THEORETICALLY INFERRED MASSES OF THE WHITE DWARF
COMPONENTS OF COMMON NOVA SYSTEMS

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1. INTRODUCTION

Questions concerning the origin and evolution of cataclysmic variables continue to be the subject of considerable inquiry and debate. Significant boundary conditions upon theoretical models may be imposed by our increasing knowledge of the characteristics of specific systems. It is the purpose of this contribution to argue that, within the framework of the thermonuclear runaway model, the classical novae are most reasonably interpreted as systems characterized by relatively massive white dwarf components.

It is worth noting at the outset that the few existing determinations of the masses of the white dwarf components of classical nova systems are at least consistent with this viewpoint. Warner (1973) inferred masses 1.1 $M_\odot$ for V603 Aql and 1.0 $M_\odot$ for DQ Her. Robinson (1976) determined the mass for DQ Her to be 1.09 $M_\odot$. More recently, Hutchings (1979a,b) estimated the masses of the white dwarf components of both HR Del and DQ Her to be $\sim M_\odot$.

The arguments presented in this paper arise within the framework of the thermonuclear runaway model, the basic validity of which has been confirmed by numerical hydrodynamic studies (Starrfield et al., 1972, 1978; Sparks et al.,1978; Prialnik et al., 1978, 1979). A survey of those features of the model relevant to our present discussion is presented in the following section. Theoretical and observational considerations which support the view that relatively massive white dwarfs typify classical nova systems are then enumerated.

2. THE RUNAWAY MODEL

The basic features of the runaway model may be summarized briefly as follows. Accretion of hydrogen-rich matter onto the white dwarf component of a nova binary system ultimately gives rise to the establishment of degenerate conditions at the base of a reconstituted hydrogen envelope. The initiation of thermonuclear burning under these conditions leads to runaway, insuring a rapid rise in the luminosity to bolometric

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maximum. Following maximum, a phase of essentially hydrostatic evolution is encountered which continues through exhaustion of the accreted hydrogen fuel; this latter stage of evolution provides extremely important clues to the nature of the nova event. Subsequently, the system will return rapidly to minimum light, the evidence being that the post-nova configuration substantially mimics that of the pre-nova (Robinson 1975).

The post-runaway nova white dwarf structure we are considering consists of a degenerate carbon-oxygen core, an inert helium layer, and an overlying hydrogen shell in which burning is proceeding. The structure and evolution mimic, in substantially every important way, those of models which have previously been constructed in studies of the evolution of the central stars of planetary nebulae to white dwarfs. Paczynski (1971) has surveyed this evolution for stars of 0.6, 0.8, and 1.2 $M_\odot$ of Population I composition (X = 0.7, Z = 0.03). His results, together with those of other workers, enabled him to establish a core mass-luminosity relation characterizing such models:

$$L_P/L_\odot = 59250\ (M_{CORE}/M_\odot - 0.522)$$

Subsequent studies by Iben (1977) and by Becker and Iben (1979) have shown that this relation is dependent upon the total stellar (core plus envelope) mass, but its general validity for the low envelope mass configurations we are considering is established. Significantly, the luminosities for such configurations are at levels approaching the Eddington limit:

$$L_E/L_\odot = \frac{4\pi cGM}{\kappa_{es} L_\odot} = 3.7 \times 10^4\ (M_{CORE}/M_\odot)$$

where κ_{es} is the Thomson scattering opacity. Since this point will prove crucial in our subsequent discussions, <u>we emphasize that the hydrogen-shell-burning hydrostatic remnants of nova outbursts obey the above core mass-luminosity relation</u> (see, for example: Starrfield et al., 1978; Sparks et al., 1978; Prialnik et al., 1979).

Several other features of the nova configurations deserve mention. The standard model consists of a white dwarf of low intrinsic luminosity ($\sim 10^{-3} - 10^{-2}\ L_\odot$), a necessary condition to insure degeneracy of the matter at the base of the envelope prior to the onset of nuclear burning. The mass of the accreted hydrogen envelope necessary to induce runaway is a function of the mass of the underlying white dwarf. For initial models with luminosities approaching $\sim 10^{-2}\ L_\odot$, the required envelope masses are found to be approximately 2×10^{-4}, 10^{-4} and $2 \times 10^{-5}\ M_\odot$ for white dwarf masses 0.8, 1.0, and 1.25 $M_\odot$, respectively (Truran et al., 1977; Taam and Faulkner, 1975; Taam 1979).

