The Long-term Secular Mass Accretion Rate of the Recurrent Nova T Pyxidis

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Abstract

We present Hubble Space Telescope ultraviolet spectroscopy of the recurrent nova T Pyxidis obtained more than five years after its 2011 outburst, indicating that the system might not have yet reached its deep quiescent state. The ultraviolet data exhibit a 20% decline in the continuum flux from the pre-outburst deep quiescence state to the post-outburst near quiescent state. We suggest that a decline across each recurring nova eruption might help explain the proposed 2 mag steady decline of the system since 1866. Using an improved version of our accretion disk model as well as International Ultraviolet Explorer ultraviolet and optical data, and the 4.8 kpc distance derived by Sokoloski et al. (and confirmed by De Gennaro Aquino et al.), we corroborate our previous findings that the quiescent mass accretion rate in T Pyx is of the order of $10^{-6} M_{\odot} yr^{-1}$. Such a large mass accretion rate would imply that the mass of the white dwarf is increasing with time. However, with the just-released Gaia DR 2 distance of $\sim 3.3$ kpc (after submission of the first version of this manuscript), we find a mass accretion rate more in line with the estimate of Patterson et al., of the order of $10^{-7} M_{\odot} yr^{-1}$. Our results predict powerful soft X-ray or extreme ultraviolet emission from the hot inner region of the high accretion rate disk. Using constraining X-ray observations and assuming that the accretion disk does not depart too much from the standard model, we are left with two possible scenarios. The disk either emits mainly extreme ultraviolet radiation, which, at a distance of 4.8 kpc, is completely absorbed by the interstellar medium, or the hot inner disk, emitting soft X-rays, is masked by the bulging disk seen at a higher inclination.

Key words: novae, cataclysmic variables – stars: individual (T Pyxidis) – white dwarfs

1. Introduction

Cataclysmic variables (CVs; see Warner 1995 for a review) are semi-detached interacting binaries with periods ranging from a fraction of an hour to days. In these systems, a white dwarf (WD) primary accretes hydrogen-rich material from a secondary star filling its Roche lobe. If the WD has a weak or negligible magnetic field, the matter is accreted onto the WD by means of an accretion disk. After enough material is accreted, the temperature and pressure at the base of the accreted layer are high enough to trigger the CNO burning cycle of hydrogen, and the entire layer undergoes a thermonuclear runaway known as the classical nova eruption (Schatzman 1949; Paczynski 1965; Starrfield et al. 1972). CVs for which more than one nova eruption has been observed are classified as recurrent novae (RNe). If the WD accretes more mass during quiescence than it ejects during classical nova eruptions, then it is believed that it might grow to reach the Chandrasekhar limit and explode as a Type Ia supernova (SN Ia; Whelan & Iben 1973; Nomoto 1982). This is known as the single-degenerate (SD) path to SN Ia, as opposed to the double-degenerate (DD) scenario in which two CO WDs in a short period binary system merge (Iben & Tutukov 1984; Webbink 1984). CV systems, in theory, could also lead to SNe Ia via the DD channel if they evolve into a double WD binary in which the total mass exceeds the Chandrasekhar limit and with a period shorter than $\sim 13$ hr (see Livio & Pringle 2011 for a review). Because of their massive WDs accreting at a high rate, RNe in general are considered to be ideal SN Ia progenitor candidates (SD channel), and for that reason, they have been studied more extensively than other CVs.

1.1. The Prototypical Recurrent Nova, T Pyxidis

T Pyx is a famous RN, having erupted six times since 1890 (Waagan et al. 2011; Schaefer et al. 2013). With a recurrence time of only $\sim 20$ years (though the last quiescence interval was twice as long; see Figure 1), the theory predicts that T Pyx must have a massive WD accreting at a high rate (Starrfield et al. 1985; Yaron et al. 2005). As it is often the case with systems that are extensively observed, more questions arise than are being answered, and T Pyx remains a poorly understood system.

T Pyx is surrounded by a nova shell remnant of ejected matter with a radius of 5 arcsec (Duerbeck & Seitter 1979; Williams 1982) as well as a faint outer halo that is twice as large (Shara et al. 1989). An analysis of the expanding knots in the nova shell (Schaefer et al. 2010) suggests that fast ejected material from the most recent RN eruptions is catching up and colliding with some slow-moving material previously ejected in a classical nova eruption in 1866. Schaefer et al. (2010) further proposed that T Pyx was an ordinary CV until it underwent an eruption in 1866, increasing its accretion rate to a value several orders of magnitude larger than expected for its binary period. The enhanced mass transfer is believed to be due to a strong wind from the secondary star, itself driven by irradiation from the accretion-heated WD and inner disk (Knigge et al. 2000). This self-sustained feedback loop between the primary and secondary is believed to be a transient phase:
as the accretion rate has been slowly declining, T Pyx has faded ∼2 mag since its 1866 eruption (Schaefer et al. 2010). Some authors (Patterson et al. 1998; Knigge et al. 2000) have suggested that since 1866 (Schaefer et al. 2010), T Pyx might have been in a super-soft X-ray source (SSS) phase. However, Selvelli et al. (2008) exclude the presence of quasi-steady burning on the WD surface, and X-ray data (Greiner & Di Stefano 2002; Selvelli et al. 2008; Balman 2010) do not provide observational support for this scenario.

It is clear that during the long period of quiescence between the classical nova eruptions, T Pyx is dominated by emission from its accretion disk and that the mass accretion rate is very high (Selvelli et al. 2008; Godon et al. 2014). In order to properly model the accretion disk, it is important to consider the binary system parameters, as the accretion disk model is defined by the mass of the central star, the radius of the central star (giving the lower limit for the inner radius of the disk), the binary separation (to help assess the outer radii of the disk), the inclination, and of course, the mass accretion rate. Furthermore, as the theoretical spectrum is being scaled to the observed spectrum, the reddening as well as the distance to the system become the most important parameters of all.

1.2. System Parameters

All the system parameters are listed in Table 1 and discussed here below.

Distance—Until five years ago the distance to T Pyx was not known, and it was assumed to be of the order of about 1 kpc to a few kiloparsecs; e.g., Selvelli et al. (1995) and Patterson et al. (1998) assumed 3.5 kpc. More recently, Sokoloski et al. (2013) and De Gennaro Aquino et al. (2014) found a distance of 4.8–5.0 kpc (respectively), and after we submitted a first version of this manuscript, Gaia DR2 data (Prusti et al. 2016; Brown et al. 2018; Eyer et al. 2018) revealed a parallax of 0.305119199 mas with an error of 0.041850770 mas, giving a distance of 3277 pc (between 2882 and 3798 pc). This is
the reason why in a preliminary analysis of the archival International Ultraviolet Explorer (IUE) spectra of T Pyx, we assumed a distance of 1 kpc (and reddening of $E(B - V) = 0.25 \pm 0.05$), and found a mass accretion rate of only $10^{-8} M_\odot \text{yr}^{-1}$ (Sion et al. 2010). In our more recent analysis, assuming $d = 4.8$ kpc (and $E(B - V) = 0.35 \pm 0.05$), we found a mass accretion rate two orders of magnitude larger (Godon et al. 2014). In the present work, we initially assumed $d = 4.8$ kpc, but then we took into account the just-released distance from Gaia DR2, which brings the mass accretion of T Pyx closer to $10^{-7} M_\odot \text{yr}^{-1}$. This demonstrates the importance of the distance (and reddening; see below) in determining the correct mass accretion rate of the system.

**Reddening**—At a distance of a few kiloparsecs, and with a galactic extinction of $E(B - V) = 0.25$ in that direction (Schlegel et al. 1998), one can expect the reddening toward T Pyx to be at least of that same order of magnitude, namely $E(B - V) \sim 0.25$ or larger. Indeed, using co-added and merged IUE (SWP+LWP) spectra (with the latest improved data reduction) of T Pyx and adopting the extinction curve of Savage & Mathis (1979), Gilmozzi & Selvelli (2007) obtained $E(B - V) = 0.25 \pm 0.02$ from the 2175 Å dust absorption feature (“bump”). On the other hand, however, using diffuse interstellar bands, Shore et al. (2011) found an extinction of $E(B - V) = 0.49 \pm 0.17$, basically double that found by Gilmozzi & Selvelli (2007). Since an error of 0.05 in $E(B - V)$ (which is quite typical for CV; Verbunt 1987) can produce a change in the UV flux of ~20% at 3000 Å and as much as ~50% at 1300 Å, the large discrepancy between the derived values of $E(B - V)$ for T Pyxidis is frustrating. The matter is further complicated by the fact that deriving the reddening from the 2175 Å bump is accurate to within about 20%, and the extinction curve itself is an average throughout the Galaxy and could be different in different directions (Fitzpatrick 1999). If the reddening toward T Pyxidis is larger than the Galactic reddening in that direction (i.e., $E(B - V) > 0.25$), then the obvious culprit is obscuration by the material that has repeatedly been ejected during the recurring nova eruptions. Whether the “extinction properties” of the ejected material are identical to those of the Galactic ISM is also questionable. It is, therefore, safe to assume for T Pyxidis a reddening value $E(B - V) = 0.35 \pm 0.10$. It is within this context of uncertainty that in Godon et al. (2014) we carried out a UV spectral analysis assuming different values for $E(B - V)$, ranging from 0.25 to 0.50 (even though we derived $E(B - V) = 0.35 \pm 0.05$ using the 2175 Å feature from the combined and merged IUE and Galaxy Evolution Explorer (GALEX) spectra).

