The Return of the Bursts: Thermonuclear Flashes from Circinus X-1

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THE RETURN OF THE BURSTS: THERMONUCLEAR FLASHES FROM CIRCINUS X-1

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ABSTRACT
We report the detection of 15 X-ray bursts with RXTE and Swift observations of the peculiar X-ray binary Circinus X-1 during its May 2010 X-ray re-brightening. These are the first X-ray bursts observed from the source after the initial discovery by Tennant and collaborators, twenty-five years ago. By studying their spectral evolution, we firmly identify nine of the bursts as type I (thermonuclear) X-ray bursts. We obtain an arcsecond location of the bursts that confirms once and for all the identification of Cir X-1 as a type I X-ray burst source, and therefore as a low magnetic field accreting neutron star. The first five bursts observed by RXTE are weak and show approximately symmetric light curves, without detectable signs of cooling along the burst decay. We discuss their possible nature. Finally, we explore a scenario to explain why Cir X-1 shows thermonuclear bursts now but not in the past, when it was extensively observed and accreting at a similar rate.

Subject headings: binaries: close — X-rays: individual (Cir X-1) — stars: neutron — X-rays: binaries — accretion, accretion disks

1. INTRODUCTION
Discovered during the early years of X-ray astronomy\textsuperscript{1}\textsuperscript{2} and frequently observed ever since, the peculiar X-ray binary Cir X-1 was initially classified as a black hole candidate (BHC), due to spectral and variability similarities to Cyg X-1 (Toor 1977). Its $\sim 16.6$ day period, discovered in the X-ray band by\textsuperscript{3}\textsuperscript{4}\textsuperscript{5}\textsuperscript{6}\textsuperscript{7}\textsuperscript{8}\textsuperscript{9}, and observed at different epochs and wavelengths, is attributed to enhanced accretion near periastron passage in a highly eccentric orbit\textsuperscript{10}. See also\textsuperscript{11}.

Thermonuclear explosions on the surface of accreting neutron stars (type I X-ray bursts; see, e.g.,\textsuperscript{12} Strohmayer & Bildsten\textsuperscript{13} for a recent review) are one of the few signatures that allow us to identify unambiguously a compact object as a neutron star (NS). The defining observational property of type I X-ray bursts is a mainly thermal spectrum with black body temperature that decays along the burst tail (“cooling tail”); e.g.\textsuperscript{14} Lewin et al.\textsuperscript{15} 1993). In 1984–1985, 11 X-ray bursts were discovered in EXOSAT\textsuperscript{16} observations of Cir X-1 (Tennant et al.\textsuperscript{17} 1986a,b). Three of these could be identified as type I X-ray bursts based on their cooling tails (Tennant et al.\textsuperscript{18} 1986a), while a type II identification (see\textsuperscript{19} e.g.\textsuperscript{20} Lewin et al.\textsuperscript{21} 1993) could not be discarded for the remaining eight bursts. The discovery of type I X-ray bursts led to the conclusion that the compact object in Cir X-1 is a NS (Tennant et al.\textsuperscript{22} 1986a,b). Since then many X-ray missions have observed Cir X-1 but no X-ray bursts were detected (see, e.g., Galloway et al.\textsuperscript{23} 2008 for a search of 2.7 Msec of Cir X-1 data from RXTE).

