CNO ABUNDANCES AND NOVA OUTBURST STRENGTHS

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ABSTRACT

Simple theories of hydrogen shell flashes on accreting white dwarfs are used to find the requisite conditions for classical novae. It is shown that enhancement of CNO abundances, relative to the Sun, is necessary for fast novae yet slow novae, such as DQ Her, can still occur with large CNO abundances. An analysis of observational data indicates that the white dwarfs in nova binaries have masses typically 1.1 $M_{\odot}$. For some old novae, the accretion rate, deduced from the accretion disk luminosity, is too high to permit a strong enough hydrogen flash to give the observed nova strength. Some possible resolutions to this paradox are suggested.

Recurrent novae are probably not thermonuclear runaways on accreting white dwarfs.

1. INTRODUCTION

It is now generally accepted that classical novae are the results of thermonuclear runaways in hydrogen-rich white dwarf envelopes accreted from a binary companion (Gallagher & Starrfield 1978 and references therein). Hydrogen shell flashes on accreting white dwarfs may be relevant to symbiotic stars (Paczynski & Zytkow 1978) and also play a role in the evolution of type I supernova progenitors. For these reasons it is of interest to know how the hydrogen-flash strength depends on the binary system properties, i.e. mass transfer rate, white dwarf mass and luminosity etc. In the following section we investigate this dependence by use of simple models of the "accretion" and "expansion" phases of the flash evolution. Particular attention is paid to the possibility that the CNO abundances in the accreted envelope are greatly enhanced relative to the Sun. Such CNO enhancements have been observed in the ejecta of a number of classical novae (Ferland & Shields 1978, Williams et al 1978, Gallagher et al 1980, Stickland et al 1981, Williams 1982) and may also be present in the accretion disk (Williams, this volume). Further it has been suggested that CNO enhancement is necessary to give fast

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novae (Starrfield, Truran & Sparks 1978).

In addition to outlining the conditions necessary for the occurrence of classical novae, our simple models can be used to interpret observational data and give a handle on white dwarf masses, accretion rates, etc. in nova systems. Brief results of such an investigation are given in the final section along with discussion as to why the kinetic energy of nova ejecta is small when compared to the binding energy and nuclear energy of the accreted envelope and whether or not recurrent novae are thermonuclear powered.

2. DEPENDENCE OF FLASH STRENGTH ON BINARY SYSTEM PROPERTIES

To survey how the hydrogen flash strength depends on the binary system properties we need to consider two stages of the flash: i) an "accretion" phase, in which the mass of hydrogen-rich envelope, M_{env}, is determined and ii) an "expansion" phase, in which the flash strength is related to white dwarf mass, M_{env}, and envelope composition.

2.1. The Accretion Phase

We consider a pure carbon white dwarf of mass M_{WD}, radius R_{WD} and luminosity, L_{WD}, accreting hydrogen-rich material at rate F. Spherical symmetry is assumed throughout.

The white dwarf envelope remains in thermal equilibrium if

$$F \frac{\mathcal{R}}{\mu} T_c << L_{WD} \tag{2.1}$$

(T_c is the white dwarf central temperature) i.e. the thermal timescale must be less than the accretion timescale (MacDonald 1980). Otherwise, gravitational energy released in the envelope increases the surface luminosity above L_{WD}. We consider first the low accretion rate regime for which condition (2.1) is satisfied.

To find M_{env}, the envelope mass at the onset of the thermonuclear runaway, the usual stellar structure equations are integrated inwards from the photosphere at $r = R_{WD}$ down to the envelope-core boundary. M_{env} is taken to be the minimum envelope mass such that the following three criteria are simultaneously satisfied:

A) The total nuclear energy production in the accreted material, L_{nuc}, is greater than L_{WD} (note L_{nuc} is not included in L in the envelope integration). Physically, this means that the white dwarf cannot radiate away the energy produced by thermonuclear reactions.

B) The thermonuclear timescale at the base of the accreted material is shorter than the timescale on which T_a, the temperature at the base of the accreted material, is changing due to accretion alone, i.e.

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$$C_P \dot{T}_a \leq \varepsilon_{nuc} \quad . \tag{2.2}$$

C) Conduction into the core is unimportant. We quantify this last condition by calculating conduction and nuclear timescales, t_{con} and t_{nuc} respectively, defined by

$$t_{con} = 2 \frac{\ell^2}{C} \tag{2.3}$$

$$t_{nuc} = \frac{C_P T}{\eta \, \varepsilon_{nuc}} \tag{2.4}$$

where 2ℓ is the thickness of the energy generation zone

$$2\ell = \frac{L_{nuc}}{4\pi R^2 \rho \, \varepsilon_{nuc}} \tag{2.5}$$

C is the conduction coefficient (evaluated for core composition)

$$C = \frac{4acT^3}{3\kappa C_P \rho^2} \tag{2.6}$$

and

$$\eta = \left.\frac{\partial \ln \varepsilon_{nuc}}{\partial \ln T}\right|_P \quad . \tag{2.7}$$

In the above all quantities are evaluated in the burning zone at the base of the accreted material. Conduction is taken to be negligible when

$$t_{con} > t_{nuc} \tag{2.8}$$

We now consider the high accretion rate regime for which condition (2.1) is severely violated. As discussed in MacDonald (1980), the accreted material attains a quasi-equilibrium with thermal energy generation rate

$$\varepsilon_{th} \simeq FT \frac{\partial S}{\partial m} \tag{2.9}$$

The structure equations are again solved but with an energy generation term given by equation (2.9). The procedure used to find M_{env} is to guess the photospheric luminosity and integrate from the surface inwards

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to the point where L = 0. (This is a justified approximation because the accretion luminosity is much greater than L_{WD}). L_{nuc} and $\dot{T}_a$ are then evaluated. A second guess for the photospheric luminosity is then used and the procedure repeated. From these two guesses we estimate a third photospheric luminosity such that criteria A and B are approximately satisfied. (Conduction into the core has not been considered for this case). We then iterate until the minimum accreted mass for which criteria A and B are simultaneously satisfied is found.

