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 (Cir X-1) during its 2010 May X-ray re-brightening. These are the first X-ray bursts observed from the source after the initial discovery by Tennant and collaborators, 25 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.

Key words: accretion, accretion disks – binaries: close – stars: neutron – X-rays: binaries – X-rays: individual (Cir X-1)

1. INTRODUCTION

Discovered during the early years of X-ray astronomy (Margon et al. 1971) and frequently observed ever since, the peculiar X-ray binary Circinus X-1 (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 ~16.6 day period, discovered in the X-ray band by Kaluzienski et al. (1976) and observed at different epochs and wavelengths, is attributed to enhanced accretion near periastron passage in a highly eccentric orbit (Murdin et al. 1980; see also Jonker et al. 2007).

Thermonuclear explosions on the surface of accreting neutron stars (type I X-ray bursts; see, e.g., Strohmayer & Bildsten 2006, for a recent review) are one of the few signatures that allow us to unambiguously identify a compact object as a neutron star (NS). The defining observational property of type I X-ray bursts is a mainly thermal spectrum with blackbody temperature that declines along the burst tail (“cooling tail”; e.g., Lewin et al. 1993). In 1984–1985, 11 X-ray bursts were discovered in EXOSAT observations of Cir X-1 (Tennant et al. 1986a, 1986b). Three of these could be identified as type I X-ray bursts based on their cooling tails (Tennant et al. 1986b), while a type II identification (see, e.g., Lewin et al. 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 an NS (Tennant et al. 1986b). Since then many X-ray missions have observed Cir X-1 but no X-ray bursts were detected (see, e.g., Galloway et al. 2008, for a search of 2.7 Ms of Cir X-1 data from RXTE).

Despite the BHC similarities (Toor 1977; van der Klis 1994, which are not unique to this source), the fast X-ray variability of Cir X-1 has been described as similar to Z sources, the most luminous NS-low-mass X-ray binaries (LMXBs), and the less luminous NS-LMXBs (atoll sources) (see Oosterbroek et al. 1995; Shirey et al. 1998; Soleri et al. 2009, 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, has led to the speculation that the compact object in Cir X-1 may be a BH and that the X-ray bursts discovered by Tennant et al. (1986a, 1986b) came from a nearby system in the EXOSAT ∼0.75 field of view (FOV). The most recent indication that Cir X-1 is indeed an NS is the detection of twin kilohertz quasi-periodic oscillations (kHz QPOs; Boutloukos et al. 2006). Although this phenomenon can be considered a proof of the NS nature of the accretor (van der Klis 2006), 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 Linares et al. (2010b), these are the first X-ray bursts observed from Cir X-1 after the initial discovery, 25 years ago (Tennant et al. 1986a, 1986b). We identify nine of them as thermonuclear -type I- X-ray bursts and obtain an arcsecond location fully consistent with the position of Cir X-1, unambiguously identifying Cir X-1 as a low magnetic field accreting NS. We discuss the nature of the bursts and the burning regime, as 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 2010 May 7, MAXI-GSC observations detected an X-ray re-brightening of Cir X-1 after two years of very low flux (below ~70 mCrab and with an average flux of ~10 mCrab; Nakajima

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of all layers and available Proportional Counter Units (PCUs),
grouped the resulting spectra to have a minimum of 15 counts per
bin and added a 1% systematic error to all channels. For each 1 s
spectrum, we corrected for dead time following the PCA team
directions8 and created a response matrix using pearsrP (v. 11.7).
Following the standard approach in 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 blackbody model (wabs*bbodyrad, 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 Iaria et al.
(2001), 1.6 × 1022 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 blackbody 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 based on
the type I X-ray bursts from Tennant et al. 1986b).

In Table 1, we present the properties of all X-ray bursts
detected by RXTE. A detailed inspection of these properties reveals
two clearly distinct flavors: bursts R1–R5 (the “early bursts”) have
long rise times (7.3–10.2 s), moderate energy output (total
energy of (1.3–3.7) × 1058 erg), and show approximately sym-
metric profiles. On the other hand, bursts R6–R12 feature shorter
rise times (1.8–5.3 s), are more energetic ((5.3–11) × 1058 erg),
and present prototypical type I X-ray burst (fast rise exponential-
ential decay (FRED) like) light curves. In Figure 3, we show the
spectral evolution of bursts R2, R4, R10, and R12, two represen-
tative examples of each class. The peak luminosities of the early
bursts were systematically lower than those of bursts R6–R12,
and the persistent pre-burst luminosities were higher on average
in the early bursts than in bursts R6–R12, although with overlaps
(see Table 1). Besides the above-mentioned FRED-like profile,
bursts R6–R12 all show clear cooling trends along their decays
(see Figure 3), and we therefore classify them unequivocally as
type I (thermonuclear) X-ray bursts. The early bursts (R1–R5)
showed little or no signs of cooling along the tail, with blackbody
temperature approximately constant in the range 1.2–1.8 keV;
we discuss their possible origins in Section 3 and argue that they
are most likely also of thermonuclear nature.

