The \textit{XMM–Newton} detection of extended emission from the nova remnant of T Pyxidis

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\textbf{ABSTRACT}

We report the detection of an extended X-ray nebulosity with an elongation from north-east to south-west in excess of 15 arcsec in a radial profile and imaging of the recurrent nova T Pyx using the archival data obtained with the X-ray Multi-Mirror Mission (\textit{XMM–Newton}), European Photon Imaging Camera (pn instrument). The signal-to-noise ratio in the extended emission (above the point source and the background) is 5.2 over the 0.3–9.0 keV energy range and 4.9 over the 0.3–1.5 keV energy range. We calculate an absorbed X-ray flux of $2.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ with a luminosity of $6.0 \times 10^{32}$ erg s$^{-1}$ from the remnant nova in the 0.3–10.0 keV band. The source spectrum is not physically consistent with a blackbody emission model as a single model or a part of a two-component model fitted to the \textit{XMM–Newton} data ($kT_{BB} > 1$ keV). The spectrum is best described by two MEKAL plasma emission models with temperatures at $0.2^{+0.7}_{-0.7}$ keV and $1.3^{+1.0}_{-0.9}$ keV. The neutral hydrogen column density derived from the fits is significantly more in the hotter X-ray component than the cooler one which we may be attributed to the elemental enhancement of nitrogen and oxygen in the cold material within the remnant. The shock speed calculated from the softer X-ray component of the spectrum is 300–800 km s$^{-1}$ and is consistent with the expansion speeds of the nova remnant derived from the \textit{Hubble Space Telescope} and ground-based optical wavelength data. Our results suggest that the detected X-ray emission may be dominated by shock-heated gas from the nova remnant.

\textbf{Key words:} radiation mechanisms; thermal – shock waves – binaries: close – stars: individual: T Pyxidis – novae, cataclysmic variables – X-rays: stars.

\section{1 INTRODUCTION}

Classical nova (CN) outbursts are the explosive ignition of accreted material on the surface of the white dwarf (WD) in a cataclysmic variable (CV) as a result of a thermonuclear runaway causing the ejection of $10^{-7}$ to $10^{-3}$ M$_\odot$ of material at velocities up to several thousand kilometres per second (Shara 1989; Livio 1994; Starrfield 2001; Bode & Evans 2008). Though there has only been one previous (and one very marginal) detection of old CN remnants in the X-ray wavelengths (Balman & Ögelman 1999; Balman 2005, 2006; Pekin & Balman 2008), CNe have been detected in the hard X-rays (above 1 keV) as a result of accretion, wind–wind and/or blast wave interaction in the outburst stage (O’Brien, Lloyd & Bode 1994; Krautter et al. 1996; Balman, Krautter & Ögelman 1998; Mukai & Ishida 2001; Orio et al. 2001; Hernanz & Sala 2002; Ness et al. 2003; Hernanz & Sala 2007; Page et al. 2009). Recurrent novae (RNe) are a type of CNe where outbursts recur with intervals of several decades (Webbink et al. 1987; Hachisu & Kato 2001; Bode & Evans 2008). In general, these systems are expected to have high accretion rates of $10^{-6}$ to $10^{-7}$ M$_\odot$ yr$^{-1}$ on to massive WDs close to the Chandrasekhar limit; occurrence of recurrent outbursts in relatively less massive WDs is also possible (Starrfield, Sparks & Truran 1985; Prialnik & Kovetz 1995; Yaron et al. 2005). RNe are detected in the hard X-rays in the outburst stage as a result of wind–wind and/or blast wave interaction during the outburst stage (Greiner & Di Stefano 2002; Orio et al. 2005; Bode et al. 2006; Sokoloski et al. 2006; Drake et al. 2009; Ness et al. 2009). Recently, extended emission from RN RS Oph has been discovered, plausibly associated with its radio jet (Luna et al. 2009).

RN T Pyx has five recorded outbursts in 1890, 1902, 1920, 1944 and 1966 (Webbink et al. 1987). Ground-based CCD observations (Shara et al. 1989) show the existence of at least two of the shells extending to a size of $\sim 20$ arcsec in diameter and also a faint [O iii] shell has been found. \textit{Hubble Space Telescope} (\textit{HST}; 1994–2007) and ground-based imaging of the shell around T Pyx show thousands of knots in H$_\alpha$ and [N ii] with expansion velocities of about 350–715 km s$^{-1}$, with shell expansion speed around 500 km s$^{-1}$ (Shara et al. 2006; Sokoloski et al. 2006; Drake et al. 2009; Ness et al. 2009). Recently, extended emission from RN RS Oph has been discovered, plausibly associated with its radio jet (Luna et al. 2009).

