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Assisted stellar suicide: the wind-driven evolution of the recurrent nova T Pyxidis

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Abstract. We show that the extremely high luminosity of the short-period recurrent nova T Pyx in quiescence can be understood if this system is a wind-driven supersoft x-ray source (SSS). In this scenario, a strong, radiation-induced wind is excited from the secondary star and accelerates the binary evolution. The accretion rate is therefore much higher than in an ordinary cataclysmic binary at the same orbital period, as is the luminosity of the white dwarf primary. In the steady state, the enhanced luminosity is just sufficient to maintain the wind from the secondary. The accretion rate and luminosity predicted by the wind-driven model for T Pyx are in good agreement with the observational evidence. X-ray observations with Chandra or XMM may be able to confirm T Pyx's status as a SSS.

T Pyx's lifetime in the wind-driven state is on the order of a million years. Its ultimate fate is not certain, but the system may very well end up destroying itself, either via the complete evaporation of the secondary star, or in a Type Ia supernova if the white dwarf reaches the Chandrasekhar limit. Thus either the primary, the secondary, or both may currently be committing assisted stellar suicide.

Key words: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual: T Pyx – stars: mass loss – supernovae: general

1. Introduction

The recurrent nova T Pyx is the most prolific of all recurrent novae, with a mean outburst recurrence time of only 22 years. But even away from outburst, T Pyx's observational characteristics are remarkable. Most importantly, its quiescent bolometric luminosity is $L_{\rm bol} \gtrsim 10^{36}$ ergs s^{-1} (Patterson et al. 1998). This is much higher than expected for a short-period cataclysmic variable (CV) like T Pyx, whose orbital period of $P_{\rm orb} = 1.8$ hr places it well below the period gap.

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The implied disagreement with theoretical expectations is severe. For reasonable estimates of T Pyx's system parameters, the standard model of CV evolution predicts mass transfer to be driven by gravitational radiation at a rate of $\dot{M}_{\rm gr} \simeq 4 \times 10^{-11}$ M$_{\odot}$ yr^{-1}. The corresponding accretion luminosity is only $L \simeq 9 \times 10^{32}$ erg s^{-1}. Thus the gap between T Pyx's observed luminosity and the theoretically predicted value spans at least three orders of magnitude.

In order to account for T Pyx's extreme luminosity without having to postulate a similarly extreme mass-transfer rate for the system, it has been suggested that, even in quiescence, the system may be powered predominantly by nuclear burning on the surface of the white dwarf (WD), rather than by accretion (e.g. Webbink et al. 1987; Patterson et al. 1998). However, even this can only reduce the luminosity gap by about an order of magnitude (c.f. Section 2.2). Thus regardless of the actual mode of radiation energy release, T Pyx's extreme luminosity implies an accretion rate $\dot{M}_{\rm acc} \gtrsim (4 - 40) \times 10^{-9}$ M$_{\odot}$ yr^{-1}. This lower limit is in line with estimates based on theoretical nova models: in order to reproduce T Pyx's short outburst recurrence time, an accretion rate $\dot{M}_{\rm acc} \gtrsim 10^{-8}$ M$_{\odot}$ yr^{-1} appears to be required (Livio & Truran 1992; Prialnik & Kovetz 1995; Contini & Prialnik 1997).

Clearly, T Pyx poses a fundamental challenge to our understanding of CV evolution. Put concisely, the question is this: *why is T Pyx's accretion rate so abnormally high relative to "ordinary" CVs?* The answer we propose in this *Letter* is that T Pyx has left the standard CV evolutionary track completely and is instead currently evolving as a wind-driven supersoft X-ray source.

2. T Pyx as a Wind-driven Supersoft X-ray Source

2.1. Motivation

T Pyx's observational characteristics in quiescence are clearly extreme among CVs. However, as recently pointed out by Patterson et al. (1998) they are actually a good

match to the properties of the supersoft x-ray sources (SSSs). Despite this empirical connection, the standard model for binary SSSs – thermal-timescale mass transfer from a companion initially more massive than the WD – cannot work for T Pyx: the shortest orbital period found in the detailed study of this phase by Deutschmann (1998) is about 6 hr, much longer than T Pyx's 1.8 hr. In fact, King et al. (2000) find that the two shortest-period systems among known binary SSSs – RX J0537.7−7034 ($P_{\mathrm{orb}} \simeq 3.5$ hr) and SMC 13 ($P_{\mathrm{orb}} \simeq 4.1$ hr) – are already difficult to account for within the thermal-timescale mass-transfer framework, even allowing for non-conservative evolution.

