RECURRENT NOVAE

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ABSTRACT. An examination of the existing observational material on all the objects classified as recurrent novae, reveals that only T Pyx, U Sco, T CrB and RS Oph deserve such a classification. We review the properties of outbursts powered by thermonuclear runaways and accretion events and determine their observational consequences. We conclude that the outbursts of T CrB and RS Oph are very probably caused by accretion events from a giant companion onto a main sequence star. The outbursts of T Pyx and U Sco may be powered by thermonuclear runaways on the surface of white dwarfs with masses close to the Chandrasekhar limit. However, some questions, in particular regarding the composition of the accreted material in U Sco remain to be answered.

1. INTRODUCTION

Recurrent novae (RN) are intermediate between classical novae (CN) and dwarf novae (DN) in terms of their recurrence timescales (~ 10-80 yr) and magnitude ranges in outburst (~ 7-11 mag). Before we start discussing these systems, we would like to adopt the definition proposed by Webbink, Livio, Truran and Orio (1987, hereafter WLTO) in order to avoid ambiguity with CN and DN:

RN are systems which exhibited two or more distinct outbursts, reaching absolute magnitudes at maximum comparable with those of CN, and in which the ejection of a discrete shell in outburst, at velocities $V_{ej} \gtrsim 200$ km s^{-1}, has been observed.

Based on this definition, WLTO were able to exclude a number of systems, traditionally classified as RN from this group. These include:

<u>WZ Sge</u>
Now recognized as a DN of the SU UMa type (Patterson et al. 1981, Vogt 1981).

<u>VY Aqr</u>
Had extremely frequent eruptions (e.g. in 1907, 1929, 1934, 1939, 1940, 1942, 1958, 1962, 1964, 1965, 1966, 1967, 1973, 1983,

J. Mikolajewska et al. (eds.), The Symbiotic Phenomenon, 323–334.
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https://doi.org/10.1017/S0252921100103781 Published online by Cambridge University Press

1986, 1987, (see IAUC 4414 for the last one). Also, its spectrum at minimum strongly resembles that of a DN. This system is thus a DN.

V1195 Oph

The small amplitude of the outburst, its length, and the light curve (Plaut 1968) are fairly convincing that this system is a DN.

V616 Mon

This object is really a soft x-ray transient, possibly containing a black hole (McClintock and Remillard 1986).

RZ Leo

This system had confirmed outbursts in 1918 and 1984. Based on the small amplitude of the eruption, the abrupt decline to minimum and the spectrum during the decline (Cristiani et al. 1985), WLTO concluded that this system is a DN, possibly similar to WZ Sge.

V 1017 Sgr

An examination of the light curves of this symbiotic system by WLTO, revealed the fact that it is very probably a CN (which had a nova-type outburst in 1919), which has also undergone DN eruptions (in 1901 and 1973). This makes the system similar to V446 Her, Q Cyg, V 3890 Sgr, Nova Vul (1979), WY Sge, GK Per and possibly BV Cen (see Livio 1987 and references therein). The fact that the system is a cataclysmic variable, coupled with the BVRI colors at maximum, (which are consistent with the presence of an accretion disk, Vidal and Rodgers 1974), suggest that the G5 IIIp star in this system (Kraft 1964) fills its Roche lobe. Attempts for a spectroscopic orbit determination are thus strongly encouraged. The orbital period can be expected to be in the range 2-20 days.

V529 Ori

A study of the history of this object (Ashworth 1981) demonstrated that there is only one reliable observation of the system. It is therefore not a RN.

The above discussion leaves only four systems which fall under our definition of RNe: T Pyx, U Sco, T CrB and RS Oph. Before examining these systems in some detail we would like to discuss some aspects of the physics of thermonuclear runaways (TNR) and accretion events. This will help us to determine the applicability of theoretical models to specific RN outbursts.