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et al. 1997; O’Brien & Cohen 1998; Schaefer, Pagnotta & Shara 2010). The HST observations support an interacting shells model producing the clumping, shock heating and emission lines. Schaefer et al. (2010) show that most of the knots have not decelerated and are powered by the RN outbursts and originate from a CN outburst of the year 1866. T Pyx is suggested to be a wind-driven source (due to the high mass accretion rate of $M \sim 1 \times 10^{-7}$ M$_{\odot}$ yr$^{-1}$) and a supersoft X-ray source (SSS) (Patterson et al. 1998). On the other hand, Greiner & Di Stefano (2002) report a ROSAT non-detection of the source in 1998 December excluding the possibility of the existence of a SSS. Gilmozzi & Selvelli (2007) and Selvelli et al. (2008) show that the UV + opt + IR spectrum of T Pyx is dominated by the accretion disc and the continuum in the UV can be represented by a blackbody of $T \sim 34,000$ K with $M \sim 1 \times 10^{-8}$ M$_{\odot}$ yr$^{-1}$. Their detailed study based on the UV data excludes the possibility that T Pyx is a SSS and Selvelli et al. (2008) uses this X-ray Multi-Mirror Mission (XMM–Newton) data set to show that a SSS nature is not supported.

2 THE DATA AND OBSERVATION

The XMM–Newton Observatory (Jansen et al. 2001) has three 1500 cm$^2$ X-ray telescopes each with an European Photon Imaging Camera (EPIC) at the focus; two of which have Multi-Object Spectrometer (MOS) CCDs (Turner et al. 2001) and the last one uses pn CCDs (Strüder et al. 2001) for data recording. T Pyx was observed (pointed observation) by XMM–Newton for a duration of 51 ks between 2006 November 9 UT 19:22:59 and 2006 November 10 UT 09:02:31 with a slight off-axis angle of about 1 arcmin. A medium optical blocking filter was used with all the EPIC cameras and the pn, MOS1 and MOS2. Instruments were operated in the full-frame imaging mode. We analysed the pipeline-processed data using Science Analysis Software (SAS) version 8.0.5. Data (single- and double-pixel events, i.e. patterns 0–4 with Flag = 0 option) were extracted from a circular region of radius 15 arcsec for pn, MOS1 and MOS2 in order to perform spectral analysis together with the background events extracted from a source-free zone normalized to the source-extraction area. In this Letter, we will present an image obtained by the EPIC pn since it has more source photons due to its better sensitivity compared with the MOS1 and MOS2 instruments. However, we simultaneously use EPIC pn, EPIC MOS1 and EPIC MOS2 data to determine the X-ray spectrum of the source and increase the number of data points in the fitting process. We cleaned the pipeline-processed event file from the existing flaring episodes by creating user-selected good time intervals (gti) with a count rate threshold $<0.08$ counts s$^{-1}$ for the two MOS and $<0.11$ counts s$^{-1}$ for the pn instruments over the 0.3–9.0 keV energy range. This method cleaned the flares. Within the extraction area indicated above, the final source count rates were $0.007 \pm 0.001$ counts s$^{-1}$ for pn, $0.003 \pm 0.001$ counts s$^{-1}$ for MOS1 and MOS2 with the effective exposure times of 30.6, 39.7 and 38.8 ks for the pn, MOS1 and MOS2 instruments, respectively.

3 ANALYSIS AND RESULTS

3.1 The X-ray image and the radial profile of T Pyx

The pipeline-processed and cleaned event files are used to calculate the X-ray image of T Pyx and its vicinity. The largest size of the shell of T Pyx is determined to be 10 arcsec in radius (see Section 1). Fig. 1 shows an X-ray intensity image between 0.3 and 9.0 keV obtained from the EPIC pn data. The EPIC pn pixels are binned by 20 pixels (each 0.05 arcsec) and the PI channels are filtered between 0.3 and 9.0 keV in order to create an image with a pixel resolution of 1 arcsec in the sky. The image is then smoothed by a (variable) Gaussian of $\sigma = 1–2$ arcsec using a minimum significance of 1 and a maximum significance of $3\sigma$. Since adequate filtering on the background events are used (see Section 2), the background has not been subtracted out from the image. The small red circle indicates the position of T Pyx. Additionally, in Fig. 1, the X-ray intensity contours are overlaid using linear increments of intensity. The image shows asymmetry in the emission around the central source position with a minimum elongation from the north-east to the south-west of about 15 arcsec in size (as opposed to the width of the source as detected in the image of about 5 arcsec only).

