

The secrets of T Pyxidis

II. A recurrent nova that will not become a SN Ia

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ABSTRACT

Aims. We compare the observed and theoretical parameters for the quiescent and outburst phases of the recurring nova T Pyx.

Methods. IUE data were used to derive the disk luminosity and the mass accretion rate, and to exclude the presence of quasi-steady burning at the WD surface. XMM-NEWTON data were used to verify this conclusion.

Results. By various methods, we obtained $L_{\text{disk}} \sim 70 L_{\odot}$ and $\dot{M} \sim 1.1 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. These values were about twice as high in the pre-1966-outburst epoch. This allowed the first direct estimate of the total mass accreted before outburst, $M_{\text{accr}} = \dot{M}_{\text{pre-OB}} \cdot \Delta t$, and its comparison with the critical ignition mass M_{ign} . We found M_{accr} and M_{ign} to be in perfect agreement (with a value close to $5 \times 10^{-7} M_{\odot}$) for $M_1 \sim 1.37 M_{\odot}$, which provides a confirmation of the thermonuclear runaway theory. The comparison of the observed parameters of the eruption phase, with the corresponding values in the grid of models by Yaron and collaborators, provides satisfactory agreement for values of M_1 close to $1.35 M_{\odot}$ and $\log \dot{M}$ between -8.0 and -7.0 , but the observed value of the decay time t_3 is higher than expected. 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, cataclysmic variables – stars: supernovae: general – X-rays: binaries – ultraviolet: general

1. Introduction

Classical novae (CNe) are semi-detached binary systems in which a white dwarf (WD) primary star accretes hydrogen-rich matter, by means of an accretion disk, from a companion star which fills its Roche lobe. The “classical nova” outburst is a thermonuclear runaway (TNR) process on the surface of a white dwarf that is produced when, due to the gradual accumulation of hydrogen-rich material on its surface, the pressure at the bottom of the accreted layer, which is partially or fully degenerate, becomes sufficiently high ($P \geq 10^{18}$ – $10^{20} \text{ dyn cm}^{-2}$) for nuclear ignition of hydrogen to begin. The critical mass for ignition M_{ign} depends primarily on the mass of the white dwarf as $M_{\text{ign}} \sim M_1^{-7/3}$, although more detailed models show that the ignition mass also depends on both the mass accretion rate \dot{M} and the core WD temperature (Priyalnik & Kovetz 1995; Townsley & Bildsten 2004; Yaron et al. 2005; see also Sect. 8).

Recurrent novae (RNe) are a subclass of classical novae characterized by outbursts with recurrence time of the order of decades. We refer to Webbink et al. (hereinafter WLTO, 1987) as the seminal paper on the nature of recurrent novae and to Warner (1995), Hachisu & Kato (2001), and Shore (2008) for further considerations of this topic. 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; WLTO 1987; Livio 1994). However, nova models (Priyalnik & Kovetz 1995; Yaron et al. 2005; see also Sect. 8) appear to evade these strict requirements and allow the occurrence of recurrent outbursts also in a (slightly) less massive WD. 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. Studies of the ejecta of RNe indicate a mass between 10^{-6} – $10^{-7} M_{\odot}$, instead of the 10^{-4} – $10^{-5} M_{\odot}$ observed in “classical” novae (Gehrz et al. 1998; Hernanz & Jose 1998; Starrfield 1999).

RNe represent a convenient laboratory to compare the predictions of the TNR theory with the observations. From the observed \dot{M} and the observed duration of the inter-outburst interval, in principle, 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} , which can be estimated by spectroscopic methods (and, in principle, by photometric methods if dP/P can be accurately measured, Livio 1991). 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 ejecta of RNe have an almost “solar” chemical composition and are not enriched in “heavy” elements, such as carbon, oxygen and neon. This has been taken as an indication that the massive white dwarf in RNe is not eroded, will gain mass after each cycle of accretion and ejection, and will eventually explode as a type Ia supernova (Hachisu & Kato 2002).

In Gilmozzi & Selvelli (2007, hereinafter Paper I), 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 $F_{\lambda} = 4.28 \times 10^{-6} \lambda^{-2.33} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$, while the continuum in the UV range can also be well represented by a single blackbody of $T \sim 34\,000 \text{ K}$. The observed UV continuum distribution of T Pyx has remained remarkably constant in both slope and intensity during 16 years of IUE observations.

In the present study, we use this basic result from the IUE data and other considerations, to constrain the relevant parameters of the system and to attempt to understand the elusive nature of its outbursts. The five recorded outbursts of T Pyx occurred in 1890, 1902, 1920, 1944, and 1966, with a mean recurrence time of $19 \pm 5.3 \text{ yrs}$ (WLTO). All outbursts were similar in photometric behavior and characterized by a decay time $t_3 \sim 90^{\text{d}}$, a speed class that is substantially slower than in other RNe. We divide the paper into several self-contained sections.

In Sect. 2, we discuss the problem of distance, which we determine to be $3500 \pm 500 \text{ pc}$. In Sect. 3, we analyze the mass function of the system. Using observational data and other considerations, we obtain $1.25 < M_1 < 1.4 M_{\odot}$, $M_2 \sim 0.24 M_{\odot}$, or $M_2 \sim 0.12 M_{\odot}$ (depending on the as yet uncertain period), and $i = 25 \pm 5 \text{ degrees}$. In Sect. 4, we derive the absolute magnitude at minimum $M_v = 2.53 \pm 0.23$. In Sect. 5, we calculate the bolometric disk luminosity $L_{\text{disk}} \sim 70 L_{\odot}$.

In Sect. 6 we use various methods to determine the mass accretion rate. The value depends on M_{WD} , and is $\dot{M} \sim 1.3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ for $M_{\text{WD}} = 1.33 M_{\odot}$. In Sect. 7, we derive the accretion rate before the 1966 outburst, and find that it is about twice the value measured with IUE. In Sect. 8, we compare the accreted mass before the last outburst as determined from the \dot{M} derived in Sect. 7, $M_{\text{accr}} \sim 4.5 \times 10^{-7} M_{\odot}$, with theoretical calculations of the ignition mass. We find good agreement (including the inter-outburst interval) for $M_{\text{WD}} \sim 1.37 M_{\odot}$. In Sect. 9, we compare the observations of T Pyx with the theoretical models of Yaron et al. (2005), finding good agreement for all parameters with the exception of t_3 .

In Sect. 10, we reanalyze the historical data of the outbursts and reach the inescapable conclusion that the mass ejected in the explosion is $M_{\text{ej}} \sim 10^{-4} - 10^{-5} M_{\odot}$, about a factor 100 higher than the accreted mass. This discrepancy is discussed in detail in Sect. 11, and leads to the conclusion that the WD loses mass during the outbursts. In Sect. 12, we revisit the parameters of the extended nebula around T Pyx, and demonstrate why the nebula cannot be used to derive information about the mass ejected during outburst. Section 13 discusses the mass balance and infers that T Pyx is not destined to become a SN Ia as often postulated for recurrent novae. Far from increasing its mass towards the Chandrasekhar limit, the WD in T Pyx is being eroded.

In Sect. 14, we discuss the hypothesis that the WD in T Pyx is undergoing steady nuclear burning on its surface, and show that it is incompatible with both historical and UV observations.

In Sect. 15, we report about XMM observations confirming our analysis by directly disproving the hypothesis.

In Sect. 16, we discuss the recurrence time, and predict that the long awaited next outburst will occur around A.D. 2025. Section 17 reports our conclusions.

2. The distance

An accurate knowledge of distance is fundamental to the determination of the disk luminosity L_{disk} (and M_v), the mass accretion rate \dot{M} , and the mass of the observed nebula surrounding the system M_{neb} (not to be confused with the mass ejected during outburst, M_{ej}).

In this section, we revisit the problem of determining the distance to T Pyx. We adopt a new accurate determination of the reddening, $E_{B-V} = 0.25 \pm 0.02$, which is based on the depth of the $\lambda 2175 \text{ \AA}$ interstellar absorption feature (see Paper I).

An estimate of the absolute magnitude at maximum M_V^{max} can be obtained from the optical decay time t_2 or t_3 by extending to a recurrent nova such as T Pyx, the applicability of the Maximum Magnitude versus Rate of Decline (MMRD) relations obtained using data of classical novae.

This is justified by the fact that it is clearly established that the same kind of physical process for the outburst is involved i.e. a TNR on an accreting WD. The suggestion that recurrent novae in M 31 are fainter than predicted by the MMRD curve (Della Valle & Livio 1998), applies only to the RNe subset that, unlike T Pyx, displays a short t_3 . The long t_3 of T Pyx, the spectral behavior during outburst and the quantity of mass ejected (see Sect. 10) indicate that the same mechanism is operating as in CNe.

The optical decay time of T Pyx is well determined (Mayall 1967; Chincarini & Rosino 1969; Duerbeck 1987,b; WLTO 1987; Warner 1995) with $t_2 \sim 62^{\text{d}}$ and $t_3 \sim 92^{\text{d}}$. From these values, we derived four different estimates for M_v^{max} (-7.01 , -6.75 , -7.00 , -6.64) using the S-shaped MMRD relation of Della Valle & Livio (1995), and the two linear and the one S-shaped relations of Downes & Duerbeck (2000), respectively.

An additional estimate of the distance can be obtained by assuming that T Pyx, as a moderately fast nova, radiated at near-Eddington luminosity at maximum. This provides

$$L_{\text{Edd}}/L_{\odot} = 4.6 \times 10^4 (M_1/M_{\odot} - 0.26). \quad (1)$$

For a massive white dwarf ($M_1 \sim 1.35 M_{\odot}$), this corresponds to $M_{\text{bol}}^{\text{max}} \sim -6.98$. Close to the epoch of maximum light the observed color index showed oscillations about an average value of $(B - V) = 0.35$ (Eggen et al. 1967; Eggen 1968), or, after correction for reddening, $(B - V)_o \sim 0.10$. Van den Bergh & Younger (1987) found that novae at maximum light have $(B - V)_o = +0.23 \pm 0.06$, while Warner (1976) reported that the intrinsic color of novae close to maximum is $(B - V)_o \sim 0.0$. The intermediate value for T Pyx was $(B - V)_o \sim 0.10$, which is indicative of a temperature lower than $10\,000 \text{ K}$ and suggests that, close to maximum light, the nova radiated mostly in the optical. Since the bolometric correction is quite small in this case ($BC \sim -0.20$), it follows that $M_v^{\text{max}} = -6.78$, which is quite close to the values obtained above from the four MMRD relations.

The mean value of the five estimates for M_v^{max} is -6.83 , with a median value -6.79 and a formal standard deviation $\sigma = 0.16$. The five estimates are intermediate between the value (-6.4) reported by Payne-Gaposchkin (1957), Catchpole (1968), and Warner (1995) and the single value (-7.47) given by Duerbeck (1981).

Adopting $M_v^{\max} = -6.81$, $A_V = 3.15 \times E(B - V) = 0.79$ and $m_v^{\max} \sim 6.7$ (Catchpole 1968; Warner 1995; Chincarini & Rosino 1969), one obtains a distance $d = 10^{(1+(m-M-A)/5)} \sim 3500$ pc. The uncertainties in the individual parameters (0.16 for M_v^{\max} , 0.1 for m_v^{\max} , 0.06 for A_V) correspond to an uncertainty of about 330 pc in the distance, i.e. to a relative uncertainty of the order of 10 percent.

A further estimate of the distance can be obtained by comparing the dereddened flux of T Pyx at 1600 Å with the accretion disk models by Wade & Hubeny (1998). As mentioned in Paper I, the most appropriate descriptions of the shape and depth of the lines (models *ee* and *jj* at low inclination angles) correspond to high values of white-dwarf mass and accretion rate, although they provide a continuum that is too steep. In any case, these high M_1 , high \dot{M} models, (we have extrapolated \dot{M} to values as high as $\log \dot{M} = -7.5$) clearly show that the ratio $F_{1600}^{\text{model}}/F_{1600}^{\text{obs.}}$ is about 1000. Applying a scaling of a factor of $\sim(1000)^{0.5} = 31.5$ to the model distance (100 pc) would reconcile these two values. The derived value of ~ 3150 pc is in fair agreement with the assumed distance of 3500 pc.

We recall that a range of distances to T Pyx can be found in the literature. Catchpole (1969) derived a lower limit of 1050 pc from the equivalent width of the CaII K line ($EW \sim 400$ mÅ) and the EW -distance relationship derived by Beals & Oke (1953) for stars close to the Galactic plane. The EW measurement of Catchpole is however quite uncertain because of possible contamination by emission lines and the low quality of the spectra (the CaII K line falls close to the edge of the spectrum and only two spectra were of sufficient signal in that region).

