4. RELATED OBJECTS

RECURRENT NOVAE

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ABSTRACT

Thermonuclear models of recurrent novae demand white dwarf accretors near the Chandrasekhar mass. In this case, the known recurrent novae should possess classical counterparts bearing the same structural parameters and space distribution, save for having only marginally less massive white dwarfs. Furthermore, recurrent novae should occur exclusively on ONeMg white dwarfs, and display in their ejecta either neon-group overabundances (if the white dwarfs are eroded through an outburst cycle) or no heavy element enhancements whatever (if the white dwarfs increase in mass).

The known recurrent novae are reviewed in the light of these and other characteristics of thermonuclear runaway models, and also in terms of accretion-powered events, with special attention to the difficulties encountered by both models. Pivotal tests to distinguish between between thermonuclear and accretion models rely on the fact that the latter require far more mass transferred than the former to produce the same outburst energetics. Thus, photospheric opacities in thermonuclear recurrent novae are dominated by scattering; those in recurrent accretion events by true absorption. Orbital period changes through outburst are 10^3 times greater in accretion models than in thermonuclear models.

I. INTRODUCTION

In the development of our understanding of the nova phenomenon, the small group of recurrent novae have played a pivotal role. The recurrent nova T Coronae Borealis (1866, 1946) was the first cataclysmic variable to be observed spectroscopically (Huggins 1866). It was also the first erstwhile nova to have been observed prior to outburst, having been cataloged ten years earlier as BD +26°2765. This observation finally laid to rest any belief that novae might indeed be "new stars." As T CrB returned to the brightness level at which it had been observed prior to outburst, the notion was planted that novae could well be recurrent events. That suspicion was realized in 1933 with the second recorded outburst of RS Ophiuchi, an event which prompted Kukarkin and Parenago (1934) to propose their famous amplitude-recurrence time scale relationship for cataclysmic variables, both novae and dwarf novae. That relationship was brilliantly confirmed when T CrB itself, having been selected as a nova with a short probable recurrence time scale, erupted 1946.

In the years since these events, our understanding of nova and dwarf nova outbursts has deepened to the point that we now realize beyond any reasonable doubt that these two classes of outbursts are triggered by entirely different physical mechanisms, even though they occur in binary systems of remarkable underlying similarity. Classical novae bear the distinct hallmarks (not least among them, the peculiar chemical compositions of their ejecta) of thermonuclear runaways on white dwarf stars. Dwarf novae, on the other hand, are powered by the release of gravitational potential energy in accretion disks, as revealed by variations in their eclipse morphology during outburst. Where, then, do the intermediate, recurrent novae, fit into this picture? What mechanism powers their outbursts? These questions we shall address here.

II. OUTBURST MECHANISMS

Both thermonuclear and accretion models have been proposed for recurrent novae. Rather than to summarize the critical features of both models here, I shall leave that point to the discussion of the different distinct subclasses of recurrent novae below, where we shall see as well what difficulties observations of individual systems pose for both models. At present, the thermonuclear models are rather more well-developed than accretion models, primarily because the approach to thermonuclear runaway, and thus the elucidation of conditions which lead to it, can be modeled quasi-statically. In contrast, accretion models (at least in a form applicable to recurrent novae) demand a multi-dimensional hydrodynamic treatment from the outset.

The conditions which produce rapid recurrence in thermonuclear models imply certain properties which recurrent novae powered by this mechanism should possess. Detailed numerical models show that, to a very good approximation, the pressure needed to achieve thermonuclear runaway at the base of an accreted envelope on a white dwarf is a constant (call it P_{crit}):

$$P_{crit} = \frac{GMM_e}{4\pi R^4} \quad , \tag{1}$$

where M_e is the mass of the accreted envelope, M the mass of the white dwarf, and R its radius (*cf.*, *e.g.*, Truran and Livio, 1986). The white dwarf radius of course depends only on its mass:

$$R = R_o \, (x^{-2/3} - x^{2/3}) \quad , \tag{2}$$

where $x \equiv M/M_{Ch} < 1$ (M_{Ch} is the Chandrasekhar mass), and R_o is a constant (Nauenberg, 1972). Thus, the envelope mass needed to reach ignition is a strong function only of the mass of the white dwarf,

$$M_e = \frac{4\pi R_o^4 P_{crit}}{GM_{Ch}} x^{-11/3} (1 - x^{4/3})^4 \qquad (3)$$

and decreases rapidly as the mass of the white dwarf approaches the Chandrasekhar mass, as is well-known.