We have updated our dereddening software, and in the present work we carry out a new estimate of the reddening giving $E(B - V) = 0.30 \pm 0.05$ (see Section 3.2). Our results for this value of $E(B - V)$ are completely consistent with our previous results in Godon et al. (2014).

**Disk Models and Mass Accretion Rates**—A mass accretion rate of $\sim 10^{-8} M_\odot \text{yr}^{-1}$ was derived by Selvelli et al. (2008) by scaling the flux of two Wade & Hubeny (1998) disk models at 1600 Å. The first model had $M_{\text{wd}} = 1.03 M_\odot$ with $M = 10^{-8} M_\odot \text{yr}^{-1}$, and the second model had $M_{\text{wd}} = 1.21 M_\odot$ with $M = 10^{-5.5} M_\odot \text{yr}^{-1}$. However, the flux at a given wavelength for a given mass accretion rate and a given WD mass cannot be scaled to much higher values of $M$ and larger $M_{\text{wd}}$ (e.g., 1.35 $M_\odot$), as the Planckian peak moves to shorter wavelengths with increasing values of $M$ and $M_{\text{wd}}$. Instead, one should rather use a realistic accretion disk model for the values of $M$ and $M_{\text{wd}}$ in question and fit the entire wavelength range rather than one given wavelength (which at 1600 Å does not include the far-ultraviolet (FUV) spectrum). Furthermore, the size of the accretion disk in T Pyx is such that the truncation of the outer disk, either due to tidal forcing (near ~0.3$a$, where $a$ is the binary separation) or just to the size of the Roche lobe ($\sim 0.6a$), has to be taken into account. In our accretion disk models, the outer disk has a lower temperature, significantly contributing to the UV and optical ranges, while the inner disk contributes to the EUV (especially at the higher mass accretion rate inferred from the data). In the present work, we take the inner and outer radius of the disk into account to generate realistic disk models. Our models (see Section 3, Table 4) have outer disk temperatures of ~20,000 K and ~40,000 K, which are hotter than the ~10,000 K models of Wade & Hubeny (1998) used by Selvelli et al. (2008), and therefore have a smaller outer radius and provide less flux for the same $M$, justifying our higher $M$ results.

**Inclination**—It has been shown that the inclination of the binary system is possibly low, somewhere between 10° and 30°, based on the near, narrowly stationary emission lines (Webbink et al. 1987; Uthas et al. 2010). However, Patterson et al. (2017) suggest a higher binary inclination $i \approx 50° – 60°$, as inferred from Hubble Space Telescope (HST) imaging and radial velocities of the 2011 ejected shell, as well as from the soft X-ray eclipse (Tofflemire et al. 2013), interpreting the emission lines as arising in an accretion disk wind (Sokoloski et al. 2013). While it is possible for strong X-ray modulation to occur even at low inclination, as is the case for BG CMi (Hellier et al. 1993) with $i \approx 30°$ (maybe due to stream disk overflow falling to smaller radii near the WD itself), we

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**Table 1**

| Parameter | Units | Value | References |
|-----------|-------|-------|------------|
| $M_{\text{wd}}$ | $M_\odot$ | 0.7–1.35 | Uthas et al. (2010), Starrfield et al. (1985), Webbink et al. (1987), Schaefer et al. (2010) |
| $R_{\text{wd}}$ | km | 2000–8500 | Assuming a 30,000 K WD with a mass $M_{\text{wd}} = 1.35 M_\odot$, and $M_{\text{wd}} = 0.7 M_\odot$, respectively. |
| $M_2$ | $M_\odot$ | 0.12–0.14 | Knigge et al. (2000), Uthas et al. (2010) |
| $R_2$ | km | $1.18 \times 10^5$ | Knigge et al. (2000) ($R_2 = 0.17 R_\odot$) |
| $i$ | deg | 10–30 | Webbink et al. (1987), Uthas et al. (2010). Patterson et al. (2017) suggest $i \sim 50° – 60°$ |
| $d$ | kpc | 4.8±0.5 | Sokoloski et al. (2013); De Gennaro Aquino et al. (2014). Gaia DR2 data implies $d \sim 3.3$ kpc. |
| $P$ | hr | 1.8295 | Schaefer et al. (1992), Patterson et al. (1998), Uthas et al. (2010), Patterson et al. (2017) |
| $E(B - V)$ | | 0.25–0.50 | Gilmozzi & Selvelli (2007), Shore et al. (2013), Godon et al. (2014) |
| $a$ | km | 5–6×10^5 | The values are for $M_{\text{wd}} = 0.7 M_\odot$, and $M_{\text{wd}} = 1.35 M_\odot$, respectively. |

5 https://irsa.ipac.caltech.edu/applications/DUST/
consider here also a larger inclination to check how this assumption affects our results (we generate disk models assuming \( i = 20^\circ \) and \( i = 60^\circ \)).

The WD and Secondary—Because of the short recurrence time and large \( M \) between the classical nova eruptions, it is expected, on theoretical grounds, that the WD in the system is massive, close to 1.35 \( M_\odot \) (Starrfield et al. 1985; Webbink et al. 1987; Schaefer et al. 2010). However, in their optical radial velocity study of emission line velocities, Uthas et al. (2010) derived a mass ratio of \( q = 0.20 \) and an inclination of \( i = 10^\circ \), and assuming \( 0.14 \, M_\odot \) for the secondary, they inferred a WD mass as low as \( 0.7 \, M_\odot \). Consequently, in the present work, we consider both options: \( M_{\text{wd}} = 0.70 \, M_\odot \) and \( 1.35 \, M_\odot \). The radius of the WD is then taken directly from the mass–radius relation for a non-zero-temperature WD (e.g., Woods 1995): \(~8500\, \text{km}\) for 0.7 \( M_\odot \) mass, and \(~2000\, \text{km}\) for 1.35 \( M_\odot \) mass, assuming that the WD has a temperature of 30,000 K. As to the secondary, its mass is not known, but it has been estimated to be as low as 0.06 \( M_\odot \) for a high inclination (Patterson et al. 2017), and as large as 0.3 \( M_\odot \) (see Selvelli et al. 2008 for a review). In the following, we will assume that the secondary mass is \( \approx 0.13 \, M_\odot \) (Knigge et al. 2000; Uthas et al. 2010). We also assume that the radius of the secondary is its Roche lobe radius. Since the secondary mass and radius do not significantly affect the disk parameters, we do not consider different values here.

The Binary Separation—In order to model the disk, we need to know its size and therefore the binary separation. Using Kepler’s Law, we find a binary separation \( a \approx 5 \times 10^2 \) km assuming a 0.7 \( M_\odot \) WD mass, and \( a \approx 6 \times 10^3 \) km for a 1.35 \( M_\odot \) WD mass, corresponding to 0.72 \( R_\odot \) and 0.86 \( R_\odot \), respectively.

In the present work, using the Sokoloski et al. (2013) distance of 4.8 kpc, we confirm our previously derived mass accretion rate of \( \dot{M} \sim 10^{-8} \, M_\odot \) (Godon et al. 2014) with our newly improved synthetic disk spectra to model the ultraviolet (UV) spectra of T Pyx obtained during quiescence (pre- and post-outburst). However, using the Gaia DR2 data, we derive a distance of 3.3 kpc, which lowers the mass accretion rate to the order of \( 10^{-9} \, M_\odot \, \text{yr}^{-1} \). We further extend our analysis into the optical and find that our results are not inconsistent with the optical data. The UV data further show that the mass accretion rate has slightly decreased in comparison to its pre-outburst value four years after the outburst. We present the data in Section 2, give an overview of our spectral modeling in Section 3, present the results in Section 4 and discuss them in Section 5, and we conclude in Section 6 with a short summary.

2. IUE Archival Data and HST Observations

2.1. The Pre-outburst, Outburst, and Decline UV Spectra

There are 58 pre-outburst IUE spectra of T Pyx, which were collected between 1979 and 1996 (Szkody et al. 1991; Gilmozzi & Selvelli 2007; Selvelli et al. 2008) consisting of 17 spectra with wavelength coverage 1851–3300 Å (LWP) and 31 spectra with wavelength coverage 1150–1978 Å (SWP). Of these, one spectrum (1979) seems to be off-target, and several others are spectra of the background sky near T Pyx. Consequently, in the present work, we use 36 SWP spectra together with 14 LWP spectra obtained over a period of 17 years (1980–1996; see Table 2), exhibiting the same continuum flux level within \( \pm 9\% \). The 9\% fluctuation in the continuum flux level is detected on a timescale as small as \(~1\) day and could be due, for example, to a hot spot and/or to the stream disk material overflowing the disk and partially veiling the accretion disk at given orbital phases. Since this fluctuation in flux is not very large and the S/N of each individual spectrum is rather low, we carry out the same procedure as in Godon et al. (2014) and combine these spectra together to obtain a pre-outburst spectrum of T Pyx that can be used to assess the continuum flux level change of the post-outburst spectra. Details of IUE exposures are listed in Table 2 (in chronological order) together with a GALEX pre-outburst spectrum obtained in 2005.