Catchpole (1969), using the two spectra of the highest signal-to-noise-ratio found that the K line of calcium corresponds to radial velocity of $+20$ km s $^{-1}$. According to Catchpole (1969), this velocity agrees well with that of material travelling with the Galactic rotation in the direction of T Pyx; since this direction is, however, close to a node of the rotation curve, the Beals & Oke (1953) method cannot be used to determine the distance.

Warner (1976), used the calibration given by Munch (1968) for stars close to a node in the Galactic rotation curve, and indicated that a star with a measurement of 0.4 Å for the K line should be at least at a distance of 2 kpc.

In a study of the IS Ca II K line towards O- and B-type stars in the Galactic disk, Hunter et al. (2006), presented a new calibration of the the total column density of Ca II K versus distance. In a plot of $\log N(K)$ versus $\log d$, the estimated distance of 3500 pc ($\log d = 3.545$) would correspond to $\log N(\text{CaII}) \sim 13.0$. The EW of the K line measured by Catchpole (1969) corresponds to a column density of 4.9×10^{12} ($\log N = 12.69$), which would correspond to a distance of 2200 pc. However, this value of column density is a lower limit, because the medium is not optically thin in the K line, and a yet higher value of distance is expected.

By applying T Pyx theoretical predictions for light curves of CVs in outburst, Kato (1990) estimated a distance close to 4000 pc, by comparing the observed magnitude at outburst with the theoretical absolute magnitude prediction at outburst.

In the following, we assume a distance of $d = 3500 \pm 350$ pc. A discussion of the critical role played by distance in the interpretation of the nature of T Pyx is given in Sect. 11.1.

3. The system parameters

We aim to determine both the disk luminosity and the mass accretion rate of T Pyx. This requires prior knowledge of 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:

$$\frac{(M_2 \cdot \sin i)^3}{(M_1 + M_2)^2} = 1.037 \times 10^{-7} \cdot K_1^3 \cdot P \quad (2)$$

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

For T Pyx, the situation, “*prima facie*”, does not appear encouraging because no system parameter (not even the orbital period) have been accurately measured. Therefore, one has to start from a restricted range of values corresponding to the most accurately known parameters in the mass function equation, based on theoretical or semi-empirical considerations, and derive the corresponding range of allowed solutions for the unknown relevant parameters.

3.1. The orbital period(s) and K_1

There have been several attempts to measure the orbital period of T Pyx, although, disappointingly, they have resulted in a wide range of values (see Paper I); this is a clear indication that there is no definite photometric clock associated with the system.

Patterson et al. (1998) detected a stable photometric wave at $P_h = 1^{\text{h}}829 \pm 0^{\text{m}}002$ (a value close to that of the “most probable” photometric period $P_h = 1^{\text{h}}828$ of Schaefer et al. 1992), although this interpretation is inconsistent with the presence of another signal at $2^{\text{h}}635$.

The only spectroscopic determination of the period is that by Vogt et al. (1990), who, in a preliminary study based on a large number (101) of spectra of limited resolution (~ 3 Å), reported a spectroscopic period of $P_h \sim 3^{\text{h}}439$, without quoting uncertainties. This spectroscopic period is almost twice the photometric value determined by Szkody & Feinswog (1988) in the infrared. In other CVs, this behavior is generally interpreted as evidence of ellipsoidal variations in the companion, in a system observed at a high inclination angle. This is not the case for T Pyx because, as convincingly shown in Paper I, the companion does not contribute to the J light curve, unless the distance is less than 200 pc.

In the following, we consider system solutions for both $P_h = 1^{\text{h}}829$ (photometric, Patterson et al. 1998) and $P_h = 3^{\text{h}}439$ (spectroscopic, Vogt et al. 1990). The inclusion of the spectroscopic period could be criticized since it is the result of a preliminary analysis that has not been confirmed by subsequent studies. However, given the complex photometric period structure and in the absence of a definite physical interpretation of the stable signal with $P_h = 1^{\text{h}}829$ (that could even arise from the rotation of a magnetic white dwarf), we believe that the spectroscopic results should be considered, since, in any case, they have not been challenged by similar studies.

Vogt et al. (1990) found that the projected orbital velocity K_1 of the primary, derived from an analysis of radial velocities of the emission lines, is approximately 24 ± 5 km s $^{-1}$. Taking into account the limited resolution and the large number of spectra, this value is probably an upper limit. We assume that this value of K_1 is representative of the primary star radial velocity (independently of the period being considered), although we are aware of the problems encountered in associating radial velocity changes with the motion of the WD.

3.2. The mass of the primary

Both theoretical considerations and observational determinations (although limited) indicate that the WD masses in classical nova systems are about $1.0 M_{\odot}$, i.e. higher than inferred from the standard field WD mass distribution (Ritter et al. 1991). Theoretical models of recurrent novae require an even more massive white dwarf (WLTO, Shara 1989; Livio 1994). Therefore, in the following, we allow the mass of the primary, M_1 , to vary between 1.25 and $1.4 M_{\odot}$.

3.3. The mass of the secondary

In the absence of any direct information about the secondary (the accretion disk is the dominant luminosity source from the UV to the infrared, Paper I), we can estimate its mass M_2 on the basis of the commonly accepted assumptions that: a) the secondary fills its Roche lobe; b) its radius R_2 is determined by the Roche geometry; and c) the secondary star obeys a mass-radius relation valid for low mass main sequence stars. In this standard description, the radius of the secondary is well approximated by the equivalent radius R_L of the Roche lobe itself, i.e. $R_2 \sim R_L$ and the spherical volume of the secondary is assumed to equal the volume of its Roche lobe. The equivalent volume radii of the Roche lobe are given in tabular form by several authors (Plavec & Kratochvil 1964; Kopal 1972; Eggleton 1983; Mochnacky 1984). For our purposes, it is convenient however to use the analytical approximation by Paczinsky (1971), which is valid for $M_2/M_1 \leq 0.8$:

$$R_L/A = 0.457256(M_2/(M_1 + M_2))^{1/3} \quad (3)$$

where we have introduced a new value for the constant (instead of 0.46224) because it yields results that differ by less than 1% from those tabulated by Eggleton (1983) and Mochnacky (1984).

By combining Eq. (3) with Kepler's third law:

$$A = 0.50557 M_{\text{tot}}^{1/3} P_h^{2/3} \quad (4)$$

one obtains an approximate relation between P , M_2 , and R_2 ($\sim R_L$):

$$P_h = 8.997 R_2^{3/2} M_2^{-1/2}. \quad (5)$$

In the crude assumption $M_2 \sim R_2$, this provides an approximate relation: $M_2 = 0.111 P_h$ by which a rough estimate of the mass of the secondary can be obtained if the orbital period is known. In general, however, the $R - M$ relation for the low MS stars is described more accurately by a relation of the form:

$$R_2 \sim \beta M_2^{\alpha}. \quad (6)$$

By combining Eqs. (5) and (6), we derive a more general relation between M_2 and P_h :

$$M_2 = P_h^{(2/(3\alpha-1))} \cdot 8.997^{(2/(1-3\alpha))} \cdot \beta^{(3/(1-3\alpha))}. \quad (7)$$

Values for the parameters α and β of the low mass main-sequence stars were derived from observational data and theoretical considerations. In particular, Warner (1995) assumed that $R_2 = M_2^{13/15}$ (which provides an approximate fit to the data set by Webbink 1990) and derived $M = 0.065 \times P^{1.25}$, while Smith & Dhillon (1998) found a constitutive relation $R_2 = 0.91 M_2^{0.75}$ and derived $M = 0.038 \times P^{1.58}$.

Patterson et al. (2005) derived an empirical mass-radius sequence for CV secondaries based on masses and radii measured

Table 1. M_2 for $P_h = 1.829$ and $P_h = 3.439$ from various $M_2 - P$ relations or different α and β values in the literature (see text).

	$P_h = 1.829$	$P_h = 3.439$
Patterson et al.	0.134	0.234
Smith & Dhillon	0.100	0.267
Knigge	0.140	0.236
Warner	0.138	0.304
Equation (7)	0.121	0.227

primarily for the superhumping CVs. They found that $R_2 = 0.62 \times M_2^{0.61}$ for P shorter than 2.3 h, and $R_2 = 0.92 \times M_2^{0.71}$ for P longer than 2.5 h, and derived $M_2 = 0.032 \times P^{2.38}$ ($P \leq 2.3$) and $M_2 = 0.026 \times P^{1.78}$ ($P \geq 2.5$). We inserted the α and β values of Patterson et al. (2005) in Eq. (7) and obtained slightly different results, that is, $M_2 = 0.02823 P^{2.41}$ (short P) and $M_2 = 0.02554 P^{1.77}$ (long P).

Knigge (2006) obtained an independent $M_2 - R_2$ relation by revisiting and updating the mass-radius relationship for CV secondaries determined by Patterson et al. (2005). We have fitted with a power-law the data contained in his Table 3 and derived $M_2 - P$ relations for short P and long P systems. The relations are

$$\begin{aligned} M_2 &= 0.0371 \times P^{2.2022} & (P \leq 2.2), \\ M_2 &= 0.02024 \times P^{1.9802} & (P \geq 3.2). \end{aligned} \quad (8)$$

Table 1 provides the M_2 values obtained by these various methods, for $P_h = 1^{\text{h}}829$ (photometric) and $P_h = 3^{\text{h}}439$ (spectroscopic).

In the following, we therefore study the system solutions for $M_2 = 0.12 \pm 0.02 M_{\odot}$ and $M_2 = 0.24 \pm 0.02 M_{\odot}$, separately. The corresponding spectral types are in the range M3V–M5V (Kirkpatrick et al. 1991; Legget 1992).

3.4. The system inclination

The above derived range of allowed values for the system parameters (M_1 : 1.25– $1.4 M_{\odot}$, $M_2 = 0.12 M_{\odot}$ (for $P_h = 1^{\text{h}}829$), $M_2 = 0.24 M_{\odot}$ (for $P_h = 3^{\text{h}}439$), K_1 : $24 \pm 5 \text{ km s}^{-1}$) can be inserted into Eq. (2) to find the corresponding range of solutions for the system inclination, which is considered to be a free parameter.

Table 2 clearly shows that, given the observational and theoretical constraints for P , K_1 , M_1 , and M_2 , the solutions for the inclination i are in the range between 20 and 30 degrees, a value close to 25 degrees being the most likely value. In particular, for $M_1 \sim 1.35 M_{\odot}$, (see also the following) the solutions for i do not change significantly, and for $P_h = 1^{\text{h}}829$ ($M_2 = 0.12 M_{\odot}$) and $P_h = 3^{\text{h}}439$ ($M_2 = 0.24 M_{\odot}$) are close to 30 and 20 degrees, respectively (see also Fig. 1).

Patterson et al. (1998) suggested that T Pyx is being observed at low system inclination, i.e. $i \sim 10^{\circ} - 20^{\circ}$, due to the low amplitude of the orbital signal. Shabbaz et al. (1997) estimated the binary inclination i of T Pyx by measuring the separation of the H_{α} emission-line peaks, and obtained a lower limit of $\sim 6^{\circ}$. A low system inclination is also 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 (Paper I). 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.

It should therefore be noted that, in spite of the large uncertainties in the observational data, the adoption of plausible theoretical assumptions and some semi-empirical constraints has

Table 2. The system inclination for $M_1 = 1.25\text{--}1.40 M_\odot$ and $K_1 = 24 \pm 5 \text{ km s}^{-1}$ for the cases (1) $P_h = 1^{\text{h}}829$, $M_2 = 0.12$; and (2) $P_h = 3^{\text{h}}439$, $M_2 = 0.24$.