Each burst was searched for burst oscillations in the range
10–2048 Hz. We searched for signals using the entire burst
and shorter (4 s) time windows. We found no events where the
significance exceeded 3σ after accounting for numbers of trials.

2.1. RXTE

We performed a search for X-ray bursts in all (26) RXTE
observations of Cir X-1 taken between 2010 May 11 and June
1 using 1 s time resolution Proportional Counter Array (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 the present work
as R1–R12 (the first nine were reported in Linares et al. 2010b;
say also Papitto et al. 2010a). Two pairs of consecutive X-ray
bursts were detected on May 15 and May 17, with wait times
of ~20 minutes. On May 20, RXTE observed three consecutive
type I X-ray bursts (as shown in Figure 2) with slightly longer
wait times (~28 and ~31 minutes).

In order to study their spectral evolution, we performed time-
resolved spectroscopy of all the X-ray bursts. We extracted PCA
spectra in 1 s steps using event mode data (E_125us_64M_0_1s)

We processed the XRT data using xrtpipeline with standard quality cuts. Exposure maps and ancillary response files were created using xrtexmap 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 40 \times 40 pixel box for the window timing (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 pileup of the XRT in PC mode at the collected count rates (more than \sim 15 counts s^{-1} 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 a type I X-ray burst). Due to the low count rates collected by

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{PCA 0.5 s time resolution light curve of the three consecutive bursts detected on 2010 May 20 (R6–R8). Insets show zoomed 150 s long light curves of each burst.}
\end{figure}

\begin{table}[h]
\centering
\caption{Properties of the 15 X-ray Bursts from Cir X-1 Analyzed in This Work}
\begin{tabular}{cccccccc}
\hline
ID & Obs.\textsuperscript{a} & Peak Time & Orbital Phase & Net Peak\textsuperscript{b} & Rise\textsuperscript{c} & L\textsubscript{peak}\textsuperscript{d} & Energy\textsuperscript{d} & L\textsubscript{pers}\textsuperscript{d} & Wait\textsuperscript{e} & \alpha\textsuperscript{f} \\
\hline
R1 & 02-03 & 55331.46840 & 0.570 & 153.1 [1] & 9.6 ± 0.5 & 1.3 ± 0.9 & 1.3 ± 0.6 & 4.6 ± 0.3 & ... & ... \\
R2 & 02-03 & 55331.48227 & 0.572 & 220.2 [1] & 7.3 ± 0.5 & 2.0 ± 0.8 & 3.5 ± 1.7 & 4.4 ± 0.2 & 20.0 & 129 \\
R3 & 02-02 & 55332.17123 & 0.61 & 153 [1] & 8.8 ± 0.5 & 1.3 ± 0.8 & 1.5 ± 0.7 & 5.6 ± 0.3 & ... & ... \\
R4 & 02-00 & 55333.55562 & 0.697 & 279.1 [1] & 7.5 ± 0.5 & 2.5 ± 0.8 & 3.7 ± 1.6 & 4.7 ± 0.3 & ... & ... \\
R5 & 02-00 & 55333.56971 & 0.698 & 241.7 [1] & 10.2 ± 0.5 & 2.2 ± 0.9 & 2.4 ± 1.1 & 5.3 ± 0.3 & 20.2 & 238 \\
R6 & 02-04 & 55336.09307 & 0.851 & 453.1 [1] & 2.0 ± 0.5 & 4.2 ± 0.8 & 5.8 ± 1.9 & 4.2 ± 0.2 & ... & ... \\
R7 & 02-04 & 55336.11231 & 0.852 & 393.9 [1] & 2.2 ± 0.5 & 3.6 ± 0.9 & 5.3 ± 1.8 & 4.0 ± 0.2 & 27.7 & 87 \\
R8 & 02-04 & 55336.13367 & 0.853 & 453.9 [1] & 5.3 ± 0.5 & 4.1 ± 0.9 & 5.5 ± 1.9 & 4.6 ± 0.2 & 30.8 & 152 \\
R9 & 03-02 & 55341.06464 & 1.15 & 724.5 [2] & 5.1 ± 0.5 & 3.5 ± 0.6 & 11 ± 3.8 & 4.8 ± 0.2 & ... & ... \\
R10 & 03-03 & 55343.35345 & 1.29 & 795.7 [2] & 2.5 ± 0.5 & 3.8 ± 0.5 & 7.6 ± 1.8 & 1.7 ± 0.1 & ... & ... \\
R11 & 03-04 & 55343.75671 & 1.31 & 937.4 [2] & 1.8 ± 0.5 & 4.4 ± 0.5 & 8.6 ± 2.0 & 1.6 ± 0.1 & ... & ... \\
R12 & 04-00 & 55344.20388 & 1.34 & 1057.7 [2] & 1.8 ± 0.5 & 4.5 ± 0.5 & 9.7 ± 2.5 & 1.5 ± 0.1 & ... & ... \\
\hline
S1 & 032(WT) & 55344.50460 & 1.36 & \sim 15 & \sim 1 & ... & ... & ... & ... & ... \\
S2 & 033(WT) & 55344.84431 & 1.38 & \sim 35 & \sim 1 & ... & ... & ... & ... & ... \\
S3 & 034(PC) & 55346.02417 & 1.45 & \gtrsim 15 & \lesssim 2.5 & ... & 7 & ... & ... & ... \\
\hline
\end{tabular}
\end{table}