For intermediate values of F we find the accreted mass by interpolating between the low and high F results. We take

$$M_{env} = \frac{M_{LO} + x\, M_{HI}}{1 + x} \tag{2.10}$$

where M_{LO} and M_{HI} are the low and high F accreted masses and

$$x = \left(\frac{\mathcal{R} F T_c}{\mu L_{WD}}\right)^2 \tag{2.11}$$

As a test of this simple model we give in table 1 a comparison with the results of a number of detailed numerical calculations. In all cases the composition of accreted material is essentially solar. The mean error in our approximate values is 24% and, in general, our approximate value is an underestimate. We feel that this accuracy is good

Table 1. Comparison of accretion model with detailed calculations.

$M_{WD}/M_\odot$	$L_{WD}/L_\odot$	$F(M_\odot y^{-1})$	$M_{det}/M_\odot$	$M_{sim}/M_\odot$	ref.
0.456	$7\ \times10^{-4}$	10^{-13}	6.89×10^{-4}	4.00×10^{-4}	2
0.5	5.7×10^{-2}	10^{-10}	5.01×10^{-4}	4.16×10^{-4}	4
1.0	$5\ \times10^{-4}$	10^{-10}	$2\ \times10^{-4}$	1.37×10^{-4}	1
1.0	10^{-3}	10^{-13}	$2.4\ \times10^{-4}$	1.64×10^{-4}	2
1.0	10^{-3}	10^{-10}	1.38×10^{-4}	1.35×10^{-4}	4
1.0	10^{-3}	10^{-8}	5.85×10^{-5}	6.11×10^{-5}	3
1.0	$5\ \times10^{-3}$	10^{-10}	$1\ \times10^{-4}$	9.47×10^{-5}	1
1.0	9.8×10^{-2}	10^{-10}	5.25×10^{-5}	6.49×10^{-5}	4
1.0	9.8×10^{-2}	10^{-7}	3.63×10^{-5}	2.91×10^{-5}	4

Refs: 1) Taam & Faulkner 1975, 2) Taam 1977, 3) Kutter & Sparks 1979, 4) MacDonald 1979, 1980

enough for a parameter space survey. M_{env} is found to depend most sensitively on M_{WD}. This is simply because surface gravity and hence pressure gradient increase steeply with M_{WD} so that less mass has to be accreted onto higher mass white dwarfs before thermonuclear temperatures and densities are reached. In figures 1 and 2 we show how M_{env} depends on F and L_{WD} for two envelope compositions, X = 0.7, Z_{CNO} = 0.014 and X = 0.35, Z_{CNO} = 0.507 respectively. M_{WD} = 1.0 $M_\odot$ in both cases. We see that the higher mass envelopes occur for low F and low L_{WD}. In this case the onset of nuclear burning is due to the pp chains rather than the CNO cycle and hence there is only a weak dependence on composition via opacity and molecular weight. However for high L_{WD} or high F the thermonuclear runaway is initiated by the CNO cycle and a higher CNO abundance leads to a significantly smaller accreted mass.

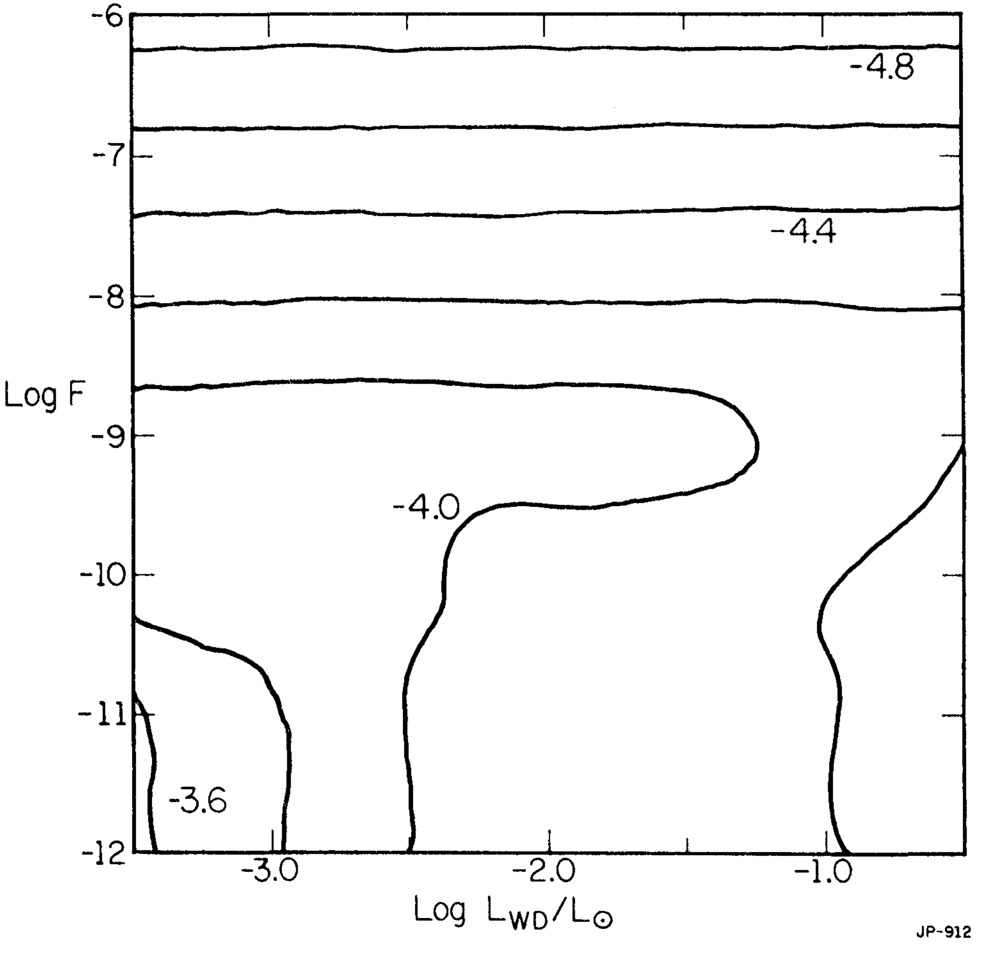

Figure 1. Contours of accreted mass in L_{WD} - F space for X = 0.7, Z_{CNO} = 0.014 and M_{WD} = 1.0 $M_\odot$. Contours are labelled with log $M_{env}/M_\odot$.