Despite the BHC similarities, (Toor\textsuperscript{24} 1977, van der Klis\textsuperscript{25} 1994, which are not unique to this source), the fast X-ray variability of Cir X-1 has been described as similar to the most luminous NS-LMXBs (Z-sources) and the less luminous NS-LMXBs (atoll sources) (see, Oosterbroek et al.\textsuperscript{26} 1995, Shirey et al.\textsuperscript{27} 1998, Soleri et al.\textsuperscript{28} 2003, and references therein). The complex phenomenology observed in this source, together with the lack of coherent pulsations and the fact that no X-ray bursts have been detected since 1985, have led to the speculation that the compact object in Cir X-1 may be a BH, and that the X-ray bursts discovered by\textsuperscript{1}\textsuperscript{2} Tighe et al.\textsuperscript{1} (1986a,b) came from a nearby system in the EXOSAT $\sim 0.75^\circ$ FoV. The most recent indication that Cir X-1 is indeed a NS is the detection of twin kilohertz quasi-periodic oscillations (kHz QPOs;\textsuperscript{29} Boutejouskos et al.\textsuperscript{30} 2006). Although this phenomenon can be considered a proof of the NS nature of the accretor (van der Klis\textsuperscript{31} 2000), the very peculiar properties of these kHz QPOs prevented a conclusive consensus on the identification of the compact object in Cir X-1.

In this Letter, we report the detection of 15 X-ray bursts from RXTE and Swift observations of Cir X-1. As noted by\textsuperscript{32} Linares et al.\textsuperscript{33} (2010b), these are the first X-ray bursts observed from Cir X-1 after the initial discovery; 25 years ago (Tennant et al.\textsuperscript{34} 1986a,b). We identify 9 of them as thermonuclear -type I- X-ray bursts and obtain an arc-second location fully consistent with the position of Cir X-1, unambiguously identifying Cir X-1 as a low magnetic field accreting neutron star. We discuss the nature of the bursts and the burning regime, as

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well as different scenarios that may explain the change in their properties. Finally, we address the question of why Cir X-1 has not shown type I X-ray bursts in the last 25 years, and why it shows them now.

2. DATA ANALYSIS AND RESULTS

On May 7th, 2010, MAXI-GSC observations detected an X-ray re-brightening of Cir X-1 after two years of very low flux (below \(70 \text{ mCrab}\) and with an average flux of \(\sim 10 \text{ mCrab}\) [Nakajima et al. 2010, see also Fig. 1 right]). Monitoring observations with RXTE started on May 11th, 2010.

2.1. RXTE

We performed a search for X-ray bursts in all (26) RXTE-PCA observations of Cir X-1 taken between May 11th and June 1st, 2010, using 1 s time resolution PCA light curves (Standard 1 mode: full 2–60 keV energy band). We find a total of 12 X-ray bursts that we label in their properties. Finally, we address the question of why Cir X-1 has not shown type I X-ray bursts in the last 25 years, and why it shows them now.

We present in Table 1 the properties of all X-ray bursts detected by RXTE. Detailed inspection of these properties reveals two clearly distinct flavors: bursts R1-R5 (the “early bursts”) have long rise times (7.3–11 s), moderate energy output (total energy of \([1.3–3.7] \times 10^{38} \text{ erg}\) and present prototypical type I X-ray burst analysis (e.g. Kuulkers et al. 2002), we subtracted a 100-s pre-burst spectrum to account for background, non-burst emission (which includes instrumental background and accretion flux). We use the same pre-burst spectrum to measure the 0.5–50 keV persistent flux prior to each burst, as a proxy for the mass accretion rate at the time of ignition. We fitted each 1-s burst spectrum in the 2.5–25.0 keV energy range within XSPEC (v. 12.5) with an absorbed black body model (wabs*bbbodyrad, with abundances from Anders & Ebihara 1982). Given that the PCA bandpass is not well suited for constraining the absorbing column density, we fixed this parameter to the value found by Jaria et al. 2001, \(1.6 \times 10^{22} \text{ cm}^{-2}\) (absorption can be substantially higher near periastron passage, see e.g. Schulz et al. 2008, but none of the bursts analyzed herein occurred around phase 1). All luminosities, energies and black-body radii presented in this work use a fiducial distance of 7.8 kpc, yet the range of distance estimates must be considered (e.g. Jonker & Nelemans 2004 find a distance to Cir X-1 between 7.8 and 10.5 kpc).
We found an X-ray burst in the second observation (Papitto et al. 2010a). We report the detection of a third X-ray burst with Swift-XRT in a photon-counting (PC) mode observation that took place on May 29th (S3, see below).