2. OUTBURSTS POWERED BY THERMONUCLEAR RUNAWAYS

The success of TNRs in explaining CN outbursts suggests the possibility that a similar mechanism might be operating in RN. The basic problem that has to be solved in this context is that of the recurrence timescale, τ_{rec}, which is much shorter in RN than in CN. The most important physical parameters determining τ_{rec} are the mass of the white dwarf M_{WD}, the accretion rate $\dot{M}$ and to a lesser extent the white dwarf's luminosity L_{WD} and the heavy element contents of the accreted material, Z. Ignoring for the moment the effects which may be introduced by variations in L_{WD} and in Z, TNRs occur when the pressure at the base of the accreted envelope reaches a critical

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value (Fujimoto 1982, MacDonald 1983, Truran and Livio 1986) of the order of $P_{crit} \simeq 2 \times 10^{19}$ dyne cm^{-2}. The pressure at the white dwarf-envelope interface is given by

$$P_{base} \approx \frac{GM_{WD}\,\Delta M_{acc}}{4\pi R_{WD}^4}\,, \qquad (1)$$

where ΔM_{acc} is the mass of the accreted material. We thus obtain a recurrence timescale of

$$\tau_{rec} \simeq 1.2 \times 10^4 \left(\frac{\dot{M}}{10^{-8} M_\odot yr^{-1}}\right)^{-1} \left(\frac{M_{WD}}{M_\odot}\right)^{-1} \left(\frac{R_{WD}}{6 \times 10^8 cm}\right)^4 yr. \qquad (2)$$

Using a mass-radius relation for the white dwarf, we can, therefore, obtain the recurrence time as a function of the white dwarf mass (for a given accretion rate), this is shown in Fig. 1. Two things become immediately apparent from the figure: (1) accretion rates in excess of 10^{-8} $M_\odot$/yr are required, in order to obtain the recurrence times observed in RNe, (2) for accretion rates typical to cataclysmic variables (e.g. Patterson 1984), the mass of the white dwarf must be larger than 1.3 $M_\odot$.

In fact, the situation is further complicated by the fact that for accretion rates above a certain critical value $\dot{M}_{weak}$ (which depends on the white dwarf mass), TNRs are considerably weakened because of the strong compressional heating which results in ignition under only mildly degenerate conditions (Kutter and Sparks 1980, Prialnik et al. 1982). For $\dot{M} > \dot{M}_{weak}$, no mass ejection is obtained and thus, such outbursts do not satisfy our definition of RNe. The exact value of $\dot{M}_{weak}$ depends somewhat on L_{WD} and Z. In Fig. 1 we have plotted recurrence times as a function of M_{WD}, based on average values of $\dot{M}_{weak}$ (the dashed curve) taken from numerical results. From this plot we see that in order to obtain recurrence times shorter than 50 years, the mass of the white dwarf must be close to the Chandrasekhar limit (and $\dot{M} \gtrsim 1.7 \times 10^{-8}$ $M_\odot$/yr).

The above constraints on the white dwarf mass and the accretion rate have important consequences for the luminosity obtained from TNR powered models. The maximum luminosity obtained from shell burning is always comparable to that given by Paczynski's (1971) core mass-luminosity relation. Since Paczynski's luminosity is very close to the Eddington limit for very massive white dwarfs (the two luminosities cross at $M_{WD} \sim 1.39$ $M_\odot$), we can predict that the maximum luminosity of a TNR powered RN should be

$$L_{max} \gtrsim L_{EDD} \simeq 5.2 \times 10^4 L_\odot \left(\frac{M_{WD}}{1.38 M_\odot}\right) \qquad (3)$$

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At quiescence the bolometric luminosity of the system must exceed the accretion luminosity, thus

$$L_{BOL} \gtrsim \frac{GM_{WD}\dot{M}}{R_{WD}} \approx 270\ L_{\odot} \left(\frac{M_{WD}}{1.38\ M_{\odot}}\right) \frac{\dot{M}}{(1.7\mathrm{x}10^{-8} M_{\odot}\mathrm{yr}^{-1})} \left(\frac{R_{WD}}{1.9\mathrm{x}10^{8}\mathrm{cm}}\right)^{-1}. \quad (4)$$

Furthermore, if accretion takes place via a disk, then we can use the calculations of Warner (1987) and of WLTO to obtain the absolute visual magnitude M_V. We find that TNR powered RNe, must occupy at quiescence the region curve the upper curve in Fig. 2.

