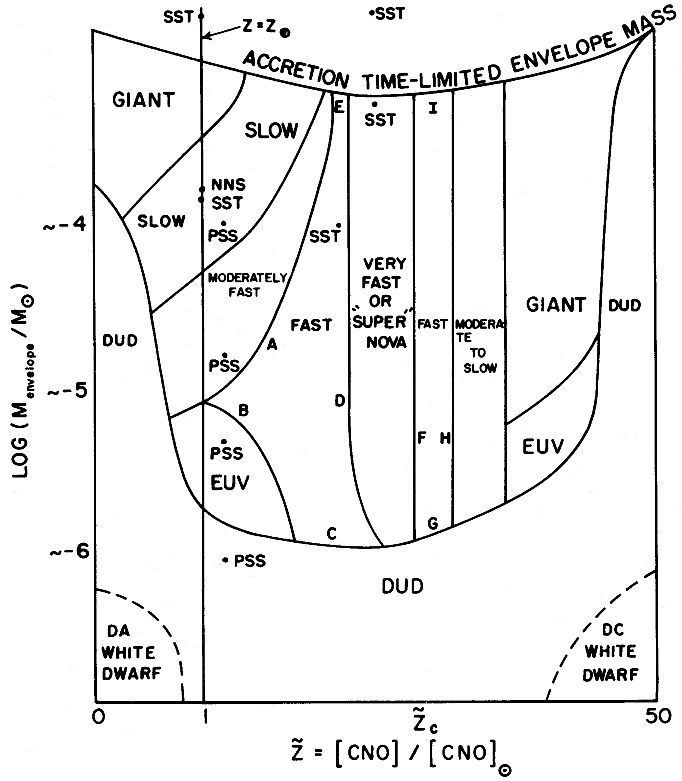

FIG. 1.—A semiquantitative sketch of the (envelope mass, CNO abundance)-plane for a hydrogen envelope on a white dwarf, and the resulting type of nova. The initialed points are the results of detailed numerical simulations, covering the range $0.8 \lesssim M_{\rm WD}/M_\odot \lesssim 1.30$. The white dwarf mass, however, has been taken constant in the figure for simplicity's sake. The white dwarf luminosity $L_{\rm WD}$ is also assumed constant and low. A similar figure exists for all $M_{\rm WD}$. As $M_{\rm WD}$ increases, all the regions in the figure move downward.

$M_{\rm WD}$ changes. In particular, as $M_{\rm WD}$ increases, all the regions in Figure 1 move downwards; qualitatively the figure is unchanged.

d) *The Parameters' Effects*

The luminosity $L_{\rm WD}$ of the accreting WD is an important parameter for the final outcome. When the luminosity is very high, no violent TNR occurs (Paczyński and Żytkow 1979; Sion, Acierno, and Tomczyk 1979). As we have already mentioned, $L_{\rm WD}$ also controls $\tau_{\rm TNR}$.

Once the mass of the WD core and its luminosity are fixed, the value of $M_{\rm envel}$ depends on $\dot{m}$ only. There is a limit to $M_{\rm envel}$ for two reasons:

1. The rate $\dot{m}$ can increase only to the point where the accretion luminosity reaches the Eddington limit. At this point further continuous accretion is prevented by the outgoing radiation.
2. The TNR rise time decreases with increasing $M_{\rm envel}$, and hence at a certain $M_{\rm envel}$ the time scale for the TNR will be much shorter than the time scale for accretion, leading to a limit for $M_{\rm envel}$.

TABLE 1

MODELS OF LOW-*Z* HYDROGEN-RICH ENVELOPES ON WHITE DWARFS AND RESULTING EVOLUTION

$M_{\rm env}$ ($M_\odot$)	$M_{\rm WD}$ ($M_\odot$)	*Z*	Author[a]	Result
1.00×10^{-5}..............	1.25	0.03	PSS (1979)	Fast nova
1.25×10^{-4}..............	1.25	0.02	SST (1978)	Slow nova
1.63×10^{-4}..............	1.30	0.02	NNS (1979)	Slow nova
2.5×10^{-5}...............	0.80	0.03	SPS (1977)	No thermonuclear runaway
3.5×10^{-5}...............	0.80	0.03	SPS (1977)	Hot UV white dwarf; no mass ejection
1.0×10^{-4}...............	0.80	0.03	PSS (1978)	Slow nova
1.4×10^{-3}...............	1.00	0.03	SST (1974)	Blue supergiant (smothered runaway)

[a] PSS (1979), Prialnik *et al.* 1979. SST (1978), Sparks *et al.* 1978. NNS (1979), Nariai *et al.* 1979. SPS (1977), Shara *et al.* 1977. PSS (1978), Prialnik *et al.* 1978. SST (1974), Starrfield *et al.* 1974.