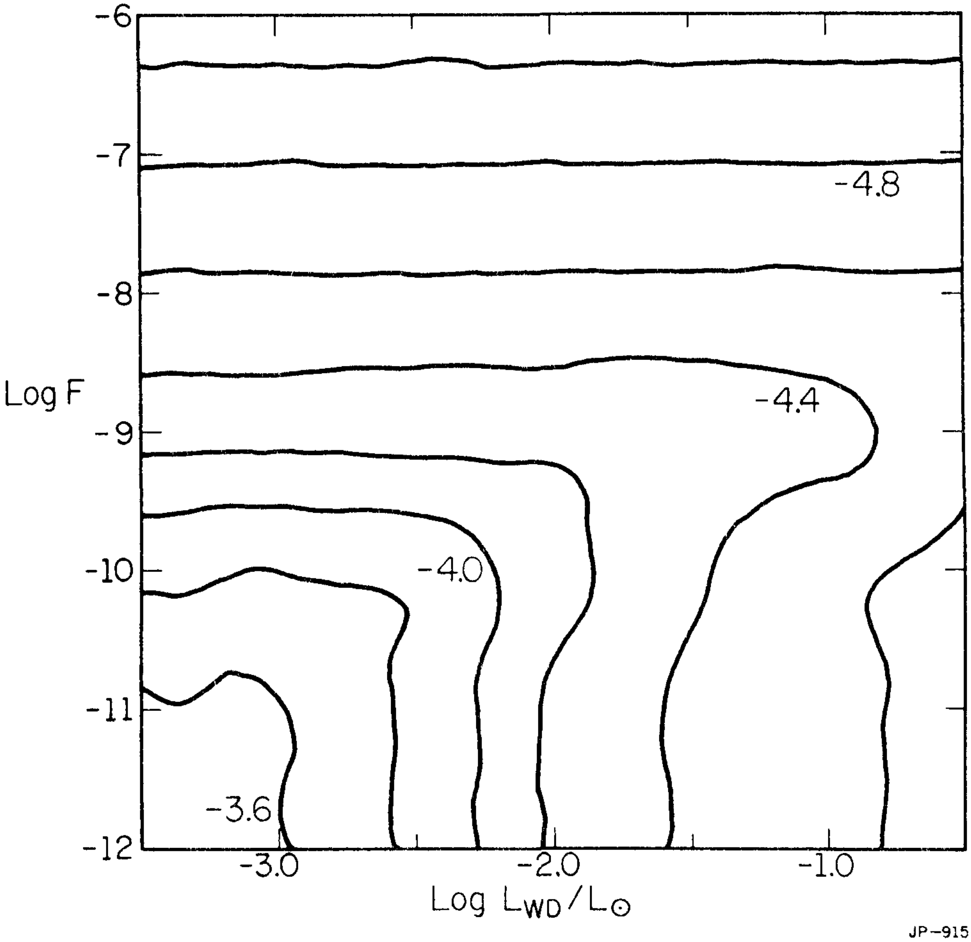

Figure 2. As figure 1, but for X = 0.35, Z_{CNO} = 0.507.

2.2. The Expansion Phase

The thermonuclear runaway proceeds to increase the shell source temperature, T_{ss}, until radiation pressure causes envelope expansion and subsequent cooling. Just after maximum T_{ss} is reached the envelope is convective throughout. Also the bulk of the envelope remains convective during the expansion towards maximum photospheric radius. The convective energy transport is efficient so we can approximate the envelope structure by an adiabat. In this phase only radiation and gas pressure are important. This allows us to find the envelope structure analytically in terms of β, the ratio of gas pressure to total pressure:

$$P = P_o \frac{(1-\beta)^{5/3}}{\beta^{8/3}} \exp(32/3\beta) \tag{2.12}$$

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$$\rho = \rho_o \frac{1-\beta}{\beta} \exp(8/\beta) \tag{2.13}$$

$$T = T_o \left(\frac{1-\beta}{\beta}\right)^{2/3} \exp(8/3\beta) \tag{2.14}$$

where $$P_o = \frac{\mathcal{R}}{\mu} \rho_o T_o = \frac{1}{3} a T_o^4 . \tag{2.15}$$

Further, at maximum T_{ss} and for some time after, the envelope is in hydrostatic equilibrium. If we take P = 0 at r = R, solving the hydrostatic support equation gives

$$r = \frac{R}{1 + q\, I(\beta)} \tag{2.16}$$

where $$I(\beta) = \frac{(1-\beta)^{2/3}}{\beta^{5/3}} \frac{8-3\beta}{2} \exp(8/3\beta) \tag{2.17}$$

and $$q = \frac{\mathcal{R} T_o}{\mu} \frac{R}{GM_{WD}} \tag{2.18}$$

The mass of the accreted envelope is then given by

$$M_{env}/M_s = q^4 \int_{\beta_{in}}^{1} \frac{J(\beta)}{[1+qI(\beta)]^4} d\beta \tag{2.19}$$

where $$M_s = 4\pi \left(\frac{\mu}{\mathcal{R}}\right)^4 \frac{a}{3} (GM_{WD})^3 \tag{2.20}$$

$$J(\beta) = \frac{\beta-1}{\beta} I'(\beta) \exp(8/\beta) \tag{2.21}$$

and β_{in} is the value of β at the base of the accreted envelope. β_{in} is found from