We also constructed radial profiles in the 0.3–9.0, 0.3–1.5 and 2.0–9.0 keV energy bands from images created at 1-arcsec pixel resolution (unsmoothed images) using the sas task ERADIAL keeping the centroid fixed at the source position (J2000) of T Pyx. ERADIAL is a routine to extract a radial profile of a source in an image field and fit a point spread function (PSF) to it. Fig. 2 shows the radial profiles and the normalized EPIC pn PSF (to the source counts in the radial bins 2–4 arcsec from the position of T Pyx) in three different energy bands. The solid line is the normalized PSF and the data are indicated by open squares and vertical error bars. A fitted background (using radial profiles) is also added to the PSFs during the normalization process. The top and middle panels of Fig. 2 show significant deviation between the PSF and the radial profile from 6 arcsec out to 10–30 arcsec from the location of the central binary system, and the bottom panel shows marginal variations. The EPIC pn PSF is described in Ghizzardi (2002) with a King profile (model) whose core radius and power-law index are calculated to be about 6–4 arcsec and $-1.5$–$1.4$, respectively, for off-axis angles $\leq 1$ arcmin over the entire energy band of XMM–Newton.

A King profile is described by $A[1 + (r/r_0)^2]^{-\alpha}$ where $r_0$ is the core radius and $\alpha$ is the power-law index. We fitted the radial profiles (in Fig. 2) with a composite model of a King profile and a constant for the background. The fit to the radial profile in the top panel yields a $\chi^2$ value of 1.3 with the best-fitting core radius in a range 0.2–1.0 arcsec and the power-law index between 0.4 and 0.7 (ranges correspond to errors at 99 per cent confidence level). Freezing the two parameters to the acceptable values of the EPIC pn

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**Figure 1.** The X-ray image of the vicinity of T Pyx in the 0.3–9.0 keV range. The pixel resolution is 1 arcsec. North is up and west is towards the right-hand side. The small red circle shows the location of the binary system. Overlaid are the X-ray contours with linear intensity increments.
PSF (6 arcsec and $-1.5$) changes the $\chi^2_{\nu}$ value to 5.5. The fit to the radial profile in the soft energies (the middle panel of Fig. 2) yields a core radius in a range 1.9–4.0 arcsec and the power-law index is between 0.5 and 0.8 (ranges correspond to errors at 99 per cent confidence level). $\chi^2_{\nu}$ of this fit is 1.0. This is also not consistent with the King profile parameters of the EPIC pn PSF (at $3\sigma$ confidence level). Fixing the core radius at 6 arcsec and the power-law index to $-1.5$ results in a $\chi^2_{\nu}$ of 2.4. None of the fits to the radial profile of the soft band yields parameters consistent with the EPIC pn PSF at $3\sigma$ confidence level. The fit to the profile in the bottom panel (hard energies) yields a $\chi^2_{\nu}$ lower than 2 when parameters are fixed at the expected values of the EPIC pn PSF.

Using the radial profiles, we calculate a signal-to-noise ratio (S/N) of 5.2 in the 0.3–9.0 keV and a ratio of 4.9 in the 0.3–1.5 keV range for the extended emission from T Pyx (S/N is $S/\sqrt{B+P}$; $S$ is the net extended source counts, $B$ is the total background counts and $P$ is the counts within the PSF in an annular region of inner radius 6 arcsec and outer radius 16 arcsec). We also searched the XMM–Newton archival data base for pointed observations of CVs and checked how the PSF normalized with the radial profiles using the same method and found that GK Per shows a similar discrepancy from the point-source distribution as would be expected since GK Per is an extended X-ray source. Furthermore, we checked the radial profiles of other close by weak sources in the field of T Pyx and found that the radial profiles mostly obey the model PSF (taking the off-axis angles into account).

