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ON THE COOLING TAILS OF THERMONUCLEAR X-RAY BURSTS: THE IGR J17480—2446 LINK

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ABSTRACT

The neutron star transient and 11 Hz X-ray pulsar IGR J17480—2446, recently discovered in the globular cluster Terzan 5, showed unprecedented bursting activity during its 2010 October–November outburst. We analyzed all X-ray bursts detected with the Rossi X-ray Timing Explorer and find strong evidence that they all have a thermonuclear origin, despite the fact that many do not show the canonical spectral softening along the decay imprinted on type I X-ray bursts by the cooling of the neutron star photosphere. We show that the persistent-to-burst power ratio is fully consistent with the accretion-to-thermonuclear efficiency ratio along the whole outburst, as is typical for type I X-ray bursts. The burst energy, peak luminosity, and daily-averaged spectral profiles all evolve smoothly throughout the outburst, in parallel with the persistent (non-burst) luminosity. We also find that the peak-burst to persistent luminosity ratio determines whether or not cooling is present in the bursts from IGR J17480—2446, and argue that the apparent lack of cooling is due to the “non-cooling” bursts having both a lower peak temperature and a higher non-burst (persistent) emission. We conclude that the detection of cooling along the decay is a sufficient, but not a necessary condition to identify an X-ray burst as thermonuclear. Finally, we compare these findings with X-ray bursts from other rapidly accreting neutron stars.

Key words: accretion, accretion disks – binaries: close – globular clusters: individual (Terzan 5) – stars: neutron – X-rays: binaries – X-rays: individual (IGR J17480—2446)

Online-only material: color figure

1. INTRODUCTION

Since soon after their discovery (Grindlay et al. 1976), the distinctive property of thermonuclear bursts from accreting neutron stars (NSs) has been the presence of a thermal spectrum with temperature decreasing along the burst decay (Swank et al. 1977; Hoffman et al. 1977, 1978). Such “cooling tails” are attributed to the NS photosphere cooling down after the fast injection of heat from nuclear reactions, deeper in the ocean. An X-ray burst showing a cooling tail is classified as a type I X-ray burst and identified as thermonuclear. On the other hand, a different kind of X-ray bursts, with integrated energies similar to or greater than the accretion energy radiated between bursts, was classified as type II and identified with spasmodic accretion events onto an NS (Lewin et al. 1993, and references therein). Thousands of type I X-ray bursts have been observed from more than 90 NS low-mass X-ray binaries (NS-LMXBs) to date (e.g., Cornelisse et al. 2003; Galloway et al. 2008). Their thermonuclear nature bears little or no doubt and models have met with considerable success in reproducing many of their properties (e.g., Strohmayer & Bildsten 2006, and references therein). Type II bursts have only been detected with confidence from two sources (the “rapid burst” MXB 1730—335 and the “bursting pulsar” GRO J1744—28; Lewin et al. 1993; Kouveliotou et al. 1996, respectively). This, and the fact that bursts from these two sources showed different spectral properties, has led to a somewhat ambiguous definition of type II bursts. In some cases type II bursts have been implicitly defined as X-ray bursts lacking cooling tails (e.g., Kuulkers et al. 2002; Galloway et al. 2008), while in other cases they are simply described as “spasmodic accretion events,” a definition that lacks a strict observational criterion. An X-ray transient in the direction of the globular cluster Terzan 5 was detected with INTEGRAL on 2010 October 10 (Bordas et al. 2010) and showed a type I X-ray burst one day later (Chenevez et al. 2010). Pulsations and burst oscillations at ~11 Hz were discovered with Rossi X-ray Timing Explorer (RXTE) on 2010 October 13 (Strohmayer & Markwardt 2010; Altamirano et al. 2010, respectively). This, together with the Chandra localization (Pooley et al. 2010), showed that the source was a new transient NS-LMXB, which was named IGR J17480—2446 (previously identified as a quiescent LMXB candidate by Heinke et al. 2006, labeled CX25 or CXOGLb J174804.8—244648). We refer to it hereafter as T5X2, as this is the second bright X-ray source discovered in Terzan 5. T5X2 is in a 21 hr orbit (Papitto et al. 2011) and contains the slowest rotating NS among the type I X-ray burst sources with known spin. Linares et al. (2010a) discovered millihertz quasi-periodic oscillations during the peak of the outburst (see also M. Linares et al. 2011, in preparation).