Relevant parameters for nova models involving white dwarfs of 0.8, 1.0, and 1.25 $M_\odot$ are summarized in the Table. Included are the binding energy per gram of the initial envelope configuration, the envelope mass, the total binding energy of the envelope, the luminosity (Lp) predicted by the Paczynski relation, the Eddington luminosity (L_E), and, for purposes of our subsequent discussion, the photospheric radius consistent with an effective temperature 10^4 K at luminosity Lp and the ratio of this radius to that for a typical Roche lobe ($\sim 5 \times 10^{10}$ cm).

Table

Characteristics of Nova White Dwarf Models

$M_{WD}/M_\odot$	0.8	1.0	1.25
Binding Energy/gram	1.4×10^{17}	2.1×10^{17}	4.2×10^{17}
$M_{envelope}/M_\odot$	2×10^{-4}	10^{-4}	2×10^{-5}
Envelope Binding Energy (ergs)	6×10^{46}	4×10^{46}	2×10^{46}
$L_P/L_\odot$	1.7×10^4	2.9×10^4	4.4×10^4
$L_E/L_\odot$	3.4×10^4	4.2×10^4	5.3×10^4
L_P/L_E	0.50	0.69	0.83
R_{MAX} (cm)	3×10^{12}	4×10^{12}	5×10^{12}
$R_{MAX}/R_{ROCHE\ LOBE}$	60	80	100

3. INFERENCES REGARDING WHITE DWARF MASSES

The single and seemingly self-evident truth which underlies much of the discussion which is to follow is that turnoff of a nova demands the virtual exhaustion of the available hydrogen fuel. Model calculations indeed reveal this to be the case. The hydrogen in the envelope must either be consumed in thermonuclear burning or otherwise lost from the system on a rapid timescale. Evolution on a nuclear timescale (assuming no mass loss)

$$\tau_{NUC} \approx 800 \text{ years} \frac{(M_{envl}/10^{-4}\ M_\odot)}{(L/10^4\ L_\odot)}$$

is inconsistent with observations. Rather, since the integrated photon luminosities of novae $\sim 10^{46}$ ergs imply burning of only $\sim 10^{-6}$ $M_\odot$ of hydrogen into helium, it appears that some mechanism of mass loss must be effective in removing a substantial fraction of the envelope. Given this constraint, existing estimates of the masses of nova ejecta $\sim 10^{-5}$-10^{-4} $M_\odot$ are themselves suggestive of the fact that we are dealing with relatively massive white dwarfs; for a 0.5 $M_\odot$ white dwarf, the mass of the envelope to be ejected would be $\gtrsim 10^{-3}$ $M_\odot$.

Similarly viewed in this context, the model characteristics summarized in the table strongly suggest that more massive white dwarfs represent more promising candidates. While the binding energy per gram of the envelope increases with increasing mass, the envelope mass necessary to

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induce runaway on more massive dwarfs is significantly less: the total energy requirements for dispersing the envelope are therefore reduced. Simultaneously, we note both that more massive systems evolve at higher luminosities and that their luminosities represent a greater fraction of the Eddington value. The possibility of substantial wind driven mass loss is therefore increased. Bath and Shaviv (1976) and Bath (1978) have considered this question and demonstrated that an optically thick wind model for the postmaximum phase provides a natural explanation of many observed features of classical novae. In a related study, Hartwick and Hutchings (1978) obtained good agreement with the light curves of several galactic novae as well as M31 novae, assuming ejected masses in the range $(0.8 - 2) \times 10^{-5}\ M_\odot$ (again consistent with the envelope masses characterizing more massive white dwarfs). A word of caution may be in order here. Since the radii of nova remnants at visual maximum typically exceed the Roche lobe dimensions by a large factor (see tabled values), the possibility clearly exists for the occurrence of other modes of mass loss. However, even for such extended configurations the bulk of the envelope matter resides at significantly lower radii.

We turn finally to a further characteristic of the thermonuclear runaway model which may ultimately allow a definitive statement regarding the typical masses of white dwarfs in nova systems. Given the applicability of the Paczynski core mass-luminosity relation to the postmaximum constant bolometric luminosity phase of a nova's evolution, the combination of an accurate distance determination and complete (bolometric) light curve information can in principle provide a measure of the white dwarf mass. While further theoretical studies are required to confirm some details of this behavior in the context of nova evolution, it is instructive to proceed on this assumption.

