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UV and X-ray observations of T Pyx, a recurrent nova that will not become a SN Ia

P. Selvelli[1], R. González-Riestra[2], R. Gilmozzi[3], and A. Cassatella[4]

[1] INAF-Osservatorio Astronomico di Trieste, Via Tiepolo 11 - Trieste, I-34143 Trieste, Italy
[2] XMM-Newton Science Operations Centre, ESAC, P.O. Box 78, 28691 Villanueva de la Cañada, Madrid (Spain)
[3] European Southern Observatory, Karl-Schwarzschild-Str 2, D-85748 Garching bei München, Germany
[4] INAF-IFSI, Via del Fosso del Cavaliere 100, 00133 Roma, Italy, and Dipartimento di Fisica, Università Roma Tre, 00146 Roma, Italy

Abstract. We have accurately determined, from UV and other observations, the accretion disk luminosity of T Pyx during both the pre- and post-1966 inter-outburst phases. For $M_1 \sim 1.37$ $M_\odot$, we have found that $\dot{M}_{pre-OB} \sim 2.2 \times 10^{-8}$ $M_\odot$ yr^{-1}. By combining the measured accretion rate with the duration of the inter-outburst phase (Δt = 22 yrs), the total accreted mass is inferred to be $M_{accr}=\dot{M}_{pre-OB} \cdot \Delta t \sim 5.2 \times 10^{-7}$ $M_\odot$. This value is in excellent agreement with the theoretical ignition mass (M_{ign}) $\sim 5.0 \times 10^{-7} M_\odot$ expected for a massive white dwarf accreting at the quoted rate. However, the long duration of the optically thick phase during the recorded outbursts of T Pyx, a spectroscopic behavior typical of classical novae, and the persistence of P Cyg profiles, constrains the ejected mass M_{ign} to within 10^{-5} - 10^{-4} $M_\odot$. Therefore, T Pyx ejects far more material than it has accreted, and the mass of the white dwarf will not increase to the Chandrasekhar limit as generally believed in recurrent novae. A detailed study based on the UV data excludes the possibility that T Pyx belongs to the class of the supersoft X-ray sources, as has been postulated. XMM-NEWTON observations have revealed a weak, hard source and confirmed this interpretation.

Key words. Stars: novae - X-rays: binaries - Stars: supernovae: general

1. Introduction

Recurrent novae (RNe) are a subclass of classical novae characterized by outbursts with recurrence time of the order of decades. Solid theoretical considerations indicate that a model of a recurrent outburst requires a high accretion rate $\dot{M}$ (10^{-8}-10^{-7} $M_\odot$) onto a WD of mass close to the Chandrasekhar mass limit (Starrfield 1985; Webbink et al. 1987; Livio 1994). The ejecta of RNe are expected to be less massive than those of CNe. This is because on the surface of the massive WD expected in a RN, the critical conditions for ignition are reached with a far less massive envelope.

RNe represent a convenient laboratory to compare the predictions of the TNR theory with the observations. In fact, from the observed $\dot{M}$ and the observed duration of the

Send offprint requests to: P. Selvelli

inter-outburst interval, one can obtain a direct estimate of the total mass accreted (M_{accr}) between two successive outbursts. This quantity can be compared with both the (theoretical) critical ignition mass M_{ign} and the mass of the ejected shell M_{ej}. A similar comparison cannot be made in the case of CNe because the amount of mass accreted prior to outburst is badly determined due to their long inter-outburst interval.

Observations of RNe in quiescence and outburst can also be used to determine the secular balance between the total accreted mass M_{accr} and that ejected in the explosive phase M_{ej}, and therefore to investigate the possible role of RNe as progenitors of SN Ia.

The five recorded outbursts of T Pyx occurred in 1890, 1902, 1920, 1944, and 1966, with a mean recurrence time of 19±5.3 yrs. All outbursts were similar in photometric behavior and characterized by a decay time $t_3 \sim 90^d$, a speed class that is substantially slower than in other RNe.

2. The UV observations

In Gilmozzi and Selvelli (2007), we studied the UV spectrum of T Pyx in detail and our main conclusion was that the spectral energy distribution (SED) is dominated by an accretion disk in the UV+opt+IR ranges, with a distribution that, after correction for reddening E_{B-V}=0.25, is described by a power law $F_\lambda = 4.28 \times 10^{-6}\ \lambda^{-2.33}$ erg cm^{-2} s^{-1} Å^{-1}, close to that predicted by theoretical optically thick accretion disk models . The observed UV continuum distribution of T Pyx (see Fig.1)has remained remarkably constant in both slope and intensity during 16 years of *IUE* observations.