M_1 (M_\odot)	K_1 (km s^{-1})	i ($P = 1^{\text{h}}83$) (degrees)	i ($P = 3^{\text{h}}44$) (degrees)
1.25	19	22.9	14.7
1.25	24	29.4	18.7
1.25	29	36.4	22.8
1.30	19	23.5	15.0
1.30	24	30.2	19.1
1.30	29	37.4	23.3
1.35	19	24.0	15.4
1.35	24	31.0	19.6
1.35	29	38.4	23.9
1.40	19	24.6	15.7
1.40	24	31.7	20.0
1.40	29	39.5	24.4

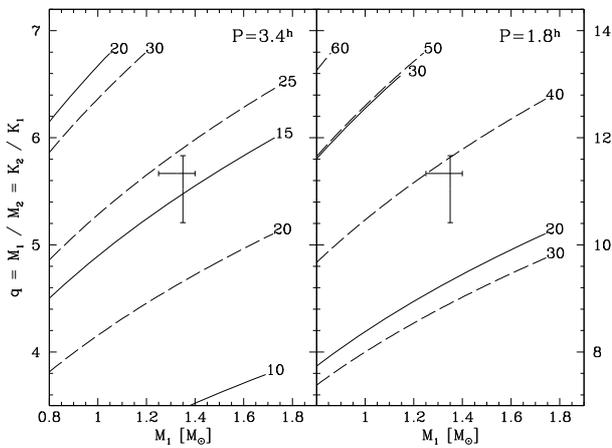


Fig. 1. The q vs. M_1 plane for $P_h = 3^{\text{h}}439$ and $P_h = 1^{\text{h}}829$. The lines of constant inclination refer to $K_1 = 19 \text{ km s}^{-1}$ (solid) and $K_1 = 29 \text{ km s}^{-1}$ (dashed), spanning the error range in the value of K_1 . The values of i are indicated. The error bars represent the ranges in M_1 and M_2 discussed in the text.

enabled a quite restricted range for the values of the system inclination to be defined. In the following we will assume $i = 25 \pm 5$ degrees for the system inclination angle.

4. The absolute magnitude at minimum

During the quiescent phase after the 1967 outburst, the average optical magnitude of T Pyx is $m_v = 15.3 \pm 0.05$ (Warner 1995; Duerbeck 1987,b; Schaefer 1992); for $d = 3500 \pm 350 \text{ pc}$ and $A_V = 0.79 \pm 0.06$, we obtain an (observed) absolute magnitude at minimum $M_v^{\text{obs}} = 1.79 \pm 0.21$ (Warner 1995, defined this to be the *apparent* absolute magnitude since the observed flux in quiescence depends on the inclination angle).

Assuming that the visual radiation originates in a non-irradiated disk (Paper I), we correct the apparent absolute magnitude $M_v^{\text{obs}}(i)$ for the inclination angle of the disk (see Warner 1987, 1995) by a term $\Delta M_v(i)$ to obtain the “standard” or “reference” absolute magnitude:

$$M_v^{\text{corr}} = M_v^{\text{obs}}(i) - \Delta M_v(i) \quad (9)$$

where $\Delta M_v(i) = -2.5 \log(2 \cos i)$ according to WLTO (1987), or $\Delta M_v(i) = -2.5 \log[(1 + 1.5 \cos i) \cos i]$ according to Paczynski & Schwarzenberg-Czerny (1980).

For $i \sim 25^\circ$, one obtains a correction of $\Delta M_v(i) \sim 0.74 \pm 0.06$, by averaging these two relations, and $M_v^{\text{corr}} = +2.53 \pm 0.22$ for the absolute magnitude, averaged over all aspect angles. This value is about 1.4 mag brighter than the mean absolute magnitude of nova remnants in the same speed class (see Fig. 2.20 and Table 4.6 of Warner 1995). It is also about 2.0 mag brighter than the mean absolute magnitude of novae at minimum, as obtained from the values given in Table 6 of Downes & Duerbeck (2000).

The T Pyx remnant is therefore one of the brightest nova remnants, its absolute magnitude $M_v^{\text{corr}} = +2.53$ being close to that of the ex-nova HR Del, whose corrected value, $M_v^{\text{corr}} = 2.30$, implies that it is a quite luminous object (see also Paper I).

5. The disk luminosity from IUE and optical data

As shown in Paper I, the integrated UV continuum flux of T Pyx in the wavelength range 1180–3230 Å, after correction for reddening, is $1.94 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$. For $d = 3500 \pm 350 \text{ pc}$, the corresponding integrated luminosity of the UV continuum is:

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

where the 20 percent is caused by the 10 percent uncertainty in the distance. Most old novae have L_{UV} in the range 1–20 L_\odot , with V 841 Oph at $\sim 24 L_\odot$ (Gilmozzi et al. 1994), and V603 Aql and RR Pic at $\sim 11 L_\odot$ and $\sim 3 L_\odot$, respectively (Selvelli 2004). Therefore, T Pyx is also quite bright in the UV and, again, is challenged only by HR Del that has $L_{\text{UV}} = 56 L_\odot$ (Selvelli & Friedjung 2002).

In the following, we assume that the observed UV and optical luminosity arise from an accretion disk heated by viscous dissipation of gravitational energy. This agrees with the behavior of similar objects, like old novae and nova-like stars. This assumption is also strongly supported by the fact that the continuum energy distribution in the UV range is well reproduced (Paper I) by a power-law with spectral index $\lambda^{-2.33}$, as predicted by theoretical optically thick accretion disk models radiating as a sum of blackbodies.

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 $\lambda \leq 1200 \text{ Å}$. The radiation emitted at wavelengths shorter than $\text{Ly}\alpha$ is strongly absorbed and the energy is redistributed to longer wavelengths (Nofar et al. 1992; Wade & Hubeny 1998).

The integration (from $\lambda \sim 1000 \text{ Å}$ 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 $3.6 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, which corresponds to a bolometric luminosity of $5.24 \times 10^{35} \text{ erg s}^{-1} \sim 136.5 L_\odot$. 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 $70 \pm 15 L_\odot$, 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. We note that the Wade & Hubeny (1998) models indicate (their Fig. 8) that in the UV region close to 1200 Å (where the effect is larger) the limb-darkening correction, from i of about 25 degrees to i of about 60 degrees, corresponds to a flux reduction of about 30 percent (this is limb darkening alone, and the geometric projection factor $\cos i$ is not included).

A rough estimate of the 4π averaged bolometric disk luminosity can also be obtained from $M_v^{\text{corr}} = +2.53$. Adopting an average disk temperature of about 28 000 K (the UV continuum indicates $\sim 34\,000$ K, although this is too hot to match the optical fluxes), the corresponding bolometric correction is $B.C. \sim -2.7$, and $L_{\text{bol}} \sim 92.9 L_{\odot}$, in fair agreement with the previous estimate. In this comparison, we neglected the effects of temperature stratification in the accretion disk.

6. The mass accretion rate

One could in principle estimate the mass accretion rate \dot{M} by comparing the observed spectral distribution with that of proper accretion disk models. This approach is not viable in our case for the following reasons: a) the spectral index of model disks that consist of blackbodies is hardly sensitive to the mass accretion rate \dot{M} ; b) most models providing \dot{M} as a function of the continuum slope do not include the case of a massive WD with high accretion rates; c) disk models depend on a large number of parameters, so that model fitting does not generally provide unique results.

Alternatively, if, as in our case, one can make 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:

$$\dot{M} = (2R_1 L_{\text{disk}})/(GM_1). \quad (10)$$

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:

$$\dot{M} = 5.23 \times 10^{-10} \phi L_{\text{disk}}/L_{\odot} \quad \text{with} \quad (11)$$

$$\phi = (R_1/M_1)/(R_{1o}/M_{1o}) = 0.1235 \cdot R_1/M_1, \quad (12)$$

where R_1 is the WD radius in $10^{-3} R_{\odot}$, $R_{1o} = 8.10 \times 10^{-3} R_{\odot}$ 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 & 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:

$$R_1/R_{\odot} = -0.01315M_1^2 + 0.01777M_1 + 0.00347. \quad (13)$$

The upper curve in Fig. 2 is a plot of the standard $R_1 \sim M_1^{-1/3}$ relation, which is generally valid for $M_1 \leq 1.0 M_{\odot}$, while the lower curve represents the quadratic fit to the average values for M_1 in the range 1.0 to $1.4 M_{\odot}$, with a relative uncertainty of $\sigma_{R_1}/R_1 = 0.07$.

Columns 2–4 in Table 3 indicate R_1 , ϕ , and \dot{M} for M_1 in the range 1.00– $1.4 M_{\odot}$. We note that $\phi = 1.00$ for $M_1 = 1.0 M_{\odot}$, and decreases to about 0.23 for $M_1 = 1.4 M_{\odot}$. The accretion rate \dot{M} in Table 3 is calculated for the (present) luminosity $L_{\text{disk}} \sim 70 L_{\odot}$, derived from UV data. In the case of a massive WD, the mass accretion rate is close to $1.1 \pm 0.3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. 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 .

An independent confirmation of these values for the mass accretion rate can be obtained from the mass accretion rate versus boundary layer luminosity ($\dot{M} - L_{\text{BL}}$) relation given in Table 2 of Patterson & Raymond (1985), if one assumes that $L_{\text{BL}} \sim L_{\text{disk}}$.

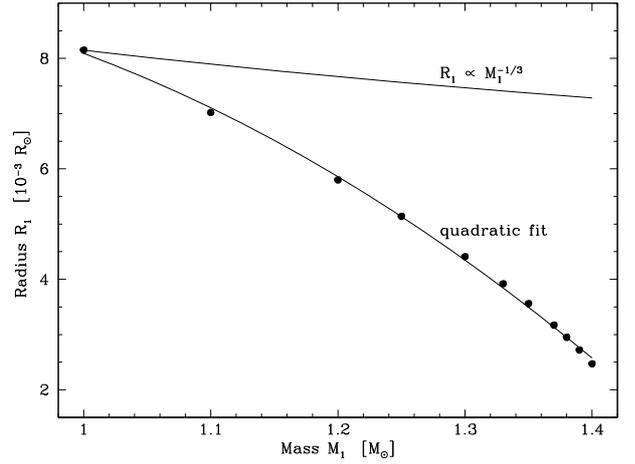


Fig. 2. The lower curve represents a quadratic fit to the average values of the WD radius as a function of M_1 derived from various WD radius-mass relations in the literature (dots). The upper curve is the standard $R_1 \sim M_1^{-1/3}$ relation.

Table 3. M_1 , R_1 , the factor $\phi = (R_1/M_1)/(R_{1o}/M_{1o})$, the post-1967 mass accretion rate \dot{M} (for $L_{\text{disk}} = 70 L_{\odot}$), the ignition mass, and the recurrence time $\tau = M_{\text{ign}}/\dot{M}$ (see Sect. 8).

M_1 (M_{\odot})	R_1 ($10^{-3} R_{\odot}$)	ϕ	\dot{M} ($10^{-8} M_{\odot} \text{ yr}^{-1}$)	M_{ign} ($10^{-7} M_{\odot}$)	τ (yrs)
1.00	8.10	1.000	3.66	108.78	297.2
1.05	7.63	0.897	3.28	92.88	283.2
1.10	7.10	0.797	2.92	77.75	266.3
1.15	6.51	0.699	2.56	63.32	247.3
1.20	5.85	0.602	2.20	49.19	223.6
1.25	5.14	0.508	1.86	35.21	189.3
1.30	4.35	0.413	1.51	22.22	147.1
1.33	3.85	0.357	1.31	14.78	112.8
1.35	3.51	0.321	1.17	10.35	88.5
1.36	3.33	0.302	1.11	8.26	74.4
1.37	3.15	0.284	1.04	6.35	61.1
1.38	2.96	0.265	0.97	4.61	47.5
1.39	2.78	0.247	0.90	3.06	34.0
1.40	2.60	0.229	0.84	1.78	21.2

Their Table 2 indicates that (for $M_1 = 1.0$) a mass accretion rate \dot{M} of $1.6 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$, close to that derived above, would correspond to a luminosity of $1.3 \times 10^{35} \text{ erg s}^{-1}$. With the same \dot{M} , a larger luminosity is expected by extrapolation to M_1 values close to $1.3 M_{\odot}$, in close agreement with the value found for L_{disk} ($2.70 \times 10^{35} \text{ erg s}^{-1}$).

The $L_{1640} - \dot{M}$ relation reported in the same Table 2 does not, however, provide a consistent result. The average (de-reddened) flux on earth in the HeII 1640 line is $6.32 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Paper I) and the corresponding luminosity for $d = 3500 \text{ pc}$ is $9.3 \times 10^{32} \text{ erg s}^{-1}$. Table 2 of Patterson & Raymond (1985) indicates instead a $L_{1640} = 1.2 \times 10^{32} \text{ erg s}^{-1}$ for $\dot{M} = 10^{18} \text{ g s}^{-1} = 1.587 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$, $M_1 = 1$, and extrapolation to higher M_1 values does not appear to be able of reproducing the observed HeII luminosity. In T Pyx there is probably a nebular contribution to L_{1640} that is added to that produced by the BL. It should also be emphasized that the HeII 1640 emission line exhibits significant changes, while the UV continuum remains constant in intensity and slope (see Paper I). This behavior casts doubts about the suitability of the $L_{1640} - \dot{M}$ method for the specific case of T Pyx.

