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TYPE I SUPERNOVAE AND ACCRETION-INDUCED COLLAPSES FROM CATACLYSMIC VARIABLES?

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ABSTRACT

We examine the possibility that the white dwarfs in cataclysmic variables might grow in mass to the Chandrasekhar limit. We demonstrate that the masses of the white dwarfs in classical nova systems generally decrease as a result of nova explosions. We present observational and theoretical evidence in support of the view that the masses of the white dwarfs in recurrent nova systems increase. The critical parameters for which a mass increase is obtained are approximately $M_{WD} > 1.2\ M_\odot$ and $\dot{M} > 10^{-8}\ M_\odot\ yr^{-1}$. The systems in which the white dwarfs are most likely to reach the Chandrasekhar limit are those which satisfy the above limits on the mass of the white dwarf and on the accretion rate and in which, in addition, the secondary stars are transferring helium-rich material. A subclass of the recurrent novae satisfies all of these conditions. The cataclysmic variable systems in which the white dwarf components can grow to the Chandrasekhar limit are most likely to produce an accretion-induced collapes, rather than a Type Ia supernova. We calculate the rate of these events and find it to be consistent with the birth rate of low-mass X-ray binaries.

Subject headings: novae, cataclysmic variables — stars: evolution — stars: statistics — supernovae: general — white dwarfs

1. INTRODUCTION

A large number of recent works have examined the possibility that white dwarfs (WDs) can grow by accretion to the Chandrasekhar limit, thus yielding either an accretion-induced collapse (AIC) (Bailyn & Grindlay 1990; Romani 1990; Nomoto & Kondo 1990; Canal, Isern, & Labay 1990) or a Type Ia supernova (Wheeler 1990, and references therein). In particular, Wheeler (1990) argued that cataclysmic variables (CVs) can evolve to an explosive endpoint, in contradiction to earlier conclusions by MacDonald (1984). Moreover, Starrfield, Sparks, & Truran (1985) and Starrfield et al. (1991) have argued specifically that recurrent novae which involve thermonuclear runaways on massive ONeMg white dwarfs may ultimately give rise to Type I supernovae.

In the present work, we shall not discuss in detail the question of whether an AIC or a Type Ia SN is the more likely product (see Nomoto & Kondo [1990] for a recent examination of this point). Rather, we will be concerned with the general question as to whether the white dwarf's mass in a CV can grow to the Chandrasekhar mass. Our analysis concentrates specifically on recent developments in our understanding of recurrent novae (RNs) and their relation to the entire population of classical nova (CNs) systems.

Since RNs will turn out to be the prime candidates for the growth of the white dwarf mass, we discuss RNs in § 2 and CVs in general in § 3. Statistical considerations are presented in § 4. A summary and conclusions follow.

2. RECURRENT NOVAE

2.1. *General Properties*

The number of objects in the class of RNs has increased significantly in the last year, due to the discovery of three new RNs. Presently, the class consists of eight objects: T CrB, RS Oph, V745 Sco, V3890 Sgr, U Sco, V394 CrA, Nova LMC 1990 No. 2, and T Pyx. Other objects previously classified as RNs were rejected by Webbink et al. (1987; hereafter WLTO; see also Webbink 1990). The years of the recorded outbursts and the orbital periods (when known) for the RNs are given in Table 1.

In spite of the fact that they include a small number of objects, RNs seem to fall into three different groups (see WLTO). The first group consists of T CrB, RS Oph, V745 Sco, and V3890 Sgr. These systems all seem to contain late-type giants. In T CrB and RS Oph, the giants have been classified as M4.1 III and K5.7 II–III, respectively (Kenyon & Fernandez-Castro 1987). In V745 Sco, TiO bands of an M6–6.5 III star have been identified (e.g., Duerbeck, Schwarz, & Augusteijn 1989; Spyromilio & Whitelock 1989), while the spectrum of V3890 Sgr was found to be similar to that of V745 Sco (Wagner, Bertram, and Starrfield 1990) and of RS Oph (Sekiguchi 1990).

The second distinctive group of RNs consists of U Sco, V394 CrA, and, probably, Nova LMC 1990 No. 2. These are extremely fast novae ($t_3 \sim 5$–10 days), and their spectra are characterized by the fact that the narrow He II λ4686 emission line is much stronger than Hβ (e.g., Sekiguchi et al. 1988, 1989, 1990; Shore et al. 1990). The third group of RNs presently consists only of T Pyx, which is quite unique in its rather slow light curve development ($t_3 = 88^d$; Duerbeck 1987) and short orbital period ($P = 2.3783$ hr or 2.6403 hr; Schaefer 1990).

2.2. *The Outburst Mechanism*

Scrutiny of possible outburst mechanisms, based on the observational data that was available in 1986, led WLTO to propose that the outbursts of U Sco (and therefore, by similarity, of V394 CrA and of Nova LMC 1990 No. 2) and of T Pyx are caused by thermonuclear runaways (TNRs) on the surfaces of massive white dwarfs, while they concluded that the outbursts of T CrB and RS Oph (and therefore perhaps also of V745 Sco and V3890 Sgr) are better explained in terms of

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TABLE 1

RECURRENT NOVAE

System	Years of Recorded Outbursts	Orbital Period
T Pyxidis	1890, 1902, 1920, 1944, 1966	2.3783 hr or 2.6403 hr
U Scorpii	1863, 1906, 1936, 1979, 1987	1.2344 day
V394 CrA	1949, 1987	0.7577 day
Nova LMC 1990 no. 2	1968, 1990	
T Coronae Borealis	1866, 1946	227.53 day
RS Ophiuchi	1898, 1933, 1958, 1967, 1985	230 day
V745 Scorpii	1937, 1989	
V3890 Sagittarii	1962, 1990	

accretion events onto main-sequence stars. We shall discuss later some new observational evidence which seems to indicate that the outbursts of T CrB and RS Oph (and therefore probably also of V745 Sco and V3890 Sgr) may also be caused by TNRs on white dwarfs. For the moment, however, we shall concentrate on the "U Sco-like" objects since, in spite of the fact that WLTO suggested a TNR model for their outbursts, these same authors were quick to point out a number of serious difficulties that such a model encounters (see also Truran et al. 1988; Duschl, Livio, & Truran 1990). We shall first review briefly the essential ingredients of TNR models for RNs, their associated difficulties, and possible solutions to these difficulties, since the properties of the systems that can be inferred from these models are absolutely crucial to the determination of the likelihood that the white dwarf mass grows to the Chandrasekhar limit.