The recurrence frequency of a nova system (number of outbursts per year) is just $\nu = \dot{M}/M_e$, where $\dot{M}$ is the mass accretion rate. In general, $\dot{M}$ is principally a function of the properties of the donor star, and only weakly dependent on those of the white dwarf. For the purposes of the following argument, we may therefore regard it as a constant. Thus, the recurrence frequency is dominated by the mass-radius relation for massive white dwarfs, strongly selecting cataclysmic binaries with white dwarfs of nearly Chandrasekhar mass: $\nu \sim (1 - x^{4/3})^{-4}$ as $x \rightarrow 1$. The *distribution* of recurrence frequencies is

$$n(\nu) = n(x) \frac{x}{\nu} \left| \frac{d \ln \nu}{d \ln x} \right|^{-1}$$

$$= n(x) \frac{4\pi R_o^4 P_{crit}}{G\dot{M}} x^{-8/3} [1 - x^{4/3}]^4 \left[1 + \frac{8}{3} \frac{(1 + x^{4/3})}{(1 - x^{4/3})}\right]^{-1} \qquad (4)$$

where n(x) is the distribution of white dwarf masses in nova binaries. So long as n(x) is slowly-varying near the Chandrasekhar limit, $n(\nu)$ is dominated by the mass-radius relation of massive white dwarfs, and decreases rapidly in that limit: $n(\nu) \sim (1 - x^{4/3})^5 \sim \nu^{-5/4}$. The *cumulative* distribution of nova frequencies greater than some threshold frequency, ν_o, should thus increase monotonically toward smaller frequencies: $N(\nu > \nu_o) \sim (\nu_o^{-1/4} - \nu_{max}^{-1/4})$, where ν_{max} is the maximum recurrence frequency thermonuclear models are capable of sustaining. (In fact, ν_{max} itself increases rapidly as white dwarfs approach the Chandrasekhar mass, implying that $N(\nu > \nu_o)$ should increase more rapidly as ν_o decreases than given by this simple estimate.) Modeling efforts imply that the observed recurrence frequencies among recurrent novae seem to be near ν_{max}. We may therefore infer that *the known recurrent novae should be accompanied by a much more extensive population of nova binaries sharing the same structural features (orbital periods, secondary stars, mass transfer rates, etc.) and the same spatial distribution, differing only in having slightly less massive white dwarfs, and therefore somewhat longer outburst recurrence intervals*.

The strong selection in favor of the most massive white dwarfs implies as well that recurrent novae should occur on ONeMg white dwarfs, and not the CO white dwarfs most prevalent among ordinary novae. If the white dwarfs in recurrent novae are being eroded by successive outbursts, as implied by the CNO enhancements seen in the ejecta of most common novae, we should find recurrent systems among the so-called '*neon*' novae. If, on the other hand, the white dwarfs in this extreme grow in mass through successive outbursts, then recurrent novae should show *no heavy element enhancements*, only redistribution among the CNO isotopes.

III. THE RECURRENT NOVAE

Let us examine now the observed systems which fall into the class of recurrent novae. As in the recent review by Webbink, *et al.* (1987), we adopt as criteria for membership that recurrent novae have undergone two or more recorded outbursts, (i) reaching typical nova luminosities ($M_V \leq -5.5$), and (ii) producing high-velocity ejecta ($v_{exp} \geq 300$ km s^{-1}) in outburst. Nova V394 CrA (Duerbeck 1988; Sekiguchi, *et al.* 1989) may now be added to the four objects previously satisfying these criteria (T CrB, RS Oph, T Pyx, and U Sco). To the list of those objects rejected by Webbink, *et al.*, as recurrent novae, we now add V404 Cyg, which is a recurrent X-ray transient (Marsden, *et al.* 1989), and AS Psc, which is a dwarf nova (Sharov 1987).