Another estimate of \dot{M} can be obtained by direct application of the $M_v - \dot{M}$ relations reported in the literature. WLTO (1987) derived a relation between the absolute optical magnitude and the accretion rate for the “reference” disk model (Warner 1987), after correction for the disk inclination:

$$M_v^{\text{corr.}} = -9.48 - 5/3 \cdot \log(M_1 \cdot \dot{M}) \quad (14)$$

where M_1 is in solar masses and \dot{M} is in solar masses per year. In the case of T Pyx, for M_1 in the range 1.25–1.4 M_\odot , one obtains values of \dot{M} close to $5.0 \times 10^{-8} M_\odot \text{ yr}^{-1}$. It should be noted, however, that in the $M_v - \dot{M}$ relation given by WLTO there is no explicit dependence on R_1 , which strongly depends on M_1 , especially for massive WDs. If \dot{M} is corrected for the factor $\phi = (R_1/M_1)/(R_{1o}/M_{1o})$ one obtains that $\dot{M}(1.25) = 3.50 \times 10^{-8} M_\odot \text{ yr}^{-1}$ and $\dot{M}(1.40) = 1.60 \times 10^{-8} M_\odot \text{ yr}^{-1}$. If one instead adopts the Paczynski & Schwarzenberg-Czerny (1980) correction for i , the corresponding \dot{M} values are $2.85 \times 10^{-8} M_\odot \text{ yr}^{-1}$ and $1.22 \times 10^{-8} M_\odot \text{ yr}^{-1}$ respectively.

Lipkin et al. (2001) improved the $\dot{M} - M_v$ relations presented by Retter & Leibowitz (1998) and Retter & Naylor (2000) and derived the new relation

$$\dot{M}_{17} = M_1^{-4/3} \times 10^{(5.69 - 0.4M_v^{\text{corr.}})} \quad (15)$$

where \dot{M}_{17} is the mass transfer rate in 10^{17} g s^{-1} and $M_v^{\text{corr.}}$ is the inclination-corrected absolute magnitude of the disk. The factor $M_1^{-4/3}$ comes from the factor R_1/M_1 in the assumption, generally valid for WDs with $M \leq 1 M_\odot$, that $MR^3 = \text{const.}$ However, this $R_1 - M_1$ relation (polytropes) is not applicable if the WD is massive because in this case R_1 decreases with a far steeper slope as M_1 increases (see Sect. 6 and Fig. 2). The adoption of the standard $R_1 \sim M_1^{-1/3}$ relation for massive WD has the effect of overestimating R_1 and in turn overestimating \dot{M} . This is especially true for $M_1 \sim 1.4$, for which the difference between the R_1 values estimated from the $R_1 \sim M_1^{-1/3}$ relation and the more general $R_1 - M_1$ relations (Hamada & Salpeter 1961; Nauenberg 1972; Anderson 1988; Politano et al. 1990; Livio 1994) reaches its maximum value (Fig. 2).

The Lipkin et al. (2001) formula corrected for the proper R_1/M_1 ratio in massive white dwarfs according to the ϕ factors of Table 3, provides values of $\dot{M} = 1.38 \times 10^{-8}$ and 0.59×10^{-8} for white dwarfs with $M_1 = 1.25 M_\odot$ and $M_1 = 1.40 M_\odot$, respectively. These values are about one half of the corresponding values obtained from the WLTO formula. It should be noted, however, that, in the derivation of Lipkin et al. (2001) formula there is the assumption that $L_v/L_{\text{bol}} \sim 0.14$. In the case of T Pyx, this L_v/L_{bol} ratio is lower by a factor of about two and therefore the \dot{M} derived using their formula is underestimated by a similar amount. In conclusion, the various methods provide quite consistent results and we can confidently assume that the mass accretion rate derived from “recent” UV and optical data is $1.86 \pm 0.4 \times 10^{-8} M_\odot \text{ yr}^{-1}$ for $M_1 = 1.25$, and $0.84 \pm 0.2 \times 10^{-8} M_\odot \text{ yr}^{-1}$ for $M_1 = 1.40 M_\odot$. For an intermediate value of $M_1 = 1.33 M_\odot$ we obtain that $\dot{M} \sim 1.3 \times 10^{-8} M_\odot \text{ yr}^{-1}$.

Table 4 summarizes the adopted values of the basic parameters and their estimated errors.

7. The pre-1966-outburst mass accretion rate

Schaefer (2005) published a large collection of quiescent B -magnitudes for the recurrent novae T Pyx and U Sco using information from archival plates, from the literature, and from his own collection of CCD magnitudes. The photometric data of

Table 4. The basic quantities.

Quantity	Value
M_v^{max}	-6.81 ± 0.16
m_v^{max}	6.7 ± 0.1
A_v	0.79 ± 0.06
Distance	$3500 \pm 350 \text{ pc}$
m_v	15.30 ± 0.05
M_v	1.79 ± 0.21
i	$25 \pm 5 \text{ degrees}$
$\Delta m_v(i)$	0.74 ± 0.06
M_v^{corr}	2.53 ± 0.23
L_{UV}	$74 \pm 15 L_\odot$
L_{disk}	$70 \pm 15 L_\odot$
M_1	$\sim 1.36 M_\odot$
\dot{M}	$1.1 \pm 0.25 \times 10^{-8} M_\odot \text{ yr}^{-1}$
$\dot{M}_{\text{pre-OB}}$	$2.2 \pm 0.5 \times 10^{-8} M_\odot \text{ yr}^{-1}$

T Pyx start in 1890 and therefore cover all of the known inter-outburst intervals.

According to these data, 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 deduce 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 $\dot{M}_{\text{pre-OB}}$, was about twice the values of \dot{M} for post 1967, obtained in the previous section.

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

These are the values that are compared in Sects. 8 and 9 with the theoretical models of nova. The post-1967 accretion values (Table 3) are considered in Sect. 16 in the context of the “missing” outburst and the next expected outburst.

8. 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

$$P_{\text{ign}} = (G \cdot M_1 \cdot M_{\text{ign}})/(4\pi R_1^4) \quad (16)$$

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 (see Table 3 and Fig. 2). In any case, massive white dwarfs need to accrete a small amount of mass to reach the critical conditions.

For a given M_1 value, the critical ignition mass has been calculated by various authors and the reported values (for a given M_1) differ from each other mostly in the choice of the critical pressure at the base of the accreted envelope, which varies between 2.0×10^{19} and $6.0 \times 10^{19} \text{ dynes cm}^{-2}$ (see Gehrz et al. 1998; Starrfield et al. 1998a,b,c; Livio & Truran 1992;

Hernanz & José 1998; Truran 1998). These studies indicate that a lower limit to M_{ign} (for a massive white dwarf with M_1 close to $1.4 M_{\odot}$) is in the range $2.0\text{--}4.0 \times 10^{-6} M_{\odot}$. However, as first pointed out by MacDonald (1983) and in more detail by Shara (1989) and Prialnik & 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 & Bildsten (2004) confirmed that the earlier prescriptions for ignition, based on the simple scaling $M_{\text{ign}} \propto R^4 M_1^{-1}$ 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} . At the high \dot{M} values typical of most CVs, the critical pressure can decrease to values as low as $3 \times 10^{18} \text{ dyn cm}^{-2}$, and the critical mass decreases accordingly. Thus, in a massive white dwarf accreting at significantly high rates, one expects a value for M_{ign} as low as $2\text{--}4 \times 10^{-7} M_{\odot}$.

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

$$\log M_{\text{ign}} = -2.862 + 1.542 \cdot M_1^{-1.436} \ln(1.429 - M_1) + -0.19(\log \dot{M} + 10)^{1.484} \quad (17)$$

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

Table 5 indicates (for various M_1 and hence R_1 values) $\dot{M}_{\text{pre-OB}}$, the theoretical M_{ign} , the accreted mass $M_{\text{accr}} = \Delta t \cdot \dot{M}_{\text{pre-OB}}$, where $\Delta t = 22$ yrs is the pre-1966 inter-outburst interval, and $\tau = M_{\text{ign}}/\dot{M}_{\text{pre-OB}}$, that is, the expected recurrence time in years. The mass accretion rate and M_{ign} were calculated using the quadratic fit for R_1 as a function of M_1 for massive white dwarfs derived in Sect. 6 (see also Table 3), and not the approximation $R_1 \propto M_1^{-1/3}$. Table 5 clearly shows that, after allowances for errors in the estimate of $\dot{M}_{\text{pre-OB}}$, the expected recurrence time $\tau = M_{\text{ign}}/\dot{M}_{\text{pre-OB}}$ is close to the observed value (22 yr) for $M_1 \sim 1.36\text{--}1.38 M_{\odot}$ corresponding to M_{ign} and M_{accr} in the range 3.0 to $6.0 \times 10^{-7} M_{\odot}$.

This agrees with the estimate of Kato (1990) that the white dwarf mass for T Pyx is between 1.3 and $1.4 M_{\odot}$, while in a subsequent paper Kato & Hachisu (1991) assumed $M_1 = 1.33 M_{\odot}$.

We confirmed the results for M_{ign} using the approximate relation for the ignition mass as a function of M_1 and \dot{M} given by Kolb et al. (2001):

$$M_{\text{ign}} = 4.4 \times 10^{-4} \cdot R_1^4 \cdot M_1^{-1} \cdot \dot{M}^{-1/3} \quad (18)$$

(where M_{ign} and M_1 are in M_{\odot} , R_1 is in 10^9 cm , and \dot{M} is in $10^{-9} M_{\odot} \text{ yr}^{-1}$) and obtained $M_{\text{ign}} = 2.72 \times 10^{-7} M_{\odot}$. A similar result is also obtained by graphical interpolation in Fig. 5 of Kahabka & Van Den Heuvel (1997), which for $M_1 \sim 1.37$ and $\dot{M} \sim 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ provides an ignition mass close to $3.0 \times 10^{-7} M_{\odot}$ (we note, however, that these parameters fall within a region in which only weak flashes are expected). In addition, we derived P_{ign} as a function of \dot{M} and the WD temperature from Fig. 3 of Yaron et al. (2005), and found that $P_{\text{ign}} \sim 4.8 \times 10^{18}$ for $\dot{M} = 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ (we note that in this regime there is a weak dependence on the WD temperature). The insertion of this value of P_{ign} in Eq. (16) gives $M_{\text{ign}} = 3.8 \times 10^{-7} M_{\odot}$.

The consistency of all these results confirms that in the case of T Pyx the ignition mass was close to $4.5 \times 10^{-7} M_{\odot}$.

In the recurrent nova T Pyx, the theoretical ignition mass and observed accreted mass are in excellent agreement for a

Table 5. M_1 , the estimated pre-1967-outburst accretion rate $\dot{M}_{\text{pre-OB}}$ (for $L_{\text{disk}} = 140 L_{\odot}$), the theoretical ignition mass M_{ign} , the accreted mass $M_{\text{accr}} = 22 \cdot \dot{M}_{\text{pre-OB}}$ and the expected recurrence time $\tau = M_{\text{ign}}/\dot{M}_{\text{pre-OB}}$.

M_1 (M_{\odot})	$\dot{M}_{\text{pre-OB}}$ ($10^{-8} M_{\odot} \text{ yr}^{-1}$)	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

massive WD, which provides new, independent support of the TNR theory. Theoretical expectations have received only limited confirmation because studies of the system parameters (in U Sco, T Cr B) have provided contradictory results.

9. Comparison with the nova models of Yaron et al. (2005)

The realization that three basic and independent parameters, the white dwarf mass M_1 , the temperature of its isothermal core T_c , and the mass transfer rate \dot{M} , control the behavior of a CN eruption, and the improvements in computer power and codes, has enabled an increase in sophistication in simulating a nova outburst. Prialnik & Kovetz (1995) presented an extended grid of multicycle nova evolution models that have been extensively used by researchers. Each observed nova characteristic (e.g. peak luminosity, recurrence time, duration of the high luminosity phase, outburst amplitude, mass of ejecta, average outflow velocity, etc.) can be reproduced by a particular combinations of values of M_1 , T_c , and \dot{M} . Following this earlier study, Yaron et al. (2005) extended and refined the resolution in the grid of models, including a considerable number of new parameter combinations. The full grid covers the entire range of observed characteristics, even those of peculiar objects.

By matching the observed characteristics of a particular nova with its theoretical counterpart, it is therefore possible to derive information about the mass and temperature of the white dwarf and its average accretion rate. Therefore, the grids in Tables 2 and 3 of Yaron et al. (2005) can be used to determine a set of fundamental parameters that provides the closest agreement with the observed data.