A TNR is obtained at the base of the accreted hydrogen layer once the time scale for energy generation by the nuclear reactions becomes shorter than the energy transport time scale. This translates into a critical ignition mass (envelope mass) which has to be accreted prior to the thermonuclear runaway. The results of detailed numerical calculations can be quite adequately represented by the expression (Truran & Livio 1986; Ritter et al. 1991)

$$\frac{\Delta M_{\rm ign}}{M_\odot} \simeq 6.3 \times 10^{-5}\left[\left(\frac{R_{\rm WD}}{0.01\ R_\odot}\right)^4\left(\frac{M_{\rm WD}}{M_\odot}\right)^{-1}\right]^{0.7} . \qquad (1)$$

In combination with a mass-radius relation for the white dwarf (e.g., Nauenberg 1972), we can obtain an expression for the recurrence time scale of nova-type outbursts caused by TNRs as

$$\tau_{\rm rec} \simeq 8.66 \times 10^4\ {\rm yr}\left(\frac{\dot{M}}{10^{-9}\ M_\odot\ {\rm yr}^{-1}}\right)^{-1} \times\left[1.54\left(\frac{M_{\rm WD}}{M_\odot}\right)^{-7/3} - 2.0\left(\frac{M_{\rm WD}}{M_\odot}\right)^{-1} + 0.65\left(\frac{M_{\rm WD}}{M_\odot}\right)^{1/3}\right]^{0.7} . \qquad (2)$$

The recurrence time scale as a function of the WD mass is shown in Figure 1, for different mean values of the accretion rate $\dot{M}$. Also shown in Figure 1 are the shortest recurrence time scales of the eight RNs (we ignore for the moment the possibility that the outbursts of some of them may be caused by other mechanisms).

One thing that becomes immediately clear from Figure 1 is the fact that, in order to obtain the extremely short recurrence time scales characterizing RNs, *very high accretion rates are required.* This raises the important question as to whether nova-like outbursts can occur under such conditions. Theoretical calculations have shown that, at very high accretion rates compressional heating leads to ignition under only mildly degenerate conditions, which results in weak TNRs (or even stable burning) and at best a relatively weak nova-type outburst (e.g., MacDonald 1984; Fujimoto 1982). It is important, therefore, to establish whether nova outbursts can be obtained at all at the accretion rates that seem to be implied by Figure 1. In Figure 2, we show the critical lines obtained by the semianalytical calculations of MacDonald (1983) and Fujimoto (1982). According to these calculations, the different types of outbursts (e.g., slow nova, fast nova, etc.) can be obtained only for systems which are located below the respective lines in the $(M_{\rm WD},\ \dot{M})$ plane. Detailed numerical calculations reveal, however, that while the qualitative concept expressed by the lines in Figure 2 is correct, the exact location of the "nova dud line" is quite different from the one obtained by the semianalytical calculations. Figure 2 shows representative calculations which produced strong nova-type outbursts and which are located significantly above the lines of MacDonald (1983) and Fujimoto (1982). The deviation is particularly large for high WD masses, $M_{\rm WD} \geq 1.35\ M_\odot$. Nevertheless, a number of numerical calculations have indeed produced only very weak outbursts (e.g., Kutter & Sparks 1980; Prialnik et al. 1982; Kovetz & Prialnik 1985). These calculations are presented in

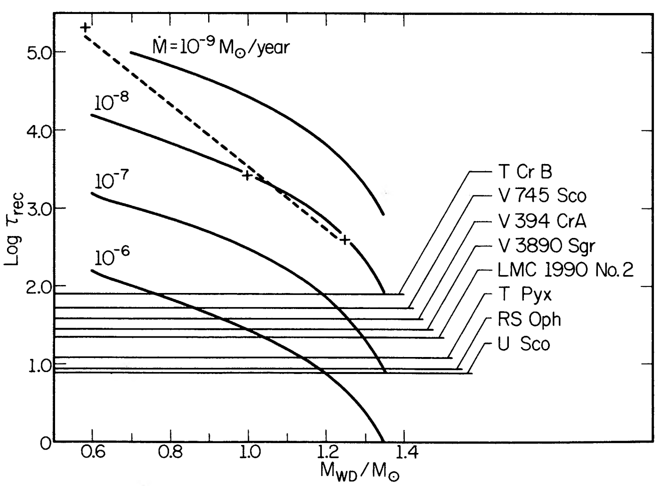

FIG. 1.—The recurrence time scale as a function of the white dwarf mass for different accretion rates. The shortest recurrence time scales of the recurrent novae are indicated. An approximate "nova dud line" (see text) is indicated by a dashed line. The points marked SST and SSS indicate calculations that resulted in strong outbursts by Starrfield, Sparks, & Truran (1985) and Starrfield, Sparks, & Shaviv (1988a), respectively.

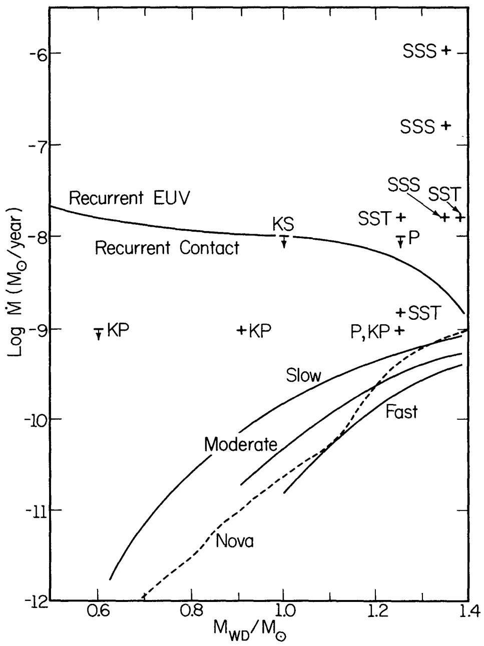

FIG. 2.—The critical lines below which novae of different speed classes are obtained (*dashed lines*) are according to MacDonald (1984). The lines which separate novae from recurrent contact and recurrent EUV systems (*solid lines*) are according to Fujimoto (1982). The points indicate successful nova calculations by Starrfield et al. (1985, SST), Starrfield et al. (1988a, SSS), Prialnik et al. (1982, P), and Kovetz & Prialnik (1985, KP). The upper limits indicate calculations which did not result in strong outbursts by Prialnik et al. (1982, P), Kovetz & Prialnik (1985, KP), and Kutter & Sparks (1980, KS). An approximate " nova dud line " (see text) would pass through the marked upper limits.