Even though there are only five objects which qualify as recurrent novae by these criteria, it is clear that they form a very inhomogeneous class. For example, T Pyx is distinctly different in quiescent appearance and outburst characteristics from all other examples. On the other hand, U Sco and V394 CrA bear such a strong resemblance to each other that they can be considered a distinct subclass, as can T CrB and RS Oph. Let us now examine the salient characteristics of each subclass, noting where relevant those difficulties which these characteristics pose for the thermonuclear and accretion models of recurrent novae.

T Pyxidis (1890, 1902, 1920, 1944, 1966)

T Pyx is unique among the recurrent novae in its slow light curve development ($t_3 = 88^d$; Duerbeck 1987). The absolute magnitude-rate of decline relationship for classical novae, applied to this system, would place it at a distance of ~4.4 kpc from the Sun, 0.74 kpc above the galactic plane. Its outburst light curve, while somewhat fragmentary in the first four outbursts, appears to repeat quite faithfully. At outburst maximum, T Pyx shows an emission-line spectrum (Catchpole 1969), as expected for a nova with a very small envelope mass (see below). A nebular shell has been resolved around T Pyx, and shows approximately solar abundances (Williams 1982), as expected for a massive white dwarf accumulating mass through an outburst cycle. At minimum light, T Pyx is extremely blue: $(B-V)_o = -0.26$, $(U-B)_o = -1.25$ (Webbink, *et al.* 1987). These colors imply that it is a very short period cataclysmic binary, with a large accretion rate: $\dot{M} \approx 2.3 \times 10^{-8}\ M_\odot yr^{-1}\ (d/4.4\ \mathrm{kpc})^{4/3}$. The short orbital period has been confirmed spectroscopically by Barrera and Vogt (1990), who find $P_{orb} = 0^{d}\!.143338$ with $K_{em} = 29.1$ km s^{-1}. The orbital period implies a companion mass $M_2 = 0.34\ M_\odot$. The relatively large emission line widths, $\sigma_{em} = 489$ km s^{-1} (Williams 1983), combined with the small velocity amplitude, imply a small mass ratio for this system, $M_2/M_1 = 0.11 \overset{\times}{\div} 1.6$, and thus a very massive white dwarf ($M_1 \geq M_{Ch}$) and small orbital inclination ($i \approx 18°$ for $M_1 = M_{Ch}$). In every respect, *save its relatively large distance from the galactic plane*, T Pyx *conforms to the* properties one would expect of a thermonuclear-powered recurrent nova.

U Scorpii (1863, 1906, 1936, 1979, 1987) and V394 Coronae Australis (1949, 1987)

In contrast with T Pyx, U Sco and V394 CrA are two of the fastest novae known. Indeed, as often noted in the past, the very rapid decline of U Sco from outburst ($t_3 = 5^d$; Duerbeck 1987) is associated among classical novae with markedly super-Eddington luminosities at maximum, implying an uncomfortably large distance to this object (d ~ 20-40 kpc), given its modest apparent brightness at maximum. V394 CrA appears to have differed in its rate of decline between its two known outbursts ($t_3 = 10^d$ in 1949; $t_3 = 5\overset{d}{.}5$ in 1987; Duerbeck 1988), but it also appears to lie at a great distance from the Sun (d ~ 7-12 kpc). Even if the peak visual luminosities reach only the Eddington limit (for Chandrasekhar mass white dwarfs), U Sco and V394 CrA lie 10 kpc and 5 kpc from the Sun, respectively, and at their relatively high galactic latitudes ($b = 21\overset{\circ}{.}9$ and $b = -7\overset{\circ}{.}7$) lie 3.9 kpc and 0.67 kpc from the galactic plane. The sheer improbability of such large values of $|z|$ suggests that the distances of these two systems have been greatly overestimated. If this were the case, however, it becomes difficult to understand the very high ejection velocities (~7500 km s^{-1} and ~4000 km s^{-1}, respectively) which appear during outburst (Sekiguchi, *et al.* 1988, 1989). Both systems show modest light curve variations from outburst to outburst, a troublesome, but perhaps not serious, feature for thermonuclear models to explain.