3.2 The XMM–Newton spectrum of T Pyx

We performed spectral analysis of the EPIC data using the SAS task ESPECGET and derived the spectra of the source and the background together with the appropriate response matrices and ancillary files. How the photons were extracted is described in Section 2. The EPIC pn, EPIC MOS1 and EPIC MOS2 spectra were simultaneously fitted to derive spectral parameters of the emission arising from 15 arcsec (radius of the circular photon-extraction region) of the source position. The spectral analysis was performed using XSPEC version 12.5.1 (Arnaud 1996). A constant factor was included in the spectral fitting to allow for a normalization uncertainty between the EPIC pn and EPIC MOS instruments. We grouped the pn and MOS spectral energy channels in groups of 100–150 to improve the statistical quality of the spectra. The fits were conducted in the 0.3–9.0 keV range. At first, we fitted a single blackbody or a composite model spectrum where one component was a blackbody model to check the SSS scenario for the binary system. We find that the fits yield temperatures in excess of 1 keV as the best-fitting value, which is inconsistent with the SSS scenario in accordance with the results of Selvelli et al. (2008). Next, assuming that the emission is of the accretion shocks or the shocks in the nova ejecta, the three spectra were fitted with a single or two MEKAL emission models representing thermal plasma emission in collisional equilibrium (Liedahl, Osterheld & Goldstein 1995). For the intervening absorption ($N_{H}$) we used the TBabs multiplicative model in XSPEC (Wilms, Allen & McCray 2000). The $N_{H}$ was let to vary in order to account for any intrinsic absorption. All abundances were assumed at their solar values. We find that the best fits to the data using a single or two MEKAL models [TBabs*MEKAL or TBabs*[MEKAL + MEKAL]] yield unbounded plasma temperatures in excess of 70 keV with reduced $\chi^2$ values of 1.3–1.5. High shock temperatures may be achieved in accretion shocks;
however, we note that T Pyx is a non-magnetic CV and such systems show X-ray shock temperatures of 3–10 keV, in general (Baskill, Wheatley & Osborne 2005). Such high temperatures (≈70 keV) are mostly achieved by some intermediate polar nuclei (a subclass of magnetic CVs) which T Pyx does not belong to (see de Martino et al. 2008; Brunschweiger et al. 2009). We find that these fits are inconsistent with the accreting CV observations. Such high X-ray temperatures are also not in accordance with the hard X-ray observations of CNe/RNe (see the references in Section 1). Furthermore, in the fitting process, we used some other plasma emission models like CEMKL and MKCFLOW within the xspec software (instead of MEKAL model) that are largely used for the accreting CVs. The resulting X-ray temperatures are also unbounded and above 99 keV for CEMKL and 21–73 keV (lowT–highT) for MKCFLOW, they are also inconsistent with CV observations. Finally, a successful fit was achieved using two different absorption components together with the two different temperature MEKAL models (TBabs*MEKAL + TBabs*MEKAL) with a reduced $\chi^2$ of 1.0 for 15 degrees of freedom. Fig. 3 shows the EPIC pn, EPIC MOS1 and EPIC MOS2 spectra fitted with this composite model. We derive for the first emission component an $N_{H1}$ of $0.6^{+0.3}_{-0.2} \times 10^{22}$ cm$^{-2}$, $kT_1$ of 0.2$^{+0.7}_{-0.1}$ keV and a normalization of $2.9^{+160.0}_{-10^{-4}}$. The second emission component has an $N_{H2}$ of $5.5^{+11.3}_{-4.0} \times 10^{22}$ cm$^{-2}$, $kT_2$ of 1.3$^{+1.9}_{-0.4}$ keV and a normalization of $4.5^{+5.3}_{-1.7} \times 10^{-4}$. Spectral uncertainties are given at 90 per cent confidence level ($\Delta \chi^2 = 2.71$ for a single parameter). The best-fitting results above indicate an absorbed X-ray flux of $2.3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ and an unabsorbed X-ray flux of $3.7 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ which translates to an X-ray luminosity of $6.0 \times 10^{32}$ erg s$^{-1}$ at the source distance of 3.5 kpc (distance from Selvelli et al. 2008) in the energy range 0.3–10.0 keV. We also checked the existence of two spectral components by creating spectra in two annular photon-extraction regions: (1) inner radius of 0 arcsec and outer radius of 6 arcsec and (2) inner radius of 7.5 arcsec and outer radius of 15 arcsec, centred on T Pyx. We find a spectrum similar to that in Fig. 3 in the inner extraction region. However, the spectrum of the outer annulus shows only a 65 per cent decrease in the emission below 1.5 keV and no emission above 1.5 keV. There is no need for a second harder X-ray spectral component.

4 DISCUSSION

The spectrum of T Pyx is well described by two different plasmas in ionization equilibrium at different temperatures. We stress that the expected SSS is not detected and the radial profiles deviate significantly from the PSF of EPIC pn. If one assumes that all the detected luminosity is due to accretion, then this yields an accretion rate less than a few $\times 10^{-10} M_\odot$ yr$^{-1}$ for the system in contradiction with the optical and UV measurements by a factor of 10–100. This strengthens the possibility that most of the detected emission is of the nova remnant in the X-rays rather than the point source.