Figure 2 as upper limits on the accretion rate, and the approximate " nova dud line " that is obtained from them is shown in Figure 1. *When the existence of this nova dud line is taken into account we find that, for the known RNs to be explained in terms of TNRs, these systems must satisfy* $M_{WD} \geq 1.3\ M_{\odot}$, $\dot{M} \geq 10^{-8}\ M_{\odot}\ yr^{-1}$.

These conditions make these systems obvious candidates for growth of the WD mass to the Chandrasekhar limit, since their WD masses may already be quite close to the limit and they accrete at a high rate. In order to determine whether the Chandrasekhar limit can indeed be reached, we must first be able to determine whether the mass of the WD increases or decreases as it undergoes frequent nova outbursts. However, before we examine this important question, we must establish the fact that the outbursts of (at least some fraction of) the recurrent nova systems are indeed produced by TNRs. To this goal, we must reexamine various difficulties that have been pointed out for TNR models for the outbursts of RNs, in order to determine if these difficulties can be overcome.

The first difficulty that has been identified has already been discussed above. It is associated with the existence of the nova dud line. In fact, MacDonald (1983) and Prialnik et al. (1982) concluded that RNs are not powered by TNRs, because of the high accretion rates they found to be required. As we have noted, however, the nova dud line obtained by detailed numerical computations is quite different from the semi-analytical one and does allow the production of strong outbursts for sufficiently high WD masses, even at high accretion rates. In fact, the calculation of Starrfield et al. (1985) produced a strong TNR with a recurrence time of 33 yr, for a case involving accretion at $\dot{M} = 1.6 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ onto a 1.38 $M_{\odot}$ WD. Similarly, the calculation of Starrfield et al. (1988a) yielded a recurrence time of ~ 2 yr for accretion at $\dot{M} = 1.1 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ onto a 1.35 $M_{\odot}$ WD.

A second difficulty that was pointed out by WLTO was associated with observations of U Sco at quiescence (see also Duschl et al. 1990). WLTO noted that, if the FWZI of the He II emission lines observed by Hanes (1985) at quiescence (2560 km s^{-1}) are to be interpreted as resulting from Keplerian motion around a massive WD, then this would imply that the accretion disk in the system is observed nearly face on (at $i \sim 7°$). WLTO calculated the luminosity of such an accretion disk and concluded that, for a WD near the Chandrasekhar limit accreting at $\dot{M} \gtrsim 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$, the observed luminosity of U Sco at quiescence ($V = 17.9$) would put U Sco at an uncomfortably large distance (in fact it would make it an extragalactic object, see Fig. 3). The recent discovery that U Sco is an eclipsing system seen almost edge-on (Schaefer 1990) has resolved this difficulty (see Fig. 3) and the distance to U Sco is found to be in the range 5–15 kpc. A similar distance range is obtained from the requirement that the secondary (evolved) companion must fill its Roche lobe (Schaefer 1990). Also, if we assume that the system is essentially identical (in outburst) to LMC 1990 no. 2, then the fact that U Sco is about a factor 10 brighter (Shore et al. 1990), puts it at a distance of ~ 15 kpc. A fit of a theoretical light curve to the observed light curve in the decay phase gives a distance in the range 3.6–8.6 kpc (Kato 1990).

A third difficulty in modeling the outbursts of U Sco, V394 Cr A, and LMC 1990 No. 2 by TNRs is associated with their spectra, both in outburst and at quiescence. The abundance analysis for the outburst stage indicates an overabundance of helium: He/H ~ 2 by number (Barlow et al. 1981; Williams et al. 1981; Sekiguchi et al. 1988; Sekiguchi et al. 1990). Further-

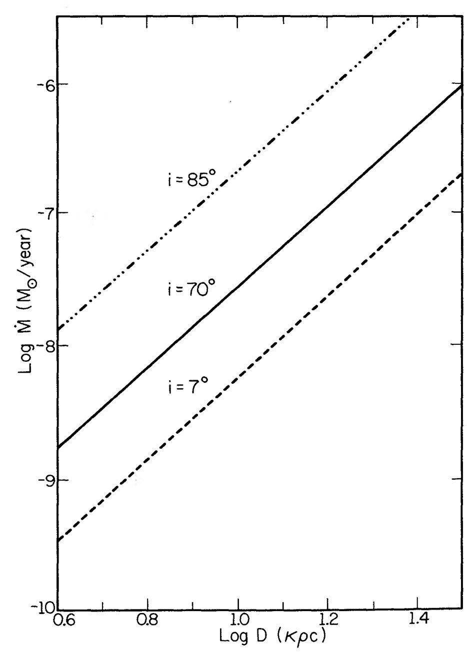

FIG. 3.—The distance-accretion rate relation implied for U Sco by its luminosity at quiescence. It is assumed that the luminosity is generated in a standard accretion disk. The different lines correspond to different inclination angles.

more, He II λ4686 is much stronger than Hβ even in quiescence (Hanes 1985; Duerbeck & Seitter 1990; Williams et al. 1981; Sekiguchi et al. 1990), which may indicate an overabundance of helium relative to hydrogen in the accreted material. The reason why hydrogen depletion may present a difficulty for TNR models is evident from the ratio of the specific nuclear energy to the specific binding energy, given by (Truran et al. 1988)

$$\frac{\epsilon_{\rm nuc}}{\epsilon_{\rm bind}} \simeq 6.5 X_{\rm H}\left(\frac{M_{\rm WD}}{1.38\ M_\odot}\right)^{-1}\left(\frac{R_{\rm WD}}{1.9\times10^8\ {\rm cm}}\right), \quad (3)$$