$$R = R_{WD} [1 + q\, I(\beta_{in})] \tag{2.22}$$

For a given value of R, the envelope structure is now completely known. The envelope evolution is then determined from the energy conservation equation,

$$\frac{d(U+V)}{dt} = L_{nuc} - L_* \tag{2.23}$$

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where U and V, the internal and gravitational energies of the accreted envelope respectively, are given by integrals over the envelope. L_{nuc} is the total nuclear energy generation in the envelope and L_* is the energy radiated at the photosphere,

$$L_* = L_{ed}\,(1-\beta_p)\,\frac{(32-24\beta_p)}{(32-24\beta_p-3\beta_p^2)} \tag{2.24}$$

where L_{ed} is the Eddington luminosity and β_p is the value of β at the photosphere, taken to be at optical depth $\tau = 2/3$. Electron scattering is the dominant opacity source and hence

$$L_{ed} = \frac{4\pi cGM_{WD}}{\kappa_{es}} = \frac{6.5 \times 10^4}{1+X}\,\frac{M_{WD}}{M_\odot}\,L_\odot \tag{2.25}$$

For given M_{WD}, M_{env} and envelope composition, we find the early evolution of the nova by integrating equation (2.23) from the time of maximum T_{ss} until either i) the expansion velocity, $v_{exp} = \dot{R}$, exceeds the escape velocity, v_{esc}, so that some mass is ejected or ii) $v_{exp} < 0$ i.e. the envelope has reached an equilibrium radius without any ejection of matter.

We quantify the strength of the nova outburst by the value of v_{exp} when escape velocity is reached. For M_{WD} close to the Chandrasekhar limit, M_{ch}, we also allow for the change in X and μ due to nuclear conversion of H into He.

Fujimoto (1982) has shown that, for solar CNO abundances, the flash strength depends mainly on the "proper" pressure in the shell source.

$$P_* = \frac{GM_{WD}}{4\pi R_{WD}^4}\,M_{env} \tag{2.26}$$

The present calculations are in exact agreement with this conclusion. We find, as did Fujimoto, that $P_* \gtrsim 10^{20}$ dynes cm^{-2} is required for ejection with solar CNO abundances. With Z = 0.51, the critical value of P_* is reduced to $\sim 2 \times 10^{19}$ dynes cm^{-2}, indicating that substantially smaller envelope masses are sufficient for nova outbursts to occur, when the CNO nuclei are enhanced.

Figures 3 and 4 are contour diagrams of v_{exp} at the time when $v_{exp} = v_{esc}$ for the two compositions considered above. Also shown are the regions of (M_{WD}-M_{env}) space which our simple accretion model predict to be realisable. We see that no ejection of material is possible for solar CNO unless $M_{WD} \gtrsim 1.1\ M_\odot$ and the ejection velocity will be low ($\lesssim$ 250 km s^{-1}) even for optimal conditions. For $Z_{CNO} = 0.51$ ejection occurs if $M_{WD} \gtrsim 0.8\ M_\odot$. Further the highest ejection velocity, $\sim$ 1600 km s^{-1}, is comparable to the principal absorption velocities observed in the fastest known nova, V1500 Cyg (Duerbeck & Wolf 1977). This clearly shows that strongly enhanced CNO abundances are necessary for fast novae. However slow novae such as DQ Her can also occur with CNO greatly enhanced if the envelope mass is sufficiently small.

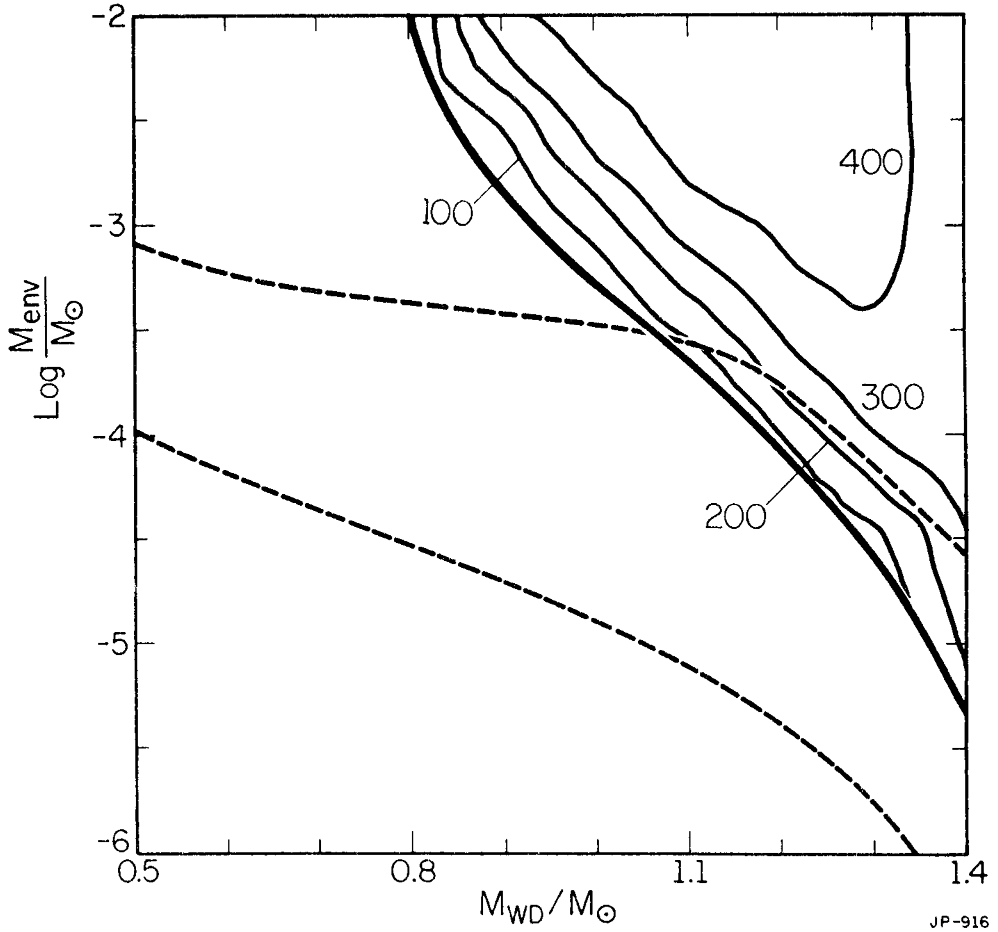

Figure 3. Contours of expansion velocity, v_{exp}, when it equals escape velocity in M_{WD}-M_{env} space for X = 0.7, Z_{CNO} = 0.014. Contours are labelled with v_{exp} in km s^{-1}. Also shown (dashed lines) is the domain of M_{WD}-M_{env} space accessible by accreting white dwarfs.

