3. THEORY

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

CLASSICAL NOVAE IN THE CONTEXT OF THE EVOLUTION OF CATACLYSMIC BINARIES

Hans Ritter
Max-Planck-Institut für Physik und Astrophysik
Karl-Schwarzschild-Straße 1
D–8046 Garching
Fed. Rep. Germany

ABSTRACT

In this paper we explore to what extent the TNR model of nova outbursts and our current concepts of the formation and secular evolution of cataclysmic binaries are compatible. Specifically we address the following questions: 1) whether observational selection can explain the high white dwarf masses attributed to novae, 2) whether novae on white dwarfs in the mass range $0.6M_{\odot} \lesssim M \lesssim 0.9M_{\odot}$ can occur and how much they could contribute to the observed nova frequency, and 3) whether the high mass transfer rates imposed on the white dwarf in systems above the period gap can be accommodated by the TNR model of nova outbursts.

INTRODUCTION

Since the photometric observations by Walker (1956) of the old nova DQ Her and the pioneering spectroscopic study by Kraft (1964) of ten old novae it is clear that nova explosions occur in close binary systems which form a subgroup of the cataclysmic binaries (CBs). In fact, the main properties of the postnova binaries match those of the other CBs so closely that it would be difficult to distinguish the former from the latter were it not for the fact that the former are known to have undergone a classical nova outburst in recorded history. Based on this similarity it is only natural to propose that old novae are normal CBs, i.e. that they are short-period double stars in which a white dwarf (hereafter the primary) accretes hydrogen-rich matter from a low-mass companion (hereafter the secondary) which fills its critical Roche lobe (see e.g. Warner (1976) for a review and Ritter (1987) for a compilation of basic orbital parameters). However, if this is true then the ignition conditions of the thermonuclear runaway (TNR) on the white dwarf and thus the frequency of occurrence of nova explosions are subject to constraints which, in turn, are related to the intrinsic distribution of orbital parameters of newly formed CBs (hereafter zero age CBs = ZACBs) and to the secular evolution of CBs. The interrelations between the three subjects, specifically the question whether classical novae can fit consistently into the scheme of CB evolution is the subject of this paper.

That we are facing here a real problem is best seen by considering how CBs populate the (M_1, $\dot{M}_1$)-plane. (Here M_1 is the mass of the white dwarf and $\dot{M}_1$ its accretion rate). Properties of the ZACBs combined with a model of the secular evolution of CBs, details of which will be discussed

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

in the subsequent sections 2 and 3, yield an intrinsic CB population in which most of the systems have a white dwarf of rather low mass (86% have $M_1 < 0.9M_\odot$, see Table 1) and, at least a sizeable fraction of them, a rather high mass transfer rate ($10^{-9}M_\odot \mathrm{yr}^{-1} \lesssim \dot{M}_1 \lesssim 10^{-8}M_\odot \mathrm{yr}^{-1}$). On the other hand, according to standard TNR models (for a brief discussion see section 4) novae occur in a quite different area of the (M_1, $\dot{M}_1$)-plane, namely where $M_1 \gtrsim 1M_\odot$ and $\dot{M}_1 \lesssim 10^{-9}M_\odot \mathrm{yr}^{-1}$. Considering the small degree of overlap of the two populations, we wish to discuss the following problems:

1) Despite the fact that there is not a single white dwarf mass in a postnova binary that is accurately known, there is strong circumstantial evidence that the majority of the known classical novae occurred on a massive white dwarf ($M_1 \gtrsim 1M_\odot$) and a fair fraction of them even on a O-Ne-Mg white dwarf with $M_1 \gtrsim 1.3M_\odot$ (Truran, 1989). Given the fact that intrinsically the majority of the white dwarfs in CBs have a much lower mass (see Table 1 and Politano (1988), Politano and Webbink (1989a,b)), we must therefore ask whether observational selection as proposed by Truran and Livio (1986, 1989) or Politano et al. (1989) is strong enough to account for the observations.

2) In a large fraction of the intrinsic CB population the combination of (M_1, $\dot{M}_1$) is such that the accreted hydrogen will not be sufficiently degenerate to allow for a strong nova explosion. Nevertheless, it is unavoidable that the accreted hydrogen ignites sooner or later and that, after iginition, the hydrogen-rich envelope either has to be burnt to helium or to be expelled from the white dwarf. Therefore, we must ask how such events would look to a distant observer, whether they are distinguishable from ordinary novae and, after correction for observational selection, how much they contribute to the observed nova frequency.

3) Successful models of the secular evolution of CBs (see below, section 3) require that systems with orbital periods $P \gtrsim 3$ hrs have a mass transfer rate $-\dot{M}_2 \gtrsim 2\,10^{-9}M_\odot \mathrm{yr}^{-1}$. This lower limit on $-\dot{M}_2$ is at best marginally consistent with the upper limit of $\dot{M}_1 \lesssim 10^{-9}M_\odot \mathrm{yr}^{-1}$ required by the TNR model for a strong nova outburst. Therefore, we must ask ourselves whether the TNR model and/or that of the secular evolution could be modified in such a way that the acceptable ranges of $\dot{M}_1$ have more overlap. Furthermore we should also consider the possibility that, contrary to what is usually assumed, nova binaries are not typical CBs and explore the (observational) consequences of this possibility.