where $X_{\rm H}$ is the mass fraction of hydrogen in the (accreted) envelope material. We thus see that, for very low values of $X_{\rm H}$ ($X_{\rm H} \sim 0.11$ is indicated by the observations), a rapid expansion accompanied by mass ejection (as observed in U Sco, V394 CrA, and LMC 1990 No. 2) is largely impeded. The calculations of Truran et al. (1988) indeed failed to reproduce the outburst characteristics of U Sco for $X_{\rm H} < 0.65$. It should be noted, however, that large uncertainties exist in the calculation of the expansion phase in novae (see, e.g., Truran et al. 1992 for a discussion). Indeed, in a simulation in which the efficiency of convection was increased and the opacities were artificially increased by a factor 2 (which perhaps better represents the real line opacities in the expanding envelope), Starrfield et al. (1988a) were able to obtain a moderately strong outburst even with $X_{\rm H} = 0.11$. Furthermore, the observed light curve in the decay phase is very well fitted by models which use $X_{\rm H} \simeq 0.11$ (Kato 1990). It seems, therefore, that the difficulties associated with reproducing the outburst characteristics for low $X_{\rm H}$ may simply represent the result of the present, relatively poor treatments of the radiation-matter interaction in the expansion phase. Nevertheless, the question of the possibility for the secondary to transfer helium-rich material, from the evolutionary point of view, definitely deserves further consideration (see, e.g., WLTO). Similarly, it should be established beyond doubt that the observed spectra (with He II λ4686 much stronger than Hβ) indeed indicate an overabundance of helium and cannot be produced, for example, by a density (collisional ionization) effect (for strong density effects, see, e.g., Hummer & Storey 1987; Almog & Netzer 1989). The observed overabundance almost certainly cannot represent a pure temperature effect (R. E. Williams 1990, private communication). We shall discuss the helium abundance again in § 3, in relation to the mass growth.

From the above discussion, we therefore conclude that at least the outbursts of the recurrent novae T Pyx, U Sco, V394 CrA, and Nova LMC 1990 No. 2 are very likely to be caused by TNRs which result from accretion at a very high rate ($\dot{M} > 10^{-8}\ M_\odot\ {\rm yr}^{-1}$) onto a very massive WD ($M_{\rm WD} > 1.3\ M_\odot$). We have not discussed T Pyx specifically, but all of its characteristics make it in fact the recurrent nova with the strongest similarity to CNs (see WLTO for discussion). We should emphasize, however, that if future observations find the mass of the white dwarf in any of these systems to be significantly lower than 1.3 $M_\odot$, this would pose severe difficulties for a TNR model for that system, and it should therefore be excluded from our discussions in the following sections.

The situation concerning T CrB and RS Oph (and the other objects of this subclass, V745 Sco and V3890 Sgr) is more complicated. In fact, based on the observations then available, Webbink (1976), Livio, Truran, & Webbink (1986) and WLTO suggested that the outbursts of these RNs are caused by accretion events onto main-sequence stars. However, a number of recent observations (Selvelli, Cassatella, & Gilmozzi 1990; S. Starrfield, private communication) suggest the possibility that the outbursts of T CrB and RS Oph are rather caused by TNRs on the surfaces of WDs. Since these objects are not "classical" CVs (they contain giants), we shall not discuss them any further in the present work.

3. DOES THE MASS OF THE WHITE DWARF GROW IN CVS?

Clearly the most important question to be considered in our attempt to determine whether the white dwarfs in CVs can reach the Chandrasekhar limit is the following: Can the white dwarfs grow in mass? We shall proceed to address this question from both the observational and the theoretical points of view.

3.1. *The Implications of Adundances in Novae Ejecta*

The abundance determinations for the ejecta of novae are crucial to the question of the evolution of the white dwarf mass. We shall therefore briefly review the observational situation. Table 2 gives an updated list of the most reliable abundance determinations for classical novae (Truran 1990). Figure 4 shows the location of all the systems in the (Z, Y) plane (we are grateful to Mariko Kato for suggesting this presentation). Also shown in the figure are two lines indicating the expected Z-Y relations if the specified accreted layers are mixed directly with core material (this assumes there to be no residual helium

TABLE 2

HEAVY ELEMENT ABUNDANCES IN NOVAE

Object	Year	Ref.	H	He	C	N	O	Ne	Na	Mg	Al	Si	S	Fe
			Mass Fractions											
RR Pic	1925	1	0.53	0.43	0.0039	0.022	0.0058	0.011						
HR Del	1967	2	0.45	0.48	0.027	0.047	0.0030							
T Aur	1891	3	0.47	0.40	0.079	0.051								
PW Vul	1984	4	0.69	0.25	0.0033	0.049	0.014							
V1500 Cyg	1975	5	0.49	0.21	0.070	0.075	0.13	0.023						
V1668 Cyg	1978	6	0.45	0.23	0.047	0.14	0.13	0.0068						
V693 CrA	1981	7	0.29	0.32	0.046	0.080	0.12	0.17	0.0016	0.0076	0.0043	0.0022		
GQ Mus	1983	4	0.27	0.32	0.016	0.19	0.19	0.0034		0.0014	0.00056	0.0028	0.0016	0.00047
DQ Her	1934	8	0.34	0.095	0.045	0.23	0.29							
V1370 Aql	1982	9	0.053	0.088	0.035	0.14	0.051	0.52		0.0067		0.0018	0.10	0.0045

REFERENCES.—(1) Williams & Gallagher 1979; (2) Tylenda 1978; (3) Gallagher et al. 1980; (4) Saizar et al. 1991; (5) Ferland & Shields 1978; (6) Stickland et al. 1981; (7) Williams et al. 1985; (8) Williams et al. 1978; (9) Snijders et al. 1987.

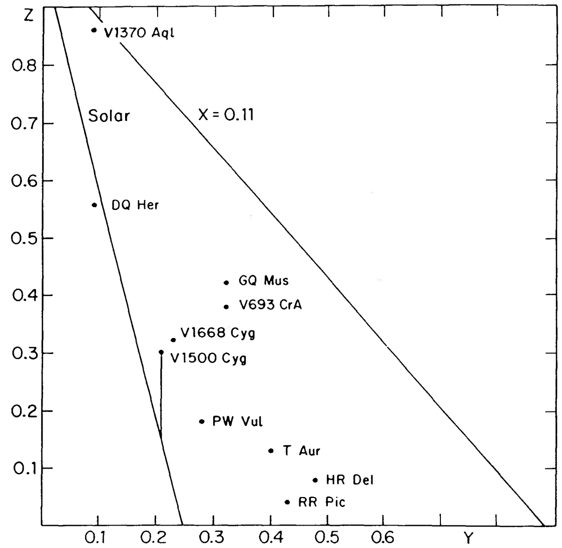

FIG. 4.—The location of different nova systems in the heavy-element–helium (Z, Y) mass fraction plane. The lines represent the expected Z-Y relation if the accreted layer is mixed with core material. The line marked "solar" represents a solar composition for the accreted material. The line marked "$X = 0.11$" represents the accretion of helium-rich material (see text). The range in Z indicated by the observations of V1500 cyg is marked by the vertical line.