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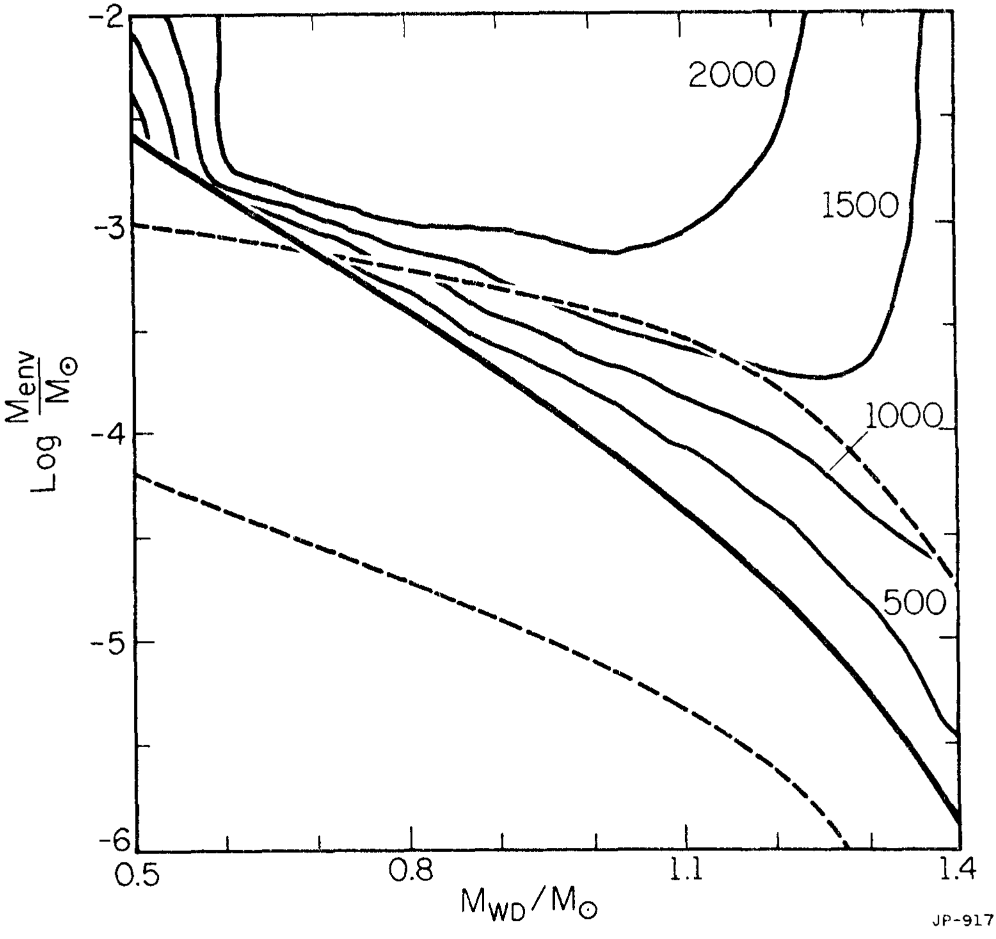

Figure 4. As figure 3, but for X = 0.35, Z_{CNO} = 0.507.

3. DISCUSSION AND CONCLUSIONS

In table 2 we have collected together abundance estimates for the ejecta of a number of recent novae and translated them into mass fractions. Also given are decline time, t_3, principal absorption velocity, v_{princ}, and ejecta mass estimate, M_{ej}, adjusted to the given distance, D. The most uncertain of these quantities are the ejecta masses which are usually determined from emission line strengths with the assumption of a uniform nebula. Clumping in the ejecta will lead to an overestimate of M_{ej}. Conversely only the mass of ionized hydrogen is measured and M_{ej} may be underestimated if neutral hydrogen is present. Taking this data at face value we can, in principle, find the masses of the white dwarfs on which these particular novae occurred. We need to make one further assumption: that all the material above the shell source is ejected so that $M_{env} = M_{ej}$. Starrfield (1979) has considered the timescale on which novae turnoff and concluded that the bulk of the envelope must be ejected by some means on a timescale short compared to the nu-

Table 2. Abundances and ejecta masses.

Object	D(kpc)	t_3(d)	v_{princ}(kms^{-1})	$M_{ej}/M_\odot$	X	Y	Z_{CNO}	ref.
V1500 Cyg 1975	1.6	4	1600	$3x10^{-4}$	0.49	0.21	0.28	1,2
CP Lac 1936	1.3	10	1300	$3x10^{-5}$	0.60	0.26	0.13	3,4
V1668 Cyg 1978	3.9	24	740	$2x10^{-4}$	0.47	0.22	0.31	5
IV Cep 1971	3.6	42	1000	$8x10^{-5}$	0.40	0.21	0.39	4,6
DQ Her 1934	0.42	100	310	$5x10^{-5}$	0.30	0.17	0.53	7
RR Pic 1925	0.48	150	300	$3x10^{-4}$	0.49	0.45	0.04	8
HR Del 1967	0.86	220	350	$1x10^{-4}$	0.43	0.47	0.073	9

Refs: 1) Ferland 1978, 2) Ferland & Shields 1978, 3) Pottasch 1959, 4) Ferland 1979, 5) Stickland et al 1981, 6) Pacheco 1977, 7) Williams et al 1978, 8) Williams & Gallagher 1979, 9) Tylenda 1979 clear burning timescale in order to give the observed rapid decline in visual luminosity. Thus the assumption of $M_{ej} \approx M_{env}$ appears justified at the present time. We then find that the white dwarfs in classical novae have mean mass, $\overline{M}_{WD} = 1.10 \pm 0.08\ M_{\odot}$.