T Pyx was later observed with HST/Space Telescope Imaging Spectrograph (STIS; \(~1150–2900\, \text{Å}\)) first during its outburst while the spectrum was dominated by broad and strong emission lines with a flux level 10–100 times larger than in quiescence (Shore et al. 2013; De Gennaro Aquino et al. 2014), then with STIS and the Cosmic Origins Spectrograph (COS; \(~900–1725\, \text{Å}\)) during its late decline from outburst (De Gennaro Aquino et al. 2014; Godon et al. 2014) as its flux level reached its pre-outburst value and the emission lines almost vanished, and more recently with COS (\(~900–2150\, \text{Å}\)) as the system continues to decline (as reported here; see the next subsection) with a continuum flux level slightly below its pre-outburst spectrum. The observation log of the HST post-outburst exposures is listed in Table 3 (also in chronological order). Each HST spectrum consists of several exposures obtained successively. For that reason, in Table 3 we mark in bold the date of the first exposure to help differentiate between the actual spectra obtained at different epochs.

The first six HST spectra (obtained between 2011 May and 2013 July) were presented and analyzed in Godon et al. (2014) and De Gennaro Aquino et al. (2014) and showed that by December 2012, the continuum flux level had reached its pre-outburst value (see Figure 2) and remained constant thereafter (the 2013 July spectrum was basically identical to the 2012 December spectrum). The AAVSO light curve of the system (Figure 1b) also indicated that by \(~2013\) the light curve had reached its quiescence level. The system, therefore, seemed to have returned to exactly the same quiescent state. The 2012 December and 2013 July post-outburst HST spectra agree very well with the pre-outburst IUE and GALEX spectra, as shown in Figure 3 (except for detector edge noise in GALEX and IUE). As a result of this, in Godon et al. (2014), we modeled the combined HST and IUE spectra with an accretion disk, yielding a mass accretion rate \( \dot{M} \approx 2 \times 10^{-7} \, M_\odot \, \text{yr}^{-1} \).

2.2. The 2015 and 2016 Late Decline/Quiescent HST/COS Spectra

We obtained two additional HST/COS FUV spectra: the first one more than two years after the last HST spectrum, namely in 2015 October, and the second one in 2016 June.

For each two-orbit observation, we used two different FUV COS configurations, each taking one orbit and in time tag mode. In the first orbit, COS was configured with the G140L grating centered at 1105 Å, from which we extracted one spectral segment from 1150 to 2150 Å. In the second orbit, we used the G130M grating centered at 1055 Å, from which we extracted two spectral segments from 900 to 1045 Å and from 1055 to 1200 Å. The data were collected through the primary science aperture of 2.5 arcsec diameter and processed with CALCOS version 3.1.8 (Hodge et al. 2007; Hodge 2011) through the pipeline, which produces, for each HST orbit, four sub-exposures generated by shifting the position of the spectrum on the detector by 20 Å each time. This strategy is
used to reduce detector effects associated with COS. A description of the COS four position sub-exposures and detector artifacts can be found in Godon et al. (2017a). For the first orbit (COS G140L 1105), the effective good exposure time of each sub-exposure was a little less than ∼200 s. For the second orbit (COS G130M 1055), the exposure time for each sub-exposure was ∼866 s. The resulting spectrum covers the Lyman series down to its cutoff wavelength, including the Lyα region. Due to detector artifacts (especially near the edges), the resulting spectrum is not very reliable in the region where the segments overlap (1150–1200 Å) and in the shortest wavelengths (<1000 Å; see Figures 4(a) and (b)).

The 2015 October spectrum exhibits a net drop (of ∼20%) in the continuum flux level when compared to the 2012 December —2013 July HST spectra and IUE pre-outburst spectrum (see Figure 4(a)). The 2016 June spectrum has a continuum flux slightly higher than the 2015 October spectrum, but still well below the pre-outburst level (see Figure 4(b)).

To better emphasize the continuum flux changes, we average the spectra over the wavelength region 1400–1700 Å, omitting

| Telescope | Data ID | Date (UT) yyyy mm dd | Time (UT) hh:mm:ss | Exp. Time seconds |
|-----------|---------|-----------------------|---------------------|-------------------|
| IUE       | SWP08973 | 1980 Nov 05           | 04:09:56            | 12,900            |
| IUE       | SWP29318 | 1986 Sep 27           | 18:22:55            | 16,200            |
| IUE       | SWP32218 | 1987 Nov 02           | 12:12:44            | 16,800            |
| IUE       | SWP32899 | 1988 Feb 11           | 07:27:19            | 12,780            |
| IUE       | SWP33034 | 1988 Mar 03           | 04:29:13            | 23,580            |
| IUE       | SWP34696 | 1988 Nov 05           | 14:01:04            | 17,160            |
| IUE       | SWP37536 | 1989 Nov 07           | 14:12:10            | 16,800            |
| IUE       | SWP43442 | 1991 Dec 22           | 10:20:50            | 15,600            |
| IUE       | SWP44182 | 1992 Mar 16           | 03:55:48            | 15,000            |
| IUE       | SWP44948 | 1992 Jun 17           | 22:09:41            | 16,800            |
| IUE       | SWP46605 | 1992 Dec 28           | 12:15:49            | 16,320            |
| IUE       | SWP47057 | 1993 Feb 27           | 06:09:34            | 16,500            |
| IUE       | SWP47323 | 1993 Mar 20           | 04:47:40            | 20,100            |
| IUE       | SWP47328 | 1993 Mar 21           | 05:30:39            | 18,000            |
| IUE       | SWP47332 | 1993 Mar 22           | 04:05:15            | 23,100            |
| IUE       | SWP49365 | 1993 Nov 29           | 11:49:59            | 9600              |
| IUE       | SWP49366 | 1993 Nov 29           | 15:25:32            | 10,680            |
| IUE       | SWP50099 | 1994 Feb 24           | 06:07:47            | 11,400            |
| IUE       | SWP50100 | 1994 Feb 24           | 09:47:40            | 10,800            |
| IUE       | SWP50596 | 1994 Apr 20           | 01:58:50            | 24,480            |
| IUE       | SWP52886 | 1994 Nov 23           | 12:27:47            | 9000              |
| IUE       | SWP52887 | 1994 Nov 23           | 15:52:41            | 9480              |
| IUE       | SWP53810 | 1995 Feb 02           | 04:04:13            | 11,400            |
| IUE       | SWP54590 | 1995 May 03           | 23:48:06            | 11,100            |
| IUE       | SWP54591 | 1995 May 04           | 03:30:52            | 11,700            |
| IUE       | SWP56240 | 1995 Nov 26           | 19:15:40            | 12,000            |
| IUE       | SWP57030 | 1996 May 01           | 23:24:57            | 12,000            |
| IUE       | SWP57031 | 1996 May 02           | 03:10:44            | 12,600            |
| IUE       | SWP57032 | 1996 May 02           | 23:16:03            | 12,000            |
| IUE       | SWP57033 | 1996 May 03           | 03:04:57            | 12,000            |
| IUE       | SWP57034 | 1996 May 03           | 08:05:54            | 10,800            |
| IUE       | SWP57035 | 1996 May 03           | 13:03:18            | 6600              |
| IUE       | SWP57039 | 1996 May 04           | 03:19:54            | 7799              |
| IUE       | SWP57042 | 1996 May 04           | 09:41:57            | 9899              |
| IUE       | SWP57047 | 1996 May 05           | 02:23:20            | 10,800            |
| IUE       | SWP57055 | 1996 May 06           | 03:05:51            | 10,800            |
| IUE       | LWR07724 | 1980 Nov 05           | 02:08:20            | 7200              |
| IUE       | LWPO9204 | 1986 Sep 27           | 16:15:42            | 7200              |
| IUE       | LWPI1996 | 1987 Nov 02           | 17:00:13            | 6600              |
| IUE       | LWPI2644 | 1988 Feb 11           | 05:20:34            | 7200              |
| IUE       | LWPI2791 | 1988 Mar 03           | 07:29:37            | 12,780            |
| IUE       | LWPI4383 | 1988 Nov 05           | 11:44:47            | 7800              |
| IUE       | LWPI6757 | 1989 Nov 07           | 11:52:47            | 7800              |
| IUE       | LWPI2052 | 1991 Dec 22           | 14:45:26            | 7200              |
| IUE       | LWPI22608| 1992 Mar 15           | 08:09:57            | 9600              |
| IUE       | LWPI23317| 1992 Jun 18           | 02:54:33            | 6900              |
| IUE       | LWPI24612| 1992 Dec 28           | 09:48:28            | 8400              |
| IUE       | LWPI25020| 1993 Feb 27           | 10:55:54            | 6600              |
| IUE       | LWPI32286| 1996 May 05           | 13:37:15            | 5700              |
| IUE       | LWPI32287| 1996 May 06           | 11:26:01            | 6600              |
| GALEX      | GI2_023004_T_PYX| 2005 Dec 20            | 03:30:05            | 880              |
the emission lines. Namely, the averaged flux is given by

\[ \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda, \]

with \( \lambda_1 = 1400 \text{ Å} \) and \( \lambda_2 = 1700 \text{ Å} \). We present the averaged UV flux of the pre-outburst (IUE + GALEX) and post-outburst (HST) spectra in Figure 5. The first obvious behavior is the 9% fluctuation in the flux level seen in the IUE data and present even on a timescale of \( \sim 1 \) day (year 1996). The GALEX flux data point, obtained at the end of 2005, is rather low, but not inconsistent with the IUE data. The HST post-eruption data show that the 2012 December and 2013 July data points fall within the range of values of the pre-outburst IUE data and explain how they were interpreted as the system having come back to its exact pre-eruption quiescent state (Godon et al. 2014). Only the 2015 October and 2016 June data points reveal that the system has apparently not yet reached quiescence and the UV continuum flux level is still decreasing. The 2016 data point seems to bounce back compared to the 2015 data point; however, it can be understood as a “normal” modulation of the continuum flux level, namely within the \( \pm 9\% \) fluctuation. Both the 2015 and 2016 data points (with \( F_\lambda \approx 2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \)) are definitely below the averaged flux level of the pre-outburst data (with \( F_\lambda \approx 2.5 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \)), showing a drop of \( \sim 20\% \). At this stage, it is not clear whether the system has reached quiescence or will decline further.