We therefore propose that T Pyx is instead a member of an (even more) exotic class of SSSs – the *wind-driven supersoft sources*. The existence of this class has recently been suggested by van Teeseling & King (1998, hereafter VK98; see also King & van Teeseling 1998, hereafter KV98). These authors show that if the secondary star in a close binary system like T Pyx is strongly irradiated by soft x-rays, a powerful wind may be driven from its surface. Under certain conditions, the mass and angular momentum loss in this wind can dominate the binary evolution, which in turn can drive mass transfer at a rate comparable to the wind mass-loss rate. If the wind-driven mass-transfer rate is high enough to power the irradiating source, a self-sustaining, stable, wind-driven state is created. All that is required in this scenario is an event to trigger the wind-driven evolution.

2.2. Theoretical Background

We take as our starting point Equation 7 in VK98, which gives the expected mass-loss rate from a low-mass, near-main-sequence secondary star irradiated by intense soft x-ray emission from the vicinity of the primary as

$$\dot{M}_{w2} \simeq -3 \times 10^{-7} \phi \frac{r_2}{a_{11}} (m_2 L_{37} \eta_s)^{1/2} \ \mathrm{M_\odot yr^{-1}}. \qquad (1)$$

In this equation, $m_2 = M_2/M_\odot$ and $r_2 = R_2/R_\odot$ are the mass and radius of the secondary, $a_{11} = a/(10^{11} \ \mathrm{cm})$ is the binary separation and $L_{37} = L/(10^{37} \ \mathrm{erg \ s^{-1}})$ is the luminosity of the irradiating source. The factor η_s measures the efficiency of the irradiating spectrum in producing the wind, and ϕ measures the area of the mass-losing regions on the secondary's surface, relative to πR_2^2.

The irradiating luminosity is most conveniently parameterized in terms of the luminosity expected for steady shell burning, L_{sb}, which is

$$L_{\mathrm{sb}} = 2.9 \times 10^{37} \left(\frac{\dot{M}_{\mathrm{acc}}}{10^{-7} \ \mathrm{M_\odot \ yr^{-1}}} \right) \ \mathrm{erg \ s^{-1}} \qquad (2)$$

(Iben 1982). Defining $L_{\mathrm{sb},37} = L_{\mathrm{sb}}/(10^{37} \ \mathrm{erg \ s^{-1}})$, we therefore write the irradiating luminosity as

$$L_{37} = \eta_a L_{\mathrm{sb},37} = 2.9 \eta_a \left(\frac{\dot{M}_{\mathrm{acc}}}{10^{-7} \ \mathrm{M_\odot \ yr^{-1}}} \right) \qquad (3)$$

and use the numerical factor $\eta_a \leq 1$ as a measure of the efficiency with which the accreted material is actually converted into luminosity. Thus $\eta_a = 1$ for steady shell burning, whereas $\eta_a = L_{\mathrm{acc}}/L_{\mathrm{sb}} \lesssim 0.3$ for accretion onto a massive WD in the absence of any nuclear processing ($L_{\mathrm{acc}} = GM_1 \dot{M}_{\mathrm{acc}}/R_1$). Combining Equations 1 and 3 yields

$$\begin{aligned} \dot{M}_{\mathrm{acc}} &= -g\dot{M}_{w2} \\ &\simeq 1.2 \times 10^{-6} g^2 \phi^2 \eta_a \eta_s \left(\frac{q^{5/2}}{1+q} \right)^{2/3} m_1 \ \mathrm{M_\odot \ yr^{-1}}. \end{aligned} \qquad (4)$$

Here, $g = -\dot{M}_{\mathrm{acc}}/\dot{M}_{w2}$ is the dimensionless accretion rate (measured in units of the wind mass-loss rate), $m_1 = M_1/M_\odot$, and we have used Paczyński's (1971) approximation for R_{L2}/a to recast r_2/a_{11} in terms of q. Here, R_{L2} denotes the volume-averaged Roche-lobe radius of the secondary. If a stationary, stable, wind-driven state exists, the accretion rate in it must be given by Equation 4.