The exact numerical values can change somewhat, depending for example on the white dwarf luminosity. A large number of numerical simulations of TNRs on the surface of a 1.38 $M_{\odot}$ white dwarf, have shown that the dependence of the recurrence timescale on L_{WD} can be fitted approximately by the relation $\tau_{rec} \sim L_{WD}^{-0.28}$ (Livio, Hayes and Truran 1987).

2. OUTBURSTS POWERED BY ACCRETION

Accretion powered outbursts can occur in principle in (at least) three different ways. (i) An instability associated with the mass losing component, causing bursts of mass transfer. (ii) An instability in the accretion disk. (iii) A time dependent accretion rate, modulated by orbital eccentricity. Unfortunately all of these mechanisms suffer from large uncertainties, thus making their predictive power rather uncertain.

Dynamical instability of the red component has been particularly emphasized by Bath (1969, 1972, 1975) as a mechanism for dwarf nova eruptions. Recent two-dimensional numerical calculations by Edwards and Pringle (1987) have shown that short bursts of mass transfer are indeed obtained this way, for a polytropic equation of state with n = 3/2. While it is not clear yet from these calculations, whether the amount of mass transferred by low mass main sequence stars is sufficient to power DN eruptions, lobe-filling giants are found to transfer ~ 10^{-4} $M_{\odot}$ (see discussion of T CrB below). These models are not sufficiently developed to predict the recurrence time of the outbursts. All that can be said at this point is that τ_{rec} should be longer than the timescale for the envelope to regain its thermal equilibrium, thus (for parameters appropriate for T CrB)

$$\tau_{rec} \gtrsim \frac{R_{gas}\ T\ \Delta M_t}{\Delta L} \simeq 6.3 \left(\frac{T}{10^5 K}\right) \left(\frac{\Delta M_t}{6\mathrm{x}10^{-3}\ M_{\odot}}\right) \left(\frac{\Delta L}{0.1L}\right)^{-1} \mathrm{yr} \quad (5)$$

where ΔM_t is the mass that has been affected by the instability and ΔL is the luminosity deficit obtained in the mass transfer process.

Disk instability models produce a limit cycle behavior in which the disk undergoes transitions between a low and high viscosity

https://doi.org/10.1017/S0252921100103781 Published online by Cambridge University Press

states (e.g. Meyer and Meyer-Hofmeister 1984, Smak 1984, Lin, Papaloizou and Faulkner 1985, Cannizzo, Wheeler and Polidan 1986 and references therein). These transitions are a consequence of the double-valued nature of the viscosity - surface density functional relation. Matter in the disk accumulates, until the surface density Σ at some radius exceeds a certain critical value, at which point that annulus becomes thermally unstable, subsequently dragging the entire disk to the high state. An important property shared by the models of all the different groups working on disk instabilities, is that above a certain critical accretion rate, $\dot{M}_{crit}$, the disk lies on the stable (high-temperature) branch of the T_{eff}-Σ curve. Thus, eruptions caused by a disk instability can be expected only if the accretion rate (onto a 1 $M_\odot$ white dwarf) satisfies (e.g. Shafter, Wheeler and Cannizzo 1986)

$$\dot{M} \lesssim \dot{M}_{crit} \simeq 3 \times 10^{-9} P_4^{1.8} M_\odot/yr \tag{6}$$

where P_4 is the orbital period (in units of 4 hours). If this condition is translated to an absolute visual magnitude at quiescence, it requires that <u>RNe powered by a disk instability, should occupy at quiescence only the region below the lower curve in Fig. 2</u>.