A much more serious difficulty in understanding U Sco and V394 CrA arises from their very peculiar spectra, both in outburst and in quiescence, and the anomalous abundances deduced therefrom. They strongly resemble each other in quiescence, with He II λ4686 much stronger than Hβ. Indeed, the presence of hydrogen in the quiescent spectrum of U Sco was only finally demonstrated by Duerbeck and Seitter (1990). Hydrogen is more readily evident in their outburst spectra, but even there He II is by far the most prominent species in optical spectra. Abundance analyses of both outburst and quiescent spectra of U Sco indicate a marked overabundance of helium (20 times solar), but normal CNO group abundances (Williams, *et al.* 1981). The redistribution of CNO nuclei into nitrogen, which is enhanced, shows that the ejecta have been subjected to moderately hot hydrogen burning, but it cannot be stated with certainty that this occurred on the white dwarf component, rather than much earlier, in the interior of the donor star. If correct, the very high helium abundance deduced for matter being transferred in quiescence poses a severe problem in accounting for the outburst energetics in a thermonuclear model (Truran, *et al.* 1988). No other nova is known to share the spectroscopic anomalies displayed by these two systems. In light of our earlier discussion, this fact in itself must raise some doubts about the validity of applying a thermonuclear model to them, but no accretion model has succeeded in accounting for their behavior either.

An important key to understanding these two systems would be the determination of their orbital periods. U Sco and V394 CrA are both unusual in revealing clear spectroscopic features of their donor stars at minimum (Hanes 1985; Duerbeck and Seitter 1990). Both have relatively warm donors, as such stars go among cataclysmic binaries: spectral type G3-6 in U Sco; K in V394 CrA. From the apparent brightnesses of these systems at minimum, and the fraction of light which their donors contribute, it is possible to estimate the angular diameters of the the donors using a spectral type-surface brightness relation (*e.g.*, Popper 1980). On the assumption that the donors exactly fill their Roche lobes, one may then estimate their orbital periods, given assumed distances. For U Sco, one finds $P_{orb} \approx 3^d\ (d/10\ \mathrm{kpc})^{3/2}$; for V394 CrA, $P_{orb} \approx 1\overset{d}{.}5\ (d/5\ \mathrm{kpc})^{3/2}$. Among canonical cataclysmic variables, only nova GK Per has an orbital period comparable with these estimates, and it does not share the other spectroscopic peculiarities of U Sco and V394 CrA. Conversely, the distances of these objects, and hence their true outburst luminosities and scale heights, could be deduced directly from their orbital periods, providing strong constraints on possible outburst models.

T Coronae Borealis (1866, 1946) and RS Ophiuchi (1898, 1933, 1958, 1967, 1985)

Both T CrB and RS Oph share an extremely rapid development of their outburst light curves (t_3 = $6\overset{d}{.}8$ and $9\overset{d}{.}5$, respectively, with $t_{rise} \leq 1^d$ in both cases; Duerbeck 1987), and an unusual spectroscopic evolution during decline which is nearly unique to these objects (see, *e.g.*, Payne-Gaposchkin 1957). In both systems, the outburst light curves repeat faithfully from one outburst to the next. Both objects show strong spectral continua at maximum. Initial ejection velocities (~5000 km s^{-1}) are among the highest observed in novae, but they are gradually replaced by lower and lower velocity systems, contrary to the usual velocity evolution in novae. During decline, intense, high-excitation coronal lines appear (e.g., ~1 $L_\odot$ in [Fe XIV] λ5303 alone in T CrB). This behavior points clearly to an initial strong shock wave which propagates outward through the circumstellar wind of the giant components present in both systems (Bode and Kahn 1985; Wallerstein and Garnavich 1986). It is possible, or even likely, that the weak (~ few × 10^{31} erg s^{-1}) soft X-ray emission detected from both objects at minimum arises from these shocked circumstellar winds, rather than from the hot components themselves. The falling density in the winds can easily lead to cooling time scales, in the outer reaches of material lost since the last outburst, of the same order as the recurrence time scale, or even greater.