For purposes of illustration, we examine the situation for Nova Cygni 1975 (V1500 Cyg). Ultraviolet observations by Wu and Kester (1977) at 100 days after visual maximum indicate a bolometric luminosity $3 \times 10^4\ L_\odot$, assuming a distance of 1.5 kpc. This is well below the luminosity at maximum of $5 \times 10^5\ L_\odot$, leading them to state that Nova Cygni did not experience a constant luminosity phase like that observed for FH Ser (Gallagher and Starrfield, 1976). In point of fact, it is the luminosity at 100 days which represents that characterizing the constant luminosity phase and which, therefore, is to be used in conjunction with the core mass-luminosity relation to determine the white dwarf mass. The early visual peak in this nova light curve is a transient luminosity feature, characteristic of the fast novae (Truran, 1979a,b), which is well in excess of the Eddington limit. In contrast, for a slow nova like HR Del 1967 the luminosity at visual maximum provides a fair measure of that characterizing the constant luminosity phase. For a distance of 810 parsecs (Webbink and Gallagher, 1979), the bolometric luminosity for HR Del at this stage is $2.3 \times 10^4\ L_\odot$. The corresponding estimates of the white dwarf masses are $1\ M_\odot$ for Nova Cygni and $0.9\ M_\odot$ for HR Del.

It is also extremely interesting to note that the slowest novae studied by Arp (1956) in the Andromeda nebula were found to reach -6.2 absolute magnitude, corresponding to white dwarf masses $\sim 0.9\ M_\odot$. Here, we may of course be encountering selection effects, the sample having been limited by luminosity considerations. The same may be true, though to a lesser degree, for galactic novae. The basic statement to be made in this paper is simply that <u>observed</u> novae involve more massive white dwarfs.

The critical observational uncertainties influencing our mass estimates are those pertaining to the distance determinations: a factor two error in the adopted luminosity can alter the mass estimate by up to several tenths of a solar mass. Theoretically, there exist serious questions associated with the possibility that high rates of wind driven mass loss characterize the constant luminosity phase. If our earlier arguments are correct, mass loss rates 10^{-6} - 10^{-5} $M_{\odot}$/year may be demanded to insure turnoff of novae on the observed timescales. For a solar mass white dwarf of surface binding energy $\sim 2 \times 10^{17}$ ergs/gram, the corresponding mass loss luminosities are $\sim 3 \times 10^{3}$ - 3×10^{4} $L_{\odot}$. The required mass-loss luminosity is thus seen to be of the order of the photon luminosity. If, as seems appropriate to this writer, a correct core mass-luminosity relation must take into consideration the total (photon + mass loss) luminosity, then our previous estimates of the white dwarf masses will likely need to be revised upward.

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REFERENCES

Arp. H. C. 1976, Astr. J., 61, 15.
Bath, G. T. 1978, Mon. Not. R. Astr. Soc., 182, 35.
Bath, G. T. and Shaviv, G. 1976, Mon. Not. R. Astr. Soc., 175, 305.
Becker, S. A. and Iben, I. Jr. 1979, Astrophys. J., in press.
Gallagher, J. S. and Starrfield, S. 1976, Mon. Not. R. Astr. Soc., 176, 53.
Hartwick, F. D. A. and Hutchings, J. B. 1978, Astrophys. J., 226, 203.
Hutchings, J. B. 1979a, "The Cataclysmic Binary HR Del".
Hutchings, J. B. 1979b, "The Interactive Binary in Nova DQ Herculis".
Iben, I. Jr. 1977, Astrophys. J., 217, 788.
Paczynski, B. 1971, Acta Astron., 21, 417.
Prialnik, D., Shara, M. M., and Shaviv, G. 1978, Astr. Astrophys., 62, 339.
Prialnik, D., Shara, M. M., and Shaviv, G. 1979, Astr. Astrophys., 72, 192.
Robinson, E. L. 1975, Astr. J., 80, 515.
Robinson, E. L. 1976, Astrophys. J., 203, 485.
Sparks, W. M., Starrfield, S., and Truran, J. W. 1978, Astrophys. J., 220, 1063.
Starrfield, S., Truran, J. W., and Sparks, W. M. 1978, Astrophys. J., 226, 186.
Starrfield, S., Truran, J. W., Sparks, W. M., and Kutter, G. S. 1972, Astrophys. J., 176, 169.
Taam, R. 1979, Astrophys. J., in press.
Taam, R. and Faulkner, J. 1975, Astrophys. J., 198, 435.
Truran, J. W. 1979a, these proceedings.
Truran, J. W. 1979b, "The Early Development of Fast Nova Light Curves".
Truran, J. W., Starrfield, S., Strittmatter, P. A., Wyatt, S. P., and Sparks, W. M. 1977, Astrophys. J., 211, 539.
Warner, B. 1973, Mon. Not. R. Astr. Soc., 162, 189.
Webbink, R. W. and Gallagher, J. S. 1979, private communication.
Wu, C.-C. and Kester, D. 1977, Astron. Astrophys., 58, 331.