Before we discuss these problems in more detail (sections 5–7), we briefly summarize in sections 2–4 the ingredients of our subject, namely the properties of ZACBs, the basic concepts of the secular evolution of CBs and finally the key points of the TNR model of classical novae.

2 PROPERTIES OF ZACBs

Until not very long ago our knowledge about the intrinsic properties of newly formed CBs, in particular about the mass spectrum of the white dwarfs, was rudimentary at best. Recently, however, Politano (1988, 1989) and Politano and Webbink (1989a,b) presented results of extensive model calculations aimed at determining the properties of ZACBs. Specifically they compute the birth rate of ZACBs per unit area of the galactic plane, $\dot{\Sigma}_{\mathrm{ZACB}}(t)$, as a function of time t and the distribution of that birthrate over the initial values of the masses of the binary components ($M_{1,i}$, $M_{2,i}$). The mass spectrum of the white dwarfs of newly formed CBs is then given by

$$\frac{d\dot{\Sigma}_{\mathrm{ZACB}}}{dM_{1,i}} = \int_0^{M_{2,\mathrm{crit}}} \frac{\partial^2 \dot{\Sigma}_{\mathrm{ZACB}}}{\partial M_{1,i} \partial M_{2,i}} dM_{2,i} \quad , \tag{1}$$

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

where $M_{2,\rm crit}$ is the highest value of M_2 that allows for dynamically and thermally stable mass transfer during the subsequent evolution. Information about the mass distributions of the CO-white dwarfs in ZACBs after 10^{10} yr of constant star formation is given in Table 1. These numbers show that the mean white dwarf mass is rather low, i.e. $\langle M_1 \rangle \approx 0.76 M_\odot$, that 86% of the white dwarfs have a mass $M_1 < 0.9 M_\odot$ and less than 10% a mass $M_1 > 1 M_\odot$. For further details the reader is referred to Politano (1988) and Politano and Webbink (1989a,b).

3) SECULAR EVOLUTION OF CBs

One of the most important pieces of information about the structure and evolution of CBs is the observed distribution of orbital periods shown in Figure 1. Its main characteristics are: 1) About 2/3 of the CBs have orbital periods in the range 3 hrs $\lesssim P \lesssim 0^d.6$. 2) About 1/3 of the systems have periods in the range 80 min $\lesssim P \lesssim$ 2 hrs. 3) There is an almost total deficiency of CBs in the period range 2 hrs $\lesssim P \lesssim$ 3 hrs. This is usually referred to as the period gap. It is clear that any successful theoretical model for the secular evolution of CBs has to account for the observed period distribution, in particular for the occurrence of the period gap. Therefore, much attention has been devoted to explaining the gap. The currently most popular explanation is the model of disrupted magnetic braking (Spruit and Ritter, 1983; Rappaport, Verbunt and Joss, 1983). This model and many other aspects of the long-term evolution of CBs have recently been reviewed by Ritter (1986a) and King (1988). Here we restrict ourselves to a brief description of the period gap model because it is of relevance for the subsequent discussion. For a more detailed presentation the reader is referred to the above-mentioned papers.

The stability of CBs against mass transfer implies that the observed mass transfer must be driven by some outer force. In the vast majority of CBs this can only occur via the systemic loss of orbital angular momentum. Viable mechanisms for this are gravitational radiation and/or a magnetically coupled stellar wind from the secondary ("magnetic braking"). Nuclear evolution of the secondary is in general unimportant. It can drive a significant mass transfer only if the secondary's mass is $M_2 \gtrsim 1 M_\odot$, i.e. if the system's orbital period is $P \gtrsim 10$ hrs. In the framework of the period gap model, mass transfer in systems above the gap, i.e. with $P \gtrsim 3$ hrs, is driven by the combined action of magnetic braking and gravitational radiation, while in systems below the gap, i.e. with $P \lesssim 2$ hrs, it is essentially only gravitational radiation. In this model, the gap occurs as a consequence of a sudden drop of the angular momentum loss rate due to magnetic braking at the upper edge of the gap. This, in turn, causes the secondary, which is driven significantly out of thermal equilibrium due to mass loss, to detach from its Roche lobe and to stop transferring mass. Thus the systems cross the gap as detached binaries and, therefore, are virtually invisible. In the framework of this model, the orbital period at the lower edge of the gap, P_l, is a direct measure for the secondary's mass when the system crosses the gap, while the width of the gap $\Delta P = P_u - P_l$ yields a lower limit of the secondary's mass loss rate above the gap (Ritter, 1985). With $P_u \approx 3$ hrs and $P_l \approx 2$ hrs the corresponding values are $M_2 \approx 0.2 M_\odot$ and $-\dot{M}_2 \gtrsim 2\ 10^{-9} M_\odot\ \rm yr^{-1}$ (Spruit and Ritter, 1983; Mc Dermott and Taam, 1989). Thus, the observed width of the period gap sets a lower limit to the mass transfer rate in systems above the gap and it is this lower limit of $-\dot{M}_2 \gtrsim 2\ 10^{-9} M_\odot \rm yr^{-1}$ which is of particular interest in the subsequent discussion.