We processed the XRT data using xrtpipeline with standard quality cuts. Exposure maps and ancillary response files were created using xrtexppsf and xrtmkarf, respectively. The latest response matrix files (v11) were taken from the calibration database. Spectra were grouped to contain a minimum of 10 and 20 photons per bin for burst and persistent spectra, respectively. We extracted source events from a 40x40 pixel box for the WT data and from a 9-40 pixel annulus for the PC data.

Table 1 presents the main properties of the three Swift bursts (S1-S3). The analysis of S3 is affected by severe pile-up of the XRT in PC mode at the collected count rates (more than \( \sim 15 \) c/s at the peak). The burst profile is also typical of type I X-ray bursts, and we consider it likely that this is a type I X-ray burst. Due to the low count rates collected by the XRT the spectral information that can be extracted from S1-S2 is limited. However, by extracting three spectra along the tail of bursts S1 and S2 (and using a pre-burst spectrum as background; Sec. 2.1) we are able to constrain the black-body temperature and we find evidence of cooling in both bursts. The light curves show typical FRED profiles and the temperatures and black body radii that we find are fully consistent with those measured by Linares et al. 2010a; see also Papitto et al. 2010a). We fitted the persistent spectra of the four Swift observations in order to measure the flux evolution around the bursts. We show the resulting 2–10 keV absorbed flux in Figure 1 (right). No other sources were detected in the XRT FoV during the May 29 PC mode observation (Papitto et al. 2010a). We obtain, using xrtcentroid, the following position: R.A.\( =15^\circ20\arcmin0.73^\arcsec\), DEC\( =57^\circ09\arcmin58.7^\arcsec\) (J2000.0), with a 90% confidence error radius of 3.5 arcsec. We also obtain a UVOT-enhanced 

