ON THE MASSES OF THE WHITE DWARFS IN CLASSICAL NOVA SYSTEMS

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I. INTRODUCTION

Significant progress in our understanding of the nature of the outbursts of the classical novae has occurred over the past two decades (see, e.g., reviews by Truran 1982; Starrfield 1986). Their outbursts are now understood to be driven by thermonuclear runaways proceeding in the accreted hydrogen-rich shells on the white dwarf components of close binary systems. Critical parameters which serve to dictate the varied characteristics of the observed outbursts include the intrinsic white dwarf luminosity, the rate of mass accretion, the composition of the envelope matter prior to runaway, and the white dwarf mass.

Our concern in this paper is specifically with the question of the white dwarf mass. The expected average mass of isolated white dwarfs in the interstellar medium is ~ 0.6 - 0.7 $M_{\odot}$; this follows straightforwardly from the assumption of a Salpeter (1955) stellar mass function and standard stellar evolution theory, and is confirmed by observations (Koester, Schulz, and Weidemann 1979). The question arises as to whether white dwarf masses in this range should be typical of the white dwarfs in close binary systems. We seek to provide a partial answer to this question, for the specific case of classical nova systems, on the basis of observations of the dynamical evolution of novae in outburst (Section II) and of the abundances in nova nebular ejecta (Section III). We then provide an estimate of the average mass of the white dwarf component of observed classical nova systems (Section IV), on the basis of theoretical arguments concerning the critical envelope mass necessary to trigger runaway on a white dwarf of specified mass. Finally, we review existing mass estimates for novae and discuss these in the light of theoretical models.

II. DYNAMICAL INDICATIONS

There exists a large number of observations which point towards a very dynamical nature of many nova outbursts. These dynamical indicators can, in turn, be related to a relatively high mass for the white dwarf. We shall now review some of these observation and their implications.

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(i) Speed class

Out of 65 galactic novae listed by Payne-Gasposchkin (1957), 39 can be classified as "fast" or "very fast" novae, in the sense that their rate of decline from maximum exceeds 0.08 magnitudes per day.

(ii) Super-Eddington luminosity

The Eddington luminosity for a Chandrasekhar-mass white dwarf is of the order of 5.3 x 10^4 $L_\odot$, corresponding to an absolute bolometric magnitude M_{bol} = -7.1. It is interesting to note in this regard that de Vaucouleure (1978) finds that twelve out of fifteen novae for which the distance has been determined, using expansion parallaxes or interstellar line intensities, reach absolute magnitudes brighter than -7.1. Therefore, 12 out of the 15 systems reached super-Eddington luminosities (see Truran, Shankar, Livio, and Hayes (1988), for a discussion of this point). Moreover, all of the novae designated as "fast novae" by Payne-Gaposchkin (1957) reached absolute visual magnitudes brighter than -7.1.

(iii) High expansion velocities

In a number of novae for which expansion velocity measurements exist, high velocities were indicated. A few examples are: V1500 Cyg (1975) for which a velocity of V_{exp} = 1600 km s^{-1} was measured (e.g. Ferland 1978; Ferland and Shields 1978), CP Lac (1936) where V_{exp} = 1300 km s^{-1} (e.g. Pottasch 1959; Ferland 1979), DK Lac (1950) with V_{exp} = 870 km s^{-1} (Collin-Souffrin 1977), IV Cep (1971) with V_{exp} = 1000 km s^{-1} (Pacheco 1977; Ferland 1979) and V1668 Cyg (1978) with V_{exp} = 740 km s^{-1} (Stickland et al. 1981).

We shall now argue that all of these observations (in addition to others discussed in the next sections) point towards high white dwarf masses in the observed novae. The main point to note here is that the observations described in (i) - (iii) above outline a very dynamical nature of the outburst.
Specifically: (a) High expansion velocities are clearly the signature of a dynamical event. (b) Super-Eddington luminosities can be obtained only in a configuration departing from hydrostatic equilibrium and (c) a rapid return to minimum indicates rapid expansion (which leads to cooling) and a short timescale for nuclear burning. All of these, in turn, can be obtained for relatively small envelope masses. We will now show that the theory of hydrogen shell flashes on the surface of accreting white dwarfs demonstrates that the more massive the white dwarf, the lower the mass it needs to accrete for a thermonuclear runaway (TNR) to occur. Both semi-analytical estimates (Fujimoto 1982, MacDonald 1983) and detailed numerical calculations (e.g. Prialnik et al. 1982, Starrfield, Sparks and