Unfortunately, the recurrence intervals that can be obtained in the disk instability model are very uncertain, because they depend quite sensitively on the unknown viscosity parameter in the cold state α_c. Similarly, the outburst duration is largely determined by α_H, the viscosity parameter in the hot state. In general, the recurrence interval is given by

$$\tau_{rec} \simeq \frac{\Delta M_{outburst}}{\dot{M}_s} \tag{7}$$

where $\Delta M_{outburst}$ is the mass removed during the outburst and $\dot{M}_s$ is the mass transfer rate from the secondary. A very rough estimate for τ_{rec} can be obtained by taking the viscous drift timescale in the annulus at which the instability starts. This gives (Lin and Shields 1986, Cannizzo, Shafter and Wheeler 1987),

$$\tau_{rec} \simeq 8.8 \times 10^7 [F(q)]^{0.61} \left(\frac{M_{WD}}{M_\odot}\right)^{0.67} P_4^{0.41} \left(\frac{\alpha_c}{0.1}\right)^{-1.1} \mathrm{sec} \tag{8}$$

where F(q) is a function of the mass ratio $q = M_s/M_{WD}$ given by (Eggleton 1983)

$$F(q) = \frac{0.49q^{2/3} (1+q)^{1/3}}{0.6q^{2/3} + \ln(1+q^{1/3})} \tag{9}$$

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and we have assumed that the instability starts at the outer disk edge. The timescale found in actual calculations by Cannizzo, Wheeler and Polidan (1986), is shorter than the one given by eq. (8) by a factor of about 30, due to the fact that only a small fraction of the disk's mass is accreted during an outburst. Their results show that the recurrence time is proportional to $\alpha_c^{-1.23}$.

The decay timescale of the outburst is given in the disk instability model by (Smak 1984, Cannizzo, Shafter and Wheeler 1987)

$$\tau_d \simeq 38.3\ [F(q)]^{0.45} \left(\frac{M_{WD}}{M_\odot}\right)^{0.67} P_4^{0.3} \left(\frac{\alpha_H}{0.1}\right)^{-0.8} \left(\frac{\delta r/r}{0.1}\right) \text{ days} \quad (10)$$

where $\delta r/r$ is the fractional width of the cooling front which transfers the disk back into the cold state (typically of order 0.1). From eq. (8) and the following discussion we see that for disk instabilities to produce outbursts on recurrence times typical to RNe, <u>the viscosity parameter in the cold state must be very low, $\alpha_c \lesssim 10^{-3}$</u>.

Finally, an orbital eccentricity (if it exists) cannot be the <u>only</u> cause for the outbursts of the four RNe, since for two of them (T CrB and RS Oph) the orbital parameters are known. Also, the outbursts are not periodic. Eccentricity may play a certain minor role in the outbursts of T CrB (see WLTO).

3. INDIVIDUAL SYSTEMS

We shall now review some of the properties of the four RNe and examine them in relation to possible outburst models. An extensive discussion can be found in WLTO, here we shall add some recent developments.

<u>T Pyx</u>

This relatively regular RN has undergone outbursts in 1890, 1902, 1920, 1944 and 1966 (thus it can experience an outburst any day now!). Its corrected colors are $(B-V)_o = -0.26$, $(U-B)_o = -1.25$ and $(V-R)_o = -0.11$ (WLTO and references therein). Distance estimates based on the equivalent width of the interstellar calcium K line (Catchpole 1969) and the fact that the slow outburst development indicates a luminosity at maximum not much exceeding the Eddington value, give: $1050\text{pc} \lesssim D \lesssim 4500$ pc. The absolute visual magnitude at minimum is thus $(M_v)_{min} = 2.4 \pm 1.6$, which, when combined with the colors leads to the conclusion that the system <u>cannot contain a red giant</u> (making the system different from T CrB and RS Oph, to be discussed below). This limits the orbital period of the system to $P_{orb} \lesssim$ days (rather than hundreds of days), and makes it similar to cataclysmic variables. We can compare some of the details of the observations at quiescence and at outburst with the predictions of TNR models and accretion events. The main points of agreement with