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<td><strong>Properties of the 15 X-ray bursts from Cyg X-1 analyzed in this work.</strong></td>
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<th>ID</th>
<th>OBS ID</th>
<th>Peak time (MJD)</th>
<th>Orbital phase (c/s)</th>
<th>Net peak time (s)</th>
<th>Energy( ^a ) (10(^{37} ) erg s(^{-1} ))</th>
<th>L(_{\text{pe}})(^b ) (10(^{37} ) erg s(^{-1} ))</th>
<th>Wait(^c ) (min)</th>
<th>( \alpha^d )</th>
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<tr>
<td>R1</td>
<td>02-03</td>
<td>55331.46840</td>
<td>0.570</td>
<td>153.1 [1]</td>
<td>9.6 ± 0.5</td>
<td>1.3 ± 0.9</td>
<td>1.3 ± 0.6</td>
<td>4.6 ± 0.3</td>
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<td>R2</td>
<td>02-03</td>
<td>55331.48227</td>
<td>0.572</td>
<td>220.2 [1]</td>
<td>7.3 ± 0.5</td>
<td>2.0 ± 0.8</td>
<td>3.5 ± 1.7</td>
<td>4.4 ± 0.2</td>
</tr>
<tr>
<td>R3</td>
<td>02-02</td>
<td>55332.17123</td>
<td>0.61</td>
<td>153.1 [1]</td>
<td>8.8 ± 0.5</td>
<td>1.3 ± 0.8</td>
<td>1.5 ± 0.7</td>
<td>5.6 ± 0.3</td>
</tr>
<tr>
<td>R4</td>
<td>02-00</td>
<td>55333.55562</td>
<td>0.697</td>
<td>279.1 [1]</td>
<td>7.5 ± 0.5</td>
<td>2.5 ± 0.8</td>
<td>3.7 ± 2.1</td>
<td>4.7 ± 0.3</td>
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<tr>
<td>R5</td>
<td>02-00</td>
<td>55333.56971</td>
<td>0.698</td>
<td>241.7 [1]</td>
<td>10.2 ± 0.5</td>
<td>2.2 ± 0.9</td>
<td>2.4 ± 1.1</td>
<td>5.3 ± 0.3</td>
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<tr>
<td>R6</td>
<td>02-04</td>
<td>55336.09307</td>
<td>0.851</td>
<td>453.1 [1]</td>
<td>2.0 ± 0.5</td>
<td>4.2 ± 0.8</td>
<td>5.8 ± 1.9</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>R7</td>
<td>02-04</td>
<td>55336.11231</td>
<td>0.851</td>
<td>393.9 [1]</td>
<td>2.2 ± 0.5</td>
<td>3.6 ± 0.9</td>
<td>5.3 ± 1.8</td>
<td>4.0 ± 0.2</td>
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<tr>
<td>R8</td>
<td>02-04</td>
<td>55336.13367</td>
<td>0.853</td>
<td>453.9 [1]</td>
<td>5.3 ± 0.5</td>
<td>4.1 ± 0.9</td>
<td>5.5 ± 1.9</td>
<td>4.6 ± 0.2</td>
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<tr>
<td>R9</td>
<td>03-02</td>
<td>55341.06464</td>
<td>1.15</td>
<td>724.9 [2]</td>
<td>5.1 ± 0.5</td>
<td>3.5 ± 0.6</td>
<td>11.3 ± 3.8</td>
<td>4.8 ± 0.2</td>
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<tr>
<td>R10</td>
<td>03-03</td>
<td>55343.35345</td>
<td>1.29</td>
<td>276.7 [2]</td>
<td>2.5 ± 0.5</td>
<td>3.8 ± 0.5</td>
<td>7.6 ± 1.8</td>
<td>1.7 ± 0.1</td>
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<tr>
<td>R11</td>
<td>03-04</td>
<td>55343.75671</td>
<td>1.31</td>
<td>937.4 [2]</td>
<td>1.8 ± 0.5</td>
<td>4.4 ± 0.5</td>
<td>8.6 ± 2.0</td>
<td>1.6 ± 0.1</td>
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<tr>
<td>R12</td>
<td>04-00</td>
<td>55344.20388</td>
<td>1.34</td>
<td>1057.7 [2]</td>
<td>1.8 ± 0.5</td>
<td>4.5 ± 0.5</td>
<td>9.7 ± 2.5</td>
<td>1.5 ± 0.1</td>
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\( ^a \)Observation ID, preceded by 03122-d- and 0030908- in the RXTE and Swift observations, respectively. XRT observe mode between parenthesis.

\( ^b \)Persistent level subtracted; 2.5–25.0 keV and 0.5–10.0 keV energy range for R1-R12 and S1-S3, respectively.

\( ^c \)Number of active PCUs indicated between brackets in the RXTE bursts.

\( ^d \)Defined as time from 25% to 90% of peak flux (see e.g. Galloway et al. 2008).

\( ^e \)Bolometric burst peak luminosity and total energy, after subtracting persistent emission. Persistent luminosity in the 0.5–50 keV band.

\( ^f \)Only quoted when two or more consecutive bursts are detected. Alpha parameter is defined as L\(_{\text{pe}}\) \( \times \) time wait \( \div \) total burst energy.

Fig. 2.—PCA 0.5s time resolution light curve of the three consecutive bursts detected on May 20, 2010 (R6-R8). Insets show zoomed 150 s-long light curves of each burst.

2.2. Swift

We asked for Swift ToO observations of the source to confirm the location of the bursts. Four observations were performed between 2010 May 27–29, and no bursts were detected during the first observation (Papitto et al. 2010a). We found an X-ray burst in the second observation (Papitto et al. 2010a).
We have reported the first X-ray bursts detected from Cir X-1 since 1985. A total of 15 bursts were recorded during May 15-30 2010, when source flux was in the range 0.3–0.01 Crab. The early bursts were short, low-luminosity events with recurrence times as short as 20 minutes and no evidence for cooling. Later bursts were longer and brighter, with cooling blackbody tails that clearly identify them as thermonuclear bursts. The general trend in persistent flux was downwards, but with fluctuations (Fig. 1, left). Panels show, from top to bottom: net 2.5-25.0 keV count rate (all active PCUs; see Table I), black-body temperature, black-body radius (at 7.8 kpc) and reduced \( \chi^2 \) (open circles mark spectra with less than 50 counts, not fitted).