In the case of T Pyx, a comparison of the observed parameters for the eruption phase (the recurrence time τ , the outburst amplitude A , the decay rate t_3 , the expansion velocity v_{exp}) with the corresponding values in the grid clearly indicates that the closest agreement corresponds to values that are intermediate in between 1.25 and 1.40 for M_1 , and -8.0 and -7.0 for $\log \dot{M}$; at these high \dot{M} values, the effects of the core temperature T_c are minor. Since a denser grid is not available, we calculated intermediate values by graphical and non-linear interpolation in the published values. A satisfactory agreement with the observed data comes from a model (model A) with $M_1 = 1.36$ and $\log \dot{M} = 7.5$ ($\dot{M} = 3.2 \times 10^{-8}$), which provides: $\tau \sim 20$, $v_{\text{exp}} \sim -1200$,

Table 6. A comparison between Yaron et al. (2005) grids and observations.

Param.	Model A	Model-B	Model-C	Model-D	Obs.
M_1	1.36	1.33	1.30	1.40	1.35 ± 0.05
\dot{M}	3.0×10^{-8}	5.0×10^{-8}	7.0×10^{-8}	1.0×10^{-8}	$2.4 \pm 0.6 \times 10^{-8}$
M_{ign}	6.6×10^{-7}	1.03×10^{-6}	1.40×10^{-6}	2.0×10^{-7}	$\sim 5.3 \times 10^{-7}$
M_{ej}	6.4×10^{-7}	0.93×10^{-6}	1.30×10^{-6}	2.0×10^{-7}	(see Sect. 10.2)
τ	20	20.6	19.8	20.2	22
Ampl.	7.6	6.9	6.6	8.4	8.0
$v_{\text{exp,max}}$	-1500	-720	-572	-1760	-2000
$t_{3,\text{vis}}$	12	32	45	~ 6	90

$A \sim 7.6$, $t_3 \sim 13$, and $M_{\text{ign}} \sim 5.0 \times 10^{-7}$. Following our interpolation of the data, Yaron (2007) kindly provided us with results obtained by execution of the code for other intermediate models, that is, WD masses between 1.30 and 1.33, $\log \dot{M}$ between -7 and -8 , and different WD temperatures. The closest agreement with the observed values originates in a model with $M_1 = 1.33$, $T_1 = 10^7$, $\log \dot{M} = -7.3$ (model B), although the model with $M_1 = 1.30$, $T_1 = 10^7$, and $\log \dot{M} = -7.15$ (model C) is also acceptable. In Table 6, we also include, as an illustration, a model directly obtained from the published Tables 2 and 3, for $M_1 = 1.4 M_\odot$ and $\dot{M} = 1.0 \times 10^{-8}$ (model D).

The value for M_{ign} (about $7 \times 10^{-7} M_\odot$) that corresponds to the model of Yaron et al. (2005) with $M_1 = 1.33$ and $\log \dot{M} = 7.5$, is close to that ($\sim 6.0 \times 10^{-7} M_\odot$) estimated by the observed average $\dot{M}_{\text{pre-OB}}$ (about $3.0 \times 10^{-8} M_\odot \text{ yr}^{-1}$) and the observed inter-outburst recurrence time of 22 yrs.

For T Pyx, the values of two of the independent, theoretical parameters (M_1 and \dot{M}) have been already constrained to within a limited range by theoretical considerations (M_1) or inferred by direct observations (\dot{M}). Since the model grids require similar values for M_1 and \dot{M} , the results appear to be consistent. An additional fine tuning of the model data could certainly improve the fit but the overall agreement between models and observations can be considered satisfactory: an important parameter such as the recurrence time is reproduced quite well and for the other basic quantities the discrepancy is not large.

A parameter that deserves special comment is t_3 . It is not explicitly listed in the theoretical grid but can be associated to t_{ml} , and was included by Yaron (2007) in specific calculations. The observed t_3 value is about three times longer than the expected value. Models with such long t_3 would correspond to higher M_{ign} and therefore to far more massive ejecta. Models with a longer t_3 (i.e. Model-C in Table 6) would be of too low $v_{\text{exp,max}}$ and too high M_{ign} .

In Sect. 10.2 we demonstrate that the spectroscopic observations acquired during the last outburst in 1966 indicate the ejection of a more massive shell than that expected from the simple estimate based on the quiescence $\dot{M}_{\text{pre-OB}}$ and a times interval Δt of 22 years.

Contini & Prialnik (1997) presented evolutionary calculations of TNRs on the surface of an accreting WD that simulates the observed outburst characteristics of T Pyx and found that the model that reproduces the observed characteristics of T Pyx most accurately is obtained for an accretion rate of $10^{-7} M_\odot \text{ yr}^{-1}$ onto a $1.25 M_\odot$ WD; the (theoretical) mass ejected in a single outburst is expected to be close to $1.6 \times 10^{-6} M_\odot$. They also modeled the nebular spectrum and found that the theoretical fluxes agree with those derived from observations (Williams 1982) if a distance of ~ 2 kpc is assumed. However, our detailed study of the T Pyx luminosity and mass accretion rate suggested an $\dot{M}_{\text{pre-OB}}$ value close to $3.7 \times 10^{-8} M_\odot \text{ yr}^{-1}$, onto

a $1.25 M_\odot$ WD for $d \sim 3.5$ kpc. If $d \sim 2.0$ kpc, this would imply that $\dot{M} \sim 1.2 \times 10^{-8}$, a factor of 10 lower than assumed by Contini & Prialnik (1997). We note that a distance as large as about 7.0 kpc is required to derive a luminosity corresponding to $\dot{M} \sim 10^{-7}$. See Sect. 11.1 for additional considerations of the distance.

10. The photometric and spectroscopic history of the outbursts

10.1. The long lasting optically thick phase

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 (see WLTO, 1987). A common feature of these outbursts was the far longer optical decline time ($t_3 = 90^{\text{d}}$) compared with that of other recurrent novae, which, with the exception of CI Aql ($t_3 = 33$ d) and IM Nor ($t_3 = 50$ d), are generally much faster, with t_3 of the order of days.

The well studied outburst of Dec. 1966 exhibited a sharp initial rise to a shoulder (pre-maximum halt on Dec. 10, 1966) in V of about 7.9, a near flat maximum close to $V = 7.5$ (which lasted about 30 days), a sharp peak at $V = 6.8$ on Jan. 9, 1967, and a slow decline with $t_3 \sim 90^{\text{d}}$. The first spectroscopic observations were obtained by Catchpole (1969), 12.6 days after the initial halt. The spectrum was characterized by sharp P Cyg features in the hydrogen lines and by other weak emission lines. The presence of the absorption features endured until March 5, 1967, and since then they became quite “diffuse”. Catchpole (1969), apart from the value of 850 km s^{-1} at some epochs, reported outflow velocities of the order of -2000 km s^{-1} for both absorption and emission (permitted and forbidden) components.

There is an observational gap of about 40 days in the spectra obtained by Catchpole, which was fortunately covered in part (from 09 Jan. 1967 to 16 Feb. 1967) by the spectroscopic data by Chincarini & Rosino (1969). They described the absorption system in the Balmer lines (up to H_{12}) as being particularly sharp and strong and noted an increase in the expansion velocity from -1535 km s^{-1} on Jan. 31, 1967, to -1760 km s^{-1} on Feb. 2, 1967 and -1820 km s^{-1} on Feb. 6, 1967. According to Chincarini & Rosino (1969), the mean radial velocity during the period Jan. 31–Feb. 6 determined from all measurable absorption lines was $-1810 \pm 40 \text{ km s}^{-1}$.

Outflow velocities of the order of $1500\text{--}2200 \text{ km s}^{-1}$ were also observed in previous outbursts. Adams & Joy (1920) reported the presence of “dark” components of radial velocity up to -2100 km s^{-1} a few days after maximum. Joy (1945) observed expansion velocities of 1700 km s^{-1} in forbidden emission lines in spectra taken some months after outburst. Similar values were also found by Herbig (1945) and reported by Payne-Gaposchkin (1957).

The “principal absorption system” is generally associated with the bulk of the mass ejected during outburst, and for most novae has a velocity close to that of the “nebular system” as determined from the width of the nebular emission lines (Payne-Gaposchkin 1957; McLaughlin 1956; Pottasch 1959). The v_{exp} value reported by Joy (1945) referred to observations during the nebular phase, three-four months after outburst. That the emission lines in the nebular spectrum showed velocities of the same order as those deduced from the absorption lines of the principal spectrum is an indication of near constant expansion.

We note that in the literature on T Pyx little attention has been paid to the fact that for almost three months after the initial halt T Pyx showed a strong continuum with the presence of emission and absorption lines of similar strength. The

persistence for almost three months (about t_3) of displaced absorption components in the H (and FeII) lines, which are observable by combining the spectroscopic observations of Catchpole (1969) and Chincarini & Rosino (1969) for the 1966 outburst, indicates an optically thick phase of similar duration.

In this respect, we recall that, before the outburst of 1966–1967, Mc Laughlin (1965) noted that T Pyx was exceptional among RNe since its photometric and spectroscopic behavior closely resembled that of a typical nova both close to maximum (where it remained for several weeks to within about a magnitude) and in the nebular stage.

10.2. The mass of the shell ejected in the optically thick phase

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.

Classical novae undergo an optically thick phase during which they resemble each other, a fact that can be explained by the same mechanism (i.e. flux redistribution) producing the spectrophotometric light curve (Shore 1998, 2008). To achieve flux redistribution, the material must reach column densities of the order of 10^{23} – 10^{24} cm^{-2} , which corresponds to masses of about 10^{-4} – $10^{-5} M_{\odot}$.

An optically thick stage also characterized the outbursts of T Pyx, as can be directly inferred from the lengthy period of time during which the optical magnitude was close to its maximum value, with $t_3 \sim 90^{\text{d}}$, and from the presence of absorption lines of HI and FeII, which lasted for at least 80 days.

From the duration of the optically thick phase (associated to t_2) and the observed v_{exp} , using simple assumptions, we can estimate the mass of the shell ejected during outburst. The outer radius of the shell can be estimated from the observed expansion velocity ($v_{\text{exp}} \sim 1500 \text{ km s}^{-1}$) and the time elapsed from outburst, assuming continuous ejection. This assumption is justified by the persistence of displaced absorption components with similar equivalent widths. The shell radius is:

$$R_{\text{ej}} \sim 7.7 \times 10^{14} \text{ cm} \sim 1.1 \times 10^4 R_{\odot}.$$

The corresponding shell volume is $V \sim 1.84 \times 10^{45} \text{ cm}^3$. These values are conservative because the terminal velocity was probably higher. To reproduce the optically thick stage recognized from the presence and persistence of the absorption lines, the column density must be of the order of 10^{23} cm^{-2} . Therefore, the average density in the shell must be close to 10^8 – 10^9 cm^{-3} , (we note that the density should scale as R^{-3}). This density value agrees with the spectroscopic behavior and the presence of permitted emission lines only. If we assume that the ejecta are homogeneous and consist of ionized hydrogen, the mass might be estimated as

$$M_{\text{H}} = N_{\text{e}} m_{\text{H}} V \sim 3.1 \times 10^{29} g = 1.5 \times 10^{-4} M_{\odot}. \quad (19)$$

This value is probably an upper limit because of the assumptions of continuous ejection and homogeneous shell.

In an alternative approach, following Williams (1994), one can estimate the hydrogen column density produced by an expanding shell of mass $1.0 \times 10^{-4} M_{\odot}$:

$$N_{\text{H}} \cdot R = 3.0 \times 10^{52} \cdot R^{-2} \quad [\text{cm}^{-2}]. \quad (20)$$

For T Pyx at day 60 ($=t_2$), we find that $R^2 = 5.8 \times 10^{29} [\text{cm}^2]$, and $N_{\text{H}} \cdot R \sim 5.2 \times 10^{22} [\text{cm}^{-2}]$. A mass of the ejecta higher

than 10^{-4} is therefore required to produce an optically thick stage until day 60.

It is well established that in novae, the mass of the ejected envelope is directly correlated with the optical decay time t_2 or t_3 (Livio 1994). Therefore, an independent estimate of the ejected shell mass can be derived from the relation:

$$\log M_{\text{ej}} = 0.274 \pm 0.197 \cdot \log t_2 - 4.355 \pm 0.283 \quad (21)$$

(Della Valle et al. 2002). Even after considering the large uncertainties in this relationship, a $t_2 = 62^{\text{d}}$ implies a mass for the envelope $M_{\text{ej}} \sim 10^{-4} M_{\odot}$, which is similar to the mass ejected by classical novae.