layer on top of the white dwarf). The line marked "solar" represents a solar composition of the accreted material, while that marked "X = 0.11" represents the accretion of material that is very helium rich (as seems to be the case for the RNs of the U Sco group). Figure 4 clearly indicates that a considerable dredge-up of white dwarf material has occurred in essentially all CNs for which more or less reliable abundance determinations exist. Furthermore, two of the novae in Table 2 (V693 CrA and V1370 Aql) and two other novae (QU Vul and Nova LMC 1990 no. 1) are "neon" novae, namely novae in which the ejected material is enriched in intermediate-mass elements (e.g., Sonneborn, Shore, & Starrfield 1990). In this case, we are very probably observing material from underlying ONeMg white dwarfs (e.g., Law & Ritter 1983; Truran & Livio 1986). It must be realized that, in order for the Ne rich core material to be dredged-up, the white dwarf had to erode both its overlying helium shell, the mass of which is of order (Iben & Truran 1978)

$$\log \Delta M_{\rm He} \simeq -1.835 + 1.73 M_C - 2.67 M_C^2 , \quad (4)$$

(where M_C is the mass of the underlying degenerate core), and the CO layer (of mass $\leq 2 \times 10^{-3}\ M_{\odot}$, Nomoto 1984). Thus, *the mere existence of neon novae indicates that the white dwarfs in these systems are decreasing in mass.*

This is an extremely important point which warrants further comment. It may at first appear that the heavy-element enrichments simply indicate that mixing has occurred but not that the mass of the white dwarf is necessarily decreasing. This is not the case. It must be recognized that CO white dwarfs are expected to be born with an outer helium shell of mass given approximately by equation (4) and that ONeMg white dwarfs have in addition a CO layer of mass $\sim 2 \times 10^{-3}\ M_{\odot}$. The studied mixing mechanisms have been found to produce mixing as follows: For diffusion-induced convection, Kovetz & Prialnik (1985) obtain $\Delta m_{\rm mixed}/\Delta m_{\rm accreted} \simeq 1.65$ *at most.* For the case of shear mixing, an absolute upper limit on mixing is by a factor $\lesssim 5$ (Fujimoto 1988). The mass of the accreted material for the case, e.g., of a 1 $M_{\odot}$ white dwarf is $\sim 8.5 \times 10^{-5}\ M_{\odot}$ (e.g., Truran & Livio 1986), while the initial mass of the helium layer on the same white dwarf is $\sim 1.7 \times 10^{-3}$. Therefore, there is no way in which, by mixing alone, you can achieve a CO enrichment. The problem clearly is more severe for ONeMg white dwarfs, since they have an extra $\sim 2 \times 10^{-3}\ M_{\odot}$ of CO material through which mixing would somehow have to occur. Thus, again it appears that *the mass of the WD in CNs typically decreases as a result of nova explosions.*

In sharp contrast to the situation for CNs, there is no evidence for enrichments in heavy elements in the ejecta of recurrent novae. The nebular shell that is resolved around T Pyx (Shara et al. 1989) shows approximately solar abundances (Williams 1982), and abundance analyses of both the quiescent and outburst spectra of U Sco are consistent with normal CNO abundances (e.g., Williams et al. 1981). While U Sco, V394 CrA, Nova LMC 1990 no. 2 show an extreme overabundance of helium (He/H $\sim$ 1–2 by number), this appears not to have resulted from dredge-up, since a similar overabundance is observed in *quiescence* (Hanes 1985; Duerbeck & Seitter 1990; Sekiguchi et al. 1990). Thus, the companion is probably transferring helium-rich material. (We shall discuss this point further in § 3.2.3; see also our previous discussion of U Sco in § 2.2). *It therefore appears likely that the white dwarfs in recurrent nova systems grow in mass.* We would like to emphasize, however, that a serious abundance analysis has never been performed on T Pyx. In view of the crucial importance of such an analysis, *this should be a high priority item in the observations of the future (probably very near future) outburst of this system* (see also Livio 1991).

3.2. *Theoretical Considerations*

3.2.1. *Dredge-Up and Mixing*

The observational situation outlined in § 3.2.1 above points toward the following picture: white dwarfs in which significant mixing between the accreted material and the core material occurs decrease in mass, while white dwarfs in which no significant mixing occurs increase in mass. The former situation appears to be the case for CNs while the latter characterizes RNs. This suggests that *in order to understand the conditions under which the white dwarf can grow in mass, we must have a better understanding of the mixing or dredge-up process.*

The problem of elemental mixing in novae has recently been reviewed by Livio & Truran (1991). Here we shall mention only briefly the characteristics of the different processes that are relevant to the problem at hand. Livio & Truran (1991) identified four possible mechanisms that have been suggested for elemental mixing: (1) diffusion-induced convection (Prialnik & Kovetz 1984), (2) shear mixing (e.g., Kippenhahn & Thomas 1978; Fugimoto 1988), (3) convective overshoot-induced flame propagation (Woosley 1986) and (4) convection-induced shear mixing (Kutter & Sparks 1989). In mechanism (3) [and to some degree also (4)], the mixing process is associated with the thermonuclear runaway itself and does not depend on the accretion process. If this mechanism were to dominate, we would expect RNs to exhibit comparable levels of enrichment to CNs. Since this apparently contradicts the observations (although more observations are required to establish this point firmly), we shall not discuss convective overshoot here. Diffusion-induced convection has been explored in far more detail than any of the other mechanisms; we shall therefore discuss first its possible implications for the question of the evolution of the white dwarf's mass.