In order to determine g as a function of the system parameters, one needs to calculate the mass-transfer rate due to Roche-lobe overflow (RLOF) in a semi-detached close binary system whose evolution is driven by a stellar wind from the secondary. This calculation is described in detail by VK98 and KV98. Briefly, such a system will quickly settle in a stationary state with $\dot{R}_{L2}/R_{L2} = \dot{R}_2/R_2$, provided such a state exists and is stable. The stationarity condition is sufficient to find g as

$$g = \frac{(6\beta_2 + 2q) - (5 + 3\zeta)(1+q)}{(1+q)(5 + 3\zeta - 6q)}, \qquad (5)$$

where ζ is the effective mass-radius index of the secondary (describing its reaction upon mass loss), and β_2 is the specific angular momentum of the escaping wind material, measured relative to the specific orbital angular momentum of the secondary.

Equation 5 gives the dimensionless RLOF mass-transfer rate in the stationary wind-driven state. It is identical to Equation 30 of VK98, except that we have retained the explicit dependence on β_2 (VK98 set $\beta_2 = 1$ throughout). As shown by KV98, the stationary solution is stable for system parameters appropriate to T Pyx and $\dot{M}_{w2} \propto L^{1/2} \propto \dot{M}_{\mathrm{acc}}^{1/2}$. In deriving Equation 5, it has been assumed that all of the material in the stellar wind from the secondary escapes. Also, the effects of mass loss from the primary have been ignored. In reality, T Pyx may undergo significant mass ejection during its nova eruptions, and the long term average $\dot{M}_{w1}$ may be comparable to $\dot{M}_{w2}$. However, we have verified that even strong, episodic mass loss from the primary has virtually no impact on our results for T Pyx in quiescence, unless the specific angular momentum carried away by the nova ejecta is extremely high (much higher than that of the primary). In that case, the angular momentum loss associated with nova eruptions would further accelerate (and could possibly even dominate) the binary evolution. We will return to this possibility in Section 3.

We finally consider the orbital period derivative of such a wind-driven system. If this is entirely due to *stationary* mass loss and/or transfer, we can combine Kepler's 3rd law with Paczyński's (1971) approximation for R_{L2} and differentiate logarithmically to obtain

$$\frac{\dot{P}_{\rm orb}}{P_{\rm orb}} = \frac{3\zeta - 1}{2}\frac{\dot{M}_2}{M_2} = \frac{(3\zeta - 1)(1 + g)}{2}\frac{\dot{M}_{w2}}{M_2} \qquad (6)$$

(c.f. Equation 34 in VK98). However, the period derivative measured in real systems may differ from this, since the timescale associated with such measurements is much shorter than the timescale on which the RLOF rate can adjust itself ($\tau_{\rm RLOF} \sim \frac{H}{R_2}\frac{M_2}{M_{w2}} \sim 10^4$ yr, where $H/R_2 \sim 10^{-4}$ is the scale height in the atmosphere of the secondary near the inner Lagrangian point). Thus observationally determined period changes could, for example, be due to fluctuations of $\dot{M}_{w2}$ or β_2 on timescales shorter than $\tau_{\rm RLOF}$.

2.3. Application to T Pyx

We are now ready to apply the wind-driven evolution scenario to T Pyx. For definiteness in our numerical estimates, we will adopt main-sequence-based values for the mass and radius of T Pyx's secondary: $M_2 = 0.12\ M_\odot$, $R_2 = 0.17\ R_\odot$. These follow from Kepler's law, the orbital period, Patterson's (1998) power law approximation to the the M-dwarf mass-radius relationship of Clemens et al. (1998) and Paczyński's (1971) approximation for $R_{L2} \simeq R_2$ of a Roche-lobe filling secondary star. In addition, we will use $M_1 = 1.2\ M_\odot$ as an estimate of the white dwarf mass (Contini & Prialnik 1997). We therefore take the mass ratio in T Pyx to be $q = M_2/M_1 = 0.1$. We note from the outset that even this rather low value for q could be an overestimate, since T Pyx's wind-driven evolution may already have reduced M_2 below its main-sequence value. Our assumption that the secondary is still close to the main sequence amounts to saying that wind-driving has only just begun.