The data leading to Eq. (21) suffer from a large scatter. We suspect that the ejecta expansion velocity plays also an important role and should be included in the relation. Shore (2002, 2008) suggested an approximate scaling relation for the optically thick stage:

$$M_{\text{ej}} \sim 6.0 \times 10^{-7} \epsilon N_{\text{H},24} V_3^2 t_3^2 M_{\odot}, \quad (22)$$

where V_3 is the outflow velocity in 10^3 km s^{-1} , and ϵ is the filling factor that, for this stage, can be assumed to be of the order of 0.1. For $t_3 = 90$, $f = 0.1$, $N_{\text{H},24} = 0.1$ – 1.0 , and $V_3 = 1.5$, the derived values for M_{ej} are in the range 1.5×10^{-4} – $1.5 \times 10^{-3} M_{\odot}$.

Finally, the ejected mass can be estimated using the following scaling law from Cassatella et al. (2005), which depends on the approximate assumption that the filling factor in novae ejecta is the same as in V1668 Cyg:

$$M_{\text{ej}} \sim 0.044 \cdot M_{\odot} / v_{\text{exp}}, \quad (23)$$

where v_{exp} is in km s^{-1} and the constant is set to the values of the ejected mass and the expansion velocity of V1668 Cyg (Stickland et al. 1981). Using $v_{\text{exp}} = 1500 \text{ km s}^{-1}$, one finds that for T Pyx, $M_{\text{ej}} \sim 2.93 \times 10^{-5} M_{\odot}$.

We recall that Kato & Hachisu (1991), from their models of steady-state winds for a nova with $M_1 = 1.33 X = 0.5$ and $Z = 0.02$ and the observed t_3 , suggested the ejection of a massive envelope with M_{ej} of about $10^{-5} M_{\odot}$ in a single outburst.

All the previous results agree with the considerations of Shore (1998), who pointed out that, for a typical ejection velocity of about -2000 km s^{-1} , a nova with an optical decline time longer than a week must eject a mass higher than $10^{-5} M_{\odot}$.

We also recall the fact that in classical novae close to maximum, the Balmer lines develop P-Cygni profiles, which is a clear indication that a significant amount of material was ejected during the outburst (Starrfield 1993).

Therefore, all quantitative methods and the qualitative consideration of the photometric and spectral behavior of T Pyx during the outbursts indicate the presence of a massive envelope with $M_{\text{ej}} \sim 10^{-4}$ – $10^{-5} M_{\odot}$.

11. 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 contrast significantly with the results of the UV + optical observations during quiescence and the theoretical requirements for M_{ign} , which imply a $\dot{M}_{\text{pre-OB}} \sim 2.2 \times 10^{-8}$ and a total mass for the accreted shell M_{accr} of about $\sim 5.0 \times 10^{-7} M_{\odot}$ (see Sect. 8). It is also in contrast with the conclusions of Sect. 9 that indicated that the closest agreement between the grid models and the observed properties of the system during outburst

and Q corresponds to a model with $\dot{M} \sim 3.0 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ and $M_{\text{ign}} \leq 1.3 \times 10^{-6} M_{\odot}$ (Table 6). During outburst, T Pyx has apparently ejected far more material than it has accreted.

Studies of classical novae containing a massive WD indicated that these objects eject apparently more material than theoretically predicted (Starrfield et al. 1998a,b; Vanlandingham et al. 1996; Shore 1998). These authors emphasized the significant discrepancy between the observed mass of the ejecta and the predicted critical mass of accreted nova envelopes for massive WDs ($M_{\text{WD}} \geq 1.25 M_{\odot}$), the mass of the observed shell being one order of magnitude (or more) higher than that predicted by the models.

For these CNe one could attribute the discrepancy to some inadequacy in the TNR models or in the methods to determine the nebular mass. In the case of T Pyx, the situation, however, differs because there is a serious mismatch between the shell mass indicated by the optical *observations* during outburst ($M_{\text{ej}} \sim 10^{-4} - 10^{-5} M_{\odot}$) and that determined by the UV and optical *observations* during quiescence (which give $\dot{M}_{\text{pre-OB}} \sim 2.2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ and therefore $M_{\text{accr}} \sim M_{\text{ign}} = 5.0 \times 10^{-7} M_{\odot}$). Therefore, the mass ejected during outburst is about a factor of 100 higher than both the theoretical ignition mass M_{ign} and the total mass accreted before outburst, M_{accr} .

We note that using the post 1966 value of \dot{M} instead of that inferred for the pre-outburst interval would produce an even larger discrepancy.

11.1. The role of the distance

Although M_{ej} does not depend on distance, M_{accr} does (due to its dependence on both L_{disk} and $\dot{M}_{\text{pre-OB}}$), and therefore the mismatch between M_{ej} and M_{accr} depends crucially on the assumed distance. The uncertainty in the adopted distance was found in Sect. 2 to be of the order of 10 percent. However, we note, that even the adoption of an unlikely distance of, say, 10 000 pc (at about 20σ from the estimated value) would only partially alleviate this inconsistency, and at the expense of an uncomfortably high mass accretion rate, well within the range for the onset of steady burning. This would imply characteristic temperatures and luminosities that are not observed (see also Sect. 14 for a further discussion). A larger distance would also necessarily imply that T Pyx was super-Eddington at maximum, a circumstance that appears unlikely due to its slow photometric and spectroscopic developments during outburst.

A lower distance would correspond to a lower values of L_{disk} , and hence $\dot{M}_{\text{pre-OB}}$ and M_{accr} , to values that are theoretically incompatible with the occurrence of outbursts with an average interval of 22 years. It would also exacerbate the discrepancy between the low value of M_{accr} obtained from the UV observations (and the models) and the apparently high mass of the ejecta, as inferred from the behavior during outburst. Therefore, there is not much leeway to invoke a different distance to explain the discordance.

12. The nebula revisited

The nebula surrounding T Pyx has been the target of several spectroscopic and imaging observations. Duerbeck & Seitter (1979) first reported the presence of a strong nebulosity around T Pyx, with radius $r \sim 5''$, whose origin was tentatively attributed to the 1966 outburst and whose strength was described as unusual. By the assumption of an outburst expansion velocity of -900 km s^{-1} , a low distance ($\sim 600 \text{ pcs}$) was derived.

Williams (1982) obtained spectral scans of the northern portion of the nebula of T Pyx. The spectrum was similar to that of as a typical PN, probably photoionized by radiation from the hot remnant, and lacked the strong CNO enhancements characteristic of the ejecta of classical novae.

Comparing images acquired in 1979.0 and 1982.9, Seitter (1987) found that the nebula did not increase in size during that time interval.

Shara et al. (1989) from deep narrowband CCD images confirmed the faint, extended $H_{\alpha} + \text{NII}$ halo (twice as large as the inner nebula), first reported by Duerbeck (1987,b). A smooth, small [OIII] nebula with $r \sim 2''$ was also found. Shara et al. (1989) also compared the relative sizes of the main nebula with $r \sim 5''$ in 1985 and in 1979 but failed as well to find any detectable expansion during the 6 year interval, confirming the finding of Seitter (1987). High resolution imagery data from HST was obtained by Shara et al. (1997). The nebula was resolved into more than two thousand individual knots, and a comparison between images taken at four epochs indicated that these individual knots retained a similar pattern, without any evidence of expansion. These data confirm the apparent stationarity in the $10''$ diameter nebula suggested by previous observations. Shara et al. (1997) found an upper limit of $40 \cdot (1500/\text{d}) \text{ (km s}^{-1})$ for the expansion velocity of the knots. They also detected nine distinct peaks in the brightness distribution, an indication that a multiple nebula model was required.

Many studies, disappointingly inconclusive, addressed the problem of the mass of the nebula. In this respect, it should be noted that large uncertainties are generally associated with estimates of the mass of novae ejecta, since the mass estimate depends critically on quantities that are not reliably measured, e.g.: distance, electron density, ionization structure in the nebula, geometry, and filling factor. Therefore, it is unsurprising that a range of masses for the nebula of T Pyx has been proposed in the literature.

From the nebular H_{β} intensity measured by Williams (1982), WLTO (1987) obtained a lower limit to M_{neb} of $10^{-6} M_{\odot}$, while Shara (1989), using the H_{β} intensity with the requirement $\epsilon \leq 1$ for the filling factor derived an upper limit of $1.0 \times 10^{-4} M_{\odot}$. From the intensity of the H_{α} and [NII] lines, Seitter (1987) found a mass close to $8.0 \times 10^{-5} M_{\odot}$. From the H_{α} flux and considerations based on HST imagery, Shara et al. (1997) obtained $1.3 \times 10^{-6} M_{\odot}$ to be the most reliable estimate for the nebula mass (with an assumed distance of 1500 pc), the electron density being, allegedly, the main uncertainty factor.

We add one more estimate for the mass of the nebula, based on the H_{β} flux obtained by Williams (1982) scaled to the entire nebula, after correction for the new reddening and distance. We obtain:

$$F_{\beta} \sim 4.24 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ and } L_{\beta} = 6.22 \times 10^{31} \text{ erg s}^{-1},$$

with a relative error of about 25 percent, arising from the uncertainties in the distance and the flux. By combining the two common relations:

$$L_{\beta} = 1.24 \times 10^{-25} N_{\text{e}} \cdot N^{+} \cdot (4/3) \pi R_{\text{neb}}^3 \cdot \epsilon \quad (24)$$

and

$$M_{\text{neb}} = \mu \cdot N^{+} \cdot m_{\text{H}} \cdot (4/3) \pi R_{\text{neb}}^3 \cdot \epsilon, \quad (25)$$

(where $\mu = 1.4$ is the mean atomic weight and ϵ is the filling factor), one finds that the mass of the nebula (independent of ϵ and R_{neb}) is

$$M_{\text{neb}} = 18.67 \frac{L_{\beta}}{N_{\text{e}}} g = \frac{0.584}{N_{\text{e}}} M_{\odot}. \quad (26)$$

N_e is inaccurately determined because, as noted by Williams (1982), the spectrum is too poor in number of lines to constrain the physical parameters of the nebula accurately. However, from the presence of a quite strong emission feature near 3722 Å, attributable to [OII] 3726.1 and 3728.8 one can estimate that the nebula density is less than $3.0 \times 10^3 \text{ cm}^{-3}$, since these two forbidden lines have critical density $\log N_e^{\text{crit}} = 3.5$ and 2.8, respectively. If we assume that $N_e \sim 10^3 \text{ cm}^{-3}$, a value also adopted by Shara et al. (1997) from other considerations, we find that $M_{\text{neb}} \sim 5.84 \times 10^{-4} M_\odot$.

A value of this order for the total mass of the nebula, which has apparently increased from the contribution of several successive outbursts, agrees with the ejection during outburst of a massive shell ($\sim 10^{-5} M_\odot$) as suggested in Sect. 10.2.

The fact that the nebula of T Pyx is still clearly observed despite its large distance seems hardly compatible with a mass of $10^{-6} M_\odot$ derived in previous studies. In the most well studied CNe, which on average are closer in distance than T Pyx, the ejected nebula has, at best, a similar strength and/or is barely evident a few years after outburst. We think that the peculiar strength of the nebula of T Pyx may be explained by the fact that most of the gas ejected in successive outbursts has accumulated into a nearly stationary envelope that is strongly irradiated by a more than average luminous UV central source.

Alternatively, one can guess that the observed nebula of T Pyx was produced in a peculiar event and is not associated with the recorded and/or previous outbursts. Its apparent stationarity and the lack of changes over a timescale of about fifteen years (Shara et al. 1997) supports this interpretation. Williams (1982) noted that the spectrum of the nebula around T Pyx is almost similar to typical planetary nebula, of approximately solar composition.

We emphasize that the optically thick shell discussed in Sects. 10.1 and 10.2 was observed only spectroscopically during the outburst phases, and that there is no definite, direct link with the extended nebula. Simple calculations indicate that, if $d = 3500 \text{ pc}$, the angular radius of the shell, after ten years of constant expansion at 1500 km s^{-1} , would be less than $1''$.