The results of Kovetz & Prialnik (1985) show that, if diffusion-induced convection is the dominant mixing mechanism, then $\Delta m_{\rm env}/\Delta m_{\rm acc}$ *is almost independent of the white dwarf mass, but depends strongly on the accretion rate* (see Fig. 5). Here $\Delta m_{\rm env}$ is the total mass that is affected by the mixing process and $\Delta m_{\rm acc}$ is the accreted mass. The level of heavy element enrichment is given in this case approximately by $Z \simeq 1-0.98\Delta m_{\rm acc}/\Delta m_{\rm env}$. Clearly the higher the value of Z, the stronger the TNR (e.g., Truran et al. 1992) and the higher the fraction of $\Delta m_{\rm env}$ that is ejected. For $Z > 0.3$, essentially the entire $\Delta m_{\rm env}$ is expected to be ejected. An examination of the results of Kovetz & Prialnik (1985, 1990) reveals that, in order to obtain $Z \sim 0.3$, the accretion rate must satisfy $\dot{M} \leq 3 \times 10^{-10}\ M_\odot\ {\rm yr}^{-1}$ (see Fig. 5). Thus, if diffusion-induced convection were indeed the dominant mixing mechanism, then the fact that in CNs the white dwarf mass is decreasing while in RNs it is increasing would be entirely attributable to the much higher accretion rate in RNs (the exact numerical value of the "critical" accretion rate is probably quite uncertain). There exists an additional observational point that appears to support (or is at least consistent with) the last conclusion. One could wonder why the neon novae (V693 CrA, V1370 Aql, QU Vul, and Nova LMC 1990 no. 1), which also contain massive white dwarfs (like the RNs), appear to show a mass decrease, while the RNs appear to grow in mass. Based on the above conclusion, the answer could simply be that this is a consequence of the much higher accretion rate in RNs. If this picture is correct it would mean that, independent of the white dwarf's mass, the systems in which the white dwarf grows in mass are those with the high accretion rates.

In view of the uncertainties that still exist concerning all the mixing mechanisms (see Livio & Truran 1991 for an extensive discussion), it is important to examine also possibilities other than diffusion-induced convection.

A second possibility which can be examined in general terms, without specific reference to any particular mixing

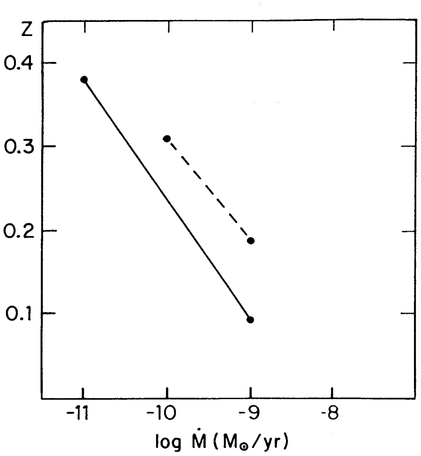

FIG. 5.—The heavy-element mass fraction as a function of the secular mean accretion rate, as obtained from diffusion-induced convection. The two lines represent the calculations of Kovetz & Prialnik (1985, *solid line*) and Kovetz & Prialnik (1990, *dashed line*).

mechanism, is that *the amount of mixing increases with increasing recurrence time between outbursts.* One can easily imagine that a mixing process that includes perhaps some combination of diffusion and shear mixing could have this general property. For example, in the model of Kippenhahn & Thomas (1978), which involves the development of a layer that is marginally stable against the Richardson criterion, the inner boundary of the mixed layer advances inward on the accretion (recurrence) time scale. An examination of equation (2) and Figure 1 reveals immediately that, if this possibility correctly represents the mixing process, *we would expect the white dwarfs to grow in mass in systems in which both $M_{\rm WD}$ and $\dot{M}$ are high.* This again is clearly consistent with the observations of RNs.

3.2.2. *Likely Binary Parameters for RNs*

Two additional points should be made. First, if we believe that the secular mean accretion rate (above the period gap) is determined by magnetic braking or a similar mechanism (e.g., Verbunt & Zwaan 1981; Mestel & Spruit 1987), then we can expect a relation of the form $\dot{M} \sim P^\alpha$ with α being some positive constant. Observations indicate that such a relation may indeed exist (Patterson 1984; but see also Warner 1987). If this is the case, then we expect RNs to be found preferentially with relatively long orbital periods (compared to other CVs). An examination of the observational situation reveals that indeed the orbital periods of U Sco and V394 CrA (1.23 days and 0.76 days respectively, Schaefer 1990) are (with the exception of GK Per), the longest known in cataclysmic binaries. Of course T CrB, RS Oph, V745 Sco, and V3890 Sgr can have high mean accretion rates due to the presence of a giant. It therefore appears that T Pyx, with an orbital period of 2.38 hr or 2.64 hr (Schaefer 1990) is presently the only RN with a short orbital period.

Incidentally, since the frequency distribution of zero-age cataclysmic binaries as a function of orbital period is expected to be a quite smooth function above $P \sim 6$ hr (e.g., Politano & Webbink 1990), then if $\dot{M} \sim P^\alpha$, we would expect the accretion rate also to behave smoothly. This means that there should exist CV systems with massive WDs and with accretion rates that are intermediate between the ones in the neon novae ($\dot{M} \sim 10^{-10}\ M_\odot\ {\rm yr}^{-1}$) and the ones in RNs ($\dot{M} > 10^{-8}\ M_\odot\ {\rm yr}^{-1}$). These systems should produce nova outbursts with intermediate recurrence times ($\tau_{\rm rec} \sim 10^2$–10^3 yr). It would therefore be of great interest to investigate the possibility that some of the known novae have experienced previously recorded outbursts a few hundred years ago.

The second point that should be mentioned is that the maximum secondary mass that is stable against dynamical or thermal time scale mass loss is related to the white dwarf's mass by $M_2^{\rm max} \simeq q_{\rm crit} M_1$ (e.g., Hjellming 1989). Thus, the systems with more massive white dwarfs (such as the RNs) contain on the average also more massive secondaries. Since the secondary star is the mass reservoir with the help of which the white dwarf's mass can grow, this means that the RNs have this advantage too, in trying to grow the white dwarf to the Chandrasekhar limit.

3.2.3. *The Composition of the Accreted Material*

As noted already in § 2, the spectra of both U Sco and V394 CrA in quiescence have a He II λ4686 line that is much stronger than Hβ. Even in outburst, the He II feature is by far the more prominent (Williams et al. 1981; Hanes 1985; Duerbeck &

Seitter 1990; Starrfield et al. 1988b). The observations seem to indicate a large overabundance of helium, He/H ~ 2 by number. An apparent large overabundance of helium was found also in Nova LMC 1990 no. 2 (He/H ~ 1: Shore et al. 1990; Sekiguchi et al. 1990). Such an overabundance of helium in the accreted material, if real, can have important consequences. An examination of equation (3) shows that the accretion of material deficient in hydrogen necessarily leads to a situation in which only a relatively small fraction of the accreted envelope is ejected, due to insufficient energy generation, thus favoring a growth in the mass of the white dwarf. Indeed, detailed numerical models which adopted a mass fraction of hydrogen of $X = 0.11$ predicted an increase in the white dwarf's mass (Truran et al. 1988; Starrfield et al. 1988a; Kato 1990).