We begin by noting that, for a low-mass secondary undergoing adiabatic mass loss, we may take $\zeta \simeq -1/3$ (VK98). Next, we consider two extreme estimates for the angular momentum loss parameter β_2. To obtain a lower limit, we note that the stellar wind material will carry away at least the specific angular momentum of the secondary, in which case $\beta_2 = 1$ (this is the case considered by VK98). On the other hand, the stellar wind material may extract angular momentum from the binary system by frictional processes. An upper limit to the amount of specific angular momentum that is likely to be extracted this way is given by the specific angular momentum of particles escaping through the outer Lagrangian points, which is $j_2 \simeq 1.65a^2\Omega$ (Sawada et al. 1984; Flannery & Ulrich 1977; Nariai 1975). Here Ω is the angular velocity of the binary system, and, in our notation, the corresponding angular momentum loss parameter is $\beta_2 = 2$. These

estimates, together with $q = 0.1$, yield $g \simeq 0.5$ ($\beta_2 = 1$) and $g \simeq 2$ ($\beta_2 = 2$). Substituting these values back into Equation 4, along with $m_1 = 1.2$, we obtain

$$\dot{M}_{\rm acc}(\text{T Pyx}) \simeq \begin{cases} 7 \times 10^{-9}\phi^2\eta_s\eta_a\ \text{M}_\odot\ \text{yr}^{-1} & \beta_2 = 1 \\ \\ 1 \times 10^{-7}\phi^2\eta_s\eta_a\ \text{M}_\odot\ \text{yr}^{-1} & \beta_2 = 2 \end{cases} \qquad (7)$$

for T Pyx if it has settled into a stationary, wind-driven state. The corresponding luminosity is given by Equation 3 as

$$L(\text{T Pyx}) \simeq \begin{cases} 2 \times 10^{36}\phi^2\eta_s\eta_a^2\ \text{erg s}^{-1} & \beta_2 = 1 \\ \\ 3 \times 10^{37}\phi^2\eta_s\eta_a^2\ \text{erg s}^{-1} & \beta_2 = 2\ . \end{cases} \qquad (8)$$

Thus wind-driving can indeed account for T Pyx's extreme accretion rate and luminosity, provided that the various efficiency factors in Equations 7 and 8 are not too far from unity.

VK98 have argued that $\eta_s \simeq 1$ in SSSs, since soft x-rays are absorbed well above the photosphere and should therefore be quite efficient at driving the wind. The factor ϕ is just the area of the mass-losing regions on the secondary divided by πR_2^2, so that mass loss from the entire front hemisphere would correspond to $\phi = 2$. We may therefore also expect $\phi \simeq 1$, even if the secondary is partially shielded by an optically thick accretion disk. However, the most interesting parameter in this context is η_a. As noted in Section 2.2, energy release by accretion yields $\eta_a \lesssim 0.3$. The upper limit in this inequality corresponds to a Carbon-core WD of maximum mass (1.4 $M_\odot$) and minimum radius ($0.002R_\odot$; Hamada-Salpeter 1961). For a 1.2 $M_\odot$ WD on the same mass-radius relation, we have $\eta \simeq 0.1$. Thus gravitational energy release alone can only meet the system's luminosity requirements if the WD is even more massive than we have assumed and $\beta_2 > 1$.