\textbf{Notes.}
\begin{itemize}
\item \textsuperscript{a} Observation ID, preceded by 95422-01- and 00030268- in the RXTE and Swift observations, respectively. XRT observing mode between parentheses.
\item \textsuperscript{b} Persistent level subtracted; 2.5–25.0 keV and 0.5–10.0 keV energy range for R1–R12 and S1–S3, respectively. The number of active PCUs is indicated between brackets in the RXTE bursts.
\item \textsuperscript{c} Defined as time from 25% to 90% of peak flux (see, e.g., Galloway et al. 2008).
\item \textsuperscript{d} Bolometric burst peak luminosity and total energy, after subtracting persistent emission. Persistent luminosity in the 0.5–50 keV band. All use a distance of 7.8 kpc (Jonker & Nelemans 2004; Section 2.1).
\item \textsuperscript{e} Only quoted when two or more consecutive bursts are detected. Alpha parameter is defined as L\textsubscript{pers} times wait time divided by the total burst energy.
\end{itemize}
background; Section 2.1) we are able to constrain the blackbody temperature and we find evidence of cooling in both bursts. The light curves show typical FRED profiles, and the temperatures and blackbody radii that we find are fully consistent with those measured by RXTE. We therefore identify S1–S2 as type I (thermonuclear) X-ray bursts.

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 (bottom). No other sources were detected in the XRT FOV during the May 29 PC mode observation (Papitto et al. 2010b). We obtain, using xrtcentroid, the following position: R.A. = 15°20′40.73, decl. = −57°09′58.7′′ (J2000.0), with a 90% confidence error radius of 3.5 arcsec. We also obtain a UVOT-enhanced XRT position (Evans et al. 2009; Goad et al. 2007) of R.A. = 15°20′40.84, decl.=−57°10′00.9′′ (J2000.0; 1.9 arcsec 90% confidence error radius). As shown in Figure 4, both positions are consistent with the Chandra position given by Iaria et al. (2008). The ~345 photons collected during burst S3 cluster around Cir X-1, with 90% of the photons within 6 arcmin of the Chandra position. We therefore conclude that Cir X-1 is the origin of bursts S1–S3 and, in all likelihood, R1–R12.

### 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 2010 May 15–30, 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 downward, but with fluctuations (Figure 1 (top), Table 1).

There are strong similarities between the 2010 bursts and those seen in 1984–1985. Tennant et al. (1986a), in 1984 December, observed eight low-luminosity bursts with wait times in the range 27–47 minutes and marginal evidence for cooling in the burst tails. In 1985 August, at a similar persistent flux, the same authors observed three 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 1984–1985 bursts genuinely originated from Cir X-1. Persistent flux when the 1984–1985 bursts were observed was ~0.1 Crab (Parkinson et al. 2003).

Our results confirm that Cir X-1 is an NS rather than a BH (the arcsec location of an X-ray burst from Cir X-1 is conclusive), but also pose two major questions. First, why have no bursts been seen from this source in the intervening 25 years? And second, 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 2010 May (Parkinson et al. 2003; Figure 1 (top) in this Letter). High accretion rates suppress thermonuclear instabilities (e.g., Cornelisse et al. 2003), which may explain the fact that no bursts were observed in this period despite extensive time on source. From 2003 April (MJD ∼ 52750), however, the average source flux decayed below ∼0.3 Crab. Between 2003 April and 2010 April, Cir X-1 was observed for more than 600 ks by the RXTE-PCA in the 0.01–0.3 Crab flux range, the same flux measured during 2010 May. No X-ray bursts were detected during this period, even though the accretion rate was similar to that seen during the 2010 May re-brightening, judging from the X-ray flux. For recurrence times similar to those observed in 2010 May, 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 2010 May observations, 0.6 hr$^{-1}$, to the 95% upper limit (Gehrels 1986) on the average burst rate between 2003 April and 2010 April, <0.018 hr$^{-1}$ (given the non-detection in 600 ks). Such an extreme difference in the bursting rate at a similar flux level suggests that an additional parameter, other than the 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. 1996, 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) or values are 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 3σ upper limits on the fractional rms amplitude of a QPO between ∼2 and ∼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. (1990). (3) Accretion instabilities would be expected to recur at the same accretion rate. The fact that bursts were not observed from 2003 to 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 Heger et al. (2007). As the accretion rate falls, these authors showed that one should first expect 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 the 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 1984–1985 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, favoring 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 a low accretion rate.

If the short bursts are thermonuclear in origin, then the question why they were not seen by RXTE on earlier occasions (from 2003 onward) 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 NS crust, which then cools over an extended period, maintaining a high temperature in the ocean even after the 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 1995, 1998; 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 1984–1985 bursting episode is unfortunately not available to cross-check this (Parkinson et al. 2003), but it is an interesting possibility.

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