A simple shocked-shell model is of thermal origin. The total power from the shocked shell, as an X-ray-emitting nebula, can be expressed as in Balman (2005, 2006) $L_x \sim 3.1 \times 10^{37} T_x^{3/2} n_x R_x^{5}$. The temperature $T$ is in units of 10$^7$ K and radius of the shell $R$ is in units of 3.1 $\times$ $10^{18}$ cm. Using $R \sim 4.2 \times 10^{-17}$ cm, $n_x \sim 1$–50 cm$^{-3}$ and $T \sim 10^{6.3}$–$10^{7.3}$ K, $L_x$ is about 1.0 $\times$ $10^{31}$–$8.0 \times 10^{33}$ erg s$^{-1}$. The detected X-ray luminosity (with XMM–Newton) is in this expected range of $L_x$ for the shocked-shell emission. The detected emission measure EM = $n_x^2 V_{ol}$ (calculated from normalization of the fit) yields an average electron density $n_e$ of about 4.7 and 5.5 cm$^{-3}$ for the colder and hotter plasma, respectively, using a volume of $3.0 \times 10^{34}$ cm$^3$ (consistent with a spherical region of 8 arcsec radius at 3.5 kpc) and a filling factor $f = 1$. If the filling factor is as low as $1 \times 10^{-4}$, then the electron density can be as high as 470–550 cm$^{-3}$ in the X-ray-emitting region. The electron density calculated for the nova shell of GK Per is of similar order 0.6–11.0 cm$^{-3}$ for $f = 1$ (Balman 2005). The spectrum of the nova remnant of GK Per also shows two plasma emission components with a significant difference of absorption between the two components (Balman 2005). Such differences can be explained by enhanced non-solar abundances of metals in cold material (possibly a shell or collection of dense knots) between the two emission components. A simple fit with the VARABS or VPHABS model (within xspec) using variable abundances for the second harder X-ray component yields an $N_{H2}$ that is similar to $N_{H1}$ within error ranges with enhanced abundances of $N/N_\odot \sim 20$ and $O/O_\odot \sim 10$. The remnant of T Pyx shows strong [N II] emission, but the...
The plasma temperatures of the two different MEKAL model components can be used to calculate the shock velocities using the general relation \( kT_s = (3/16) \mu m_\odot (v_s)^2 (T = 1.4 \times 10^7 v_s^2 \text{km s}^{-1}) \), assuming Rankine-Huguenot jump conditions in the absence of particle acceleration. We derive 400 km s\(^{-1}\) (300–800 km s\(^{-1}\) using error ranges) for the first plasma emission component and 1050 km s\(^{-1}\) for the second more absorbed plasma emission component (maximum limit 1400 km s\(^{-1}\) using error ranges). The shell expansion velocity is measured to be about 350–715 km s\(^{-1}\) (Shara et al. 1989; Shara et al. 1997; O’Brien & Cohen 1998; Schaefer et al. 2010). This is consistent with the shock speeds calculated using the spectral parameters of the softer X-ray component. The radial profiles calculated from the HST data require a multiple shell model with a particular shell found around 5–6 arcsec and an extended emission region that goes out to 10 arcsec (both measured from the position of T Pyx; Shara et al. 1997; Schaefer et al. 2010). The [N\(\text{II}\)] + H\(\alpha\) images evidently show an elongation/extension from the north-east to the south-west of the source position (see fig. 2c in Shara et al. 1989). The X-ray image indicates a similar elongation from the north-east to the south-west as well. This may be a result of the interaction between a bipolar outflow (e.g. a fast wind) during a RN outburst and the circumstellar environment (e.g. different shells) of the nova or the suggested CN remnant of 1866 by Schaefer et al. (2010).

The expansion speeds of the 1966 outburst are in a range of 850–2000 km s\(^{-1}\) (Catchpole 1969). It has been about 40 yr since the last outburst and the more absorbed (i.e. embedded) plasma emission component may belong to the most recent outburst. The expected location of the ejecta is about 2–4 arcsec (from the position of T Pyx). The expected size of the new interaction zone is within the core size of the EPIC pn PSF. The harder X-ray component may also belong to the binary system. A long observation of this source using the Chandra Observatory (yielding better statistics) can resolve this issue with the aid of its superb pixel and PSF resolution.

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