3. The binary system parameters

The determination of both the disk luminosity and the mass accretion rate of T Pyx requires prior knowledge of the distance, the system inclination angle i and the mass of the primary M_1. In the disk geometry, the inclination angle is critical to the estimate of the disk luminosity, while M_1 and R_1 (a function of M_1) are key parameters in the correlation between $\dot{M}$ and L_{disk}.

For most CVs, the determination of these and other parameters (M_2, P_{orb}, 2K) entering the mass function:

$$\frac{(M_2 \cdot sini)^3}{(M_1 + M_2)^2} = 1.037 \times 10^{-7} \cdot K_1^3 \cdot P \qquad (1)$$

is a difficult task, and accurate solutions have been obtained only for a few eclipsing systems.

For the orbital period we adopt the value $P_h = 1^h.829 \pm 0^h.002$ derived by Patterson et al. (1998) by photometric methods.

We note that this value has been very recently confirmed by high resolution spectroscopic observations made by Uthas et al. (2009) which have also revealed that the projected orbital velocity K_1 of the primary, derived from an analysis of radial velocities is approximately 20 kms^{-1}.

Given the observational and theoretical constrains for the system parameters (M_1: 1.25-1.4 $M_\odot$, M_2 = 0.12 $M_\odot$ (for $P_h = 1^h.829$), $K_1 \sim 25 \pm 5$ km s^{-1}), one derives that the solutions for the system inclination angle i (which is considered to be a free parameter) are in the range 25.5 ± 5.0 degrees (see Selvelli et al. (2008) for details). A low system inclination is consistent with the small value of the radial velocity, the sharpness of the emission lines in the optical (Warner, 1995), and the steepness of the UV and optical continua (Gilmozzi and Selvelli, 2007). However, the presence of radial velocity variations (Vogt et al. 1990), and the modulations in the photometric variations preclude an i value close to zero.

4. The disk luminosity and the mass accretion rate

The integrated UV continuum flux of T Pyx in the wavelength range 1180-3230 Å , after correction for reddening, is 1.94 × 10^{-10} erg cm^{-2}s^{-1} (Gilmozzi and Selvelli 2007).

For d = 3500 ± 350 pc (see Selvelli et al., 2008), the corresponding total luminosity of the UV continuum is:

$$L_{UV} \sim 2.85 \times 10^{35}\ erg\ s^{-1} \sim 74.2 \pm 15.0\ L_\odot.$$

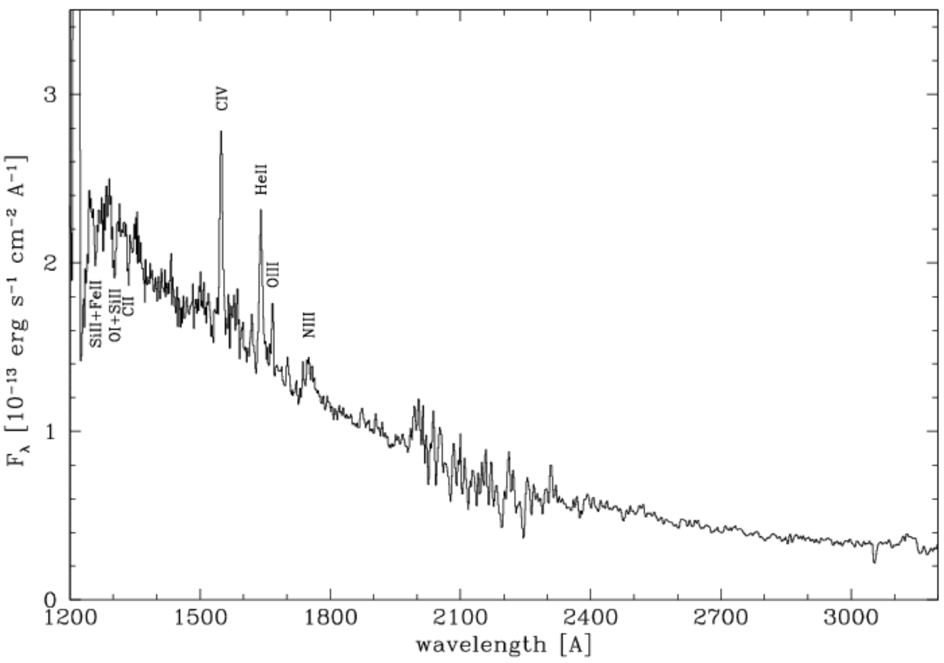

Fig. 1. Average *IUE* spectrum of T Pyx obtained by co-adding and merging 35 SW and 14 LW IUE spectra, dereddened with E_{B-V} = 0.25