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Truran 1985) have demonstrated that the strength of the outburst is determined largely by the pressure at the base of the accreted envelope. This pressure is given approximately by

$$P_b \doteq \left(GM_{WD}\Delta M_{acc}\right)/\left(4\pi R_{WD}^4\right) \qquad (1)$$

where ΔM_{acc} is the accreted mass. A TNR occurs when P_b exceeds some critical value, $P_{crit} \sim 2 \times 10^{19}$ dyne cm^{-2} (Truran and Livio 1986). Consequently, we find that ΔM_{acc} is proportional to $R^4{}_{WD}/M_{WD}$, which is a strongly decreasing function of the white dwarf mass. Therefore, massive white dwarfs ensure a low envelope mass at the time of the runaway. We would like to note, in this respect, that in the few cases in which the mass of the ejected nebula has been determined from observations (e.g. V1500 Cyg, CP Lac, IV Cep) masses of the order of 10^{-5} - 10^{-4} $M_{\odot}$ were found (admittedly with large uncertainties). These values are consistent with $M_{WD} \gtrsim 1$ $M_{\odot}$ (Truran and Livio 1986). High white dwarf masses are associated also with higher expansion velocities, simply by the fact that the escape velocity (which the expansion velocity must exceed) is higher for higher white dwarf masses. Finally, we would like to point out that an optically thick wind, which can be responsible for large mass loss, also occurs only for relatively massive white dwarfs ($M_{WD} > 0.8$ $M_{\odot}$; Kato and Hachisu 1988a,b). This is a consequence of the fact that the wind phase is obtained only following a large envelope expansion (which is obtained for massive white dwarfs, as explained above). Significant mass loss is essential in order to obtain nuclear burning timescales (and time-scales for return to minimum) which are not excessively long (compared to observations).

We can therefore conclude that the most direct observations of nova out-bursts, the light curve and expansion velocities, point towards relatively massive white dwarfs in many classical nova systems.

III. ABUNDANCE INDICATIONS

Spectroscopic studies of nova ejecta provide further support for the view that rather massive white dwarfs are common occurrences in classical nova systems. Element abundance data are now available for a number of novae. The available heavy element data, reviewed most recently by Truran (1985a,b) and Williams (1985), are presented in Table 1. Here we present specifically the mass fractions in the form of hydrogen, helium, carbon, nitrogen, oxygen, neon, sodium, magnesium, aluminum, silicon, sulphur, and iron. The available information concerning both helium and heavy-element abundances (total mass fraction Z) is collected in Table 2. For purposes of comparison, we note that solar system matter is characterized by a ratio He/H = 0.08 and a heavy-element mass fraction 0.019 (Anders and Ebihara 1982; Cameron 1982). Following Truran and Livio (1986), this table also indicates the fraction of the ejecta in the form of helium and/or heavy-element enriched matter for these 13 well-studied novae.

TABLE 1

Heavy-Element Abundances in Novae

Object	Mass Fractions									
	H	He	C	N	O	Ne	Na	Mg	Al	Si
RR Pic[1]	0.53	0.43	0.0039	0.022	0.0058	0.011	...	...	...	...
HR Del[2]	0.45	0.48	...	0.027	0.047	0.0030	...	...	...	...
T Aur[3]	0.47	0.40	...	0.079	0.051	...	...	...	...	...
V1500 Cyg[4]	0.49	0.21	0.070	0.075	0.13	0.023	...	...	...	...
V1668 Cyg[5]	0.45	0.23	0.047	0.14	0.13	0.0068	...	...	...	...
V693 Cr A[6]	0.29	0.32	0.0046	0.080	0.12	0.17	0.0016	0.0076	0.0043	0.0022
DQ Her[7]	0.34	0.095	0.045	0.23	0.29	...	...	...	...	...
V1370 Aql[8]	0.053	0.085	0.031	0.095	0.061	0.47	...	0.0092	...	0.0012

References. — (1) Williams and Gallagher 1979. (2) Tylenda 1978. (3) Gallagher et al. 1980. (4) Ferland and Shields (1978). (5) Stickland et al. 1981. (6) Williams et al. (1985). (7) Williams et al. 1978. (8) Snijders et al. 1984.

Several important conclusions can be drawn from the abundance data collected in these tables. (1) High helium to hydrogen ratios are characteristic of nova ejecta: the average for the 13 novae in Table 2 is He/H = 0.19. (2) High abundances of heavy elements, both the CNO group elements and the ONeMg group elements, characterize the ejecta particularly of the faster novae: V1500 Cyg, V1668 Cyg, V693 CrA, and V1370 Aql. (3) Substantial fractions of enriched matter are typical of both fast and slow novae: the average value for the novae listed in Table 2 is 0.38.