Circumstellar shells have been resolved in both T CrB and RS Oph, although their natures are rather different. Williams (1977) detected what seems to be a circumstellar dust shell around T CrB. RS Oph apparently also possesses a circumstellar dust shell (Callus, Evans and Albinson 1986), but it has not been resolved. However, radio observations of RS Oph obtained during its 1985 outburst clearly resolved a bipolar ejected shell, and the evolution of that shell was followed during decline (Hjellming, *et al.* 1986; Taylor, *et al.* 1989).

In quiescence, the visible spectra of both T CrB and RS Oph are dominated by late-type giants. Optical emission lines are relatively narrow (HWZI ≤ 500 km s^{-1}), and of low excitation (Hβ >> He II λ4686). Higher-excitation features, such as N V, Si IV, and C IV, are seen in the ultraviolet at minimum (*e.g.*, Cassatella, Gilmozzi, and Selvelli 1985). These systems flicker in optical light, and have strongly variable ultraviolet fluxes, implying that the ultraviolet and blue optical continua arise from accretion processes, rather than stellar photospheres. Indeed, the optical emission lines of T CrB are double-peaked, and show a classical accretion disk profile (Kraft 1958).

The long orbital periods of T CrB and RS Oph set them completely apart from novae and dwarf novae (see Table 1). The small orbital eccentricities obtained for these systems are probably fictitious: that of T CrB is attributable to ellipticity of the giant component, that of RS Oph is not statistically significant. Ultraviolet observations show that T CrB does not eclipse, but its pronounced ellipsoidal variability in visible light at minimum (Isles 1975; Lines, Lines, and McFaul 1988) suggests that the orbital inclination must be near the upper limit quoted in Table 1. RS Oph shows no apparent orbital modulation of its quiescent light curve, implying that we must see it nearly pole-on.

TABLE 1: Spectroscopic Orbits of T CrB and RS Oph

	T CrB(a)	RS Oph(b)
Sp_{cool}	M4.1III(c)	K5.7II-III(c)
P_{orb} (d)	227.53±0.02	230.
K_{cool} (km s^{-1})	23.32±0.16	9.
K_{hot} (km s^{-1})	33.76±3.21	
e	0.012±0.005	~0.07:
i	≤67°	small
$M_{cool}/M_{\odot}$	≥3.34±0.73	
$M_{hot}/M_{\odot}$	≥2.31±0.29	

(a) Kenyon and Garcia (1986) and Webbink, *et al.* (1987)
(b) Garcia (1986)
(c) Kenyon and Fernandez-Castro (1987).

T CrB shows several additional features to its outburst development which are not shared by RS Oph (see Webbink 1976; Webbink, *et al.* 1987). In 1945, 260 days before its second eruption, T CrB faded precipitously, in an event which is unique in the 123-year recorded history of this well-observed nova since it first erupted in 1866. Because the visible light of the system is dominated by the M giant, this event can only be attributed to a sudden fading of that giant. The question of whether it is associated with the outburst, or is purely coincidental, will not be settled until it next erupts. In both 1866 and 1946, T CrB faded quickly from principal maximum to its pre-outburst light level, only to brighten once again by two magnitudes 106 days later. Unlike the secondary maxima of classical novae, such as DQ Her, which recover after a dust-forming transition phase, that in T CrB is characterized by a strong optical *continuum*, upon which appear shell absorption lines. Furthermore, the undisturbed M giant dominates the spectrum between principal and secondary maxima, and it is clear from the absence of heating that the decline from principal maximum is a bolometric one, and not a result of flux redistribution outside the optical region. The decline from secondary maximum is very slow (> 10 years), and its integrated visual energy output is an order of magnitude *greater* than that in the principal maximum. Finally, we note that the two outbursts of T CrB are separated by almost precisely an integral number of orbital periods: $\Delta\phi = 128.009 \pm 0.011$. (The orbital ephemeris of RS Oph, in contrast, is not accurate enough to phase any of its outbursts prior to 1985; however, even an optimal choice of orbital period, $P_{orb} = 226^{d}.2$, gives a greater dispersion in outburst phase, $\sigma_{\phi} = 0.15$, than observed in T CrB.)