DQ Her, a slow nova with a very high CNO abundance (Williams et al 1978) has always been a problematic object for thermonuclear runaway theories of novae. We see, however, that a low accreted mass consistent with the observed ejecta mass can give a slow nova outburst even when the CNO abundances is as high as it is in DQ Her. We suggest that the differences in rates of light curve development for DQ Her and V1500 Cyg are primarily due to differences in accreted mass rather than a difference in white dwarf mass, as had been suggested by Truran (1982).

In figure 5 we show the relationship between speed class, CNO abundance and envelope mass. $M_{WD} = 1.1\ M_{\odot}$ has been adopted. $v_{princ} = 500$ km s^{-1} and $v_{princ} = 1000$ km s^{-1} have been taken to be the dividing lines

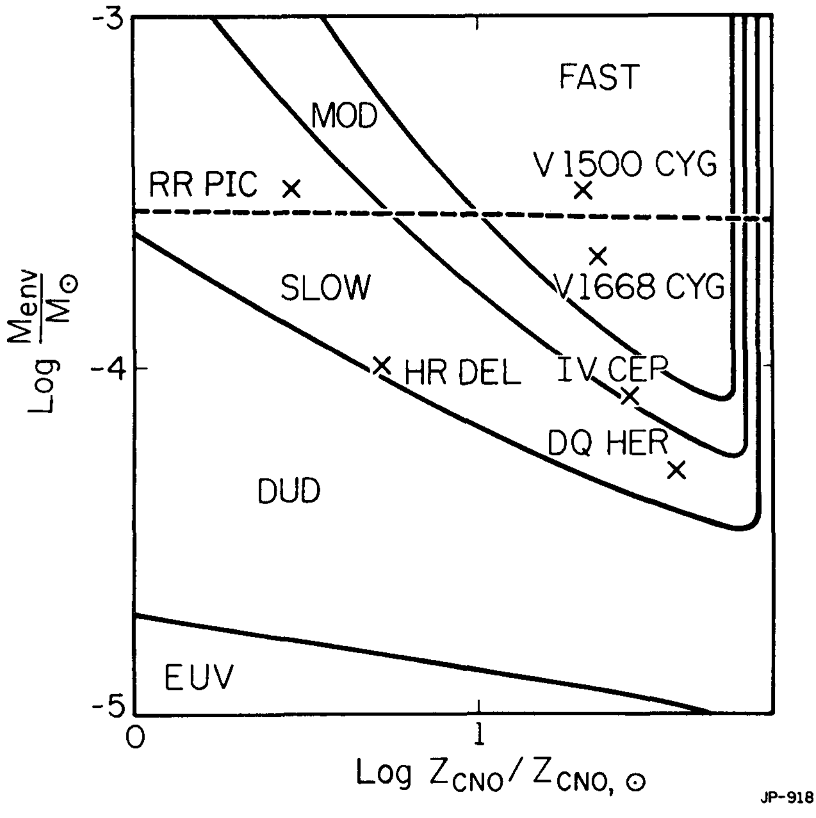

Figure 5. Nova speed class against CNO abundance and envelope mass. $M_{WD} = 1.1\ M_{\odot}$ has been assumed. The crosses mark the positions of classical novae. Also shown is the maximum envelope mass that can be accreted by a 1.1 $M_{\odot}$ white dwarf before thermonuclear runaway. See text for definition of speed classes.

between slow, moderate and fast novae. Duds are defined to be objects that do not give ejection. EUV objects are a subset of the duds which expand only slightly but brighten to near Eddington luminosity so that the bulk of their radiation is emitted in the EUV. Both novae and duds will also pass through an EUV stage as their photospheres shrink due to mass loss or consumption of nuclear fuel.

Our expansion model also gives a clue to why the deduced kinetic energy of the ejecta (see table 2) is so small when compared to the binding and nuclear energies of the accreted envelope. There are two timescales of interest: t_{nuc}, the time for the total nuclear luminosity to decrease from its maximum value to e^{-1} its maximum value and t_{therm} the timescale on which nuclear energy is being used to unbind the accreted envelope. More exactly,

$$t_{therm} = \frac{|E_{bin}|}{L_{nuc}} \tag{3.1}$$

where E_{bin} is the binding energy of the accreted envelope at the time of maximum L_{nuc}. If $t_{nuc} \gg t_{therm}$ the envelope would become unbound before L_{nuc} decreased significantly and a large amount of kinetic energy would be generated. If $t_{nuc} \ll t_{therm}$ L_{nuc} decreases too rapidly to unbind the envelope and no ejection occurs. From our expansion model we find, in general, $t_{nuc} \sim t_{therm}$ and hence a small kinetic energy results. $t_{nuc} \sim t_{therm}$ because it is the envelope expansion, which occurs on timescale $\sim t_{therm}$, that shuts off the nuclear burning.