The bolometric disk luminosity L_{disk} can be estimated from the observed UV and optical luminosity, where the bulk of the continuum radiation is emitted, after correction for the inclination and the unseen luminosity in both the infrared and at $\lambda \leq 1200$ Å. The radiation emitted at wavelengths shorter than Ly_α is strongly absorbed and the energy is redistributed to longer wavelengths (Nofar, Shaviv and Wehrse 1992, Wade and Hubeny 1998).

The integration (from $\lambda \sim 1000$ Å to the IR) of the power-law distribution which represents the observed UV and optical continuum of T Pyx, corresponds to a flux of about 3.6 $\times$ 10^{-10} erg cm^{-2} s^{-1}, which corresponds to a bolometric luminosity of 5.24 $\times$ 10^{35} erg s^{-1} $\sim$ 136.5 $L_\odot$. This value refers to the adopted inclination of about 25 degrees. After correction to the "standard" inclination of about 57 degrees and by considering an average limb-darkening factor similar to that in the optical, we obtain an angle (4π) averaged bolometric disk luminosity (hereinafter L_{disk}) of about 70 ± 15 $L_\odot$, where the relative uncertainty (21 percent) derives from the combination of the uncertainties in the distance and the inclination. We consider this to be the reference disk luminosity for the "recent", post-1967-outburst epoch.

If one makes the reasonable assumption that the disk is heated by viscous dissipation of gravitational energy, the mass accretion rate $\dot{M}$ can be obtained from the relation:

$$\dot{M} = (2R_1 L_{disk})/(GM_1) \qquad (2)$$

With this method, $\dot{M}$ is not model dependent but the knowledge of L_{disk} and M_1 is required.
Numerically, $\dot{M}$ can be represented by:

$$\dot{M} = 5.23 \times 10^{-10} \phi L_{disk}/L_\odot \quad \text{with} \qquad (3)$$

$$\phi = (R_1/M_1)/(R_{1o}/M_{1o}) = 0.1235 \cdot R_1/M_1, \quad (4)$$

where R_1 is the WD radius in 10^{-3} $R_\odot$, R_{1o} = 8.10×10^{-3} $R_\odot$ is the radius of a WD of mass M_1 = 1.0 $M_\odot$, and M_1 is in solar masses.

We obtained average values for R_1 as a function of M_1 from various WD radius-mass relations in the literature (Hamada and Salpeter 1961; Nauenberg 1972; Anderson 1988; Politano et al. 1990; Livio 1994). By fitting a quadratic function to these average values, for M_1 in the range 1.0 to 1.4 $M_\odot$, we found that:

$$R_1/R_\odot = -0.01315M_1^2 + 0.01777M_1 + 0.00347. \quad (5)$$

In the case of a massive WD with $M_1 \sim$ 1.37 $M_\odot$, as expected for T Pyx, we obtain that the mass accretion rate is close to $1.1 \pm 0.3 \times 10^{-8}$ $M_\odot$ yr^{-1}. The uncertainty in $\dot{M}$ is of the order of 23 percent and derives from the uncertainties in the distance, the correction for the inclination, and the value of R_1.

Other estimates of $\dot{M}$ can be obtained by direct application of the M_v-$\dot{M}$ relations reported in the literature (see Selvelli et al., 2008 for details).

5. The pre-1966-outburst mass accretion rate

According to the data of Schaefer (2005), during the inter-outburst phase in the years 1945-1966, T Pyx was a factor of 2 brighter in the B band than during the present quiescent phase after the 1967 outburst. Since no significant changes in the (B-V) color index were found during both of these quiescence phases, one can safely assume that in 1945-1966 T Pyx was a factor of 2 brighter also in terms of visual and bolometric flux.