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

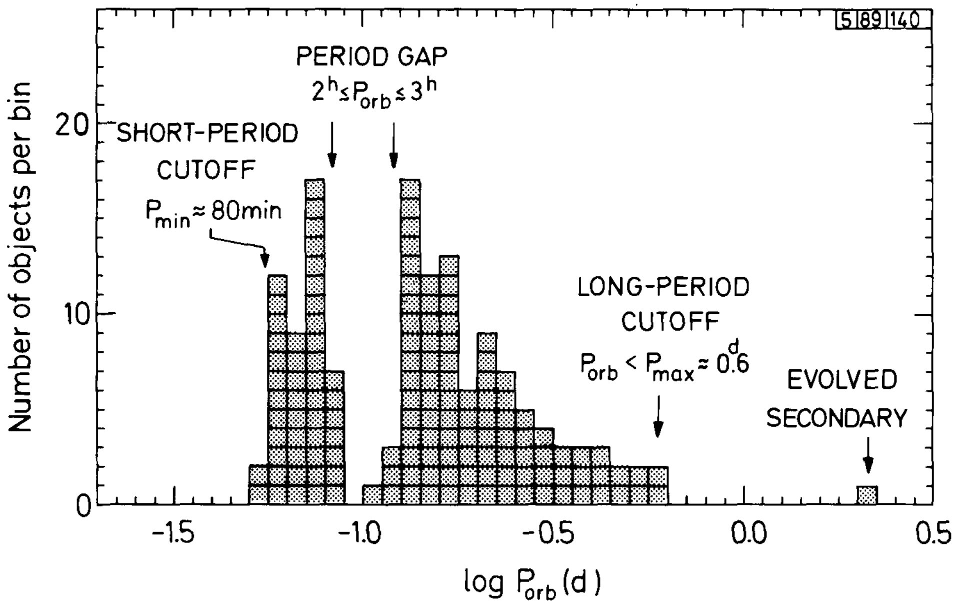

Figure 1. Histogram of the orbital periods of cataclysmic binaries. The data are taken from Ritter (1987) including some updates.

4 IMPLICATIONS OF THE TNR MODEL OF CLASSICAL NOVAE

It is by now generally accepted that the phenomenon which we call a classical nova outburst results from a TNR which is ignited at the base of a hydrogen-rich envelope of gas that has accumulated on a white dwarf prior to ignition. A detailed presentation of most of the observational and theoretical aspects of classical novae may be found in the recent review by Shara (1989), in the monograph by Bode and Evans (1989) and elsewhere in this volume (e.g. Sparks (1989), Truran (1989)). In the context of this paper we are mainly concerned with the prerequisites for a strong TNR, i.e. a nova outburst, to occur. The single most important condition for a TNR is that hydrogen burning ignites in a degenerate environment and that the degeneracy (parameter of ψ_{ign}) at ignition is sufficiently high, i.e. typically $\psi_{ign} \approx 10$, such that the Fermi temperature is $T_F \approx 10^8 K$. In order to meet this condition the underlying white dwarf has to be cool, i.e. its central temperature has to be sufficiently low, typically $T_c < 10^7 K$, and the accretion rate $\dot{M}_1$, must be low enough to prevent the accreted envelope from becoming too hot due to compressional heating. In addition, strong TNRs are favoured on massive white dwarfs and if the layer in which the TNR ignities (via the hot β-limited CNO cycle) is enriched with nuclei of the CNO group, i.e. if $Z_{CNO} \gg Z_{CNO,\odot} \approx 10^{-2}$. In fact, numerical computations (e.g. Prialnik et al. (1982)) show that a strong TNR does not occur unless $\dot{M}_1 \lesssim 10^{-9} M_\odot \mathrm{yr}^{-1}$ and $M_1 \gtrsim 1 M_\odot$. Furthermore, if heating by the boundary layer of the accreted envelope is as important as computations by Shaviv and Starrfield (1987), Starrfield et al. (1988), Prialnik et al. (1989) and Regev and Shara (1989) suggest, the above upper limit on $\dot{M}_1$ becomes smaller still, maybe as low as $\dot{M}_1 < 10^{-10} M_\odot \mathrm{yr}^{-1}$. For the following it will be important to keep these values in mind.

5 OBSERVATIONAL SELECTION AMONG CLASSICAL NOVAE IN OUTBURST

Truran and Livio (1986) were the first who recognized that the probability of detecting a classical nova going into outburst increases strongly with the mass of the white dwarf involved in the TNR. This is because the envelope mass ΔM_{ign} that is required to ignite hydrogen burning decreases rapidly with increasing white dwarf mass. In order to quantify this selection effect, Truran and Livio (1986, 1989) and Politano et al. (1989) assume that the TNR is ignited whenever a critical pressure P_{ign} at the base of the accreted envelope is reached. From the equation of hydrostatic equilibrium one then gets

$$\Delta M_{ign} = \frac{4\pi P_{ign}}{G} \frac{R_1^4}{M_1} \quad . \tag{2}$$

As is shown elsewhere in this volume (Politano et al., 1989) the resulting selection effect is so strong that about one third of all observed novae should occur on a white dwarf with $M_1 \gtrsim 1.35 M_\odot$ and more than 80% on a white dwarf with $M_1 \gtrsim 0.9 M_\odot$.