The alternative is that nuclear processing continues in T Pyx even in quiescence. This would imply that nuclear burning in T Pyx occurs both quasi-steadily (in quiescence) and explosively (during outbursts), with the former taking place at a rate slightly below the accretion rate. From an empirical point of view, this does not seem unreasonable: as noted by Patterson et al. (1998), some SSSs in the LMC and M31 are recurrent (see Kahabka 1995), and the galactic novae GQ Mus and V1974 remained luminous soft x-ray sources for several years after their nova eruptions (Shanley et al. 1995; Krautter et al. 1996). Symbiotic stars (SySs) provide another interesting point of comparison. Several classical SySs, such as Z And, exhibit erupting behaviour even though though their quiescent luminosities ($L \sim 10^3 L_\odot$) suggest nuclear processing as the dominant power source (Mürset, Nussbaumer, Schmid & Vogel 1991). In addition, the luminosities of symbiotic novae (a distinct class from the classical SySs) remain high for decades after their outbursts (Mürset & Nussbaumer 1994).

From a theoretical point of view, the situation is somewhat more difficult. The problem is that the rate at which steady nuclear processing can proceed is not, in principle, a tunable parameter. Based on 1-dimensional models, explosive and steady processing are generally expected to be mutually exclusive regimes, whose dividing line is a function of accretion rate and white dwarf mass (Iben 1982). Thus steady burning is not expected to occur for accretion rates less than $\dot{M}_{crit} \sim 1.32 \times 10^{-7} M_{WD}^{3.57}$. The accretion rates predicted by our wind-driven model are below this line (albeit by only a factor of 2.5 for $\beta = 2$ and $M_{WD} = 1.2 M_\odot$).On the other hand, nuclear processing on real WDs is unlikely to be well-described by spherically symmetric models. For example, thermonuclear runaways (TNRs) triggered by localized temperature or pressure fluctuations may not always spread and evolve into global TNRs (Shara 1982; Shankar & Arnett 1994). Quasi-steady quiescent burning in T Pyx could therefore conceivably be the collective outcome of many successive localized TNRs. The individual mini-eruptions would not necessarily be obvious observationally, provided they are sufficiently small and frequent. These localised TNRs could process non-degenerate material more slowly than it accretes, leading to the build-up of a more and more massive non-degenerate envelope and, eventually, to a global TNR.

The preceding is a highly speculative scenario, and we do not mean to endorse it too strongly. We have outlined it mainly to provide a specific illustration of the general idea that (quasi-)steady and explosive nuclear processing might take place in the same object. This general idea is not new. It was first suggested by Webbink et al. (1986) and again by Patterson et al. (1998), both times without any specific model in mind. The main achievement of the wind-driving mechanism is that, given a high radiative efficiency, T Pyx's high mass accretion rate and luminosity can be accounted for self-consistently. We do, of course, acknowledge that the requirement $\eta_a \sim 1$ implies a fair amount of fine-tuning, regardless of whether one invokes an extremely massive WD or quiescent nuclear burning. But some theoretical fine-tuning seems reasonable for a system like T Pyx, whose short orbital period, high luminosity and ability to produce nova eruptions are a unique combination among CVs and SSSs. This is not to say that the wind-driven evolutionary channel must be narrow: most other wind-driven systems may be characterized by somewhat higher accretion rates than T Pyx and may therefore be *steady* SSSs. Observationally, such steady, wind-driven SSSs may nevertheless be rare, since their evolutionary timescales would be even shorter than T Pyx's.

We finally turn to the orbital period derivative. On substituting the values for g and $\dot{M}_{w2} = -g\dot{M}_{acc}$ derived above into Equation 8 and inverting, we find that the

expected timescale for period increase due to *stationary* wind-driven mass loss and mass transfer in T Pyx is

$$\frac{P_{orb}}{\dot{P}_{orb}}\,(\text{T Pyx}) \simeq \begin{cases} 5 \times 10^6 \ \ \text{yr} & \beta_2 = 1 \\[2mm] 7 \times 10^5 \ \ \text{yr} & \beta_2 = 2 \,. \end{cases} \tag{9}$$

Patterson et al. (1998) derived $P_{orb}/\dot{P}_{orb} \simeq 3 \times 10^5$ yr from the periodic dip in T Pyx's optical light curve, but more recent timings suggest a slower rate of change. In any case, as noted in the discussion following Equation 6, the observed $\dot{P}_{orb}$ may not be a valid estimate of the stationary (long-term average) value.