The peculiar photometric and spectroscopic evolution of T CrB through outburst, and the very large mass deduced for its hot component, led to the proposal of an accretion model for its outbursts (Webbink 1976). A pulse of mass from the giant, 260 days prior to outburst, is drawn into a stream by tidal forces and thermal diffusion as it orbits the hot component. The orbit of this stream ultimately closes upon itself, colliding head-to-tail, and it collapses into a ring, an event which generates an outgoing shock wave in the ambient wind of the giant. The energy released in principal maximum is equated with the circularization energy of this stream. The ring broadens by viscous stresses into a disk, the accretion from which onto the hot component produces the secondary maximum. The ratio of energy released in the principal maximum to that released in the secondary maximum is thus equal to one-half the radius of the accretion ring orbit divided by the radius of the accreting star; the ratio observed in T CrB requires that the accretor be a main sequence star. The difference in outburst development between T CrB and RS Oph is then attributed to the more advanced state of RS Oph in long-term process of mass transfer. Its more frequent outbursts do not allow the accreting star to relax thermally to equilibrium, leaving it in a bloated state where it intercepts the mass pulse from the giant on its first periastron passage. No accretion ring is formed, and therefore no secondary maximum occurs (Livio, Truran, and Webbink 1986).

Neither thermonuclear nor accretion models are entirely successful in accounting for the basic behavior of T CrB and RS Oph. The gross energetics of principal maximum can in principle be reproduced in both models with the appropriate choice of white dwarf mass and accretion rate (thermonuclear model) or mass increment transferred (accretion model). The time scale for principal maximum poses different problems for each model: As noted above, the decline in T CrB is evidently a true bolometric decline, and observations of the recent outburst of RS Oph show that optical, infrared, and ultraviolet decline in tandem from roughly day 25 onward (Snijders 1987); thermonuclear models generally predict an extended luminosity plateau. In the context of an accretion model, principal maximum can only be understood in terms of dynamical phenomena, since viscous and thermal time scales exceed the outburst duration; even so, it is difficult to account for the extremely rapid rise to maximum in these two novae. The strength of the optical continuum would appear to pose a severe problem for thermonuclear models, since it implies photospheric densities at maximum far higher than can be accounted for with the small envelope masses needed to produce rapid recurrence (see § IV below). The observed high shock ejection velocities are difficult to understand in terms of the mildly degenerate thermonuclear runaway one would expect for rapid recurrence; in the accretion model, they can in principle be achieved, given the density contrast between accretion stream and circumstellar matter, but place severe constraints on the stream density profile to achieve such dramatic shock acceleration.

It has been argued previously that the ultraviolet flux observed in quiescence in these systems implies mass transfer rates too small to fuel recurrent thermonuclear outbursts at the observed rate (Webbink, *et al.* 1987). It now appears that this conclusion was predicated on observations in which the UV flux was, by chance, weaker than normal; a serious difficulty with thermonuclear models is thus removed. However, it must at the same time be noted that the observed emission line systems provide little evidence for a hard ultraviolet flux of the magnitude expected for rapidly accreting white dwarfs (*cf.* Kenyon and Webbink 1984), despite the presence of copious circumstellar gas in the form of the wind from the giant components. The optical emission lines are weak, and of low excitation, and even though higher-excitation species are prominent in the ultraviolet, the UV emission line systems do not differ greatly in excitation from those observed among, for example, the W Serpentis stars (Plavec 1980), which clearly contain non-degenerate accretors.