Yet the above approach is not entirely satisfactory for a number of reasons. First, as one can infer from results of Nariai and Nomoto (1979), Fujimoto (1982) and MacDonald (1984), ΔM_{ign} depends, in general, not only on M_1 but also on $\dot{M}_1$. In fact, these results suggest that P_{ign} = const. is not a good approximation. Second, the sample of novae that we observe is more likely to be magnitude limited than volume limited. Therefore, the effects of magnitude limitation, including the influence of interstellar absorption should be taken into account. Third, the accretion rate $\dot{M}_1$ is not a free parameter but rather subject to constraints from the secular evolution of CBs. In particular, the secular evolution determines the number distribution of systems as a function of $\dot{M}_1$. Fourth, one has to take into account the two-dimensional distribution of the birth rate of ZACBs, $\dot{\Sigma}_{\rm ZACB}$, over the initial masses of both components.

Taking all these additional effects into account, the frequency distribution of a visual magnitude-limited sample of classical novae in outburst is approximately (Livio et al., 1989a)

$$\frac{1}{\nu_N}\frac{d\nu_N}{dM_1} = \text{const.} L_{\rm v}^n \int_0^{M_{2,\rm crit}} \frac{1}{\Delta M_{ign}(M_1, \dot{M}_1)} \int_{M_2}^{M_{2,\rm crit}} \frac{\partial^2 \dot{\Sigma}_{\rm ZACB}}{\partial M_1 \partial M_{2,i}} dM_{2,i} dM_2 \quad . \tag{3}$$

Here $L_{\rm v}$ is the visual luminosity of a nova in outburst. As was shown by Ritter (1986b), $n = 1$ if the galactic distribution of novae is disk-like and if interstellar absorption is negligible. Including the influence of interstellar absorption one gets $n = 1/2$. For a volume-limited sample, on the other hand, one has $n = 0$.

Assuming now, that the mass of the white dwarf does not change as a result of the secular evolution, i.e. $\langle \dot{M}_1 \rangle = 0$, that $L_{\rm v}$ is approximately given by the bolometric luminosity derived from the core mass luminosity relation (e.g. Paczynski, 1970; Kippenhahn, 1980), i.e. $L_{\rm v} = L_{bol}(M_c = M_1)$, and that ΔM_{ign} may be parametrized as

$$\Delta M_{ign} = \text{const.} \left(\frac{M_1}{R_1^4}\right)^{-\alpha} \dot{M}_1^{-\beta} \tag{4}$$

we obtain

$$\frac{1}{\nu_N}\frac{d\nu_N}{dM_1} = \text{const.} L_{bol}^n(M_c = M_1) \left(\frac{M_1}{R_1^4}\right)^{\alpha} \langle \dot{M}_1^{\beta} \rangle F \frac{d\dot{\Sigma}_{\rm ZACB}}{dM_1} \quad , \tag{5}$$

where

$$F = \frac{\int_0^{M_{2,\mathrm{crit}}} \int_{M_2}^{M_{2,\mathrm{crit}}} \frac{\partial^2 \dot{\Sigma}_{\mathrm{ZACB}}}{\partial M_1 \partial M_{2,i}} dM_{2,i} dM_2}{\frac{d\dot{\Sigma}_{\mathrm{ZACB}}}{dM_1}} \approx \text{const. } q_{\mathrm{crit}} M_1 \qquad (6)$$

and $\langle \dot{M}_1^{\beta} \rangle$ is an integral mean of $\dot{M}_1^{\beta}$.

Table 1.

$\frac{M_1}{M_\odot}$	intrinsic	nova frequency $\Delta\nu_N/\nu_N$			
	$\frac{\Delta\dot{\Sigma}_{\mathrm{ZACB}}}{\dot{\Sigma}_{\mathrm{ZACB}}}$	$n = 1/2$ $\alpha = 1$	$n = 1/2$ $\alpha = 0.7$	$n = 0$ $\alpha = 1$	$n = 0$ $\alpha = 0.7$
0.5–0.6	$< 10^{-3}$	$< 10^{-3}$	0.003	0.002	0.007
0.6–0.7	0.416	0.008	0.031	0.017	0.062
0.7–0.8	0.312	0.024	0.084	0.044	0.135
0.8–0.9	0.133	0.025	0.074	0.038	0.097
0.9–1.0	0.062	0.028	0.068	0.036	0.077
1.0–1.1	0.034	0.037	0.075	0.044	0.076
1.1–1.2	0.021	0.061	0.098	0.065	0.090
1.2–1.3	0.013	0.131	0.150	0.128	0.127
1.3–1.4	0.009	0.686	0.418	0.626	0.330
$\frac{< M_1 >}{M_\odot}$	0.76	1.28	1.16	1.25	1.09

Distribution of the white dwarf masses in ZACBs and distributions of the nova frequency ν_N, corrected for observational selection, over the white dwarf masses for V-magnitude limited samples ($n = 1/2$) and volume-limited samples ($n = 0$) and two different values of $\alpha = (1, 0.7)$. The last line gives the mean white dwarf mass of the corresponding samples.