It was suggested that some of the bursts from T5X2 were type II, based on the non-detection of cooling tails (Galloway & in’t Zand 2010). Chakraborthy & Bhattacharyya (2011) have suggested a thermonuclear origin of the bursts from T5X2, as initially argued by Linares et al. (2010a), although they do not present a detailed burst spectral analysis nor do they discuss in detail the causes and implications of non-cooling thermonuclear bursts (we refer to the bursts where cooling is not detectable as “non-cooling” bursts; see Sections 3 and 4 for details). We present in this Letter strong evidence that all the bursts observed from T5X2 in 2010 were thermonuclear, even those that did not show a cooling tail and therefore cannot be classified as type I X-ray bursts. We show that the burst thermal profile evolves gradually as the persistent luminosity changes along the outburst, and as a consequence...
bursts change from type I to non-cooling and back to type I. Furthermore, we show that the presence/absence of cooling along the tail is determined by the ratio between peak-burst and persistent luminosity. We put forward an explanation for the lack of cooling, discuss the implications of these results for the identification of thermonuclear bursts, and compare them with other NS-LMXBs that show X-ray bursts at high persistent luminosities ($L_{\text{pers}}$) and inferred mass accretion rates ($\dot{M}$).

2. DATA ANALYSIS

We analyzed all 46 RXTE observations of T5X2 taken between 2010 October 13 and 2010 November 19 (MJDs 55482–55519; proposal-target number 95437-01), using data from all available proportional counter units (PCUs). After that date the source was not observable with RXTE due to solar constraints.\(^4\) We visually inspected 2 s time resolution 2–30 keV light curves throughout the outburst to search for X-ray bursts. We used Event data (or Good-Xenon when available) to perform time-resolved spectroscopy of all bursts, extracting dead-time-corrected spectra in 2 s time bins and using a $\sim$100 s long pre- or post-burst interval to extract the non-burst (persistent emission plus background) spectrum. We fitted the resulting spectra within Xspec (v 12.6.0g) using a simple blackbody model and fixing the absorbing column density to $1.2 \times 10^{22}$ cm$^{-2}$ (Heinke et al. 2006), after adding a 1\% systematic error to all channels and grouping them to a minimum of 15 counts per channel.

We use throughout this work a distance of 6.3 kpc to Terzan 5, the highest value reported by Ortolani et al. (2007) from Hubble Space Telescope photometry, which is consistent with the independent measurement of Galloway et al. (2008) based on photospheric radius expansion bursts from a burster in the same globular cluster. We note that recent measurements of the distance to Terzan 5 span the range 4.6–8.7 kpc (Cohn et al. 2011) and therefore the luminosities and energies presented herein have a systematic uncertainty of a factor $\sim$2 (factor $\sim \sqrt{2}$ for blackbody radii). We stress, however, that the distance uncertainty does not affect our conclusions as the two main parameters we use ($\alpha$ and $\beta$, as defined below) do not depend on the distance to Terzan 5.

We integrated the bolometric luminosity along each burst to find the total energy radiated, $E_b$, and defined the ratio of accretion to nuclear energy as $\alpha \equiv L_{\text{pers}} \times t_{\text{wait}}/E_b$, where $L_{\text{pers}}$ is the persistent (accretion) luminosity (see below) and $t_{\text{wait}}$ is the time since the previous burst or wait time, available when no data gaps are present before a given burst. The brighter the persistent (accretion) flux is, the fainter bursts become: between MJD 55482 and 55488 (2010 October 13 and 2010 October 19) the net peak-burst flux decreases from $\sim$75\% to $\sim$10\% of the total flux, while the non-burst count rate increases from $\sim$250 counts s$^{-1}$ PCU$^{-1}$ to $\sim$1600 counts s$^{-1}$ PCU$^{-1}$. Consequently, spectroscopy of individual bursts becomes limited by the low signal-to-noise ratio ($S/N$).