It is beyond the scope of the present work to discuss the evolutionary path which can lead to the transfer of helium-rich material. We do note, however, that the secondary stars in U Sco and V394 Cr A, both of which have long orbital periods, are significantly evolved. It is interesting also to note that the spectrum of U Sco is very similar to that of some low-mass X-ray binaries (e.g., LMC X-2) in the dominance of the He II lines (Williams, Phillips, & Heathcote 1987; Bradt & McClintock 1983). Consequently, it has in fact been speculated by Williams et al. (1987) that this may point toward the possibility that low-mass X-ray binaries form from recurrent novae via accretion-induced collapse. While we regard this type of evidence as circumstantial at best, it is certainly true (as pointed out above) that the (massive) white dwarfs in RNs that accrete helium-rich material have the best chance of growing in mass.

3.2.4. *Can the Chandrasekhar Mass be Reached?*

Even if the conditions are such that the mass of the white dwarf indeed grows, it is not clear that in most cases in CVs the Chandrasekhar mass can be reached. This depends on the accumulation ratio η and on the mass of the secondary. We define η by

$$\eta \equiv \frac{\Delta m_{\rm growth}}{\Delta m_{\rm trans}}, \tag{5}$$

where $\Delta m_{\rm growth}$ is the mass that remains on the white dwarf and $\Delta m_{\rm trans}$ is the mass transferred by the secondary. Kato & Hachisu (1989) calculated η for a variety of white dwarf masses and accretion rates, assuming that mass loss occurs mainly in an optically thick wind phase. Their calculations neglected the effects of mixing and therefore *their values of* η *should be regarded in some sense as upper limits* (for example, they could not obtain negative values of η).

From the results of Kato & Hachisu it becomes clear that, even in the case of the weakest TNRs, it is in general extremely difficult to grow white dwarfs to the Chandrasekhar mass. For example, for $M_{\rm WD} \simeq 1\ M_\odot$, they obtain $\eta \simeq 0.3$, even for an accretion rate as high as $10^{-7}\ M_\odot\ {\rm yr}^{-1}$. Consequently, for a 1 $M_\odot$ white dwarf, the secondary (of mass $M_2 \geq 0.4\ M_\odot/\eta$) needs to have a mass higher than 1.1 $M_\odot$. Such systems cannot represent CVs experiencing stable mass transfer ($M_2 > M_1$).

Wheeler (1990) attempted to speculate that the existence of the nova "dud" line offers a possibility for CVs in general to grow to the Chandrasekhar mass. His scenario was based on the notion of "core convergence" noted first by Livio (1987). The idea is that, if a system starts to the right of the "dud" line (specifically, for a given accretion rate the white dwarf initially has a higher mass than that corresponding to the point on the "dud" line; see Fig. 2), the white dwarf mass will decrease by nova explosions until the system reaches the "dud" line. Similarly, in systems to the left of the "dud" line, the white dwarf's mass will continuously increase (no nova) until the "dud" line is reached. Wheeler suggested that the subsequent evolution can be along the dud line, with the white dwarf's mass thereby increasing to the Chandrasekhar limit. Unfortunately, this scenario seems extremely unlikely, for the following reason.

1. The nova "dud" line occurs at considerably higher accretion rates than the semianalytical line used by Wheeler (see Fig. 2). This means that systems starting at relatively low accretion rates may never reach the line.

2. Even at the relatively high accretion rates ($\dot{M} > 10^{-8}\ M_\odot\ {\rm yr}^{-1}$) corresponding to the "dud" line, the accumulation ratio is very low ($\eta < 0.3$), thus placing constraints on the mass of the secondary that CVs cannot accommodate (see above discussion of the results of Kato & Hachisu 1989).

3. Wheeler's discussion neglected mass loss during helium flashes. Kato, Saio, & Hachisu (1989) showed that relatively high accumulation ratios are obtained in helium novae only for high accretion rates ($\dot{M} \geq 5 \times 10^{-7}\ M_\odot\ {\rm yr}^{-1}$, on a 1.3 $M_\odot$ WD).

4. At the "dud" line, systems are more likely to evolve to lower accretion rates (and lower WD masses) than to higher accretion rates, as a consequence of magnetic braking.

5. Systems at high $M_{\rm WD}$ and high $\dot{M}$ probably evolve away from the "dud" line, as discussed for RNs.

It therefore appears that only CV systems which contain very massive white dwarfs and for which the mass indeed increases, *such as RNs*, have a chance of growing the mass to the Chandrasekhar limit. Furthermore, systems of the U Sco subclass, which appear to accrete helium-rich material at a very high rate, are also able to avoid the mass loss associated with helium flashes (see point 3 above).

4. SOME STATISTICAL CONSIDERATIONS

From the preceding sections, it has become clear that the CV systems in which the WD can be expected to grow to the Chandrasekhar mass are those that contained a very massive WD at their zero-age cataclysmic binary (ZACB) stage and in which the mean accretion rate is very high. The exact values of the critical (lower limit) white dwarf mass and critical (lower limit) accretion rate are somewhat uncertain. Based upon the arguments presented in §§ 2 and 3, however, it seems that we can conservatively assume that only systems that have $M_{\rm WD} \geq 1.2\ M_\odot$ and $\dot{M} \geq 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ can reach the Chandrasekhar limit. We can now attempt to estimate the rate of birth of such systems. To this goal, we make the following assumptions.

1. The space density of CVs is of order $n_{\rm CV} \sim 10^{-4}\ {\rm pc}^{-3}$. This number is implied by the observations of Shara & et al. (1990), who detected dim CV-like systems. We shall also discuss the implications of the lower number deduced by Patterson (1984), of $6 \times 10^{-6}\ {\rm pc}^{-3}$.

2. We assume that mass transfer is driven by magnetic breaking (Verbunt & Zwaan 1981), giving a rate which can be approximated by

$$\dot{M}_{\rm MB} \simeq 10^{17} P_3^{5/3}\ {\rm g\,s}^{-1} \tag{6}$$

where P_3 is the orbital period in units of 3 hr.