Using the WLTO and the Lipkin et al. (2001) relations, one finds that the mass accretion rate in epochs pre-1966-outburst, hereinafter $\dot{M}_{pre-OB}$, was about twice the values of $\dot{M}$ for post 1967, obtained in the previous section.

Therefore, we estimate that the mass accretion rate $\dot{M}_{pre-OB}$ during the last pre-outburst interval (1945-1966) was between $1.68 \pm 0.4 \times 10^{-8}$ $M_\odot$ yr^{-1} and $3.72 \pm 0.8 \times 10^{-8}$ $M_\odot$ yr^{-1}, for M_1=1.25 and M_1=1.40 respectively.

6. The theoretical ignition mass and the accreted mass

A nova outburst occurs when, due to the gradual accumulation of H-rich material on the surface of the white dwarf, the pressure at the bottom of the accreted layer becomes sufficiently high for nuclear ignition of H to begin (Shara 1981, Fujimoto 1982, MacDonald 1983). Since the radius R_1 of the white dwarf varies approximately as $M_1^{-1/3}$ for $M_1 \leq 1.0$ $M_\odot$, the critical pressure for ignition

$$P_{ign} = (G \cdot M_1 \cdot M_{ign})/(4\pi R_1^4) \quad (6)$$

corresponds to a critical ignition mass M_{ign} that decreases approximately as $M_1^{-7/3}$, while, for more massive WDs M_{ign}, decreases with a steeper slope. However, as first pointed out by MacDonald (1983) and in more detail by Shara (1989) and Prialnik and Kovetz (1995), the behavior of a CN eruption and in particular the critical mass depends (apart from the WD mass) also on the mass accretion rate (since the WD is heated by accretion) and the temperature of the isothermal white dwarf core. Townsley and Bildsten (2004) confirmed that the earlier prescriptions for ignition, based on the simple scaling $M_{ign} \propto R^4$ M_1^{-1} for a unique P_{ign}, are inadequate and that a system of a given M_1 mass can have value of M_{ign} that varies by a factor of 10 for different $\dot{M}$.

The critical envelope mass M_{ign} as a function of M_1 and $\dot{M}$ can be numerically approximated to be:

$$logM_{ign} = -2.862 + 1.542 \cdot M_1^{-1.436} ln(1.429 + -M_1) - 0.19(log\dot{M} + 10)^{1.484}$$

(Kahabka and van Den Heuvel 2006) where M_1 is in $M_\odot$ and $\dot{M}$ is in $M_\odot$ yr^{-1}.

Table 1 indicates (for various M_1 and hence R_1 values) $\dot{M}_{pre-OB}$, the theoretical M_{ign}, the accreted mass M_{accr}=Δt$\cdot$ $\dot{M}_{pre-OB}$, where Δt=22 yrs is the pre-1966 inter-outburst interval, and τ=$M_{ign}/\dot{M}_{pre-OB}$, that is, the expected recurrence time in years.

Table 1 clearly shows that, after allowances for errors in the estimate of $\dot{M}_{pre-OB}$, the expected recurrence time τ = $M_{ign}/\dot{M}_{pre-OB}$ is

Table 1. M_1, the estimated pre-1967-outburst accretion rate $\dot{M}_{pre-OB}$ (for L_{disk}=140 $L_\odot$), the theoretical ignition mass M_{ign}, the accreted mass M_{accr}=22$\cdot$ $\dot{M}_{pre-OB}$ and the expected recurrence time τ=$M_{ign}/\dot{M}_{pre-OB}$.

M_1 ($M_\odot$)	$\dot{M}_{pre-OB}$ ($10^{-8} M_\odot yr^{-1}$)	M_{ign} ($10^{-7} M_\odot$)	M_{accr} ($10^{-7} M_\odot$)	τ (yrs)
1.00	7.32	77.2	16.10	105.5
1.05	6.56	67.6	14.43	103.0
1.10	5.84	56.2	12.84	96.2
1.15	5.12	45.7	11.26	89.2
1.20	4.40	36.3	9.68	82.5
1.25	3.72	25.7	8.18	69.1
1.30	3.02	16.2	6.64	53.6
1.33	2.62	11.0	5.76	42.0
1.35	2.34	7.69	5.15	32.8
1.36	2.22	6.14	4.88	27.7
1.37	2.08	4.73	4.58	22.7
1.38	1.94	3.44	4.27	17.7
1.39	1.80	2.29	3.96	12.7
1.40	1.68	1.33	3.69	7.9

close to the observed value (22 yr) for M_1 ~ 1.36 - 1.38 $M_\odot$ corresponding to M_{ign} and M_{accr} in the range 3.0 to 6.0 × 10^{-7} $M_\odot$.