The most serious difficulties for thermonuclear models come from the peculiarities displayed by T CrB. The large lower limit to the mass of the hot component (see Table 1) would appear to be fatal, as it stands, to thermonuclear models. It is highly desirable that a redetermination of the velocity amplitude of this component be undertaken, a task which would be enormously facilitated by modern digital spectra. A substantial revision would be needed (to $K_{hot} < 21.7$ km s^{-1}) if the lower limit to its mass is to be brought below the Chandrasekhar limit. However, even if this revision were to transpire, the reappearance of a hot, photospheric source months after the hot component would appear to have returned to its quiescent state (*i.e.*, the secondary maximum) is inexplicable in terms of current thermonuclear models. The pre-outburst fading of the giant must be attributed to mere accident in this case.

Finally, it must be noted once again that, if a thermonuclear model were appropriate for T CrB and RS Oph, we should expect to find many more examples of systems which structurally resemble these two among the classical, non-recurrent novae. Their apparent absence militates against such a model.

IV. PIVOTAL TESTS OF RECURRENT NOVA MECHANISMS

Clearly, arguments can be marshalled for both thermonuclear and accretion events among recurrent novae, but definitive tests to discriminate between these models have proven more elusive. There is one respect, however, in which the two model inescapably differ from each other, and that arises from the difference in energy yields per unit mass for accretion and for nuclear burning: Accretion onto a main sequence star, as proposed for T CrB and RS Oph, yields $GM/R \approx 1.9 \times 10^{15}$ erg g^{-1}; thermonuclear burning, $XQ_H \approx 4.7 \times 10^{18}$ erg g^{-1}. Therefore, to produce equal outburst energies, ~2500 times as much mass must be involved in an accretion outburst as in a thermonuclear one. This has two immediate consequences:

(1) Thermonuclear runaways recurrent on decade time scales require very massive white dwarfs with very low-mass ($\lesssim 10^{-6}$ $M_\odot$) hydrogen envelopes. Such envelopes, at visual maximum, are so tenuous that their true absorption opacities are of order 10^{-2} or less of their scattering opacities throughout the envelope. Such scattering atmospheres should produce recurrent novae with weak continua, and prominent emission-line spectra at maximum (Webbink, *et al.* 1987), as indeed observed in T Pyx. On the other hand, the much larger masses, and hence higher densities, needed to produce the same outburst by accretion should produce strong continua at maximum, as observed in T CrB and RS Oph.

(2) Orbital period changes through outburst should reflect the amount of matter involved in the outburst: $\Delta P_{orb}/P_{orb} \sim M_{env}/M_*$. For thermonuclear outbursts, fractional orbital period changes of order 10^{-6} are expected, while for accretion outbursts, they should be of order 10^{-3}. The orbital periods of T CrB and T Pyx (if confirmed) are now well-enough known to provide definitive tests at their next outbursts.