It is highly probable that the amount of CNO enrichment depends on $\dot{m}$ and the mode of accretion (via a wind with low angular momentum or through a disk with high angular momentum). This implies that only certain combinations M_{envel}–$\tilde{Z}$ are possible for a given configuration. This means that for a given case we will have allowed and forbidden regions in the $(M_{\text{envel}}, \tilde{Z})$-plane. An (energy output, $\tilde{Z}$)-correlation could result.

e) Discussion

The general picture developed here draws from, and brings coherence to, the many results obtained by SST, PSS, and NNS. We give in Table 1 a summary of some numerical results obtained by the various authors. The table includes only hydrodynamic calculations. For this reason the recent results of Paczyński and Żytkow (1978) are not included. Furthermore, Paczyński and Żytkow assumed an initial luminosity of $L = 1\,L_{\odot}$ while all other authors started with much lower values of L. Finally, SST (1974) have shown that models which neglect accretion (as do most of the models cited above) are realistic if they have an initial luminosity below $10^{-3}\,L_{\odot}$.

We did not discuss the source of CNO enrichment. This point is still unsolved. Obviously the value of $\tilde{Z}$ drastically affects the details of the TNR. For $\tilde{Z} \sim 1$ the major mechanism of mass loss is the stellar wind à la Bath and Shaviv (1976). When $\tilde{Z} \sim 10$, the mass loss is more complicated. A strong shock is formed at first, then large amounts of β-unstable nuclei are dumped into the extended envelope. Finally, a strong stellar wind cleans the WD surface almost completely of hydrogen-rich material. The transition from one type of explosion to another is a continuous one unless $\tilde{Z}$ or M_{envel} do not vary continuously (which does not seem to be the case). Hence the nova speed classes are a continuous sequence.

Colvin *et al.* (1977) tried to explain the CNO enhancement in novae as a result of mixing in the convective envelope. The results they report were obtained by stretching all parameters in the desired direction. In spite of the favorable conditions the mixing of CNO elements into the envelope is very small. The calculations of the mixing length theory, opacity, and equation of state in the envelopes of WDs involve many physical approximations which are not sufficiently well established. Large errors in the opacity of C and O, for example, can affect the size of the convective zone. Another possibility is that of shear instability mixing during accretion (Kippenhahn and Thomas 1978).

Assume that one or both of the above theories is correct and that a given mass $m \lesssim 10^{-6}\,M_{\odot}$ of the innermost part of the envelope is enriched with CNO to about 50% by mass. When this composition is diluted in a small envelope mass, the outcome will be an enriched CNO abundance in the ejecta. However, when this composition is diluted with a large envelope mass, the outcome will be a CNO abundance close to normal. This agrees well with our picture since the fast nova is obtained for low M_{envel}.

The present picture is consistent with the nova "shutoff" mechanism (envelope fuel exhaustion) mentioned earlier, as M_{envel} is small for fast novae and large for slow novae. When $\tilde{Z}$ increases, the violence of the explosion increases, and with it the velocity of ejection. This is the reason why novae with $\tilde{Z} \gg 1$ can have larger M_{envel} than novae with $\tilde{Z} \sim 1$ and still exhaust the envelope quickly.

The curves in Figure 1 are drawn only schematically. Finding the exact location of all curves in the $(M_{\text{envel}}, \tilde{Z})$-plane demands a gigantic computing effort unless a clever shortcut can be found. The results we have so far are not sufficient to delineate the curves. Nevertheless Figure 1 gives a qualitatively correct description of the dependence of nova speed class on M_{envel} and $\tilde{Z}$.

III. SUMMARY AND CONCLUSION

We can briefly summarize the main results of this paper as follows:

1. CNO enrichment $\tilde{Z}$, white dwarf mass M_{WD}, and envelope mass M_{envel} together determine the speed class of a nova.
2. $\tilde{Z}$ is determined by the accretion mechanism and convective efficiency on the WD surface.
3. M_{envel} is determined by the nature of the binary system and by the accretion rate $\dot{m}$.
4. Fast novae tend to have larger $\tilde{Z}$, larger M_{WD}, and smaller M_{envel} than slow novae, but CNO-rich slow novae and moderate CNO fast novae are permitted with certain envelope masses.
5. Our unified picture ties together well the theoretical and observational results to date.

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