### 3. Modeling

Our spectral modeling tools and technique have been previously described extensively in numerous works, such as Godon et al. (2012, 2016); as a consequence, we limit ourselves here to a brief description of the modeling but include a comprehensive account of the recent improvements we made over our previous UV spectral analysis of T Pyx in Godon et al. (2014).

#### 3.1. Modeling of the Accretion Disk Spectrum

For the disk, we assume the standard model (Shakura & Sunyaev 1973; Pringle 1981), namely, the disk is optically thick, has a negligible vertical thickness \( H/r \ll 1 \), it is axisymmetric, and the energy dissipated between shearing adjacent annuli of matter is radiated locally in the \( \pm \hat{z} \) directions. As a consequence, the temperature is solely a function of the radius \( r \) and is completely defined by the mass \( M_{\text{wd}} \) of the central star, the mass accretion rate \( \dot{M} \), and the inner radius of the disk \( R_{\text{in}} \). The luminosity and spectrum of the disk are obtained by integrating over the entire surface area of the disk from the inner radius \( R_{\text{in}} \) to the outer radius \( R_{\text{out}} \).

In order to generate a disk spectrum, we divide the disk into \( \mathcal{N} \) rings with radius \( r_i \) (i, 1, 2 ... \( \mathcal{N} \)) each with a temperature \( T(r_i) \) given by the standard disk model and defined when \( M_{\text{out}} \), \( \dot{M} \), and \( R_{\text{in}} \) are given. For each ring, a synthetic spectrum is generated by running Hubeny’s synthetic stellar atmosphere suite of codes TLUSTY, SYNSPEC, and ROTIN (Hubeny 1988; Hubeny & Lanz 1995). A final disk spectrum is then obtained by running DISKSYN, which combines the spectra of the rings together for a given inclination and takes into account Keplerian broadening and limb darkening (Wade & Hubeny 1998). TLUSTY and SYNSPEC are described in detail in Hubeny & Lanz (2017a, 2017b, 2017c).

Our present modeling includes a number of improvements we recently made as follows.

#### The Inner Disk Radius

The standard disk model, Wade & Hubeny’s (1998) disk models, and our previous disk models all

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### Table 3

| HST Instrument | Filters | Gratings | Central Wavelength | Data ID | Date (UT)* | Time (UT) | Exp. Time (seconds) |
|---------------|---------|----------|--------------------|---------|------------|-----------|-------------------|
| STIS          | E140M   | 1425     | obg101010          | 2011 May 07  | 08:01:44 | 571       |
| STIS          | E230M   | 1978     | obg101020          | 2011 May 07  | 08:26:53 | 285       |
| STIS          | E140M   | 1425     | obg1009010         | 2011 Jul 28   | 18:52:15 | 285       |
| STIS          | E230M   | 1978     | obg199020          | 2011 Oct 04   | 13:41:18 | 285       |
| STIS          | E140M   | 1425     | obg103010          | 2011 Oct 04   | 13:41:18 | 285       |
| STIS          | E230M   | 1978     | obg103020          | 2012 Mar 28   | 15:25:23 | 2457      |
| STIS          | E140M   | 1425     | obx701020          | 2012 Mar 28   | 16:50:44 | 3023      |
| COS           | G130M   | 1055     | lbx70200q          | 2012 Mar 28   | 18:36:38 | 461       |
| COS           | G130M   | 1055     | lbx7020wq          | 2012 Mar 28   | 18:47:22 | 461       |
| COS           | G130M   | 1055     | lbx7020wq          | 2012 Mar 28   | 18:58:06 | 461       |
| STIS          | E140M   | 1425     | obxs01010          | 2012 Dec 21   | 05:18:19 | 2449      |
| STIS          | E140M   | 1425     | obxs01020          | 2012 Dec 21   | 05:43:06 | 3015      |
| COS           | G130M   | 1055     | lbx02010           | 2013 Jul 26   | 08:31:37 | 1744      |
| STIS          | E140M   | 1425     | obxs03010          | 2013 Jul 26   | 08:36:35 | 2449      |
| COS           | G130M   | 1055     | lbx04010           | 2013 Jul 26   | 09:57:04 | 3015      |
| COS           | G140L   | 1105     | lcue01010          | 2015 Oct 13   | 01:00:16 | 788       |
| COS           | G130M   | 1055     | lcue02010          | 2016 Jun 01   | 02:14:18 | 788       |
| COS           | G140L   | 1105     | lcue02010          | 2016 Jun 01   | 03:41:58 | 3466      |

Note.

* To easily differentiate between the different epochs, the first exposure of each epoch is marked in bold.
assume that the inner radius of the disk corresponds to the radius of the central star $R_{\text{in}} = R_{\text{wd}}$. In other words, the radial thickness of the boundary layer is negligible: $\delta_{\text{BL}} \ll R_{\text{wd}}$ (where the size of the boundary layer is determined by the vanishing of the shear $d\Omega/dR = 0$ at $R_{\text{in}} = R_{\text{wd}} + \delta_{\text{BL}}$ (Pringle 1981), in cylindrical coordinates ($R, \phi, z$)). This assumption is valid for an optically thick boundary layer when the mass accretion rate is moderately large ($\dot{\mu} \approx 10^{-7} M_\odot$) and negligible in comparison to the Eddington limit ($\dot{\mu} \ll \dot{\mu}_{\text{Edd}}$). For a very large mass accretion rate, the size of the optically thick boundary layer increases (Godon 1996, 1997) and one has $\delta_{\text{BL}} \approx 0.1-0.5R_{\text{wd}}$ or so. When the boundary layer is optically thin (which usually happens at low mass accretion rates), its size also increases (Narayan & Popham 1993; Popham 1999).

In the present work, we take the inner radius of the accretion disk to be larger than the radius of the star ($R_{\text{in}} > R_{\text{wd}}$) to accommodate for the possible presence of an extended boundary layer. This also allows us to consider a heated WD with an inflated radius in comparison to the zero-temperature radius or a disk that is truncated by the WD magnetic field. The important point here is that we do not generate a disk model with an inner radius at $R_{\text{wd}}$ and truncate it at $R_{\text{in}}$, but rather, we generate a disk model with the inner radius at $R_{\text{in}} > R_{\text{wd}}$. Since the no-shear ($d\Omega/dR = 0$) boundary condition is imposed at the disk inner radius (rather than the WD radius), this difference produces a disk that is colder in its inner region relative to the standard disk model (it is a standard disk model with $R_{\text{wd}}$ replaced by $R_{\text{in}} > R_{\text{wd}}$). Namely, the disk radial temperature profile (Pringle 1981) can be written as

$$T(R) = T_0 \frac{R_{\text{wd}}}{R_{\text{in}}} \left( 1 - \frac{R_{\text{in}}}{R_{\text{wd}}} \right)^{3/4},$$

where $T_0 = 64,800 \, \text{K}$ and $x = R/R_{\text{in}}$ (Wade & Hubeny 1998), but now $R_{\text{in}}$ is the inner radius of the disk (Godon et al. 2017b). The maximum disk temperature, $T_{\text{max}} = 0.488T_0$ reached at
wavelengths around 1700 Å are color-coded, and the observations years are indicated as marked. For better contrast, and since they do not overlap, both the HST spectrum (in the short wavelengths) and IUE LWP spectrum (in the longer wavelengths) have been set to black. The S/N of the IUE LWP spectrum is very low and deteriorates toward the edges (as seen below 2000 Å). The GALEX spectrum (two spectral segments in red) presents a similar low S/N at its edges (including where the two segments meet around 1700–2000 Å). In spite of this, all of the spectra agree relatively well in the regions where the S/N is good.

\( x = 1.36 \), is given by

\[
T_{\text{max}} = 177,826 \text{ K} \left( \frac{M_{\text{wd}}}{M_{\odot}} \right)^{1/4} \\
\times \left( \frac{M}{10^{-6} M_{\odot} \text{ yr}^{-1}} \right)^{1/4} \left( \frac{R_{\text{in}}}{10,000 \text{ km}} \right)^{-3/4},
\]

where for convenience we have now written \( M \) in units of \( 10^{-6} M_{\odot} \text{ yr}^{-1} \), which is the order of magnitude of the mass accretion we obtained for T Pyx in Godon et al. (2014). It is then apparent that for a \( \sim 0.7 M_{\odot} \) WD with a radius of \( \sim 8500 \text{ km} \) (see Section 1.2), one has \( T_{\text{max}} \approx 150,000 \text{ K} \), while for a \( \sim 1.35 M_{\odot} \) WD with a radius of \( \sim 2000 \text{ km} \), \( T_{\text{max}} \approx 500,000 \text{ K} \).

We note, however, that the maximum disk temperature achieved in the inner region can be decreased by increasing \( R_{\text{in}} \). Our modified accretion disk models were already presented and used in Godon et al. (2017b) and Darnley et al. (2017), and further details can be found therein.