In order to study the burst spectral properties along the outburst, we divided each burst in six intervals, with the following time ranges in seconds relative to the peak-burst time: $-6 \pm 4$, $0 \pm 2$, $6 \pm 4$, $15 \pm 5$, $25 \pm 5$, and $35 \pm 5$. After rejecting individual 2 s time bins with ill-constrained spectral parameters (error larger than value), we find the daily-averaged spectral parameters (blackbody radius, temperature, and luminosity) in each of these six time intervals. Furthermore, in order to quantify the amount of cooling we define the temperature drop $\Delta T \equiv T_{\text{peak}} - T_{15}$, where $T_{\text{peak}}$ and $T_{15}$ are the daily-averaged temperatures in the time intervals 0 \pm 2 and 15 \pm 5 s, respectively. To study the persistent emission we extracted one dead-time-corrected spectrum per observation from Standard 2 data, excluding all bursts and subtracting the background spectrum given by the bright source background model. We fitted the resulting spectra with a model sum of disk blackbody, power law, and Gaussian line with energy fixed at 6.5 keV, correcting for absorption as above. We obtain the 2–50 keV persistent luminosity ($L_{\text{pers}}$) from the best-fit model. We do not apply bolometric correction when calculating $L_{\text{pers}}$, which would increase its value (and $\alpha$) by a factor of two (see, e.g., in’t Zand et al. 2007).

3. RESULTS

We find a total of 373 X-ray bursts between 2010 October 13 and 2010 November 19 (MJDs 55482–55519). Figure 1 summarizes the joint evolution of burst energetics and persistent luminosity: while $L_{\text{pers}}$ increases bursts become fainter and less energetic, whereas burst energy and luminosity increase along the outburst decay, when $L_{\text{pers}}$ drops (see also Figure 2). The first burst detected by RXTE (on 2010 October 13; MJD 55482) and all (20) bursts detected after 2010 November 11 (MJD 55511) show clear cooling tails and can be unequivocally classified as type I X-ray bursts (see also Galloway & in’t Zand 2010).

By averaging burst profiles during each day (see Figure 3; Section 2), we also find evidence of cooling until 2010 October 15 (MJD 55484) and after 2010 October 25 (MJD 55494). Between these dates (i.e., between MJDs 55485 and 55494) we do not detect cooling along the burst tail, in neither individual bursts nor daily-averaged spectral profiles. This can be seen quantitatively in the temperature drop, $\Delta T$, which is consistent with zero between MJDs 55485 and 55494 (Figure 4, top).

Both burst peak luminosity ($L_{\text{peak}}$) and burst energy ($E_b$) are anticorrelated with $L_{\text{pers}}$ and follow a smooth evolution, even when cooling becomes first undetectable and then detectable again. The presence of canonical type I X-ray bursts when $L_{\text{pers}}$ is relatively low, together with their smooth evolution into faint “non-cooling” bursts, gives strong evidence that all X-ray bursts from T5X2 are thermonuclear. The $\alpha$ values span an approximately constant range along the whole outburst, between $\sim$20 and $\sim$200, fully consistent with a thermonuclear origin of the bursts (e.g., Lewin et al. 1993). The gradual evolution of the burst rate (Linares et al. 2010a) and the presence of burst oscillations in both cooling and non-cooling bursts (Cavecchi et al. 2011) also suggest a common origin for all bursts.

Furthermore, the daily-averaged spectral profiles (Figure 3) evolve smoothly along the outburst: the peak blackbody temperature decreases from $\sim$2.3 keV to $\sim$1.7 keV between the first observation (2010 October 13; MJD 55482) and the outburst maximum (2010 October 18; MJD 55487), and later increases up to $\sim$2.2 keV on 2010 November 19 (MJD 55519; see also Figure 4, top panel). Such smooth spectral evolution further strengthens the thermonuclear identification of all bursts from T5X2. The apparent emitting area we find is remarkably low, with peak daily-averaged blackbody radii between 2 and 4 km throughout the whole outburst (Figure 3; see also discussion in Cavecchi et al. 2011).

We find that the ratio of peak-burst to persistent luminosity, $\beta \equiv L_{\text{peak}}/L_{\text{pers}}$, determines whether or not cooling is manifest in the T5X2 bursts (see Figure 4, bottom panel). For $\beta \gtrsim 0.7$, individual bursts show cooling along the tail. In the range

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\(^{4}\) RXTE and MAXI observations did not detect T5X2 after the Sun-constrained period ended on 2011 January 17 and 2010 December 27, respectively.
0.7 \gtrsim \beta \gtrsim 0.2$, we do not measure cooling in individual bursts, but we do find significant cooling in the daily-averaged temperature profiles. For $\beta \lesssim 0.2$, the imprints of cooling vanish also in the daily averages. These $\beta = [0.7, 0.2]$ critical values translate into the time ranges shown in the top panel of Figure 1 and correspond to $L_{\text{pers}} \simeq [4.7, 6.5] \times 10^{37}$ erg s$^{-1}$ and $L_{\text{peak}} \simeq [3.3, 1.3] \times 10^{37}$ erg s$^{-1}$. Comparison with sources with higher $L_{\text{pers}}$ that show both cooling and non-cooling bursts indicates that the presence or absence of measurable cooling along the burst decay does not depend solely on $L_{\text{peak}}$ or $L_{\text{pers}}$ but on their ratio $\beta$, as we discuss in detail in the following section.