We now put together the results of the accretion and expansion phase models to relate the conditions under which the hydrogen flash gives envelope ejection to the properties of the binary system. We find that, for given M_{WD} and composition, critical values of F and L_{WD} can be defined, F_c and L_c say, such that if $F \leq F_c$ and $L_{WD} \lesssim L_c$ then envelope ejection occurs and results in a nova. Simple analytic fits to F_c and L_c as functions of M_{WD} are

$$\log F_c = -8.775 - 15.088 \left(\frac{M_{WD}}{M_\odot} - 1.459\right)^2 \tag{3.2}$$

$$\log L_c = -0.629 - 5.923 \left(\frac{M_{WD}}{M_\odot} - 1.766\right)^2 \tag{3.3}$$

for Z = 0.02 and

$$\log F_c = -8.632 - 4.596 \left(\frac{M_{WD}}{M_\odot} - 1.334\right)^2 \tag{3.4}$$

$$\log L_c = -1.375 - 7.027 \left(\frac{M_{WD}}{M_\odot} - 1.308\right)^2 \tag{3.5}$$

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for $Z = 0.51$.

Similar results can be derived for each nova speed class. We content ourselves with discussion of some of the better observed novae. The most energetic classical nova observed to date is V1500 Cygni which has $v_{princ} \approx 1600$ km s^{-1} and $t_3 = 4$ days. For the ejecta mass and composition given in table 2, we find $M_{WD} = 1.04\ M_\odot$ is required. The large ejecta mass, $M_{ej} \approx 3 \times 10^{-4}\ M_\odot$, can be accreted if the accretion rate is low, $F \lesssim 10^{-11}\ M_\odot\ y^{-1}$ and the underlying white dwarf was initially cool, $L_{WD} \lesssim 10^{-3}\ L_\odot$. The absolute visual magnitude of the accretion disk can then be estimated to be $M_V \approx 9.8$ which, for distance 1.6 kpc and E(B-V) = 0.5 (Ferland 1977), corresponds to apparent magnitude $m_V \approx 22.3$. This is consistent with V1500 Cygni being too faint to appear on the Palomar Sky Survey (Beardsley et al 1975).

In quiescence, DQ Her has $m_V = 14.6$ which corresponds to $M_V = 6.1$ for distance 420 pc and 0.38 magnitudes of reddening (Ferland 1980). For our mass estimate, $M_{WD} = 1.10\ M_\odot$, we find $F \approx 8 \times 10^{-10}\ M_\odot\ y^{-1}$ from the accretion disk luminosity, in close agreement with $F = 1.1 \times 10^{-9}\ M_\odot\ y^{-1}$ found from analysis of period changes (Nelson 1976). The luminosity is then $L_{WD} \lesssim 5 \times 10^{-3}\ L_\odot$. We concluded earlier that V1500 Cygni and DQ Her essentially differed only in accreted mass. We now see that this difference is probably mainly due to a two orders of magnitude difference in accretion rate.

For a number of novae, including RR Pic, CP Lac and probably V603 Aql, we find that the accretion rates deduced from visual light in quiescence are too high, typically $\sim 10^{-8}\ M_\odot\ y^{-1}$, for the estimated ejecta mass to be accreted. It has also been pointed out that the soft X-ray emission from classical novae is 2 to 4 orders of magnitude less than predicted by boundary layer theory (Ferland et al 1982). One possible resolution to both these problems is that part of the optical luminosity is due to reprocessing by the accretion disk of UV radiation from a white dwarf that is still hot from the outburst. Alternatively the accretion rate deduced from the optical flux is correct but the secondary is in a perturbed thermal state due to the recent nova outburst and is presently transferring matter at a rate much greater than in equilibrium.

Similarities in the spectra and light curves of classical and recurrent novae have naturally led to the suggestion that recurrent novae are also thermonuclear runaways on white dwarfs. The smallest accretion times occur for white dwarf masses close to the Chandrasekhar limit, $M_{ch} = 1.454\ M_\odot$ in our model. For these high masses conversion of hydrogen to helium must be taken into account. When this is included in our expansion model we find the shortest accretion times for models that give ejection are 400 yr for $Z = 0.51$ and 450 yr for $Z = 0.02$ and occur for accretion onto 1.44 and 1.45 $M_\odot$ white dwarfs respectively. In each case the change in hydrogen mass fraction is $\Delta X \approx 0.3 - 0.4$. These minimum accretion times are much greater than the interval, typically ~ 35y, between recurrent nova outbursts. We conclude that recurrent novae are not thermonuclear runaways on accreting white dwarfs.

In addition to this theoretical argument against a thermonuclear runaway model for recurrent novae there are a number of observations which seem to rule out a thermonuclear model. The large mass estimate for the blue component of T CrB (Paczynski 1965) is inconsistent with it being a white dwarf but is consistent with the accretion model proposed by Webbink (1976). Also the luminosity of the unusual recurrent nova, WZ Sge, at maximum is much less than the Eddington limit (Fabian et al 1980) in contrast to the classical novae which always attain or exceed the Eddington limit, in agreement with the thermonuclear models. Abundance analyses of recurrent nova ejecta indicate essentially solar abundances and no significant CNO enhancement (Williams et al 1981, Williams 1982). One of these novae is U Sco which has the fastest decline rate of all novae (Payne-Gaposchkin 1957) and a very high ejection velocity $v_{ej} \sim 5000$ km s^{-1} (Barlow et al 1981). If U Sco were a thermonuclear runaway it should have a large CNO enhancement. Further the ejecta mass estimate for U Sco (Williams et al 1981) is roughly 3 orders of magnitude less than is typical of classical novae.

We have shown how the energetics of nova outbursts depend on white dwarf mass, accreted envelope mass and envelope composition. In particular, it has been shown that enhancement of CNO is necessary for fast novae. The source of this enhancement is still unclear but there are two promising enhancement mechanisms. Kippenhahn & Thomas (1978) have suggested that shear instabilities mix chemical composition and angular momentum between the accretion disk and the surface layers of the white dwarf. If the white dwarf has no outer helium layer significant carbon and/or oxygen enrichment can occur. A second possibility for CNO enrichment is a helium shell flash, initiated after a series of weak hydrogen flashes that eject little or no material. Since the nuclear energy content of helium is significantly less than hydrogen, a large helium fraction, $\Delta Y \gtrsim 0.2$, will be converted into carbon and/or oxygen and convectively mixed throughout the envelope. Shear instabilities can then mix freshly accreted solar composition material with this CO enriched material. Alternatively, since the white dwarf envelope expands to engulf the secondary during the helium flash, the red dwarf can accrete CO rich material and later transfer it back to the white dwarf. Abundance analyses of the accretion disks in old novae would show whether this pollution mechanism is a viable possibility. A first step in this direction has been taken by Williams (this volume) who finds $Z_{CNO} \sim 0.1$-0.2 for old novae disks.