The Outer Disk Radius—In our previous work (Godon et al. 2014), based on the work of Wade & Hubeny (1998), the disk was extended to a radius where the temperature reached 10,000 K. Such a radius, depending on the binary separation, mass of the WD, mass accretion rate, and state of the system, could be larger or smaller than the actual radius of the disk. We improved our modeling by choosing the outer disk radius to represent the physical radius of the disk, which can now be extended to include outer rings with a temperature as low as 3500 K.

Due to the tidal interaction of the secondary star, the size of the disk is expected to be between 0.3\( a \) (where \( a \) is the binary separation) for a mass ratio \( q = M_2/M_1 \approx 1 \), and about 0.6\( a \) for \( q \approx 0.1 \) (Paczyński 1977; Goodman 1993). T Pyx, with a binary mass ratio of \( q = 0.20 \pm 0.03 \) (Uthas et al. 2010; for a low inclination and a tidally limited disk radius), should have an outer disk radius \( R_{\text{out}} \approx 0.46 a \) (based on the work of Goodman 1993). However, some systems with a moderate mass ratio have exhibited a disk reaching all the way out to the limit of the Roche lobe radius, e.g., U Gem with a mass ratio \( q = 0.35 \) and an expected disk radius of about \( \approx 0.42 a \) has been observed in quiescence to exhibit double-peaked emission lines suggesting an outer disk radius of 0.6\( a \) (Echevarría et al. 2007). Consequently, in the present work, we consider accretion disk models with a radius of \( \approx 0.3 a \) and \( \approx 0.6 a \).

The outer disk temperature, at \( R = R_{\text{out}} \gg R_{\text{in}} \), is given by

\[
T_{\text{out}} = T_{\text{eff}}(x) \bigg|_{R=R_{\text{out}}} = T_{\odot} x^{-3/4} \bigg|_{R=R_{\text{out}}} = 364,400 \text{ K} \\
\times \left( \frac{M_{\text{wd}}}{M_{\odot}} \right)^{1/4} \left( \frac{M}{10^{-6} M_{\odot} \text{ yr}^{-1}} \right)^{1/4} \left( \frac{R_{\text{out}}}{10,000 \text{ km}} \right)^{-3/4},
\]

since \( x \gg 1 \). The outer disk temperature does not depend on the choice of the inner disk radius and, as expected, decreases with increasing \( R_{\text{out}} \). For \( R_{\text{out}} = 360,000 \text{ km} \) (\( \sim 0.6a \)), we obtain \( T_{\text{out}} \approx 24,800 \text{ K} \), and for a disk half this size (\( \sim 0.3a \)) we obtain \( T_{\text{out}} \approx 41,700 \text{ K} \) in the above equation.

Overall, for a given \( M_{\text{wd}} \) and \( M \), the inner disk temperature depends on the inner disk radius, and the outer disk temperature depends on the outer disk radius.

### 3.2. Dereddening

We updated our dereddening software and instead of using the IUERDAF task UNRED (based on Savage & Mathis 1979 and which we had been using for IUE data; Godon et al. 2014), we generated our own script using the Fitzpatrick & Massa (2007) extinction curve (with \( R = 3.1 \)).

We combine the HST, GALEX, and IUE spectra and remove the unreliable spectral portions of GALEX and IUE (see Figure 2). The interstellar extinction produces a strong and broad absorption feature centered at 2175 Å (see Figure 6), due mainly to polycyclic aromatic hydrocarbon (PAH) grains (Li & Draine 2001). We dereddened the spectrum for
different values of $E(B-V)$, using the extinction curve from Fitzpatrick & Massa (2007). The absorption features vanish for $E(B-V) = 0.30$, and we therefore adopt this value of the reddening for T Pyx. From the visual inspection of the figure alone we infer an error of 0.05. An additional 20 percent error ($\pm 0.06$) has to be taken into account when using...
the 2175 Å bump (Fitzpatrick & Massa 2007). It is worth mentioning, however, that PAHs, the dominant contributor to the 2175 Å bump, do not dominate the FUV extinction (Li & Draine 2001), and three decades ago it was already shown that the 2175 Å bump correlates poorly with the FUV extinction (Greenberg & Chlewicki 1983). This is further illustrated by the larger sample variance about the mean average Galactic extinction curve observed in the shorter wavelength of the FUV (Fitzpatrick & Massa 2007). In the present work, we therefore adopt \( E(B - V) = 0.30 \pm 0.08 \) and refer the reader to Godon et al. (2014; and to our conclusion section) for an investigation of how the assumed reddening affects our results, taking into account that in the literature the reddening toward T Pyx has been as low as 0.25 (Gilmozzi & Selvelli 2007) and as large as 0.50 (Shore et al. 2013).

### 3.3. Optical Wavelengths

In our current analysis, we extend the wavelength coverage into the optical, thereby now generating disk and WD spectra from 900 to 7500 Å. Our UV–optical disk modeling has recently been applied in the spectral analysis of the most extreme RN M31N 2008–12a (Darnley et al. 2017).

T Pyx was observed by Williams (1983) in the optical in its pre-outburst state on 1982 February 1, at UT 07:07 for 75 minutes, at the (MDM) McGraw-Hill Observatory with the 1.3 m telescope and a 2000 channel intensified Reticon spectrophotometer. An optical spectrum was obtained in the wavelength range 3500–7100 Å, thereby covering the Balmer jump. We digitally retrieved the T Pyx optical spectrum from Williams (1983) and scaled it to the pre-outburst (2008) optical spectrum obtained by Uhas et al. (2010), which is itself a flux-calibrated average of 200 spectra observed with the Magellan telescope (4000–5200 Å). We use this spectrum to verify and validate our UV disk model and fit.

### 3.4. Parameter Space

In the present work, we extend the modeling we carried out in Godon et al. (2014) over a slightly different region of the parameter space as follows. First, we assume \( E(B - V) = 0.30 \), while in Godon et al. (2014) we checked how the results vary for \( E(B - V) = 0.25, 0.35, \) and 0.50. Similarly, we currently choose an inclination \( i = 20^\circ \) rather than assuming \( i = 10^\circ \) and \( i = 30^\circ \). We therefore expect the present results to “fall” between our previous results of \( E(B - V) = 0.25 \) and 0.35 and \( i = 10^\circ \) and \( i = 30^\circ \). However, in the present work, we also check how the results are affected when assuming a large inclination, \( i = 60^\circ \), as suggested by Patterson et al. (2017). As in Godon et al. (2014), we run models for both \( M_{wd} = 0.70 M_\odot \) and \( M_{wd} = 1.35 M_\odot \). Due to size of the disk being limited between \( \sim 0.3a \) and \( \sim 0.6a \), we obtain outer disk temperatures of order \( \sim 40,000 \) K and \( \sim 20,000 \) K, respectively, while in our previous work, the disk extended to a radius where \( T \sim 10,000 \) K. We choose (as explained earlier) the inner radius of the disk to be larger than the WD radius.

Because the Gaia DR2 data (Prusti et al. 2016; Brown et al. 2018; Eyer et al. 2018) were released after the manuscript had been submitted and reviewed (and just before it was resubmitted), we include models for the Gaia distance of (see Section 1.2) \( d = 3.3^{+0.3}_{-0.2} \) kpc at the end of the Results and Discussion sections.

### 4. Results

As in Godon et al. (2014), in the following we model the co-added post-outburst HST 2012 December and 2013 July spectrum, combined with the pre-outburst co-added IUE spectra, GALEX spectrum (as shown in Figure 6), together with the pre-outburst optical spectrum. The 2015 October and 2016 June HST spectra exhibit a small drop (\( \sim 20\% \)) in flux in...
comparison to the 2012 December and 2013 July \textit{HST} spectra, but are otherwise almost identical to them. The mass accretion rate corresponding to the 2012 December and 2013 July spectra can then simply be derived by scaling our derived mass accretion rate.

Since the actual mass accretion rate is not known a priori, it has to be found by decreasing or increasing $M$ until a fit at the distance of 4.8 kpc is found. If the decrease or increase in $M$ is of the order of $\sim$40\% or smaller ($\Delta M/M < 0.4$), then it is carried out by linearly scaling the flux of the disk model; if it is larger than that ($\Delta M/M > 0.4$), then a new disk model is generated. Also, some of the parameters that are varied do not provide a noticeable change in the results and, consequently, we only list the disk models exhibiting noticeable changes. As the mass accretion rate considered here is extremely large, the contribution of the WD to the spectrum is completely negligible and, consequently, cannot be modeled. Therefore, we present here only a limited number of models.

We first started with a 1.35 $M_\odot$ WD with a radius of 2000 km and a corresponding binary separation $a \approx 600,000$ km. Since the mass accretion rate needed to scale to the distance is very large (of the order of $10^{-6} M_\odot$ yr$^{-1}$), we set the inner radius of the disk $R_{in}$ to $1.1 R_{wd}$, $1.2 R_{wd}$, and $1.5 R_{wd}$ to mimic a geometrically thick boundary layer. These models gave identical results, and we decided to adopt $R_{in} = 1.1 R_{wd}$. We first checked the results for an outer disk radius of the order of $0.3a$ (limited by tidal interaction), which, due to the discrete values of the disk’s rings in the model, gave $R_{out} = 0.27a$. For this model, model \#1 in Table 4, we obtained a mass accretion rate $M = 1.2 \times 10^{-6} M_\odot$ yr$^{-1}$ with a minimum disk temperature at $R_{out}$ of $T_{disk}^{out} = 46,700$ K. This model is presented in Figure 7 and fits the UV data relatively well up to a wavelength $\lambda \approx 2000$ Å. At longer wavelengths, the model becomes too steep, and the spectral slope of the data becomes flatter with increasing wavelength. Namely, the continuum slope in the optical is flatter than the NUV continuum slope, which itself is flatter than the FUV continuum slope. The disk model does not show any sign of the Balmer jump because the disk has a temperature $T > 45,000$ K. The observed optical spectrum does not clearly show the Balmer jump in either absorption or emission, but does show hydrogen emission lines as well as some absorption lines.