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TNR models are: (1) The light curve development and the appearance of several velocity systems are very similar to slow novae, (2) on the rise to maximum the broadband colors become redder, characteristic of an expanding photosphere, (3) the mass of the ejected shell ~ 10^{-6} $M_\odot$ is consistent with the requirements of TNR models. The main difficulty for a TNR model is presented by the colors at minimum, which are much bluer than expected from an accretion disk. WLTO suggested that nuclear burning continues in T Pyx even at minimum, producing a bolometric luminosity L_{BOL} ~ 3 x 10^3 $L_\odot$ accompanied by a strong reflection effect from the secondary. It is not yet entirely clear whether the outburst characteristics can be reproduced under such conditions, this problem is currently investigated (Livio, Hayes and Truran 1987).

On the other hand, it is quite clear that an accretion event model, similar to DN eruptions, encounters severe difficulties: (1) In DN outbursts the broadband colors become bluer, in particular near the peak. (2) In DNe the rise to maximum spans only a few orbital periods in contrast to the slow rise of T Pyx. (3) The dominance of a hot continuum source at minimum indicates that accretion at a high rate (which would make the disk stable) is ongoing.

We therefore conclude that the outbursts of T Pyx are probably powered by TNRs, although some unanswered questions still remain.

U Sco

The observed properties of this system led WLTO to conclude that this system consists of a white dwarf accreting through a hot accretion disk from a G3-6 III-IV companion. The success of Starrfield, Sparks and Truran (1985) to reproduce the gross outburst characteristics, by means of a TNR resulting from accretion of hydrogen rich material, at $\dot{M} \simeq 1.7 \times 10^{-8}$ $M_\odot$/yr, onto a 1.38 $M_\odot$ white dwarf, has further led WLTO to the suggestion that U Sco is probably powered by a TNR. The main difficulty encountered by disk instability models has been in the fact that the hot disk, implied by the observations of U Sco at quiescence, would be expected to lie on the stable branch.

Some recent developments, however cause us to re-open the question of the outburst mechanism of U Sco. (1) U Sco was detected in outburst again in May 1987 (IAUC 4395, 4396, 4397, 4399, 4405), only eight years after its previous outburst. This poses serious difficulties to TNR models, since it requires an extremely high accretion rate (see discussion in section 2). (2) The spectrum of the system at quiescence shows no hydrogen and is dominated by a helium emission line spectrum (Hanes 1985). In outburst, optical and UV observations also reveal a strong depletion of hydrogen with respect to helium, He/H ~ 8:1 by mass (Barlow et al. 1981, Williams et al. 1981). In a recent work, Truran et al. (1988) have attempted to produce TNRs for different values of H/He ratios. They found that visually bright outbursts are not obtained for H/He $\lesssim$ 1 (by mass). This is simply a consequence of the fact that the ratio of energy generated per gram in hydrogen burning, to the binding energy per gram is

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$$\frac{\epsilon_{nuc}}{\epsilon_{bind}} \simeq 6.5\, X_H \left(\frac{M_{WD}}{1.38\ M_\odot}\right)^{-1} \left(\frac{R_{WD}}{1.9 \times 10^8 \mathrm{cm}}\right) , \qquad (11)$$

where X_H is the hydrogen mass fraction. Thus, for too low values of X_H, the photosphere does not expand to ~ 10^{12} cm, which is essential in order for the outburst energy to come out in the visual.

The outburst mechanism of U Sco is thus not clear yet. Possible solutions to the outlined difficulties are:

(1) The outburst is caused by a TNR, but for a yet unknown reason, the hydrogen in the transferred material is not detected (after all hydrogen is detected in outburst).

(2) The outburst is caused by a disk instability, but the transferred material is very rich in helium. In such a case, due to the higher ionization temperature, even the hot disk implied by observations can become unstable (Smak 1983). This solution poses some difficulties from an evolutionary point of view (WLTO).