This value is consistent with the values derived by other methods (Selvelli et al. 2008) thus confirming that in the case of T Pyx the ignition mass was close to 4.5 × 10^{-7} $M_\odot$.

In conclusion, in the recurrent nova T Pyx, the theoretical ignition mass and the observed accreted mass are in excellent agreement for the case of a massive WD.

7. The long lasting optically thick phase of the outburst

That an an optically thick stage characterized the outbursts of T Pyx, can be directly inferred from the lengthy period of time during which the optical magnitude was close to its maximum value, with t_3 ~ 90^d, and from the presence of displace absorption lines of HI and FeII (at ~ -1500 km s^{-1}, which lasted for at least 80 days (Catchpole, 1969, Chincarini amd Rosino, 1969).

The similarity between the spectroscopic and photometric characteristics of the outbursts of T Pyx and those of CNe, which allegedly eject about 10^{-4} - 10^{-5} $M_\odot$, suggests in itself that during outburst T Pyx expelled a shell of comparable mass.

All quantitative methods and considerations about the photometric and spectral behavior of T Pyx during the outbursts indicate the presence of a massive envelope with M_{ej} ~ 10^{-4} -10^{-5} $M_\odot$ (for details see Selvelli et al., 2008). This agrees with the considerations of Shore (2008), who pointed out that, for a typical ejection velocity of about -2000 kms^{-1}, a nova with an optical decline time longer than a week must eject a mass higher than 10^{-5} $M_\odot$.

8. The discrepancy between the mass of the thick shell and the ignition mass

The ejection of a massive shell during the early (optically thick) outburst phase contrasts significantly with the results of the UV + optical observations during quiescence and the theoretical requirements for M_{ign}, which imply a $\dot{M}_{pre-OB}$ ~ 2.2 × 10^{-8} and a total mass for the accreted shell M_{accr} of about ~ 5.0 × 10^{-7} $M_\odot$. During outburst, T Pyx has apparently ejected far more material than it has accreted, the mass ejected during outburst being about a factor of 100 higher than both the theoretical ignition mass M_{ign} and the total mass accreted before outburst, M_{accr}. This indicates that a secular decrease in the mass of the white dwarf is expected. Therefore, evolution to become a SNIa appears to be excluded. On the other hand, the ejection of a more-massive-than-accreted shell is apparently in contrast with the observational evidence that the chemical composition of the T Pyx nebula is close to solar (Williams, 1982). This appears to exclude any erosion of the white dwarf and implies that the white dwarf does not lose mass after cycles of accretion and ejection. It is unclear whether these substantial discrepancies originates in flaws in the theoretical assumptions or the interpretation of the observations. They certainly highlight the need for accurate values of the most critical parameters of this recurrent nova, i.e. the mass and chemical composition of the shell ejected during outburst.