Comparing (2) and (4), we realize that the case of fixed ignition pressure corresponds to $\alpha = 1$ and $\beta = 0$. While the results of semi-analytical computations by Fujimoto (1982) and MacDonald (1984) agree reasonably well with results of detailed numerical computations (e.g. Nariai and Nomoto, 1979; Kovetz and Prialnik, 1985) as far as the value of α is concerned (all these computations yield $\alpha \lesssim 0.7$), this is not the case with regard to β. Whereas MacDonald's results yield $0.1 \lesssim \langle\beta\rangle \lesssim 0.5$, detailed numerical computations (e.g. Prialnik et al.; Kovetz and Prialnik, 1985; Starrfield et al., 1986; Prialnik, Kovetz and Shara, 1989) yield consistently smaller values, typically $0 \lesssim \beta \lesssim 0.2$. In cases of low $\dot{M}_1$ ($\dot{M}_1 \lesssim 10^{-10} M_\odot \mathrm{yr}^{-1}$) where diffusion becomes important (e.g. Kovetz and Prialnik, 1985; Prialnik, Kovetz and Shara, 1989) β becomes even as low as -0.2.

In order to illustrate, how different values of the parameters n and α influence selection, we show in Table 1 the results for the cases $n = 1/2, 0$ and $\alpha = 0.7, 1.0$, and using Politano's (1989) results for $\dot{\Sigma}_{\mathrm{ZACB}}$. Since $\langle \dot{M}_1 \beta \rangle$ depends only weakly on M_1 because β is so small ($-0.2 \lesssim \beta \lesssim 0.2$), we assume for simplicity $\beta = 0$.

As can be seen from Table 1, even in the case where selection is weakest ($n = 0$, $\alpha = 0.70$), about one third of all observed novae are expected to occur on a white dwarf with $M_1 > 1.3 M_\odot$. On the other hand, the contribution from low-mass white dwarfs, i.e. with masses $M_1 < 0.9 M_\odot$, is small but not totally negligible (at most 30% if $n = 0$ and $\alpha = 0.7$ and still 19% in the most realistic case $n = 1/2$, $\alpha = 0.7$). In conclusion, the more comprehensive treatment of the

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

selection effect yields qualitativly the same result as previous estimates by Truran and Livio (1986, 1989) and Politano et al. (1989).

6 NOVAE ON LOW-MASS WHITE DWARFS

Now that we know how observational selection influences the nova statistics, we can address the problem of the novae on low-mass white dwarfs. From the results presented in Table 1 it is clear that novae on white dwarfs with a mass $M_1 < 0.6M_\odot$ are virtually unobservable. This holds even more for the "novae" in the intrinsically numerous systems containing a He-white dwarf with $M_1 \lesssim 0.45M_\odot$ that are predicted by Politano (1988, 1989) and Politano and Webbink (1989a,b).

On the other hand, the contribution from white dwarfs in the mass range $0.6M_\odot \lesssim M_1 \lesssim 0.9M_\odot$ is of order 10% – 30%, dependig on the value of n and α, and thus not negligible. As detailed numerical computations by Kovetz and Prialnik (1985) have shown, nova explosions can occur on white dwarfs with a mass as low as $0.6M_\odot$ provided that the mass accretion rate is sufficiently low to allow diffusion to become effective. Thus it is possible that in CBs below the period gap, where the mass transfer rate is small, typically $5\ 10^{-11}M_\odot\mathrm{yr}^{-1}$, nova explosions do occur on white dwarfs with a mass as low as $0.6M_\odot$. In CBs above the period gap, however, where the mass transfer rates are much higher, typically $\dot{M}_1 \gtrsim 2\ 10^{-9}M_\odot\mathrm{yr}^{-1}$, the situation is different. Here hydrogen burning is likely to ignite non-degenerately. Now, the question is how much do these events contribute to the observed nova frequency and could we distinguish them from the more conventional novae. As to the first question, it is important to realize that secular evolution results in a number distribution of systems with a given $\dot{M}_1$ that is proportional to $\dot{M}_1^{-1}$. This means that CBs having a high $\dot{M}_1$, i.e. above the period gap, are itrinisically much rarer than those with a low $\dot{M}_1$, i.e. below the period gap. As a consequence only a (small) fraction, i.e. at most a few percent, among the observed novae could be associated with a (low M_1, high $\dot{M}_1$)-system. As to whether such events are observationally distinct from ordinary novae we can say the following: according to Fujimoto's (1982) results, in systems with a high $\dot{M}_1$, i.e. $10^{-9}M_\odot\mathrm{yr}^{-1} \lesssim \dot{M}_1 \lesssim 10^{-8}M_\odot\mathrm{yr}^{-1}$, the TNR is not strong enough to yield prompt ejection of the accreted envelope. Nevertheless it is strong enough to result in a slow expansion of the envelope to radii larger than the orbit of the secondary. It has only recently been realized that the secondary's interaction with the engulfing envelope, i.e. the common envelope evolution, probably results in the loss of the envelope on a short time scale and with rather high ejection velocites in all those cases where prompt ejection of the envelope fails (see e.g. Livio, 1989; Livio et al., 1989b). Thus it is likely that the (low M_1, high $\dot{M}_1$)-systems shed their envelope via common envelope interaction. A distant observer would probably classify such an event as a slow nova, like Nova Delphini 1967 = HR Del. Finally, what about the systems with $\dot{M}_1 \gtrsim 10^{-8}M_\odot\mathrm{yr}^{-1}$? These would probably not contribute to a visual magnitude-limited sample, because hydrogen ignition does not result in a significant envelope expansion. Although such objects are bolometrically bright, they remain geometrically small ($R \lesssim 1R_\odot$) and thus extremely hot. Thus they are bright in the EUV but faint in the visual and are, therefore, correspondingly suppressed in a visual magnitude-limited sample.