(3) The outburst is caused by a TNR, but the physics of the TNR development has to be modified, to allow the transport of most of the energy generated (e.g. by more efficient convection), to be deposited into only a small fraction of the envelope.

T CrB and RS Oph

These two systems are very similar, as can be seen from Table 1 and represent the short period end of S-type symbiotics. Their properties have been extensively discussed by Webbink (1976), Livio, Truran and Webbink (1986), WLTO and Garcia (1987). The models proposed by Webbink and by Livio, Truran and Webbink for the outbursts of T CrB and RS Oph are essentially identical and involve the episodical transfer of a chunk of matter of ΔM ~ 10^{-4} - 10^{-3} $M_\odot$ from the red giant onto an accreting main sequence star. The differences between the two systems, according to the model of Livio et al. (1986), arise simply because of the difference in the evolutionary status of the accreting star. Due to the higher effective accretion rate in the RS Oph system and the larger total accreted mass, the main sequence star accretor is assumed to be in a bloated configuration (R ~ 12 $R_\odot$). Consequently, the stream of matter from the giant impacts the stellar surface directly, resulting in one outburst. In T CrB the stream passes around the accreting star, either skimming its surface or colliding with itself and circularizing (thus producing the first maximum). In either case, a disk is formed subsequently and the decay of this disk produces the second maximum. A recent calculation by Edwards (1987, private communication) has shown that for a giant of the type found in T CrB, mass of the order of 10^{-4} $M_\odot$ will indeed be transferred in a mass transfer instability.

The main difference between the outbursts of T CrB and RS Oph and those of other symbiotic systems also believed to be powered by accretion events, is in the very dynamic, shock-type outbursts of RS Oph and T CrB (see Livio, Webbink and Truran 1986). This is very probably a consequence of the shorter orbital period, since the

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luminosity of the principal outburst can be expected to scale like $L_o \sim \Delta E_{kin}/\tau_{dyn} \sim P_{orb}^{-5/3}$ (the available kinetic energy is inversely proportional to the binary separation).

4. CONCLUSIONS

An examination of the observational material suggests that only four systems: U Sco, T Pyx, T CrB and RS Oph deserve a classification as recurrent novae.

The outbursts of T CrB and RS Oph are probably caused by accretion events initiated by bursts of mass transfer from giant companions onto main sequence stars. Thermonuclear runaways on the surface of very massive white dwarfs appear as a likely cause for the outbursts of U Sco and T Pyx, but a number of points have to be clarified, in particular the composition of the accreted material in U Sco, before final conclusions can be drawn.

As a final remark we would like to point out that the outbursts of RNe are expected to exhibit a smaller range than CNe. This is a consequence of the fact that either the presence of a giant (required for the accretion model) or the presence of a very massive white dwarf accreting at a high rate (required for the TNR models) result in a brighter system at minimum.

ACKNOWLEDGEMENT

This work has been supported in part by NSF grant AST 86-11500 at the University of Illinois. I would like to thank the LOC and in particular J. Mikolajewska for their support.

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NOTE ADDED IN PROOFS:

Spectral observations obtained by Sekiguchi et al. (1987, private communication) of the 1987 outburst of U Sco generally support the TNR model for the outburst. However, a similar overabundance of helium over hydrogen as seen in the previous outburst (see text) has been observed.

Observations of T CrB during quiescence (Selvelli, Cassatella and Gilmozzi, private communication) revealed a UV luminosity of the order of $2x10^{35}$ erg s^{-1}. This would require an accretion rate of the order of 10^{-6} $M_{\odot}$/yr onto a main sequence star. These authors regard this, and the absence of the CIV line in their high resolution spectrum as evidence for the presence of a white dwarf.