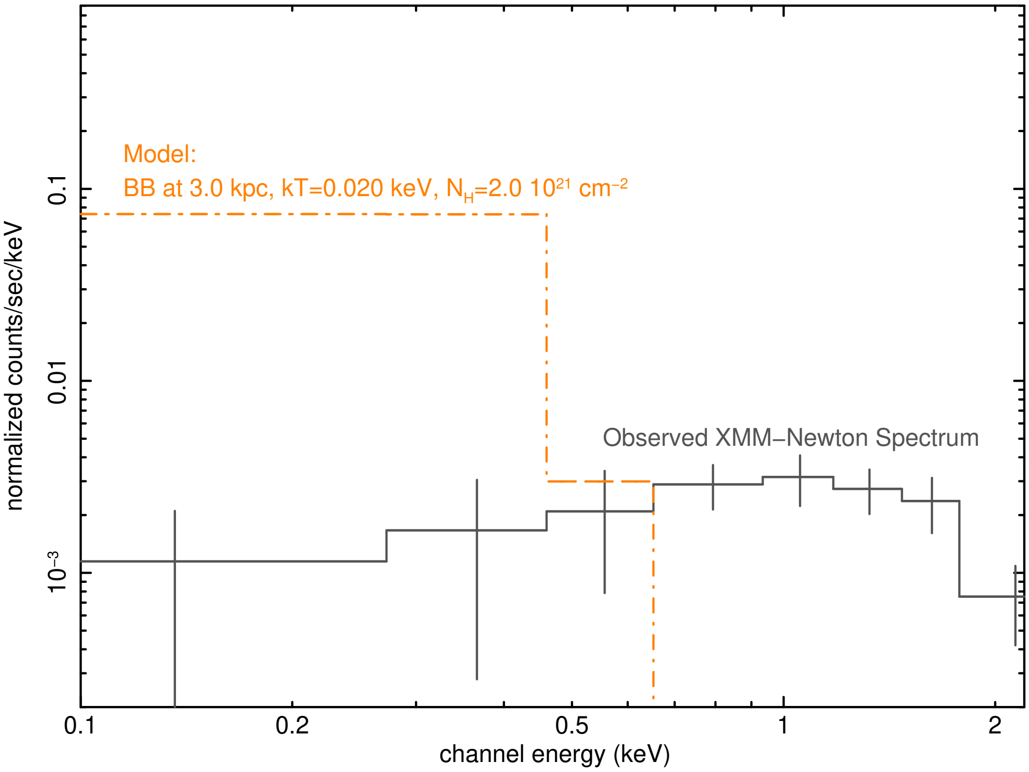

Fig. 2. The XMM-Newton EPIC-pn spectrum of T Pyx (bottom) compared with the simulations of a 20 ksec exposure of a blackbody of 2.4×10^5 K and a luminosity of 1×10^{37} erg s^{-1}, computed with the assumptions of a distance of 3000 pc and a reddening of 0.4, (dot-dashed line). The spectra shown here have been re-binned to 20 counts per bin.

9. The XMM observations

T Pyx was observed by XMM-Newton on November 10 2006. All the three EPIC cameras were operated in Full Frame mode with the Medium filter. The total useful exposure time after filtering for high radiation periods was 22.1 ksec.

Figure 2 shows the XMM-Newton EPIC-pn spectrum of T Pyx compared to a blackbody of 2.4×10^5 K and a luminosity of 1.0×10^{37} erg s^{-1}. The blackbody spectrum was simulated assuming an exposure time of 20 ksec, similar to that of the data, with two assumptions: a distance of 3500 pc and a reddening E_{B-V}=0.25 (as in this paper), and a distance of 3000 pc and a reddening of 0.4 (as assumed by Knigge et al., 2000). The presence of a supersoft component with a temperature of 2.4×10^5 K and a luminosity of 1.0×10^{37} erg s^{-1}, whose existence was postulated by both Patterson et al. (1998) and Knigge et al.(2000), can be definitely excluded.

Such a bright component would be easily visible at soft energies (i.e. below 0.5 keV), and this is not the case. Any supersoft emission, if present, would be several orders of magnitude fainter than expected.

Therefore, the XMM observations, excluding the possibilities of continuous burning and the supersoft source scenario (a massive white dwarf accreting at high rates), appear to exclude T Pyx becoming a SN Ia by means of the supersoft X-ray source channel described by Hachisu (2002, 2003).

10. Summary and conclusions

This is the first reliable determination of the mass accreted prior to a nova outburst, M_{accr}, owing to the dominance of the accretion disk luminosity over that of the secondary star at UV, optical and IR wavelengths, as well as good observational coverage during the inter-outburst phases. M_{accr} cannot be confidently determined in other cases, such as classical novae, because of their long inter-outburst interval, nor in other recurrent novae, due to the faintness of the source, the lack of systematic UV observations, or the dominance of light from the giant companion over that from the accretion disk.

The literature data of the spectroscopic and photometric evolution during the outbursts of T Pyx clearly indicate the occurrence of an optically thick phase that lasted about three months. This implies an ejected mass of $M_{ej} \sim 10^{-5}$ $M_{\odot}$ or higher, i.e. much higher than the mass of the accreted shell $M_{accr} \sim 5.2 \times 10^{-7}$ $M_{\odot}$, inferred from UV and other observations during quiescence. Therefore, in T Pyx, far more material appears to have been ejected during the last outburst than has been accreted by the white dwarf. This raises several doubts about the common assumption that the white dwarf in recurrent novae increases in mass toward the Chandrasekhar limit, and about the possible role of RNe as progenitors of SNIa.

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