7 THE $\dot{M}$-PROBLEM

Most of the known postnova binaries have an orbital period $P \gtrsim 3$ hrs. Thus, if these systems are ordinary CBs above the period gap, we must conclude that the long-term mean of the mass transfer rate is $\langle -\dot{M}_2 \rangle \gtrsim 2\ 10^{-9} M_\odot \mathrm{yr}^{-1}$, in order to be consistent with the requirements of the period gap model. On the other hand, in order to get a strong nova explosion, i.e. one that results in prompt ejection of the envelope, the standard TNR model requires that $\dot{M}_1 \lesssim 10^{-9} M_\odot \mathrm{yr}^{-1}$ and may be even much less, depending on the importance of boundary layer heating (see section 4). Because the mass transfer/accretion rate requirements of the two models are mutually incompatible, either the TNR model or that of the period gap is in serious trouble. In the following we shall discuss briefly a number of theoretical and observational consequences of various attempts that have been made to resolve the above conflict.

a) Cyclic evolution (hibernation) of novae

One possible way out of the problem is to realize that mass accretion between two subsequent outbursts need not be stationary. This is important because the above-mentioned upper limit of $\dot{M} \lesssim 10^{-9} M_\odot \mathrm{yr}^{-1}$ required in order to allow for a strong TNR even on a massive white dwarf holds only for stationary accretion. Therefore, one might ask how the limit on the mean accretion rate would change if mass transfer in CBs were nonstationary on relatively short time scales of order $10^2 - 10^4$ yr. This question has recently been addressed by Shara et al. (1986), Prialnik and Shara (1986) and Livio, Shankar and Truran (1988) in the context of the so-called hibernation scenario of classical novae. In this scenario it is assumed that after a nova outburst the mass transfer rate is high, i.e. of order of $10^{-8} M_\odot \mathrm{yr}^{-1}$ for a relatively short accretion phase of duration Δt_{accr}, during which most of the hydrogen-rich envelope involved in the subsequent outburst is accreted. After this accretion phase the postnova enters a prolonged phase of low accretion, i.e. the hibernation phase (of duration Δt_H), during which the hydrogen layer has time to cool and to become degenerate, thus allowing for a strong TNR. The hibernation scenario was proposed by Shara et al. (1986) in response to the observational facts that, on the one hand, postnovae are bright and thus have a high accretion rate of order $10^{-8} M_\odot \mathrm{yr}^{-1}$ for the first few $10 - 10^2$ yrs after the outburst, whereas, on the other hand, the two oldest postnovae known (CK Vul = Nova Vul 1670 and WY Sge = Nova Sge 1783) are now extremely faint and thus must have a very low mass transfer rate $\dot{M}_1 \lesssim 10^{-10} M_\odot \mathrm{yr}^{-1}$. The main problem with the hibernation scenario is that we know of no viable mechanism capable of modulating the mass transfer rate in the proposed way. An early suggestion by Shara et al. (1986) according to which hibernation is a consequence of mass ejection during the nova outburst was refuted by Ritter (1988). Another mechanism involves irradiation of the cool secondary by the hot nova remnant. However, in view of arguments put forward by King (1989) it is not clear whether an irradiation feedback mechanism could actually work.

What is important in the context of our problem is the fact that a white dwarf of a given mass can tolerate a higher mean accretion rate and still produce a strong TNR if the mass transfer rate is modulated in the way proposed in the hibernation scenario. In detailed numerical models which, however, ignore boundary layer heating, Prialnik and Shara (1986) and Livio, Shankar and Truran (1988) obtained strong nova outbursts on massive white dwarfs ($1 M_\odot$, $1.25 M_\odot$) for mean accretion rates as high as (4–5) $10^{-9} M_\odot \mathrm{yr}^{-1}$. Yet, in order to be consistent with the requirements of the period gap model, we still require $\langle -\dot{M}_2 \rangle \gtrsim 2\ 10^{-9} M_\odot \mathrm{yr}^{-1}$ for systems above the gap. Thus, if the mass transfer rate during the accretion phase is $-\dot{M}_2 \approx 10^{-8} M_\odot \mathrm{yr}^{-1}$, this means that the hibernation phase must be short, i.e. $\Delta t_H \lesssim 4 \Delta t_{\mathrm{accr}} \approx 10^3$ yr.

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

Thus, if boundary layer heating is not too important, it appears as if the cyclic evolution of novae through phases of high and low $\dot{M}_1$ inbetween the outbursts provides at least a partial solution of the $\dot{M}$ problem.

b) Weak TNRs and common envelope evolution

We have already discussed in section 6 the possibility that a nova envelope can be ejected via its interaction with the secondary even in cases where the underlying TNR is too weak to yield prompt ejection. If this mechanism works efficiently whenever the envelope expands beyond the orbit of the secondary and if such events appear like ordinary novae, then the $\dot{M}$ problem disappears immediately. This is because envelope expansion to radii $R >$ few $R_\odot$ is to be expected whenever $\dot{M}_1 \lesssim 10^{-8} M_\odot \mathrm{yr}^{-1}$, almost independent of the mass of the white dwarf (Fujimoto, 1982). There is thus the possibility that in all but the fastest and most energetic novae (like Nova Cyg 1975 = V1500 Cyg), the underlying TNR is in fact relatively weak, too weak to yield prompt ejection, but that envelope ejection nevertheless occurs via common envelope interaction.