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TABLE 1

A comparison of properties of T CrB and RS Oph

Property	T CrB	RS Oph
Orbital Period	227.5 days	230 days
Companion	M3 III giant	M0-M2 III giant
Ejection Velocity at Maximum	~ 5000 km/sec	~ 3500 km/sec
Evolution of Light Curve	very rapid	very rapid
Spectrum During Late Decline	High excitation forbidden emission line spectrum	High excitation forbidden emission line spectrum
τ_{rec}	80 years	22 years
Secondary Maximum	Present	Absent
$M_{hot} \sin^3 i$	$1.80 \pm 0.20\ M_\odot$	Unknown

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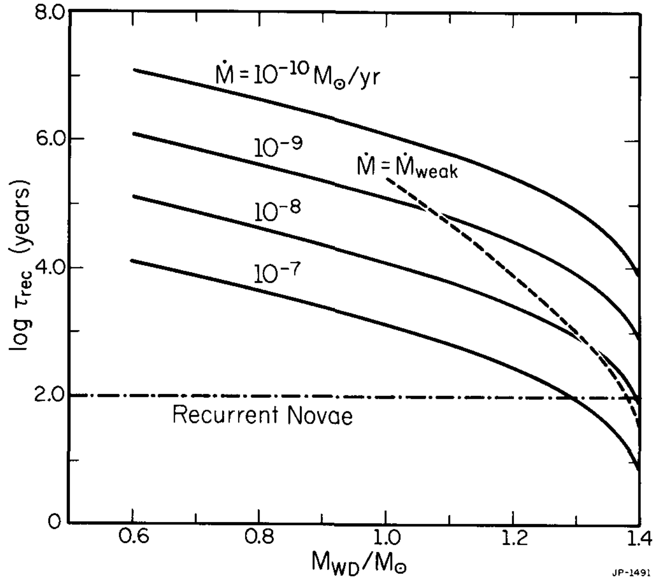

Fig. 1: The recurrence time as a function of the white dwarf mass. The dashed line gives the recurrence time for the maximum accretion rate capable of producing a strong TNR.

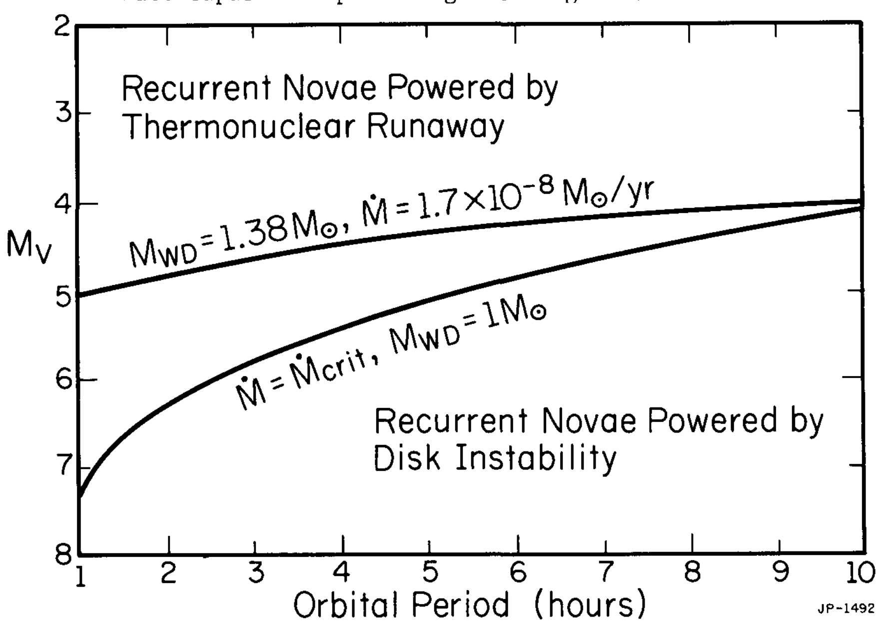

Fig. 2: The visual magnitude of the accretion disk at quiescence as a function of the orbital period. Recurrent novae powered by TNRs or disk instability must occupy the marked regions.

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