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REFERENCES

Barrera, L., and Vogt, N. 1990, in *The Physics of Classical Novae, I.A.U. Colloq. No. 122*, ed A. Cassatella (Berlin: Springer), in press.
Bode, M.F., and Kahn, F.D. 1985, *Monthly Notices R. Astr. Soc.*, **217**, 205.
Callus, C.M., Evans, A., and Albinson, J.S. 1986, *Irish Astr. J.*, **17**, 330.
Cassatella, A., Gilmozzi, R., and Selvelli, P. 1985, in *Recent Results on Cataclysmic Variables*, ed. W.R. Burke (Noordwijk: ESA SP-236), p. 213.
Catchpole, R.M. 1969, *Monthly Notices R. Astr. Soc.*, **142**, 119.
Duerbeck, H.W. 1987, *Space Sci. Rev.*, **45**, 1.
__________ 1988, *Astr. Astrophys.*, **197**, 148.
Duerbeck, H.W., and Seitter, W.C. 1990, in *The Physics of Classical Novae, I.A.U. Colloq. No. 122*, ed. A. Cassatella (Berlin: Springer), in press.
Garcia, M.R. 1986, *Astr. J.*, **91**, 1400.
Hanes, D.A. 1985, *Monthly Notices R. Astr. Soc.*, **213**, 443.
Hjellming, R.M., van Gorkom, J.H., Taylor, A.R., Seaquist, E.R., Padin, S., Davis, R.J., and Bode, M.F. 1986, *Astrophys. J. (Letters)*, **305**, L71.
Huggins, W. 1866, *Monthly Notices R. Astr. Soc.*, **26**, 275.
Isles, J.E. 1975, *J. Brit. Astr. Assoc.*, **85**, 217.
Kenyon, S.J., and Fernandez-Castro, T. 1987, *Astr. J.*, **93**, 938.
Kenyon, S.J., and Garcia, M.R. 1986, *Astr. J.*, **91**, 125.
Kenyon, S.J., and Webbink, R.F. 1984, *Astrophys. J.*, **279**, 252.
Kraft, R.P. 1958, *Astrophys. J.*, **127**, 625.
Kukarkin, B.V., and Parenago, P.P. 1934, *Perem. Zvezdy*, **4**, 251.
Lines, H.C., Lines, R.D., and McFaul, T.G. 1988, *Astr. J.*, **95**, 1505.
Livio, M., Truran, J.W., and Webbink, R.F. 1986, *Astrophys. J.*, **308**, 736.

Marsden, B.G., Wagner, R.M., Starrfield, S.G., Cassatella, A., and Hurst, G.M. 1989, *I.A.U. Circ.*, No. 4783.

Nauenberg, M. 1972, *Astrophys. J.*, **175**, 417.

Payne-Gaposchkin, C. 1957, *The Galactic Novae* (Amsterdam: North-Holland).

Plavec, M.J. 1980, in *Close Binary Stars: Observations and Interpretation, I.A.U. Symp. No. 88*, ed. M.J. Plavec, D.M. Popper, and R.K. Ulrich (Dordrecht: Reidel), p. 251.

Popper, D.M. 1980, *Ann. Rev. Astr. Astrophys.*, **18**, 115.

Sekiguchi, K., Feast, M.W., Whitelock, P.A., Overbeek, M.D., Wargau, W., and Spencer Jones, J. 1988, *Monthly Notices R. Astr. Soc.*, **234**, 281.

Sekiguchi, K., Catchpole, R.M., Fairall, A.P., Feast, M.W., Kilkenny, D., Laney, C.D., Lloyd Evans, T., Marang, F., and Parker, Q.A. 1989, *Monthly Notices R. Astr. Soc.*, **236**, 611.

Sharov, A.S. 1987, *Pis'ma Astr. Zh.*, **13**, 427 (English transl.: *Sov. Astr. Letters*, **13**, 175).

Snijders, M.A.J. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode (Utrecht: VNU Science Press), p. 51.

Taylor, A.R., Davis, R.J., Porcas, R.W., and Bode, M.F. 1989, *Monthly Notices R. Astr. Soc.*, **237**, 81.

Truran, J.W., and Livio, M. 1986, *Astrophys. J.*, **308**, 721.

Truran, J.W., Livio, M., Hayes, J., Starrfield, S., and Sparks, W.M. 1988, *Astrophys. J.*, **324**, 345.

Wallerstein, G., and Garnavich, P.M. 1986, *Pub. Astr. Soc. Pacific*, **98**, 875.

Webbink, R.F. 1976, *Nature*, **262**, 271.

Webbink, R.F., Livio, M., Truran, J.W., and Orio, M. 1987, *Astrophys. J.*, **314**, 653.

Williams, G. 1983, *Astrophys. J. Suppl.*, **53**, 523.

Williams, R.E. 1977, *Veröff. Remeis-Sternw. Bamberg*, **11**, 242.

__________ 1982, *Astrophys. J.*, **261**, 170.

Williams, R.E., Sparks, W.M., Gallagher, J.S., Ney, E.P., Starrfield, S.G., and Truran, J.W. 1981, *Astrophys. J.*, **251**, 221.