4. DISCUSSION

Our work shows that the absence of measurable cooling along the tail does not rule out the thermonuclear origin of an X-ray burst and that the type II burst classification cannot merely rely on the lack of spectral cooling. This implies that the detection of cooling along the decay is a sufficient, but not a necessary condition to identify an X-ray burst as thermonuclear. We have characterized the burst spectral properties along the whole outburst and shown that the $\beta \equiv L_{\text{peak}}/L_{\text{pers}}$ ratio determines whether or not cooling is measurable in the bursts from T5X2 (Figure 4; Section 3). Individual bursts from T5X2 with $\beta \lesssim 0.7$ do not show significant cooling along the decay. The main reason why non-cooling bursts had not been firmly identified as thermonuclear until now is that the vast majority of thermonuclear bursts have $\beta > 0.7$ (Figure 5; Galloway et al. 2008) and therefore show clear cooling tails, while only a handful of bursts with $\beta < 0.7$ had been observed to date. We stress that any X-ray burst detected with $\beta > 0.7$ should still show cooling along the tail in order for it to be identified as thermonuclear.

The gradual disappearance of spectral cooling can be attributed to a combination of two factors. First, the sensitivity to spectral cooling decreases as persistent emission rises. Our spectral fits show that blackbody area and temperature are increasingly correlated when the S/N decreases. Using a single-parameter model (keeping the blackbody temperature or emitting area fixed throughout the burst) gives statistically acceptable fits to the faint bursts, indicating that the temperature and emitting area cannot be simultaneously determined by performing standard time-resolved spectroscopy of individual faint bursts. By assuming a constant emitting area and fixing it to the average value found for the first and brightest burst, we can recover a temperature decay along the tail of the faintest bursts. Alternatively, the temperature could remain approximately constant throughout the bursts if the burning area changes size. Such “single-parameter approach,” however, has obviously severe limitations as it relies on an arbitrary choice of constant emitting area or temperature.

On the other hand, we find that as $L_{\text{pers}}$ (and hence the inferred mass accretion rate, $\dot{M}$) increases bursts become colder and less energetic, probably due to a lower ignition column depth resulting in less mass being burned. Less energetic bursts result into lower peak temperatures and a less pronounced temperature decay. Moreover, the higher $\dot{M}$ could also lead to a hotter NS photosphere between bursts as more accretion energy is being released on the NS surface, which would rise the “baseline temperature,” again smearing out the burst cooling tail (see in’t...
Zand et al. (2009, for further discussion). We thus conclude that the lack of measurable cooling is due to (1) a loss of sensitivity when persistent emission increases and (2) a decrease in burst temperature (and luminosity) when \( \dot{M} \) increases. It is likely that the NS photosphere cools down during the tails of the "non-cooling" bursts, but by an amount below our detection limit. Van Paradijs & Lewin (1986) pointed out that if a significant fraction of the persistent flux is thermally emitted from the NS surface, the "standard" burst spectral analysis (which subtracts pre-burst emission) can underestimate the blackbody radius and overestimate its temperature, in particular when the burst flux is low. The reason is that the difference between two blackbody spectra (one powered by accretion and nuclear energy minus one only powered by accretion) does not have a Planckian distribution (van Paradijs & Lewin 1986). If such systematic effect is present in the faint, high-\( \dot{M} \) bursts and increases the apparent temperature with decreasing burst flux that could also reduce the amount of cooling observed. Hence, the apparent gradual decrease in the amount of cooling (\( \Delta T \)) observed when \( \beta \) decreases (Figure 4) could be partially caused by the standard burst analysis overestimating the blackbody temperature in a gradually increasing fraction of the burst. We note, however, that the evolution of \( kT_{\text{peak}} \) is robust, i.e., bursts become intrinsically colder and less luminous when \( L_{\text{pers}} \) increases.