To summarize, our main conclusions are:

1) Enhanced CNO abundances are necessary for fast novae. Slow novae, e.g. DQ Her, can still occur if Z_{CNO} is large.

2) The mean white dwarf mass in classical nova systems is predicted to be $\sim 1.1\ M_{\odot}$.

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3) Ejection of accreted material occurs only if the proper pressure at the base of the accreted envelope is greater than a critical value, P_c, which depends strongly on composition but only weakly on white dwarf mass. We find $P_c \simeq 10^{20}$ dyne cm^{-2} for solar abundances and $P_c \simeq 2 \times 10^{19}$ dyne cm^{-2} for $Z_{CNO} = 0.5$.

4) There exist critical accretion rates and white dwarf luminosities. F_c and L_c, which both depend strongly on M_{WD} and Z_{CNO} such that both $F < F_c$ and $L_{WD} < L_c$ are necessary for a nova outburst. Accretion rates, deduced from the optical luminosity of the old nova, are found to be appreciably higher than F_c for some novae including RR Pic, CP Lac and V603 Aql. Ferland et al (1982) have suggested that some of the optical luminosity of post-novae is reprocessed UV radiation from a hot white dwarf. Alternatively, the post-outburst accretion rate may be significantly higher than average.

5) Recurrent novae are not thermonuclear runaways.

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DISCUSSION FOLLOWING J. MACDONALD'S TALK

FRIEDJUNG: I think there is a problem for old novae as far as the accretion rate is concerned, there is even a worse case of Nova Delphini where UV data indicate an accretion rate of 10^{-6} $M_\odot$/yr, which probably will have to decrease. It is possible that quite a number of old novae which we see now, have accretion rates which are much more than the accretion rates required to give the explosion.

SCHATZMAN: I have three technical questions. The initial temperature in the white dwarf is, I suppose, the one which you deduce simply from the luminosity?

MACDONALD: Yes.

SCHATZMAN: The second question concerns the screening factors which you used.

MACDONALD: It is the weak screening which is important here.

SCHATZMAN: Can you describe the way in which the matter of the white dwarf interacts with the accreted matter?

MACDONALD: This probably happens via shear instabilities between the accretion disk and the white dwarf, this is probably where the CNO enhancement comes from, as has been suggested by Kippenhahn and Thomas. We also did some work on this and have shown that this mixing does occur, but probably not on such a quick timescale as Kippenhahn and Thomas suggested. It depends very much on the ratio of the thermal timescale and the accretion timescale. You expect that for high accretion rates you get less mixing.

EVANS: Are you in a position where you can say something about the relative abundances of CNO in the ejecta?

MACDONALD: We know that the CNO process will enhance nitrogen, so you would expect to have mostly nitrogen ejected. I think you are asking about the relative abundances of carbon and oxygen, I think that depends very much on what you put in, what the initial abundance of the white dwarf is, so there is nothing definite I can say.

SION: How did you obtain the recurrence times for the hydrogen shell flashes when you addressed the question of recurrent novae?

MACDONALD: It is just the accreted mass divided by the accretion rate.

SION: Did you actually follow the detailed evolution of the shell flashes?

MACDONALD: Well, the flash occurs over a time short compared to the accretion time.

SHAVIV: First, I am happy to see that flashes are obtained with solar abundances by other investigators and also that the plane (Menvelope, Z) has been adopted by the speaker. What I want to stress is that since the calculations are approximate, and I agree that this is the best way to explore the entire parameter space, you must be careful about the limits, because those are the places where the approximate treatment is bound to give you the largest errors.

SUGIMOTO: Concerning the accuracy, you can compare your solution with others. The accretion phase was computed by Nariai and Nomoto, the expansion phase was computed semi analytically by Fujimoto.

MACDONALD: I should say that my expansion phase results agree with those of Fujimoto. He also found that there is a critical pressure needed at the base of the interface to get a nova outburst and I get exactly the same numbers as he did.

WILLIAMS: I think it is interesting to note that of all the nova ejecta that we have analyzed, the two recurrent novae don't show any evidence for CNO enhancements, in contrast to all the classical novae ejecta which do. Secondly, I am not sure how much you should worry about a comparison between your ejection velocities for the envelope and the observed ones, because I think radiation pressure associated with the outburst will certainly accelerate a substantial fraction of the envelope to higher velocities and so it may well be that you could get from your calculations just a relatively small ejection and then the radiation will accelerate it to much higher velocities. There may be some observational evidence in support of this in the sense that when one looks at the ejection velocities deduced from the different absorption spectra, as time progresses the velocities all tend to increase, which is what you would expect if radiation pressure was important.

LIVIO: May I ask which opacities did you use?

MACDONALD: This is a good question, because I had this enhanced CNO. There are now opacities calculated by Cox for this sort of abundances, but I did not have those available at the time so I took the opacities of Cox and Stewart and Cox and Taylor and used a fitting formula suggested by Christi and produced my own opacity tables.

LIVIO: The reason for my question was that our experience, especially in the expansion phase, has been that the velocities that one gets depend very critically just on this, rather than on details that happen earlier.

SUGIMOTO: It is very difficult to calculate the expansion phase very accurately when the contribution of the radiation pressure becomes very large.

ROBINSON: I am delighted that the masses you derived are similar to the ones that I get. But after my talk earlier I would have to be the first one to point out that no matter what mass you would have gotten it would have agreed with somebody's mass.

MACDONALD: I think DQ Her is the only nova system in which you can make an attempt to get the mass of the white dwarf.

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