The presence of these abundance enrichments holds important implications with respect to the typical white dwarf masses in these systems. The critical question here is how such concentrations can arise. Possible sources of these heavy-element abundance enrichments include (i) mass transfer from the secondary, (ii)

TABLE 2

Abundances in Novae

Nova	Date	He/H	Z	Reference	Enriched Fraction
T Aur	1891	0.21	0.13	1	0.36
RR Pic	1925	0.20	0.039	2	0.28
DQ Her	1934	0.08	0.56	2	0.55
CP Lac	1936	0.11±0.02	...	2	0.08
RR Tel	1946	0.19	...	2	0.24
DK Lac	1950	0.22±0.04	...	2	0.30
V446 Her	1960	0.19±0.03	...	2	0.24
V533 Her	1963	0.18±0.03	...	2	0.23
HR Del	1967	0.23±0.05	0.077	2	0.35
V1500 Cyg	1975	0.11±0.01	0.30	2	0.34
V1668 Cyg	1978	0.12	0.32	3	0.38
V693 Cr A	1981	0.28	0.38	4	0.61
V1370 Aql	1982	0.40	0.86	5	0.93

References — (1) Gallagher et al. 1980. (2) Ferland 1979. (3) Stickland et al. 1981. (4) Williams et al. 1985; Williams 1985. (5) Snijders et al. 1984.

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nuclear transformations accompanying the outburst, and (iii) outward mixing of matter from the underlying white dwarfs. Truran (1985b) and Truran and Livio (1986) have scrutinized these possibilities and concluded that neither mass transfer nor nuclear reactions accompanying the outburst are capable of explaining the observed anomalies.

It would appear, rather, that some fraction of the envelope matter and ejecta represents material which has somehow been dredged up from the core of the underlying white dwarf. Such envelope contamination can result, in principle, from shear-induced turbulent mixing between the white dwarf and the accreted material (Livio and Truran 1987), from diffusion induced convection (Kovetz and Prialnik 1985), or from convective overshooting subsequent to the runaway (Woosley 1987). Whatever the mechanism, the character of such enrichments is a function of the underlying white dwarf structure and composition. High He/H ratios can result when the accreted hydrogen-rich matter mixes with helium-shell matter on white dwarfs, but the observed enrichments of CNO and ONeMg nuclei must arise from the deeper regions of the core. This demands the presence, respectively, of carbon-oxygen and oxygen-neon-magnesium white dwarfs (Law and Ritter 1983; Williams et al. 1985). We note, in particular, that such ONeMg white dwarfs are the expected products of the evolution of stars in the mass range ~ 8 - 12 $M_\odot$ and are predicted to have masses ~ 1.2 - 1.4 $M_\odot$. The fact that two of the eight novae for which detailed heavy element abundance analyses have been performed are enriched in the ONeMg element group (with Nova Vul 1984 II being a third possible candidate) strongly suggests that a significant population of massive white dwarfs is to be found in observed classical nova systems. Selection effects which help us to understand this result are reviewed in the next section.

IV. RELATIVE FREQUENCY OF OCCURRENCE OF WHITE DWARF MASSES

In a recent work, Truran and Livio (1986) estimated the relative frequencies of occurrence of different white dwarf masses in <u>observed</u> classical nova systems. In order to obtain these estimates, they made the following assumptions:

(i) The TNR occurs when the pressure at the base of the accreted envelope reaches a critical value (Section 2, eq. 1).

(ii) The initial mass function for the progenitors of the white dwarf is given by the Salpeter (1955) mass function (see the discussion below of the effect of using different mass functions).

(iii) The relation between the progenitor mass and the white dwarf mass provided by Iben and Truran (1978), is assumed to hold throughout the white dwarf mass range. (Using a different relation for high mass white dwarfs changes the estimates somewhat, but not the conclusions.)

The relative frequencies obtained, based on these assumptions, as well as the recurrence time (for an assumed accretion rate $\dot{M}_{acc} = 10^{-9}\ M_\odot\ yr^{-1}$), are presented

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in Table 3. The first two things to note in the table are: (i) about one third of all observed novae should contain very massive ($M_{WD} \sim 1.35\ M_\odot$) white dwarfs (this is fully consistent with the observations of ONeMg white dwarfs, Section III) and (2) the average mass of the white dwarfs in observed classical nova systems is $\bar{M}_{WD} = 1.14\ M_\odot$. In fact, if instead of a Salpeter mass function (assumption (ii) above) we use the estimates of ranges of initial main-sequence masses in binary systems obtained by Iben and Tutukov (1985), we find $\bar{M}_{WD} = 1.23\ M_\odot$. On the other hand, the white dwarf mass spectrum of Politano and Webbink (1988) would result in a somewhat lower average mass. We can therefore conclude that relative frequency of occurrence arguments predict an average white dwarf mass of about 1.1 - 1.2 $M_\odot$.