Another attractive feature of this model is that it provides a natural explanation for the enhanced mass transfer in the post-nova binary required by the model of cyclic evolution. This is because envelope ejection occurs at the expense of the binary's binding energy and, therefore, results in a reduction of the orbital separation which, in turn, leads to an increase of the mass transfer rate by roughly the factor

$$\Delta \ln \dot{M}_2 \approx \frac{R_2}{H_P} \left(1 + \frac{M_1}{M_2}\right) \frac{\Delta M_{ej}}{M_1} \quad . \tag{7}$$

Here R_2 is the radius of the secondary, H_P the pressure scale height in its atmosphere and ΔM_{ej} the ejected mass. Since typically $R_2/H_P \approx 10^4$ (see e.g. Ritter, 1988) and $\Delta M_{ej}/M_1 \approx 10^{-4} \ldots 10^{-5}$ we see that $\Delta \ln \dot{M}_2$ will be of order unity at most. Incidentially, this model is in a way the exact opposite of what the original hibernation scenario (Shara et al., 1986) proposed.

Because of its importance for the nova problem, common envelope evolution following a TNR is a promising subject for future observational and theoretical investigations.

c) Modifying the model of disrupted magnetic braking

The lower limit of $-\dot{M}_2 \gtrsim 2\ 10^{-9} M_\odot \mathrm{yr}^{-1}$ required by the gap model derives from the fact that the secondary has to be driven significantly out of thermal equilibrium before entering the gap. The same effect as results from mass loss can, at least in principle, also be obtained from star spots on the secondary (Spruit and Ritter, 1983). Thus the standard gap model might be modified by including the effects of star spots. Although it is difficult to make a quantitative estimate, it is speculated that part of the secondary's radius excess could be caused by spots and part by mass loss, but now at a lower rate. However, the mass transfer rate above the gap may not be too small, say not smaller than $\sim 10^{-9} M_\odot \mathrm{yr}^{-1}$, otherwise other well-established concepts of the evolution of CBs, in particular of magnetic CBs (see e.g. King, 1988) and the existence above the gap of many systems with bright stationary accretion disks would be difficult to account for.

d) Boundary layer heating

We have already mentioned the possible impact of boundary layer heating on the TNR model of novae. Since we cannot exclude that the upper limit for getting a strong TNR is as low as $10^{-10} M_\odot \mathrm{yr}^{-1}$, we wish to discuss briefly the possibility that classical nova binaries are really systems in which $\langle \dot{M}_1 \rangle \lesssim 10^{-10} M_\odot \mathrm{yr}^{-1}$. If this is the case, then nova binaries are unlike the rest of the known CBs, contrary to what is usually assumed. They then represent a peculiar selection of CBs that have just a low enough mass transfer rate to allow for a strong TNR to occur. However, if this were the case, the period gap model predicts that novae should either show no gap at all or at best a very narrow one. Unfortunately, the number of postnovae with known orbital periods is still much too small to test that prediction. Nevertheless, it might be of interest to note that Shafter and Abbott (1989) have recently recovered the old nova Persei 1887 = V Per and found it to be an eclipsing binary with an orbital period of 2.56 hrs. Thus this object sits right in the middle of the period gap!

However, the idea that nova binaries are a particular selection of CBs with a low $\dot{M}_1$ does not really solve the $\dot{M}$ problem. We still observe the other CBs and among them those above the period gap have $\dot{M}_1 \gtrsim 2\ 10^{-9} M_\odot \mathrm{yr}^{-1}$. Sooner or later the accreted hydrogen will also ignite in these systems and we have to ask what happens to them. In this way we are quickly back to the old $\dot{M}$ problem and the most likely solution discussed above in section 7b.

8 SUMMARY AND CONCLUSIONS

The aim of this paper was to explore whether the TNR model of classical nova outbursts and our current understanding of the formation and long-term evolution of CBs, of which novae are a subgroup, are compatible. Specifically we have addressed the following three questions: 1) whether observational selection can explain the high white dwarf masses attributed to novae, 2) whether novae on white dwarfs of relatively low mass, i.e. in the range $0.6 M_\odot \lesssim M_1 \lesssim 0.9 M_\odot$, could occur and how much they could contribute to the observed nova frequency, and 3) whether the high mass transfer rates imposed on the white dwarf in CBs above the period gap can be accommodated within the TNR model of classical nova oubursts.

Using the best currently available data on the intrinsic properties of newly formed CBs (Politano, 1988, 1989; Politano and Webbink, 1989a,b) and a detailed model for observational selection, we find that the selection effect is strong enough to account for the tendency of observing novae preferentially on high-mass white dwarfs.

Novae on low-mass white dwarfs, i.e. in the mass range $0.6 M_\odot \lesssim M_1 \lesssim 0.9 M_\odot$, could contribute between 10% and 30% to the observed nova frequency. In CBs below the period gap which have a low mass transfer rate $\dot{M}_1 \lesssim 5\ 10^{-11} M_\odot \mathrm{yr}^{-1}$, a strong TNR could still develop if diffusion is sufficiently effective (Kovetz and Prialnik, 1985).