Next, we increased the disk size to a maximum value of $\approx 0.6a$ (about the size of the Roche lobe radius), which, again, due to the discrete values of the disk rings, gave $R_{out} = 0.59a$. Since this disk surface area is larger, it requires a smaller mass accretion rate to scale to a distance of 4.8 kpc. For this model, model \#2 in Table 4, we obtained $M = 5.6 \times 10^{-7} M_\odot$ yr$^{-1}$ with a minimum disk temperature of $T_{disk}^{out} = 23,500$ K at $R_{out}$. This model, shown in Figure 8, exhibits a smaller discrepancy in the optical wavelengths and starts to show a “semblance” of a Balmer jump, which is not particularly in disagreement with the optical spectrum itself. Altogether, the larger disk model (\#2) provides an overall better fit than the smaller disk model (\#1).

We then checked the effect of a higher inclination on the results. We increased the inclination from $i = 20^\circ$ to $i = 60^\circ$ in model \#2, which decreases the overall flux by about a factor of 2. Consequently, for this new model, model \#3 in Table 4, we had to increase the mass accretion rate to $1.36 \times 10^{-6} M_\odot$ yr$^{-1}$ to obtain the correct fit to the distance. This model exhibits wider and shallower absorption lines, but as the observed spectrum exhibits mainly emission lines, the fit is carried out on the continuum. This model fit is similar to models \#1 and \#2 in the UV; in the optical, however, the model is not as good as model \#2, but it is better than model \#1. For all the disk
models considered here, we found that the increase in the inclination (to $i = 60\degree$) reduces the flux level by a factor of $\sim 2$ (and therefore increasing the mass accretion rate by the same factor), due mainly to the reduced projected emitting area and somewhat to the coefficient of the limb darkening. For clarity, we only list model #3 in Table 4.

We continued by running models with a lower WD mass, $0.7 M_\odot$, agreeing with the analysis of Uthas et al. (2010), and adopted a WD radius of $8500 \text{ km}$, corresponding to a temperature of $\sim 30,000 \text{ K}$ for such a WD mass (Woods 1995). For this primary mass, the binary separation shrinks to $\sim 500,000 \text{ km}$. We chose an inner disk radius $R_{\text{in}} = 1.1 R_{\text{wd}}$ and obtained a mass accretion rate of $M = 1.92 \times 10^{-6} M_\odot \text{ yr}^{-1}$ and $M = 1.24 \times 10^{-6} M_\odot \text{ yr}^{-1}$ for an outer disk radius of $0.30a$ (model #4) and $0.61a$ (model #5), respectively. These two models gave the same fits as for the larger WD mass models, #1 and #2, and are indistinguishable from them: model #5 fits the optical region better than model #4 and presents an identical fit to model #2 shown in Figure 8. The reason for the similarity of the models lies in the fact that the region of the disk contributing to the UV has about the same temperature, as shown in Table 4 by the outer disk temperature reached at $R_{\text{in}}$ for models #4 and #5. The innermost disk is colder in the $0.7 M_\odot$ models than in the $1.35 M_\odot$ models and choosing a slightly larger inner disk radius, $R_{\text{in}} = 1.5 R_{\text{wd}}$, increases the mass accretion rate by about 10% as shown in Table 4 for models #6 and #7. The fits are, however, identical, and one cannot differentiate between the $1.1 R_{\text{wd}}$ and $1.5 R_{\text{wd}}$ models.

As stated earlier, the just-released Gaia parallax gives a distance of $3.3_{-0.4}^{+0.5} \text{ kpc}$, significantly smaller than the $4.8$–$5.0 \text{ kpc}$ of Sokoloski et al. (2013) and De Gennaro Aquino et al. (2014), thereby demanding further model fits. We, therefore, carried out post facto 12 more model fits: for $M_{\text{wd}} = 1.35 M_\odot$ and $M_{\text{wd}} = 0.70 M_\odot$, each for a disk outer radius $R_d = 0.3a$ and $R_d = 0.6a$, and for a distance of $d = 2.9$, $3.3$, and $3.8 \text{ kpc}$. These 12 models are listed in Table 4 (#9 through #20). Overall, the Gaia distance gives a mass accretion of the order of $10^{-7} M_\odot \text{ yr}^{-1}$ for $M_{\text{wd}} = 1.35 M_\odot$, and $(5–7) \times 10^{-7} M_\odot \text{ yr}^{-1}$ for $M_{\text{wd}} = 0.70 M_\odot$. In the UV range, these 12 models provide a fit to the flux continuum slope as good as models #1 and #2 in Figures 7 and 8. Our ex post facto results for the Gaia distance are discussed in the next section.

5. Discussion

Our current results agree with our previous analysis (Godon et al. 2014) that, during its quiescent state, T Pyx has a mass accretion rate $M$ of the order of $10^{-6} M_\odot \text{ yr}^{-1}$ for a distance of $4.8 \text{ kpc}$. This is about 10 times larger than the estimate from Patterson et al. (2017), who derived the mass accretion rate from the period change of the system both in quiescence and as a result of the eruption. The discrepancy between our results and Patterson et al.’s (2017) vanishes when we considered the Gaia-derived distance of $3.3 \text{ kpc}$ and a WD mass of $1.35 M_\odot$. However, the discrepancy remains for the low WD mass ($0.7 M_\odot$) assumption.

The exact value of $M$ we obtain here depends on the assumed WD mass, inclination, reddening, outer disk radius, and distance to the system. We discuss these below.

The Optical Range—An important improvement is the inclusion of the optical data, which reveal that the optical continuum slope is flatter than the NUV continuum slope, which itself is flatter than the FUV continuum slope (see Figures 7 and 8). This is contrary to the analysis of
Gilmozzi & Selvelli (2007), who claimed that the slope becomes steeper at longer wavelengths. The discrepancy is likely due to the limited number of data points used by Gilmozzi & Selvelli (2007). The slope of the optical continuum is compatible with an $\sim 8000$ K stellar atmosphere, but it does not reveal the Balmer jump (contrary to a stellar atmosphere spectrum). Also, the emitting area of an 8000 K component would have to be larger than the size of binary system to produce such a flux at such a low temperature. It is, therefore, clear that a significant contribution to the optical flux comes from the optically thick accretion disk.

We further present models #1 and #2 together with the optical data in Figure 9 on a linear scale. We display the optical spectrum from Williams (1983) together with the optical spectrum from Uthas et al. (2010) to which it was scaled. The similarity between the emission lines and slope of the continuum between the two optical spectra provides further evidence that the system remains in a relatively similar state over many years, as already demonstrated by the UV spectra shown in Figure 3. The discrepancy between model #2 and the optical data is only $\sim 2 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, and the difference between model #1 and model #2 is of the same order. This is rather small when compared to the UV flux, which is 10–100 times larger, because the disk emits only a tiny fraction of its energy in the optical band. The ex post facto models based on the Gaia distance are very similar to models #1 and #2, except for models #12, #13, and #14, which have a large disk radius ($0.6a$) and a (relatively) lower mass accretion rate ($\sim 10^{-4} M_\odot$ yr$^{-1}$). These three models have an outer disk temperature reaching $\sim 15,000$ K and exhibit a strong Balmer jump, unlike the optical spectrum. Model #13 is shown in Figure 9 for comparison. This indicates that the radius of the disk is probably closer to 0.3a than to 0.6a. The discrepancy in the optical is not inconsistent with the data, as this possibly indicates that an additional component contributing flux in the longer wavelengths is missing from our modeling. Similar results were obtained in the spectral modeling of the RN M31N 2008–12a (Darnley et al. 2017). Since we rule out an 8000 K component as the source of the optical flux, the secondary cannot possibly contribute much to the optical, unless its irradiation by the inner disk increases its temperature significantly. We also note that the optical emission from the nebula (extended shell) is rather negligible, with a continuum flux level of $\sim 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (Williams 1982), two orders of magnitude smaller than the continuum flux level of the optical spectrum.