3. The fractional birth rate of cataclysmic binaries per unit area of the galactic disk (in different WD mass and orbital period intervals) is given by the results of Politano (1988, see also Ritter et al. 1991).

Adopting the above assumptions, we obtain a rate for systems to reach the Chandrasekhar limit

$$R \simeq 1.3 \times 10^{-4}\left(\frac{n_{CV}}{10^{-4}\ \mathrm{pc}^{-3}}\right)\left(\frac{A_{\mathrm{eff}}}{10^9\ \mathrm{pc}^2}\right)\left(\frac{\Delta M_{\mathrm{av}}}{0.2\ M_\odot}\right)^{-1} \times \left(\frac{\dot{M}}{10^{-8}\ M_\odot\ \mathrm{yr}^{-1}}\right)\mathrm{yr}^{-1}\ , \quad (7)$$

where ΔM_{av} is the average mass that has to be accreted to reach the Chandrasekhar mass. If we assume rather that the critical WD mass that is required in order for the Chandrasekhar mass to be reached is 1.3 $M_\odot$, then the rate is reduced to $R \sim 9.8 \times 10^{-5}$ yr^{-1}. Clearly, if the value of $n_{CV} \simeq 6 \times 10^{-6}$ pc^{-3} (Patterson 1984) is used, then we obtain (for $M_{crit} = 1.2\ M_\odot$) $R \sim 7.8 \times 10^{-6}$ yr^{-1}.

We can attempt now to compare the above numbers with the frequencies expected for accretion-induced collapses or Type Ia supernovae. First we note that Nomoto & Kondo (1990) find that, for $M_{WD} \geq 1.2\ M_\odot$ and $\dot{M} \geq 10^{-8}\ M_\odot$ yr^{-1}, neutron star formation is expected to occur, rather than a Type Ia supernova. This is true both for the case in which the WD is of ONeMg composition (in which case collapse is triggered by electron capture on ^{24}Mg and ^{20}Ne) and for C/O white dwarfs (in which case collapse is expected to ensue as a result of carbon deflagration).

Kulkarni & Narayan (1988) estimated the birth rate of low-mass X-ray binaries (LMXB). They found a galactic birth rate of

$$R_X \simeq 1.4 \times 10^{-6} f_x^{-1}\ \mathrm{yr}^{-1}\ , \quad (8)$$

where $f_x \sim 0.33$–0.5, depending on the value of η (eq. [5] $f_x = 0.5$ for $\eta \ll 1$). The local birth rate was found to be $\sim$1.5% of the galactic rate. A comparison of equation (8) with equation (7) (and the discussion that follows eq. [7]) shows that rate at which RN systems can be expected to produce AICs is consistent with the birth rate of LMXB found by Kulkarni & Narayan. It should be noted, however, that both numbers are model-dependent and that the assumptions made in the two calculations are not entirely independent (and sometimes not even entirely consistent).

On the other hand, the rate of occurrence of SN Ia in the galaxy is estimated to be (Evans, van den Bergh, & McClure 1989)

$$R_{\mathrm{SN\ Ia}} \simeq 3 \times 10^{-3}\left(\frac{H_0}{75\ \mathrm{km\ s^{-1}\ Mpc^{-1}}}\right)^2\left(\frac{L_{\mathrm{Gal},B}}{2 \times 10^{10}\ L_\odot}\right)\mathrm{yr}^{-1} \quad (9)$$

which is significantly higher than the rate obtained from equation (7). In addition, we pointed out above that the systems which are expected to reach the Chandrasekhar limit, based on the present work, will very probably produce AICs rather than SNs Ia.

It is important to note that the present work discusses specifically only CV systems and not other systems, such as symbiotic stars, which also involve accreting white dwarfs (see, e.g., Livio, Prialnik, & Regev [1988] for a discussion of symbiotic novae).

5. SUMMARY AND CONCLUSIONS

The results of the present work lead us to the following conclusions.

1. The outbursts of all recurrent novae of the "U Sco group" are very likely powered by thermonuclear runaways on the surfaces of very massive ($M_{WD} \geq 1.3\ M_\odot$) white dwarfs. Observations of T CrB aimed at determining the mass of the hot component are strongly urged, in order to enable us to decide if this conclusion is true also for the RNs which contain late-type giants.
2. The accretion rate in all recurrent nova systems is very high ($\dot{M} \geq 10^{-8}\ M_\odot$ yr^{-1}).
3. Typically, the mass of the white dwarf in *classical nova* systems decreases as a result of nova explosions. In particular, the existence of neon novae is a demonstration of this fact.
4. The mass of the white dwarf in *recurrent nova* systems appears to be increasing. Abundance analyses of future RN outbursts are extremely important, if we wish to confirm this conclusion.
5. The critical physical parameter which determines whether the WD mass is increasing or decreasing is most likely the recurrence time scale between outbursts. This time scale serves to constrain the possible choice(s) of the elemental mixing mechanism. The critical values of the WD mass and accretion rate above which a mass increase is obtained are somewhat uncertain. It appears, however, that the white dwarf mass is increasing in systems which satisfy both $M_{WD} > 1.2\ M_\odot$ and $\dot{M} > 10^{-8}\ M_\odot$ yr^{-1}.
6. Recurrent novae likely to have relatively long orbital periods (compared to other CVs). T Pyx appears to be an exception. If the mass of the white dwarf in any of these systems is found to be significantly lower than 1.3 $M_\odot$, this system should probably be excluded from the group (its outbursts may be powered by accretion events).
7. There should exist a population of CNs with recurrence time scales in the range 10^2–10^3 yr. It would be interesting to discover previously recorded outbursts of known novae.
8. The systems in which the WD is most likely to reach the Chandrasekhar limit are those which satisfy the conditions: $M_{WD} > 1.2\ M_\odot$ and $\dot{M} > 10^{-8}\ M_\odot$ yr^{-1} and in which the secondary is transferring helium-rich material. There exists a subclass of the recurrent novae (which presently seems to include U Sco, V394 CrA, and Nova LMC 1990 No. 2) which satisfies these conditions.
9. The CV systems in which the WD can grow to the Chandrasekhar mass are most likely to produce an accretion induced collapse rather than a Type Ia supernova.
10. The rate at which CV systems reach the Chandraekhar limit (and therefore the rate of accretion-induced collapses) is consistent with the birth rate of low-mass X-ray binaries. The rate of occurrence of SN Ia in the galaxy is estimated to be significantly higher.

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