The high accretion rates $\dot{M}_1 \gtrsim 2\ 10^{-9} M_\odot \mathrm{yr}^{-1}$ imposed on the white dwarf in systems above the period gap can best be accommodated in the framework of cyclic evolution (hibernation) through phases of high and low $\dot{M}_1$ between the outburst.

Most important is the recognition that in all systems where the TNR is not strong enough to yield prompt ejection of the envelope, but $\dot{M}_1 \lesssim 10^{-8} M_\odot \mathrm{yr}^{-1}$, the interaction of the secondary with the engulfing envelope will probably result in its ejection with rather high ejection velocities and on a rather short time scale and in this way mimic a slow or moderately fast nova.

https://doi.org/10.1017/S0252921100068810 Published online by Cambridge University Press

Acknowledgements

The author is grateful to Drs. F. Meyer, M. Livio, M. Politano, J. Truran and R. Webbink for stimulating discussions, and to the IAU for travel support.

References

Bode, M.F., Evans, A. (eds.): 1989, Classical Novae, J. Wiley & Sons Ltd., Chichester

Fujimoto, M.Y.: 1982, Astrophys. J. 257, 767

King, A.R.: 1988, Quart. J. Roy. Astron. Soc. 29, 1

King, A.R.: 1989, preprint

Kippenhahn, R.: 1980, Astron. Astrophys. 102, 293

Kovetz, A., Prialnik, D.: 1985, Astrophys. J. 291, 812

Kraft, R.P.: 1964, Astrophys. J. 139, 457

Livio, M.: 1989, this volume

Livio, M., Shankar, A., Truran, J.W.: 1988, Astrophys. J. 325, 282

Livio, M., Politano, M.J., Ritter, H., Webbink, R.F.: 1989a, in preparation

Livio, M., Shankar, A., Burkert, A., Truran, J.W.: 1989b, this volume

MacDonald, J.: 1984, Astrophys. J. 283, 241

McDermott, P.N., Taam, R.E.: 1989, Astrophys. J. 342, 1019

Nariai, K., Nomoto, K.: 1979, in: White Dwarfs and Variable Degenerate Stars, IAU Coll. No. 53, H.M. van Horn and V. Weidemann (eds.), University of Rochester, N.Y., p.525

Paczynski, B.: 1970, Acta Astron. 20, 47

Politano, M.J.: 1988, Ph. D. thesis, Univ. of Illinois at Urbana-Champaign

Politano, M.J.: 1989, private communication

Politano, M.J., Webbink, R.F.: 1989a, in: White Dwarfs, IAU Coll. No. 114, G. Wegner (ed.), Lecture Notes in Physics 328, Springer Verlag, Berlin, p. 440

Politano, M.J., Webbink, R.F.: 1989b, this volume

Politano, M., Livio, M., Truran, J.W., Webbink, R.F.: 1989, this volume

Prialnik, D., Livio, M., Shaviv, G., Kovetz, A.: 1982, Astrophys. J. 257, 312

Prialnik, D., Shara, M.M.: 1986, Astrophys. J. 311, 172

Prialnik, D., Kovetz, A., Shara, M.M.: 1989, Astrophys. J. 339, 1013

Rappaport, S., Verbunt, F., Joss, P.C.: 1983, Astrophys. J. 275, 713

Regev, O., Shara, M.M.: 1989, Astrophys. J. 340, 1006

Ritter, H.: 1985, Astron. Astrophys. 145, 227

Ritter, H.: 1986a, in: The Evolution of Galactic X-ray Binaries, J. Trümper, W.H.G. Lewin and W. Brinkmann (eds.) NATO ASI Series C Vol. 167, D. Reidel, Dordrecht, p. 207

Ritter, H.: 1986b, Astron. Astrophys. 168, 105

Ritter, H.: 1987, Astron. Astrophys. Suppl. Ser. 70, 355

Ritter, H.: 1988, Astron. Astrophys. 202, 93

Shafter, A.W., Abbott, T.M.C.: 1989, Astrophys. J. Letters. 339, L75

Shara, M.M.: 1989, Publ. Astron. Soc. Pacific 101, 5

Shara, M.M., Livio, M., Moffat, A.F.J., Orio, M.: 1986, Astrophys. J. 311, 163

Shaviv, G., Starrfield, S.: 1987, Astrophys. J. Letters 321, L51

Sparks, W.M.: 1989, this volume

Spruit, H.C., Ritter, H.: 1983, Astron. Astrophys. 124, 267

Starrfield, S., Sparks, W.M., Truran, J.W.: 1986, Astrophys. J. Letters 303, L5

Starrfield, S., Sparks, W.M., Shaviv, G.: 1988, Astrophys. J. Letters 325, L35

Truran, J.W.: 1989, this volume

Truran, J.W., Livio, M.: 1986, Astrophys. J. 308, 721

Truran, J.W., Livio, M.: 1989, in: White Dwarfs, IAU Coll. No. 114, G. Wegner (ed.), Lecture Notes in Physics 328, Springer Verlag, Berlin, p. 498

Walker, M.F.: 1956, Astrophys. J. 123, 68

Warner, B.: 1976, in: Structure and Evolution of Close Binary Systems, IAU Symp. No. 73, P. Eggleton, S. Mitton and J. Whelan (eds.), D. Reidel, Dordrecht, p. 85