Table 3 has another important consequence. The mean recurrence time between outbursts (for an assumed accretion rate of $10^{-9}\ M_\odot\ yr^{-1}$) is 8900 yr. Recently, Livio (1987) has suggested that the accretion rate can be somewhat higher ($\sim 10^{-8}\ M_\odot/yr$) for a period of about 50-300 years both before and after the outburst. Thus, the mean recurrence time can be of the order of 3000-4000 yrs. For such relatively short recurrence timescales, the discrepancy between the space density of classical novae as obtained by Patterson (1984) and Duerbeck (1984), and the Bath and Shaviv (1978) estimate, largely disappears.

TABLE 3

Relative Frequencies and Recurrence Time Scales

M_{WD}	T_{rec} (yr)	$f(M_{WD})$
CO White Dwarfs:		
0.6	1.29×10^6	0.103
0.7	7.31×10^5	0.053
0.8	4.16×10^5	0.042
0.9	2.36×10^5	0.040
1.0	1.20×10^5	0.046
1.1	6.39×10^4	0.062
1.2	2.81×10^4	0.100
1.3	9.02×10^3	0.232
ONeMg White Dwarfs:		
1.35	3.98×10^3	0.322

V. OBSERVATIONS OF WHITE DWARF MASSES IN CLASSICAL NOVA SYSTEMS

The masses of the white dwarfs in classical nova systems are extremely poorly known. Table 4 (compiled from Ritter's 1988 catalog) lists all the cases for which some estimates for the mass exist. Even in this table, the masses for HR Del and RR Pic are highly uncertain. In this list, V603 Aql and GK Per are fast novae. We would also expect the mass of the white dwarf in the case of the fast nova V603 Aql to be considerably higher than the quoted value, although the possible presence of a magnetic field may complicate matters (Haefner and Metz 1985). Observations of this object in an attempt to determine the white dwarf mass are thus strongly encouraged (although this is not an easy task for a system

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with an inclination of 17°). In general, observations aimed at determining more white dwarf masses in nova systems (e.g. BT Mon is a good candidate) can be very valuable, as the present work has demonstrated.

TABLE 4

Masses of White Dwarfs in Classical Nova Systems

System	Orbital Period (days)	M_{WD} ($M_\odot$)	M secondary ($M_\odot$)
GK Per (1901)	1.996803	0.9±0.2	0.25
HR Del (1967)	0.214167 0.1775	0.9±0.1	0.58±0.01
DQ Her (1934)	0.193621	0.62±0.09	0.44±0.02
RR Pic (1925)	0.145026	0.95	0.4
V603 Aql (1918)	0.138154 0.144854	0.66±0.27	0.29±0.02

CONCLUSIONS

On the basis of the considerations reviewed in this paper, we are led to the conclusion that the typical masses of the white dwarfs in observed classical nova systems are significantly higher than the 0.6-0.7 $M_\odot$ range characteristic of single white dwarfs. This (in itself) does not imply that the average mass in close binary systems differs significantly from 0.6-0.7 $M_\odot$. Selection effects are extremely important here. We emphasize that the present work discusses the masses of the white dwarfs in nova systems that are actually observed to erupt and not in CVs in general. Therefore, the conclusion obtained here, that the masses of the WDs in observed nova systems is high, is not in conflict with other works discussing the distribution of WD masses in nova systems in general. For example, Hameury, King, Lasota, and Livio (1988) have found recently that the majority of the WDs in magnetic nova systems, should have a mass around 0.6-0.7 $M_\odot$, with a smaller group having a larger mass.

To be put even more strongly, the present work implies that the observed nova systems do not represent average CV systems (in terms of the WD mass) and cannot be assumed therefore to imply general properties of the CV population.

The estimates we provide of frequencies of occurrence of white dwarfs as a function of mass and of the average mass ~ 1.1-1.2 $M_\odot$ in active systems reveals the nature of the selection effect: more massive white dwarfs simply require less accreted matter to trigger an outburst. Dynamical arguments and abundance arguments both strongly support this conclusion. In general, we believe that the picture that emerges from our arguments concerning the role of massive white dwarfs in classical nova systems is entirely consistent with theoretical and observational constraints.

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We also wish to call attention to the fact that the higher masses typical of observed classical novae serve to define rather tightly the range of luminosities and allow the possible use of their plateau luminosities as standard candles (Truran 1982). This arises from the fact that the bolometric luminosities of the hydrogen shell-burning remnants of nova eruptions essentially obey the Paczynski (1971) core-mass-luminosity relation for AGB stars with degenerate carbon-oxygen cores. The corresponding luminosity plateaus for dwarf masses 1.0 to 1.3 $M_\odot$ range from 2.8×10^4 to 4.6×10^4 $L_\odot$, with less than a factor two variation in luminosity and magnitude range $\Delta m \lesssim 1$. Novae thus represent potentially useful probes of the distance scale out to distances of order those of nearby clusters. Recognizing that very fast novae violate this condition at peak optical light, it is best to consider only moderately fast and slow novae.

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