3. Discussion and Conclusions

We have shown that the abnormally high luminosity of the short-period recurrent nova T Pyx can be explained if the system belongs to the class of wind-driven SSSs. T Pyx's accretion rate is then much higher than that of an ordinary CV, because the system's evolution is dominated by a radiation-induced wind from the secondary star. The wind-driven evolution is self-sustaining, because the wind-induced accretion rate is sufficient to power the luminosity that excites the wind.

Our model predicts that T Pyx is an intrinsically bright soft x-ray source. T Pyx was observed serendipitously as part of the ROSAT all-sky survey, but not detected (Verbunt et al. 1997). This is not yet in conflict with a SSS model for T Pyx, because of the limited sensitivity of these observations and the relatively high column density towards the system ($N_H \simeq 2.1 \times 10^{21}$ cm^{-2}; Dickey & Lockman 1990[1]). However, a sensitive, pointed observation with Chandra or XMM could yield a detection and provide a direct estimate of the WD luminosity and temperature. For example, assuming a distance of 3 kpc (e.g. Patterson et al. 1998), the flux produced by a blackbody with $L_{WD} = 10^{37}$ ergs/s and $T_{WD} = 2.4 \times 10^5$ K is below the ROSAT detection limit, but would provide around 1000 counts in a 30 ksec observation with XMM.

If T Pyx is, in fact, a wind-driven SSS, its current evolutionary timescale is $\tau_{evol} = |M_2/\dot{M}_2| = \dot{P}_{orb}/P_{orb} \sim 10^6$ yrs. Clearly, this is an extremely short-lived evolutionary state. So how will T Pyx's evolution actually end? We can think of at least three possible outcomes. First, the mass ratio of the system may be driven so low that irradiation and wind-driving cease to be effective. Second, the wind-driven evolution may proceed until the secondary completely evaporates, leaving T Pyx as an isolated WD. Third, if the total mass of the system is somewhat higher than we have assumed, the WD may reach the Chandrasekhar limit and explode in a Type Ia supernova.

The likelihood of the last outcome depends on whether the amount of material that is ejected in each of T Pyx's

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[1] Data available online at *http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl.*

recurrent nova outbursts is significantly less than that which is accreted during each quiescent interval. Theoretically, this is plausible (e.g. Prialnik & Kovetz 1995; Livio & Truran 1992). The question might also be addressed observationally: the total mass accreted during quiescence is $\Delta M_{\mathrm{acc}} \simeq \dot{M}_{\mathrm{acc}} \tau_{\mathrm{rec}} \simeq 1 - 20 \times 10^{-7} \, M_{\odot}$. The mass ejected during an outburst can be inferred by comparing the pre- and post-outburst orbital periods, although this is sensitive to the details of the ejection process (Livio 1991; Livio et al. 1991). Such a comparison could also distinguish between wind-driven and nova-driven evolution scenarios. As noted in Section 2.2, if the specific angular momentum of the mass ejected during T Pyx's nova eruptions is very high $(j_{\mathrm{nova}} \gtrsim a^2 \Omega \, >> \, j_1)$, the angular momentum loss associated with nova eruptions could, in principle, itself drive T Pyx's high mass transfer rate. In the context of this model, the difference between pre- and post-outburst orbital periods must be relatively large. By contrast, the wind-driving model makes no such prediction.

Given the strong possibility that the system will destroy itself on a short timescale, T Pyx represents an evolutionary channel by which short-period CVs may be removed from the general CV population. The existence of such a channel is desirable from a theoretical point of view. As most recently pointed out by Patterson (1998), the observed CV population shows a significant dearth of short-period systems relative to the predictions of standard evolutionary scenarios. Whether T Pyx's "assisted stellar suicide" represents a sufficiently wide channel in this context is an important question: do most CVs eventually enter a wind-driven phase or is T Pyx really a unique system? The answer clearly depends on how wind-driving is actually triggered, an issue we have not addressed in the present work. One possibility is that triggering occurs during a period of residual nuclear burning in the aftermath of a nova eruption, though this would have to be limited to systems satisfying other constraints (e.g. low q and/or high M_{WD}).

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