**Accretion Disk Wind Contribution**—While the best accretion disk models seem to fit the observed spectra down to about 2000 Å, the models become too blue in the longer wavelengths of IUE and in the optical. Often, CV disk-dominated systems have spectra that cannot be fitted with standard disk models—the models are too blue both in the UV (Puebla et al. 2007) and in the optical (Matthews et al. 2015). It has been suggested (Matthews et al. 2015) that an accretion disk wind might be responsible for providing a continuum flux in addition to the contribution from the optically thick disk, making the observed overall spectrum redder than that from an optically thick disk model. The disk wind is also believed to be responsible for the formation of the observed sharp emission lines and for the absence of the Balmer jump when this latter is expected to be in absorption in the spectra of disk-dominated CVs. It is possible that the discrepancy between our optically thick disk model and the observed spectra is due in part to the lack of an accretion disk wind in our modeling. In the present case, however, the truncation of the outer disk model together with the high-mass accretion rate generates a theoretical spectrum that does not exhibit a Balmer jump in agreement with the observed optical spectrum.
Long-term behavior—T Pyx seems to have faded by 2 mag since the 1866 nova eruption (Schaefer 2005; Schaefer et al. 2010), and a look at its AAVSO light curve does indicate a slight decrease in the ~25 years preceding the 2011 eruption (Figure 1(a)). The light curve displaying the decline from the 2011 eruption (Figure 1(b)) shows that the system is still possibly declining, as its magnitude is still increasing. This is further reinforced by our UV light curve (Figure 5). In addition, it appears that both the optical (AAVSO) and UV light curves exhibit a drop in the quiescent magnitude/flux across the 2011 eruption: the quiescent magnitude/flux reached after the 2011 eruption (say in 2016) is lower than its pre-outburst value. This shows that the mass accretion rate in T Pyx is not only declining gradually, but it is also declining after each outburst (or at least after the last outburst), namely in “steps.” At the present time, this step consists of a 20% drop in the mass accretion rate (Figure 5).

X-ray Observations—We have used here optical data to help impose constraints on the spectral analysis, and, as in Godon et al. (2017b), we now wish to use X-ray data to further constrain and interpret the results of the spectral analysis. The main characteristics of the X-ray observations of T Pyx obtained during quiescence (Balman 2010) is the fact that the X-ray luminosity is orders of magnitude smaller than the expected disk luminosity and that it originates in the shocked nebular material rather than in the inner accretion disk or boundary layer.

In the case of a massive WD (1.35 $M_\odot$) accreting at a rate of the order of $10^{-6} M_\odot$ yr$^{-1}$ (models #1, #2, and #3), the temperature in the inner disk (even without a boundary layer) reaches a maximum of ~500,000 K and drops to ~350,000 K for $M \approx 10^{-7} M_\odot$ yr$^{-1}$. Such a high temperature component is expected to show in the soft X-ray band, and the boundary layer temperature would possibly be of the same order of magnitude. However, X-ray observations of T Pyx (Greiner & Di Stefano 2002; Selvelli et al. 2008; Balman 2010) do not provide supporting observational evidence for such an X-ray source scenario.

In contrast, if we consider the 0.7 $M_\odot$ WD mass disk models, the resulting maximum temperature in the inner disk reaches ~170,000 K at $R = 1.36 R_{\text{in}}$, dropping to ~150,000 K at $R = 2.10 R_{\text{in}}$, and to ~100,000 K at $R = 4.00 R_{\text{in}}$. This is for $R_{\text{in}} = 1.1 R_{\text{wd}}$ (models #4 and #5), and the temperature drops an additional 20% for $R_{\text{in}} = 1.5 R_{\text{wd}}$ (models #6 and #7). A slightly lower temperature is reached for models #15 through #20. As such, the disk should emit in the EUV rather than soft X-ray, with the inner disk peaking around 300 Å. The optically thick boundary layer itself could be geometrically thick (even if it is dynamically thin; Godon et al. 1995), with a similar temperature (~$10^5$ K). Such a scenario would explain the low X-ray luminosity as all the energy would be radiated in the EUV. Many CVs accreting at a high mass accretion rate have similar X-ray characteristics, namely with no sign of an optically thick boundary layer (Ferland et al. 1982), but instead a very faint hard X-ray emission with a luminosity orders of magnitude smaller than the disk luminosity (Mauche et al. 1995; van Teeseling et al. 1996; Baskill et al. 2005). A consequence of having a strong EUV source is that the radiation is expected to interact strongly with the ISM and hence the EUV luminosity is greatly reduced. EUV sources are mostly detectable out to a distance of only a few hundred parsecs and at the shortest wavelengths (Barstow et al. 2014).6

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6 The First and Second Extreme Ultraviolet Explorer (EUV) Source Catalogs (Bowyer et al. 1994, 1996) reveal a dozen magnetic CVs and few disk systems (IX Vel, SS Cyg, VW Hyi) with a very low Galactic extinction in their direction ($E(B-V) < 0.1$) or very nearby ($d \sim 200$ pc at most). The only exception is nova V1974 Cyg at ~2.5 kpc, which underwent a classical nova explosion in early 1992 (Collins et al. 1992) and was observed less than a year later with EUVE.
There is, therefore, one option that the mass of the WD is $0.7 M_\odot$ (Uthas et al. 2010), and that the accretion disk emits mostly in the EUV, and that the EUV radiation cannot reach us. The problem with this scenario is that the X-ray emission during outburst argues against a low-mass WD, and a $0.7 M_\odot$ WD accreting at a high rate grows to large radii with no outburst (Newsham et al. 2014).

We note, however, that in order for a $1.35 M_\odot$ WD accreting at a high rate ($\sim 10^{-7} - 10^{-6} M_\odot \text{yr}^{-1}$) to not exhibit X-ray emission, the inner radius of the disk has to be much larger than the anticipated WD radius (see Equation (3)). In Table 4, we list such a model, #8. In that model, we increased the inner disk radius until the maximum temperature in the inner disk drops to 150,000 K. For this to happen, we find a radius of $\sim 14,000$ km, namely seven times larger than the expected WD radius (2000 km for a $1.35 M_\odot$). For an outer disk radius of 0.59 au, the disk gives a mass accretion rate of $7.9 \times 10^{-7} M_\odot \text{yr}^{-1}$. The fit is as good as model #2. Similarly, if we consider model #13 (similar to model #8 but adjusted to the Gaia distance), we find that in order to reduce the inner disk temperature from 350,000 to 150,000 K, we need to increase the inner disk radius to 8000 km, namely four times larger than the expected WD radius. However, we find no physical explanation for the inner disk radius to be so large (T Pyx is not an intermediate polar and we do not consider disks departing from the standard model).

**Accreted Mass versus Ejected Mass**—We recapitulate our results in Figures 10(a), (b), and (c), where we compare the accreted envelope mass obtained from our analysis with the estimates of the ejected envelope mass from the literature. Our previous accreted mass estimate for $E(B - V) = 0.25$, $0.35$, and $0.50$ (all in black) were computed in Godon et al. (2014) for $i = 10^\circ$ and $30^\circ$. Our new results investigating the effects of the size of the disk for $E(B - V) = 0.30$ and $i = 20^\circ$ are in red, and as expected fall between our previous $E(B - V) = 0.25$ and $E(B - V) = 0.35$ results. The ensuing accreted envelope is more massive when assuming a smaller disk radius. Our new results investigating the effects of a large inclination are in blue and indicate that the accreted envelope mass increases by a factor of 2 when increasing the assumed inclination from $20^\circ$ to $60^\circ$. These results confirm that if we assume a distance of 4.8 kpc for most of the parameter space, the accreted envelope is larger than the ejected one, and the WD should increase its mass with time.

However, if the WD mass in T Pyx is massive and if the distance to the system is $\sim 3.3$ kpc, then T Pyx is losing more mass than it is accreting.

**6. Summary and Conclusion**

We have carried out a UV and optical spectral analysis of recent HST observations of T Pyx in its quiescent and late declining states with an improved version of our accretion disk models. Using archival IUE data, optical data, and results from X-ray observations, we show that the results heavily depend on the assumed parameters. We summarize our findings as follows.