3. DISCUSSION

We have reported the first X-ray bursts detected from Cir X-1 since 1985. A total of 15 bursts were recorded during May 15-30 2010, when source flux was in the range 0.3–0.01 Crab. The early bursts were short, low-luminosity events with recurrence times as short as 20 minutes and no evidence for cooling. Later bursts were longer and brighter, with cooling blackbody tails that clearly identify them as thermonuclear bursts. The general trend in persistent flux was downwards, but with fluctuations (Fig. 1, left). Panels show, from top to bottom: net 2.5-25.0 keV count rate (all active PCUs; see Table I), black-body temperature, black-body radius (at 7.8 kpc) and reduced \( \chi^2 \) (open circles mark spectra with less than 50 counts, not fitted).

There are strong similarities between the 2010 bursts and those seen in 1984-5. Tennant et al. (1986a), in December 1984, observed 8 low luminosity bursts with wait times in the range 27–47 minutes and marginal evidence for cooling in the burst tails. In August 1985, at a similar persistent flux, the same authors observed 3 bursts with typical type I burst properties (Tennant et al. 1986b). Peak fluxes and temperatures were similar to those we see in 2010. The fact that the earlier bursts are so similar to those seen in 2010 gives us confidence that the 1984-5 bursts genuinely originated from Cir X-1. Persistent flux when the 1984-5 bursts were observed was \( \sim 0.1 \) Crab (Parkinson et al. 2003).

Our results confirm that Cir X-1 is a neutron star rather than a black hole (the arcsec location of an X-ray burst from Cir X-1 is conclusive), but also pose two major questions. Firstly, why have no bursts been seen from this source in the intervening 25 years? And secondly, why are the burst properties so diverse? In the rest of this Section we will address these two issues.

From 1985 to 2003 the source was observed almost exclusively at persistent luminosities much higher than those measured during May 2010 (Parkinson et al. 2003; Figure 1, left in this paper). High accretion rates suppress thermonuclear instabilities (e.g. Cornélisse et al. 2003), which may explain the fact that no bursts were observed in this period despite extensive time on source. From April 2003 (MJD \( \sim 52750 \)), however, the average source flux decayed below \( \sim 0.3 \) Crab. Between April 2003 and April 2010, Cir X-1 was observed for more than 600 ks, but the RXTE-PCA in the 0.01–0.3 Crab flux range, the same flux measured during May 2010. No X-ray bursts were detected during this period, even though accretion rate was similar to that seen during the May 2010 brightening, judging from the X-ray flux. For recurrence times similar to those observed in May 2010, the chances of detecting bursts in 600 ks would be very high, if they were present. To illustrate this, one can compare the average burst rate during our May 2010 observations, \( 0.6 \) hr\(^{-1} \), to the 95% upper limit (Gehrels 1986) on the average burst rate between April 2003 and April 2010, \( < 0.018 \) hr\(^{-1} \) (given the non-detection in 600 ks). Such extreme difference in bursting rate at a similar flux level suggests that an additional parameter, other than instantaneous accretion rate, must be invoked to explain the “bursting” and “non-bursting” regimes (see below).