12.1. The filling factor

If the radius of the nebula R_{neb} is known, from the observed angular radius r ($\leq 10''$) and the distance, one can obtain the filling factor ϵ with the help of Eq. (24). After insertion of the values for $L_\beta = 6.22 \times 10^{31} \text{ erg s}^{-1}$, $R_{\text{neb}} \sim 5.2 \times 10^{17} \text{ cm}$, and $N_e \sim 1.1 N^+$, one obtains that

$$\epsilon \cdot N_e^2 \sim 1062.7.$$

Therefore, for $N_e \sim 10^3 \text{ cm}^{-3}$, ϵ is close to 10^{-3} . A filling factor of $\sim 10^{-3}$ can be obtained independently from the relation of Harrison & Stringfellow (1994):

$$\epsilon \sim N_{\text{cl}} V_{\text{cl}} / V_{\text{neb}} = 8 N_{\text{cl}}^{-1/2} \gamma^{3/2}, \quad (27)$$

where γ is the fraction of the spherical nebula intercepted by the clumps. From the figures of Shara et al. (1997), we estimate that $\gamma \sim 0.05$ and, if the number of clumps N_{cl} is ~ 2000 (Shara et al. 1997), we find that $\epsilon \sim 2 \times 10^{-3}$. We note that the filling factors estimated for the ejecta of other novae have a wide range of values, from 4×10^{-1} (Vanlandingham et al. 1999, for nova LMC 1990 No. 1), to 10^{-6} Saizar & Ferland (1994) for nova QU Vul. Williams et al. (1981) found an intermediate value, $\epsilon \sim 2 \times 10^{-3}$ for the recurrent nova U Sco. Mason et al. (2005) found $\epsilon \sim 10^{-4} - 10^{-1}$ for nova SMC 2001 and nova LMC 2002, and

Balman & Oegelman (1999) estimated $\epsilon \sim 5 \times 10^{-3} - 3 \times 10^{-1}$ for the shell of GK Per. Mason et al. (2005) have suggested $\epsilon \sim 10^{-5} - 10^{-2}$ for T Pyx.

13. The mass balance and the SNIa connection

It is accepted that type Ia supernovae represent the complete thermonuclear disruption of mass-accreting white dwarfs that reach the Chandrasekhar limit by accretion (Nomoto et al. 1984; Woosley & Weaver 1986). Within this general framework, there exist single degenerate models (Whelan & Iben 1973) in which a WD accretes from a non-degenerate companion, and double degenerate models (e.g. Iben & Tutukov 1984) that involve the merger between two WDs. Hachisu (2002, 2003) and Hachisu & Kato (2001, 2002) proposed a unified picture of binary evolution to SNe Ia in which recurrent novae could be understood to be part of the evolutionary stages of supersoft X-ray sources and symbiotic channels to SNe Ia.

The mass M_1 must be close to the Chandrasekhar limit before a recurrent nova can become a SN Ia, and the WD must also increase in the long term, after many cycles of accretion and ejection (Starrfield et al. 1985). However, in the case of T Pyx, even if M_1 were close to the limit, which is not clearly established since M_1 appears to be close to $1.37 M_\odot$, the results of the previous sections indicate that the mass balance situation is unclear:

On the one hand, the photometric and spectroscopic behavior close to outburst, as mentioned in Sect. 10.2, appear to be consistent with the ejection of a rather massive shell, while the UV data and theoretical models (at the specific M_1 and \dot{M} values) indicate that the ignition mass is low ($\sim 5.0 \times 10^{-7} M_\odot$). This indicates that during outburst the WD ejects more material than it accumulates and 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. However, this presupposes that the chemical composition of the observed nebula is representative of that of a single shell ejected during outburst.

It is unclear whether these substantial discrepancies originate 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.

In any case, the behavior of T Pyx raises several doubts about the common assumption that in recurrent novae far less material is ejected during the outburst than is accreted by the white dwarf, and therefore that its mass increases toward the Chandrasekhar limit (Starrfield 2002). In assessing whether recurrent novae could be progenitors of type Ia supernovae, we note that Hachisu & Kato (2001), discovered that, among six recurrent novae, only T Pyx is offset significantly from the region occupied in an orbital period – donor mass plane (their Fig. 3) by the progenitors of SNe Ia.

14. Neither a supersoft X-ray source, nor assisted suicide

To explain the alleged extremely blue color of T Pyx in quiescence, WLTO (1987) proposed that nuclear burning continues even during its Q state, consistent with the slow outburst development, which suggests that the accreted envelope was only weakly degenerate at the onset of TNR. Patterson et al. (1998) attributed the luminosity of T Pyx (and V Sagittae) to quasi-steady thermonuclear burning and suggested the object to be included in the class of the supersoft X-ray sources.

However, the color of T Pyx ($B - V$)_o = -0.26 used in these studies is based on a significant overcorrection for the reddening, assumed to be $E_{B-V} = 0.36$, instead of the correct value $E_{B-V} = 0.25$ (see Paper I and earlier communications, e.g. Gilmozzi et al. 1998). It is unfortunate that both the value ($B - V$)_o = -0.26 of Patterson et al. (1998) and the statement about the “extremely blue color” of T Pyx was adopted widely in the literature (see for example Anupama 2002; Parthasarathy et al. 2007). We note, incidentally, that in the same paper Patterson et al. (1998) assumed too high a reddening correction ($E_{B-V} = 0.33$) for V Sge; the IUE data suggest, instead a value close to 0.23. We recall that for T Pyx the observed ($B - V$) is about 0.14 ± 0.04 (WLTO 1987; Bruch & Engel 1994; Downes et al. 1997; Schaefer 2005; see also Table 7). This would imply that ($B - V$)_o \sim -0.11, close to the value ($B - V$)_o = -0.06 given by Szkody (1994).

Patterson et al. (1998) assumed that $M_v = 1.3$ and after a significant bolometric correction (based on the assumption of an extremely hot source being present, a consequence of the overestimate of the reddening), derived a quiescent bolometric luminosity higher than 10^{36} erg s⁻¹, which considered to be a true lower limit. This encouraged them to invoke nuclear burning on the surface of the WD as the main power source, considering the disturbingly high \dot{M} ($\geq 10^{-7} M_{\odot}$ yr⁻¹) required in the case of pure accretion power.

However, the IUE and the optical data do not appear to be reproduced by the model depicted by Patterson et al. (1998), since the following observational evidence contradicts with their conclusions:

1. One of the main results of Paper I was that the de-reddened UVOIR continuum of T Pyx is reproduced well by a single power-law $F_{\lambda} \propto \lambda^{\alpha}$ with a slope $\alpha = -2.33$, representative of a steady accretion disk. Alternatively, as shown in Paper I, the UV continuum can be well fitted by a blackbody of temperature 34 000 K. There is no way to reconcile these firm observational results with the presence of a supersoft source of typical $T \sim 3.0 \times 10^5$ K, since its expected slope in the UV region ($\alpha = -3.80$) would be inconsistent with the UV observations.
2. As shown in Sect. 5, the IUE observations in 1980–1996 and the optical and IR photometric data indicate that $L_{\text{disk}} = 2.7 \times 10^{35}$ erg s⁻¹, which corresponds to emission mainly in the directly observed UV range. Therefore, in the absence of any direct or indirect evidence of a hot source, it is unlikely that L_{disk} is higher than 10^{36} erg s⁻¹.
3. Under steady-state hydrogen-burning conditions, the accretion rate \dot{M}_{steady} can be estimated to be:

$$\dot{M}_{\text{steady}} \sim 3.7 \times 10^{-7} (M_1 - 0.4) M_{\odot} \text{ yr}^{-1}, \quad (28)$$

(Hachisu & Kato (2001), which is valid for hydrogen content $X = 0.7$. In the case of T Pyx, one calculates $\dot{M}_{\text{steady}} \sim 3.2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. This value is almost a factor of 30 higher than the value of $\dot{M} \sim 1.1 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ obtained from the IUE data for the post outburst phase.

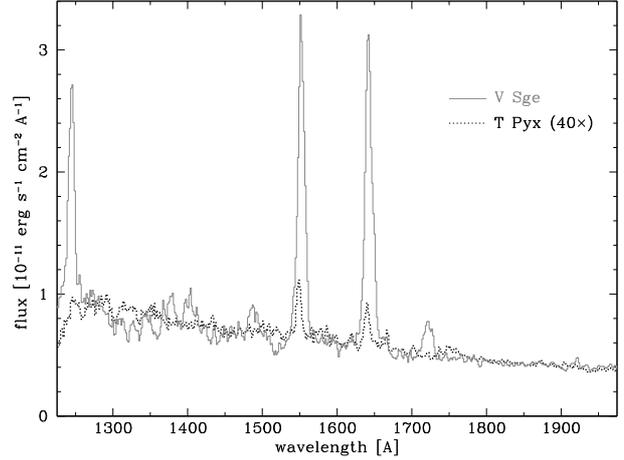


Fig. 3. Comparison between the reddening-corrected SWP spectra of the supersoft source V Sge (continuous line) and of T Pyx (dashed line). The continuum of T Pyx has been scaled to that of V Sge (multiplied by a factor 40). Note the prominence of the high ionization lines of NV λ 1240, CIV λ 1550, HeII λ 1640, and NIV λ 1719 in V Sge, in contrast with their moderate intensity or absence in T Pyx.

4. After correction for inclination, the apparent absolute magnitude of $M_v = 1.79$ corresponds to a $4-\pi$ averaged absolute magnitude of $M_v^{\text{corr}} = 2.53$, to be compared with the average value $M_v^{\text{min}} \sim 4.0$ for ex-novae (Warner 1995). This implies that T Pyx is more luminous than other ex-novae, as mentioned in Sect. 4, but is not “extremely bright”. We can explain why T Pyx is brighter than other novae in terms of repeated nova eruptions and heating of the primary, which triggers irradiation of the secondary and produces a higher than average \dot{M} .
5. The emission line spectrum of T Pyx is not that of an high excitation object: NV λ 1240 is nearly absent, HeII λ 1640 is weaker than CIV λ 1550 and barely present in several spectra, the OIV lines close to λ 1405 are absent. A comparison between the IUE spectra of T Pyx and V Sge (Fig. 3) clearly shows remarkable differences and a much lower excitation character in T Pyx. From an inspection of IUE spectra of several CVs, we also found that the spectrum of T Pyx is similar to that of the old novae V533 Her and V603 Aql and to some spectra of the intermediate polar TV Col. The old nova RR Pic definitely shows higher excitation than T Pyx, with far stronger NV and HeII emissions.

Other findings considerations also exclude the H-burning-bloated-WD hypothesis:

1. The complexity of the optical photometric behavior in T Pyx (Shaefer et al. 1992; Patterson et al. 1998) is difficult to explain if the bulk of the luminosity originates in a spherically symmetric radiation source associated with H-burning on top of a bloated white dwarf.
2. If the majority of the gas undergoes steady burning, it would be difficult to understand how the remainder that accumulates in the degenerate envelope could burn explosively every 20 years.
3. The outburst amplitude of T Pyx, ~ 8.0 mag, is close to that found for classical novae of similar t_3 and similar system inclination (Warner 1995, 2008). If, as assumed by Patterson et al. (1998), the luminosity during quiescence is greater than 10^{36} erg s⁻¹ then, with an outburst amplitude of about 8 magnitudes, the luminosity would reach 10^{40} erg s⁻¹, implying

Table 7. XMM observations compared with IUE fluxes and ground based photometry.

Filter	λ_{eff} (Å)	Observed flux (1×10^{-14})	IUE flux (1×10^{-14})	mag.
UVM2	2310	0.92	0.80	–
UVW1	2910	0.86	0.92	–
U	3440	0.70	–	14.37
B	4500	0.38	–	15.59
V	5430	0.24	–	15.49

that T Pyx is an object intermediate between a nova and a SN Ia.

To support the hypothesis of steady nuclear burning Patterson et al. (1998) considered *all* CVs of comparable P_{orb} and deduced that the \dot{M} in T Pyx was a factor of 5000 higher than in other CVs of similar P_{orb} . One should compare T Pyx with objects that are similar, that is, with recent novae. After outburst, the nova system remains in an excited state and \dot{M} increases due to the irradiation of the secondary. Patterson et al. (1998) correctly excluded from their Fig. 14 all old novae within 30 yr of the outburst because of their systematically too high luminosity levels. Adopting the same line of reasoning, T Pyx should also have been excluded. In this respect, we note that the \dot{M} of T Pyx is only slightly higher than that observed in *recent* ex-novae (e.g. RR Pic, V841Oph, HR Del, etc.) (Selvelli 2004).