1. Both the optical data (as of late 2017) and the UV data (as of mid-2016) indicate that T Pyx is still declining from its 2011 outburst.
2. Both the UV and optical data show that during the pre-outburst quiescent phase, the system was in a relatively steady state with the same continuum shape exhibiting a fluctuation of only 9% in the continuum flux level, which can possibly be attributed to orbital modulation.
3. The UV clearly reveals a drop in the accretion rate across the outburst, namely when comparing the pre-outburst spectra to the late decline post-outburst spectra. This drop is confirmed by the AAVSO light curve (Figure 1), which also exhibits a drop across the outburst. We suggest that the system possibly experiences such a drop, after each recurring nova eruption, which might contribute to the 2 mag fading since 1866.
4. The previously accepted distance of 4.8 kpc gives a large mass accretion rate ($\dot{M} \approx 10^{-6} M_\odot \text{yr}^{-1}$; 10 times larger than the estimate of Patterson et al. 2017), yielding to an accumulated envelope mass of $\approx 2.5 - 9.5 \times 10^{-5} M_\odot$ (models #1–#8). The mass ejected during the eruption is estimated to be $\sim 3 \times 10^{-5} M_\odot$ (Patterson et al. 2017). This would imply that the T Pyx WD mass increased from 1966 (post-outburst) to 2011 (post-outburst), in agreement with Newsham et al. (2014), who predict that, irrespective of the actual mass of the WD, the WD will continue to grow in mass. However, the latest distance
We have now added two thick solid blue lines for a system inclination of 60°. For clarity, we have not marked models. The three solid black lines are the accreted envelope mass estimates from the UV spectral modeling we carried out in Godon et al. (2014) assuming different values for the reddening, and for a system inclination of 10° and 30° as marked on the figure. The first ejected envelope mass [1] (black square symbol in the upper left) is the mass loss maximum estimate of Nelson et al. (2014) assuming a reddening of E(B – V) = 0.50 (Shore et al. 2013) and $M_{\text{nul}} = 0.7 M_\odot$. This ejected mass is to be compared to our accreted envelope mass for the same reddening (the upper solid black line) and same WD mass. The second ejected envelope mass [2] (dashed black line) is from Patterson et al. (2017) and was computed assuming E(B – V) = 0.35 for a range of WD masses. This ejected mass estimate is to be compared to our accreted envelope mass with the same reddening, namely the (almost horizontal) solid black line in the middle of the graph. Our estimate of the accreted envelope mass for a low reddening E(B – V) = 0.25 (as derived by Gilmozzi & Selvelli 2007) is the lower solid black line. Our previous results (assuming $d = 4.8$ kpc) indicate that the accreted mass is larger than the ejected mass and the WD mass is possibly growing with time. (b) The ejected and accreted envelope masses as a function of the WD mass as in Figure 10(a). We have now added our new results assuming a distance of 4.8 kpc (two thick red lines), using a system inclination of 20° and dereddening the spectra for E(B – V) = 0.30. The models from Table 4 are indicated with an asterisk (*) and their respective numbers, (1), (2), (4), and (5), and the thick solid red lines show the interpolation between the 0.7 $M_\odot$ and 1.35 $M_\odot$ models. For a disk tidally truncated at 0.35 $M_\odot$, the accreted mass envelope will be larger than for a disk extending all the way to the Roche lobe (0.6$\alpha$, lower thick red line). Consistent with our previous results, the present E(B – V) = 0.30 results (the two thick red lines) fall between our E(B – V) = 0.25 and 0.35 models (the two thin black lines). For clarity, we have removed the E(B – V) = 0.50 ejected and accreted mass envelope from this graph. (c) The ejected and accreted envelope masses as a function of the WD mass as in Figure 10(b). We have now added two thick solid blue lines for a system inclination of 60° (as marked on the right). Model #3 from Table 4 is marked with a large “X” sign. For clarity, we have not marked models #6 and #7, and we have removed the vertical dotted lines delimiting the WD masses 0.7 $M_\odot$ and 1.35 $M_\odot$. Increasing the inclination from 20° (in red) to 60° (in blue) results in an accreted envelope mass that is twice as large. The results presented in Figures 10(a), (b), and (c), were all obtained assuming a distance of 4.8 kpc. Our ex post facto results taking into account the shorter Gaia distance of 3.3±0.2 kpc have been marked with the thick black line parallelogram in the lower part of the graph as the closer distance reduces the mass accretion rate.

Figure 10. (a) The ejected and accreted envelope masses (Y-axis, in units of log($M_\odot$); per nova eruption) as a function of the assumed WD mass (X-axis, in units of $M_\odot$), based on the 2011 eruption and modeling of the quiescent spectra. The assumed 0.7 $M_\odot$ and 1.35 $M_\odot$ WD masses are indicated with the vertical dotted lines. The three solid black lines are the accreted envelope mass estimates from the UV spectral modeling we carried out in Godon et al. (2014) assuming different values for the reddening and for a system inclination of 10° and 30° (as marked on the figure). The first ejected envelope mass [1] (black square symbol in the upper left) is the mass loss maximum estimate of Nelson et al. (2014) assuming a reddening of E(B – V) = 0.50 (Shore et al. 2013) and $M_{\text{nul}} = 0.7 M_\odot$. This ejected mass is to be compared to our accreted envelope mass for the same reddening (the upper solid black line) and same WD mass. The second ejected envelope mass [2] (dashed black line) is from Patterson et al. (2017) and was computed assuming E(B – V) = 0.35 for a range of WD masses. This ejected mass estimate is to be compared to our accreted envelope mass with the same reddening, namely the (almost horizontal) solid black line in the middle of the graph. Our estimate of the accreted envelope mass for a low reddening E(B – V) = 0.25 (as derived by Gilmozzi & Selvelli 2007) is the lower solid black line. Our previous results (assuming $d = 4.8$ kpc) indicate that the accreted mass is larger than the ejected mass and the WD mass is possibly growing with time. (b) The ejected and accreted envelope masses as a function of the WD mass as in Figure 10(a). We have now added our new results assuming a distance of 4.8 kpc (two thick red lines), using a system inclination of 20° and dereddening the spectra for E(B – V) = 0.30. The models from Table 4 are indicated with an asterisk (*) and their respective numbers, (1), (2), (4), and (5), and the thick solid red lines show the interpolation between the 0.7 $M_\odot$ and 1.35 $M_\odot$ models. For a disk tidally truncated at 0.35 $M_\odot$, the accreted mass envelope will be larger than for a disk extending all the way to the Roche lobe (0.6$\alpha$, lower thick red line). Consistent with our previous results, the present E(B – V) = 0.30 results (the two thick red lines) fall between our E(B – V) = 0.25 and 0.35 models (the two thin black lines). For clarity, we have removed the E(B – V) = 0.50 ejected and accreted mass envelope from this graph. (c) The ejected and accreted envelope masses as a function of the WD mass as in Figure 10(b). We have now added two thick solid blue lines for a system inclination of 60° (as marked on the right). Model #3 from Table 4 is marked with a large “X” sign. For clarity, we have not marked models #6 and #7, and we have removed the vertical dotted lines delimiting the WD masses 0.7 $M_\odot$ and 1.35 $M_\odot$. Increasing the inclination from 20° (in red) to 60° (in blue) results in an accreted envelope mass that is twice as large. The results presented in Figures 10(a), (b), and (c), were all obtained assuming a distance of 4.8 kpc. Our ex post facto results taking into account the shorter Gaia distance of 3.3±0.2 kpc have been marked with the thick black line parallelogram in the lower part of the graph as the closer distance reduces the mass accretion rate.
estimate from Gaia (~3.3 kpc) gives an accumulated envelope mass as low as 4–8 $\times$ 10$^{-6}$ $M_\odot$ (models #9–#14). Only if the WD in T Pyx is as low as 0.7 $M_\odot$ does the accumulated envelope mass reach 2–5 $\times$ 10$^{-5}$ $M_\odot$ (models #15–#20).

5. Our results indicate that if T Pyx’s inclination is large, then the mass accretion rate must be larger by at least a factor of 2. A larger inclination might, as a result of an inflated disk’s self-obscuration, explain why no soft X-ray emission is observed from the inner disk and how the UV flux varies by ±9%. In this case, the system would emit soft X-rays but it would not be observed.

6. If, however, the system is not emitting any soft X-rays at all, it is possible that the WD mass might be as small as 0.7 $M_\odot$ (Uthas et al. 2010, in disagreement with the theory of Starrfield et al. 1985 and Newsham et al. 2014), with an inflated radius, and the disk inner radius might be $R_{in} \approx 1.5 R_{wd}$ to explain the low inner disk/boundary layer temperature emitting in the EUV rather than in the soft X-ray band. Such EUV radiation would be absorbed by the ISM and would not be observable at a distance of 4.8 kpc. For a 1.35 $M_\odot$ WD accreting at a high rate to peak in the EUV (rather than in the X-ray band), the inner radius of the disk would have to be 4–7 times larger than the actual radius of the 1.35 $M_\odot$ WD.

7. The reddening toward T Pyx remains largely unknown. A lower value of $E(B-V)$ = 0.25–0.35 is obtained when using the 2175 Å PAH bump, which correlates poorly with the FUV extinction, (Greenberg & Chlewicki 1983). A value twice as large, $E(B-V) \approx 0.50$, is obtained using the diffuse interstellar bands; however, $E(B-V)$ versus $W_{5}(5780.5)$ has a rather large scatter when considering the data points individually (Friedman et al. 2011). Both techniques have their limitations, and the results have to be considered for all values $E(B-V) = 0.35^{+0.15}_{-0.10}$ (Figure 10).

To conclude, we point out two possible scenarios emerging from our analysis as follows.

(i) The WD is massive, 1.35 $M_\odot$, with a small radius, and due to the high accretion rate, the inner disk emits soft X-rays which are blocked by the thick portion of the disk possibly viewed at a large inclination $i = 60^\circ$. There is no restriction on the reddening.

(ii) The inner radius of the disk is large (~10,000–15,000 km, due to either a small WD mass, 0.70 $M_\odot$, or the truncation of the inner disk), the inclination is 20° ± 10°, and the reddening is probably $E(B-V) \approx 0.25$–0.30 (to keep $M$ to a value of $\sim 10^{-6} M_\odot$ yr$^{-1}$). The inner disk and boundary layer have a maximum temperature of ~150,000 K peaking in the EUV. At a distance of a few kiloparsecs, the UV radiation is absorbed by the ISM.

In both cases, the disk is large, and the UV light is modulated by the orbital motion as matter from the L1 stream overflows the disk rim and further masks parts of the inner disk. Most importantly, the newly derived distance from the Gaia DR2 data, for the most plausible values of the WD mass (1.35$M_\odot$) and reddening ($\approx 0.3$), imply a mass accretion rate of the order of 10$^{-7} M_\odot$ yr$^{-1}$, such that the accumulated envelope mass is actually smaller than the mass ejected during the eruption, indicating that the WD mass does not grow in mass.

However, the Gaia distances for variable/binary stars have to be taken with some reservations (Eyer et al. 2018).

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Software: CalSTIS pipeline (v3.4), CalCos pipeline (v3.1.8), IRAF (v2.16.1, Tody et al. (1993)), Tlusty (v203) Synspec (v48) Rotin(v4) Disksys (v7) (Hubeny & Lanz 2017a, 2017b, 2017c), FORTRAN (77), PGPLOT (v5.2), Cygwin-X (Cygwin v1.7.16), xmgrace (Grace v2), XV (v3.10), WebPlotDigitizer (v3.9).

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