With regard to the variability in burst properties, we consider three possible scenarios. The first, which was also discussed by Tennant et al. (1986a), is that the early bursts are type II bursts, powered by accretion instabilities (see Lewin et al. 1994, and references therein). We consider this possibility unlikely, for the following reasons. (1) Rise times for the Cir X-1 early bursts are slower and (where they can be calculated) \( \alpha \) values much higher than those for typical type II bursts; (2) There is no evidence for low frequency QPOs, often observed with type II bursts. For the triple burst observation, on May 20, we estimate 3-\( \sigma \) upper limits on the fractional rms amplitude of a QPO between \( \sim 2 \) and \( \sim 8 \) Hz (1.8 Hz FWHM) of 3% (between bursts) and 7% (during bursts), lower than the typical fractional amplitudes reported by Lubin et al. (1992) and Dotani et al. (1994). (3) Accretion instabilities would be expected to recur at the same accretion rate. The fact that bursts were not observed from 2003-2010 even when the source was at a similar persistent flux would argue against this. And (4), the fact that the early bursts were observed only three days before the confirmed type I bursts, after 25 years with no bursts detected, suggests a common origin.

A second possibility is that we are observing the transition from stable thermonuclear burning of Helium at high accretion rates to unstable burning at lower rates (Bildsten 1998). This transition region permits some interesting behavior, as outlined by Heeger et al. (2007). As accretion rate falls, these authors showed that one should expect first marginally stable quasi-periodic burning (mHz QPOs), then low-luminosity short recurrence time bursts, before the eventual establishment of brighter
bursts with longer recurrence times. If the brightest fluxes observed from Cir X-1 correspond to Eddington rate accretion then this scenario is plausible, although there is no evidence for mHz QPOs in the 2010 data. This scenario might also explain the 1984-5 observations, where, interestingly, there is some evidence in the light curve for variability on ~1000 s timescales (see Figure 1 of Tennant et al. 1986a). If this is the case then Cir X-1 would be a valuable probe of this transition, since very short recurrence time bursts at high accretion rates are extremely rare (Keek et al. 2010).

The third possibility is that the accretion rate of Cir X-1 is lower, and that we are seeing short recurrence time thermonuclear bursts similar to those seen in other sources, interspersed with more regular bursts (Keek et al. 2010). In the general population of bursting sources, bursts with recurrence times of less than 40 minutes are found only at accretion rates less than 5% of the Eddington rate. If this is the case in Cir X-1 then the peak brightness observed in the RXTE era would be substantially less than Eddington. If Cir X-1 has never been accreting close to the Eddington limit, this would have implications for the determination of the distance, favouring a lower distance as proposed by Iaria et al. (2005). It would however be difficult to explain Z-source behavior from a source with such low accretion rate.

If the short bursts are thermonuclear in origin, then the question of why they were not seen by RXTE on earlier occasions (from 2003 onwards) remains. One very intriguing possibility, that would lend support to the high accretion rate scenario outlined above, is that the heating associated with a prolonged period of accretion has been acting to stabilize the burning process. Sustained accretion can heat the neutron star crust, which then cools over an extended period, maintaining a high temperature in the ocean even after accretion rate has fallen (Haensel & Zdunik 1990; Brown et al. 1998; Brown & Cumming 2009). Additional flux from below the burning layer stabilizes He burning (Bildsten 1993; Cumming & Macbeth 2004). The re-brightening of Cir X-1 in 2010 took place after a prolonged period (~2 years) of very low accretion rate, much longer than had been experienced earlier in RXTE's lifetime. This may be the first time that the crust and ocean have been able to cool sufficiently for burning to be unstable at the observed accretion rates. The accretion history in the few years prior to the 1984-5 bursting episode is unfortunately not available to cross-check this (Parkinson et al. 2003), but it is an interesting possibility.

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Fig. 4.— Swift-XRT location of Cir X-1 during its May 2010 bursting period. The grey filled circle and solid line show the Chandra position (Iaria et al. 2008, 0.6 arcsec error radius). The filled black square and circle show the Swift-XRT PC mode position and UVOT-enhanced position (Goad et al. 2007), and the dashed circles show their 3.5 and 1.9 arcsec radius respective error circles. We detect one X-ray burst during the PC mode observation (S3).