Based on the conclusions of Patterson et al. (1998) of an extremely high luminosity (L_{bol} far higher than 10^{36} erg s^{-1}), Knigge et al. (2000) investigated in detail the evolution of the T Pyx system and proposed that the system is a wind-driven supersoft X-ray source. In this scenario, a strong, radiation-induced wind is excited from the secondary star, and increases the rate of binary evolution, causing the system to destroy itself either by evaporation of the secondary star or in a type Ia SN if the WD reaches the Chandrasekhar limit. Knigge et al. (2000) therefore proposed that either the primary, the secondary, or both stars may be committing assisted stellar suicide

This scenario is, admittedly, highly speculative, and depends crucially on the unsubstantiated assumption that both the temperature and luminosity of T Pyx are extremely high. The IUE and optical data are instead consistent with a more conventional scenario of accretion power, as in other CVs, and we confidently predict that, fortunately, any form of suicide in the near future is extremely unlikely.

Finally, we note that Greiner et al. (2003) did not find T Pyx to be a supersoft X-ray source, and that T Pyx does not appear in NASA's HEASARC tool (a master compilation of EUV and X-ray databases).

15. The XMM observations

While this work was close to completion, the data for X-ray observations of T Pyx by XMM became publicly available. This prompted us to perform a preliminary analysis of the data to verify the presence or absence of a supersoft source.

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 ks. Optical Monitor data were taken simultaneously with the X-ray observations. The values (see Table 7) are consistent with the values given in Paper I (IUE and optical observations) and confirm the stability of the SED with time. The reduction of the XMM EPIC

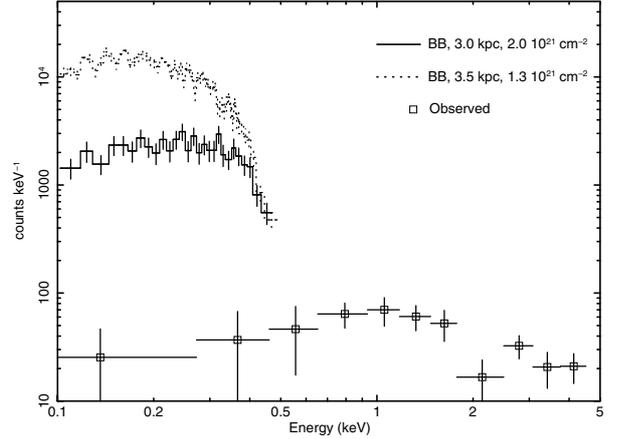


Fig. 4. The XMM-Newton EPIC-pn spectrum of T Pyx (*bottom*) compared with the simulations of a 20 ks exposure of a blackbody of 2.4×10^5 K and a luminosity of 1×10^{37} erg s^{-1} computed with two assumptions: a distance of 3500 pc and a reddening $E_{B-V} = 0.25$ (values assumed in this paper, dots), and a distance of 3000 pc and a reddening of 0.4 (values assumed by Knigge et al. 2000, continuous line). The three spectra shown here have been re-binned to 20 counts per bin.

data was carried out with SAS version 7.1, using standard methods. T Pyx was detected as a faint source that had an observed EPIC-pn count-rate of 8.5×10^{-3} cts s^{-1} and emission over the complete range 0.2–8 keV.

Figure 4 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 ks, 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.

The data are compatible with the presence of a relatively hard source of low luminosity, but their low statistical quality (227 counts in the range 0.2–8. keV) does not allow us to perform a reliable fit. We also note that extrapolation of the observed IUE spectrum (power-law) into the X-ray range would result in an unrealistically high flux, several orders of magnitude higher than observed. The existence of such a high flux was already excluded in Paper I on the basis of the intensity of the HeII 1640 Å line.

We therefore ask from which process or in which source the observed X-ray emission originates? In a CV (nova or quiescent nova) X-rays may be produced by at least three different mechanisms or regions (see Kuulkers et al. 2006; Krautter 2008):

1. Thermal emission from the hot white dwarf nova remnant in the late outburst phases. The nova becomes a strong X-ray emitter with a soft SED.
2. Emission from the inner accretion disk (BL) or the accretion columns (in magnetic CVs). One expects to observe a typical X-ray emission of CVs in quiescence, with a thermal bremsstrahlung spectrum.
3. Shocks in the circumstellar medium surrounding the nova system where the expanding nova shell and/or a nova wind

interact with each other or with pre-existing CS material. The expected hard X-ray spectrum originates from thermal bremsstrahlung with kT_{eff} temperatures 0.2–15 keV, and with $L_x \sim 10^{33}–10^{34}$ erg s⁻¹ (O’Brien et al. 1994).

4. The corona of an active dwarf M star companion.

In T Pyx, as already mentioned, the XMM data would exclude case 1. corresponding to a strong SSS source. Case 2 can also be ruled out because, for a CV accreting at the quite high rates of T Pyx, the BL is optically thick and one would expect to observe (see Patterson & Raymond 1985) only soft X-ray emission with luminosity comparable to the disk luminosity, $L_{\text{bl}} \sim L_{\text{disk}} \sim 2.7 \times 10^{35}$ erg s⁻¹. For case 4, we note that a high level of coronal heating at values of $L_x/L_{\text{bol}} \sim 10^{-3}$ persists for the active dMe stars, and the emission was detected in surveys of nearby stars (see Giampapa & Fleming 2002), although any detection would be impossible at the distance of T Pyx.

We suggest that the most likely origin of the observed hard X-ray emission is from shocks within the circumstellar envelope. We note that in GK Per, Balman et al. (2006) detected hard X-ray emission by direct imaging with Chandra. The total X-ray spectrum of the nebula consists of two thermal prominent components of emission. GK Per has a large amount of CS material, which is most likely a residual of a planetary nebula phase, and the shell remnant shows a clumpy structure similar to that observed in T Pyx by Shara et al. (1997) with HST. We recall that the studies by Orío et al. (2001) by Orío (2004) of the X-ray emission from classical and recurrent novae demonstrated that emission from shocked ejecta is expected to last about two years, but may last for up to a century, if, for example, there is pre-existing circumstellar material (as in the case of GK Per). Hernanz & Sala (2007) reported on X-ray observations of V4633 Sgr performed with XMM-Newton between 2.6 and 3.5 yr after outburst. The X-ray spectrum is dominated by thermal plasma emission, which most probably originated in the shock heated ejecta.

Unfortunately, the limited spatial resolution of the available XMM data do not enable any spatially-resolved study to be completed, because the pixel size is about 4 arcsec compared with the optical radius of the nebula which is about 5 arcsec.

Also 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).

16. The recurrence time and the next, long-awaited outburst

As reported in Paper I, we started an observing program in 1986 with IUE to monitor T Pyx prior to (and during) the expected next outburst that was supposed to occur in the late eighties of the last millennium. Unfortunately, the star successfully managed to postpone the long-awaited outburst, and at the present time (2008) has surpassed by eighteen years the longest inter-outburst interval so far recorded (24 yrs).

As mentioned in Sect. 7, Schaefer (2005) published the results of a study of the inter-outburst interval in the recurrent novae T Pyx and U Sco. From an analysis of the available data, he found that the two novae are relatively bright during short inter-eruption intervals and dim during long intervals, suggesting that the product of the inter-eruption interval times the average bolometrically corrected flux is a constant. Therefore, in the case of T Pyx, the lack of the post-1967 outburst is explained by a lower

luminosity and therefore a lower \dot{M} . From the decline in the observed quiescent B magnitude in the time intervals before and after the 1966 outburst, Schaefer (2005) also predicted that the next outburst of T Pyx will occur around 2052.

With the help of considerations in Sect. 8 and the data in Tables 3 and 5, we can further investigate this prediction. The recurrence time can be estimated from the (theoretical) M_{ign} and the observed mass accretion rate. M_{ign} depends mainly on M_1 and \dot{M} , while \dot{M} , for a given L_{disk} , is a function also of M_1 and R_1 , which, in turn, is a function of M_1 . Tables 3 and 5 list M_{ign} , \dot{M} , and the recurrence time $\tau = M_{\text{ign}}/\dot{M}$ (years) for various M_1 values. Table 5 (pre-1967 \dot{M} values) clearly shows that the observed inter-outburst interval (22 years) corresponds to M_1 values $\sim 1.36–1.38 M_{\odot}$. Table 3, which contains post 1967-outburst \dot{M} values indicates that the observed interval, which, so far, is longer than 42 years, corresponds to $M_1 \leq 1.38 M_{\odot}$. The most likely value of M_1 is therefore close to $1.37 M_{\odot}$.

We note that a reduction by a factor two in the mass accretion rate corresponds to an increase in the expected recurrence time τ by a larger factor because, for a given M_1 , M_{ign} increases as \dot{M} decreases. For the relevant values of T Pyx, the decrease by a factor of 2 in \dot{M} is accompanied by an increase by a factor of about 50 percent in M_{ign} . For the next outburst, therefore one expects an increase in the inter-outburst interval τ by a factor of approximately 3.0, to values near 60 years (see Table 3). Our prediction for the next outburst date is therefore around A.D. 2025. With this new date, contrasted with that of Schaefer (A.D. 2052), we (or at least some of us) feel a bit more confident about the chance of personally testing this prediction.

However, given the uncertainties in \dot{M} and M_{ign} , the possibility of a more imminent outburst cannot be ruled out. In this case, X-ray and other observations during the first outburst stages will be of paramount importance in determining the mass ejected in a single event.

17. Summary and conclusions

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 $\dot{M}_{\text{pre-OB}} \sim 2.2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. By combining the measured accretion rate with the duration of the inter-outburst phase ($\Delta t = 22$ yrs), the total accreted mass is inferred to be $M_{\text{accr}} = \dot{M}_{\text{pre-OB}} \cdot \Delta t \sim 5.2 \times 10^{-7} M_{\odot}$. This value is in excellent agreement with the theoretical ignition mass ($M_{\text{ign}} \sim 5.0 \times 10^{-7} M_{\odot}$ expected for a massive white dwarf accreting at the quoted rate. Therefore, both the time interval between the last two outburst and the absence of the awaited post-1967 outburst (due to the lower \dot{M} in the post-1967 time interval) are explained in a self-consistent way.

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. Unfortunately, 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.

In T Pyx, the consistency between the observed M_{accr} and the theoretical M_{ign} supports the good quality of the observations

and the reliability of the models and represents a new, direct confirmation of the validity of the TNR theory, which associates a massive white dwarf with the recurrent nova phenomenon. A detailed comparison of the observed parameters with the theoretical grids of Yaron et al. (2005) indicates that the closest agreement is obtained with a models of a rather massive white dwarf ($M_1 \sim 1.25\text{--}1.40 M_\odot$) that accretes at high \dot{M} rates ($\dot{M} \sim 10^{-8}\text{--}10^{-7} M_\odot \text{ yr}^{-1}$). However, no combination of the theoretical parameters can reproduce the observed values reliably, t_3 being the most difficult parameter to describe.

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 $M_{\text{ej}} \sim 10^{-5} M_\odot$ or higher, i.e. much higher than the mass of the accreted shell $M_{\text{accr}} \sim 5.2 \times 10^{-7} M_\odot$, inferred from UV and other observations during quiescence. Therefore, T Pyx ejected far more material than it has accreted.

There is no way to reconcile this discrepancy given the small uncertainty in the value of \dot{M} ; even if allowance is made for an uncertainty of a factor two, one obtains an upper limit to M_{accr} that is smaller by a factor of at least ten than the theoretical value of M_{ej} . Only for accretion rates higher than $4 \times 10^{-7} M_\odot \text{ yr}^{-1}$ would the accreted mass M_{accr} be comparable with the estimated ejected mass M_{ej} . However, these high rates would correspond to the steady-burning regime, while our detailed discussion of Sect. 14 definitely excluded this possibility. Further confirmation of our considerations can be found in the the very recent results of XMM observations that exclude the presence of a super-soft-source in T Pyx.

The important point is that far more material appears to have been ejected during the last outburst of T Pyx 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. We note that Della Valle & Livio (1996), based on statistical considerations on the frequency of occurrence of RNe in M 31 and LMC, deduced that RNe are not a major class of progenitors of type Ia supernovae. The behavior of T Pyx represents observational confirmation of this conclusion.

Further confirmation for other RNe is required, and this highlights the crucial need for accurate determinations of the most critical parameters of RNe, i.e. the mass accretion rate, and the mass and chemical composition of the shell ejected in a single outburst.

In the case of T Pyx, at present, useful information can be obtained from highly spatially resolved spectrophotometry of the nebula that resolves its innermost part (associated with the last eruption), whose apparent radius should be by now larger than $1''$. At the same time, spatially resolved observations of the outer portions of the nebula will shed light on its poorly known chemical composition and on its complex velocity structure.

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