**Figure 2.** Burst light curves for nine selected dates. Shown are count rate light curve of one representative burst (gray circles; PCU2; \( \sim 2-60 \text{ keV} \); not background subtracted) and daily-averaged bolometric burst luminosity (filled black circles; dotted lines show persistent luminosity, \( L_{\text{pers}} \)).

**Figure 3.** Burst spectral properties in six time bins for nine selected dates. Shown are daily-averaged blackbody temperature (filled black circles) and blackbody radius (gray circles; for a distance of 6.3 kpc, see Section 2).

**Figure 4.** Top: evolution along the T5X2 outburst of the daily-averaged peak blackbody temperature (\( T_{\text{peak}} \)) and temperature drop (\( \Delta T \); Section 2). Bottom: evolution of the ratio \( \beta \) between peak-burst and persistent luminosities. Bursts are canonical type I X-ray bursts when \( \beta \gtrsim 0.7 \). Bursts with \( \beta \lesssim 0.2 \) do not show any spectral cooling. In the range \( 0.7 \lesssim \beta \lesssim 0.2 \) individual bursts show no cooling tails, but we are able to measure significant cooling in the daily-averaged spectral profiles.
It is interesting to note that non-cooling bursts similar to the T5X2 ones presented herein were detected from Circinus X-1 (Cir X-1) in 2010 May and tentatively identified as thermonuclear bursts (Linares et al. 2010b). The “early bursts” reported by Linares et al. (2010b) did not show cooling tails, whereas later bursts became canonical type I X-ray bursts, a behavior reminiscent of T5X2 (see also Tennant et al. 1986).

We have calculated $\beta$ for all the 2010 bursts from Cir X-1 (see Figure 5). The same critical value of $\beta$ that we find for T5X2, blindly applied to Cir X-1, clearly differentiates between the cooling ($\beta > 0.7$) and non-cooling ($\beta < 0.7$) bursts. We show in Figure 5 (left) the values plotted versus $L_{\text{pers}}$ for all bursts reported by Galloway et al. (2008), together with Cir X-1 and T5X2. Furthermore, defining the signal-to-noise ratio as $S/N \equiv F_{\text{peak}}/(\sqrt{F_{\text{pers}} + F_{\text{peak}}}$ (where $F_{\text{peak}}$ and $F_{\text{pers}}$ are the peak-burst and persistent fluxes, respectively), we explore whether or not $S/N$ determines the presence of measurable cooling tails. Figure 5 (right) shows that a simple $S/N$ criterion fails to distinguish the type I and non-cooling bursts from both T5X2 and Cir X-1, indicating that the lack of measurable cooling is not merely due to low statistics and that $\beta$ provides a better criterion to identify non-cooling bursts.

To our knowledge two other NS-LMXBs, GX 17+2 and Cyg X-2, have shown non-cooling X-ray bursts that have not been conclusively identified (although a thermonuclear origin has been suggested; Kahn & Grindlay 1984; Sztajno et al. 1986; Kuulkers et al. 1995, 2002; Galloway et al. 2008). Given that they also cross the $\beta = 0.7$ boundary (Figure 5), it is not surprising that these two sources show both cooling and non-cooling bursts. The cooling bursts from GX 17+2 and Cyg X-2 occurred when $L_{\text{pers}}$ and $L_{\text{peak}}$ were considerably (~5 times when $\beta \approx 0.7$) higher than the T5X2 case presented here (Figure 5), which strongly suggests that it is $\beta$ and not simply $L_{\text{pers}}$ or $L_{\text{peak}}$ that determines whether or not cooling tails are observed. Figure 5 (right) displays a large number of cooling, canonical type I X-ray bursts with the same peak fluxes as the non-cooling bursts presented here, showing that a non-cooling burst cannot be predicted from its net peak flux alone. In all four sources discussed above the accretion luminosity at the time of the bursts was relatively high ($L_{\text{pers}} \gtrsim 5 \times 10^{37}$ erg s$^{-1}$) compared with that of most bursters, and all four sources have shown Z source behavior. This suggests that non-cooling thermonuclear bursts are an exclusive feature of high-$M$ states of NS-LMXBs. The case of T5X2 presented herein, however, remains exceptional for its extremely high burst rate (M. Linares et al. 2011, in preparation) and for the unprecedented smooth evolution between canonical type I X-ray bursts and non-cooling high-$M$ bursts. It also opens the prospect of a “hidden”, previously unrecognized, population of non-cooling bursts from rapidly accreting NSs.

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