Swift detection of an intermediately long X-ray burst from the very faint X-ray binary XMMU J174716.1–281048

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ABSTRACT
We report on the Swift detection of a thermonuclear X-ray burst from the very-faint quasi-persistent neutron star X-ray binary XMMU J174716.1–281048, which triggered the satellite’s Burst Alert Telescope (BAT) on 2010 August 13. Analysis of the BAT spectrum yields an observed bolometric peak flux of $\approx 4.5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, from which we infer a source distance of $\lesssim 8.4$ kpc. Follow-up observations with Swift’s X-ray Telescope (XRT) suggest that the event had a duration of $\approx 3$ h and a total radiated energy of $\approx 9 \times 10^{40}$ erg, which classify it as an intermediately long X-ray burst. This is only the second X-ray burst ever reported from this source. Inspection of Swift/XRT observations performed between 2007–2010 suggests that the 2–10 keV accretion luminosity of the system is $\approx 5 \times 10^{34}$ erg s$^{-1}$ for an assumed distance of 8.4 kpc. Despite being transient, XMMU J174716.1–281048 appears to have been continuously active since its discovery in 2003.

Key words: accretion, accretion discs – stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual (XMMU J174716.1–281048, IGR J17464–2811)

1 INTRODUCTION
In neutron star low-mass X-ray binaries (LMXBs), a star of (sub-) solar mass is feeding matter to the compact primary via an accretion disk. This typically gives rise to a 2–10 keV accretion luminosity of $L_{\text{X}} \approx 10^{36–38}$ erg s$^{-1}$. However, a small group of LMXBs, the very-faint systems, display sub-luminous accretion intensities of $L_{\text{X}} \approx 10^{34–36}$ erg s$^{-1}$ (Wijnands et al. 2006). Many LMXBs are transient and alternate accretion outbursts with episodes of quiescence, during which the X-ray luminosity is orders of magnitude lower.

Unstable thermonuclear burning of helium (He) and/or hydrogen (H) accreted onto the surface of a neutron star, results in a type-I X-ray burst (shortly ‘X-ray burst’ hereafter). These can temporarily outshine the accretion luminosity and are characterized by blackbody emission with a peak temperature of $kT_{\text{bb}} \approx 2–3$ keV. Typically, a fast rise is followed by a slower decay, during which the blackbody temperature decreases. Some X-ray bursts show photospheric radius expansion (PRE), as evidenced by a local peak in emitting radius associated with a drop in blackbody temperature. These are thought to reach the Eddington limit, allowing for a distance determination (Knuijkers et al. 2003).

The properties (e.g., duration, radiated energy and recurrence time) of X-ray bursts depend on the conditions of the ignition layer, such as the temperature, thickness and H abundance. These are sensitive to the mass-accretion rate onto the neutron star, and consequently the characteristics of X-ray bursts depend on the accretion regime (e.g., Fujimoto et al. 1981). Most observed X-ray bursts last for $\approx 10–100$ s, release a total energy of $E_{\text{burst}} \approx 10^{50–51}$ erg, and recur every few hours to days (e.g., Galloway et al. 2008).

Much more rare are the intermediately long X-ray bursts, which can last for tens of minutes, have a total radiated energy of $E_{\text{burst}} \approx 10^{55–56}$ erg, and are thought to recur only after many days. These are likely caused by the ignition of a thick layer of He, and are detected from neutron stars that are thought to have a relatively cold envelope, either because they accrete matter only slowly ($\lesssim 1\%$ of the Eddington rate; Cooper & Narayan 2005), or due to the fact that the accreted material is H-poor and hence heating from H-burning is absent (Cumming et al. 2006). Roughly 10% of all bursting neutron star LMXBs exhibit intermediately long X-ray bursts (e.g., Falanga et al. 2001).

1.1 XMMU J174716.1–281048
The X-ray source XMMU J174716.1–281048 (XMMU J1747 hereafter) was serendipitously discovered during XMM-Newton observations of the supernova remnant G0.9+0.1, performed on 2003 March 12 (Sidoli & Mereghetti 2003). The source displayed a 2–10 keV luminosity of $L_{\text{X}} \approx$
5 \times 10^{34} \text{ erg s}^{-1} \) (assuming a distance \( D = 8.4 \) kpc; see Sec. 2.1), but was not detected during previous XMM-Newton observations of the field obtained on 2000 September 23 (Sidoli & Mereghetti 2003). This implied that the source flux was variable by at least a factor of \( \sim 23 \) (Sidoli & Mereghetti 2003). This implied that the source was likely continuously active between 2003 and 2005, and was thus undergoing a very long accretion outburst. This idea was strengthened by the fact that XMMU J1747 was detected in outburst every time that XMM-Newton, Chandra or Swift covered the source field since \( D = 2.45 \pm 0.40 \) keV and an emitting radius of \( R_{\text{bb}} = 6.3^{+3.0}_{-1.0} \text{ km} \) (for \( D = 8.4 \) kpc; see below), yielding \( \chi^2 = 1.08 \) for 10 dof. This suggests that the BAT triggered on an X-ray burst.

On 2005 March 22, INTEGRAL detected an X-ray burst from a source designated IGR J17464–2811 (Brandt et al. 2006). As argued by Wijnands (2006), the bursting source was likely associated with XMMU J1747, establishing its nature as a neutron star LMXB. Based on the properties of the X-ray burst, Del Santo et al. (2007b) argued that the source was likely continuously active between 2003 and 2005, and was thus undergoing a very long accretion outburst. This idea was strengthened by the fact that XMMU J1747 was detected in outburst every time that XMM-Newton, Chandra or Swift covered the source field since 2003 (Campandi et al. 2009; Degenaar & Wijnands 2007; Degenaar et al. 2007; Del Santo et al. 2007b, 2009, 2010; Sidoli et al. 2002). Systems that undergo such unusually long outburst episodes are denoted as quasi Persistent X-ray transients.

On 2010 August 13 at 21:03 UT, Swift’s Burst Alert Telescope (BAT) triggered on a source located near the Galactic centre, consistent with the position of XMMU J1747 (trigger 431582; Gelbord 2010). In this Letter, we analyze the BAT data of this event, as well as the XRT follow-up observation, demonstrating that this trigger was caused by a long X-ray burst from XMMU J1747. We use archival Swift/XRT data, obtained between 2007 and 2010, to characterize the persistent emission of the source.

2 OBSERVATIONS, ANALYSIS AND RESULTS

2.1 Swift/BAT

We generated standard BAT data products using the BATGRPBAND tool. The 15–35 keV BAT lightcurve, shown in Fig. 1, is consistent with a single peak centred at \( t \approx 750 \) s and emerging from the background for \( \sim 150 \) s, with a very slow rise time of \( \sim 100 \) s. The spacecraft started slewing \( \approx 200 \) s after the burst trigger, by which time the BAT count rate had returned to the background level (see Fig. 1). Limited by a low number of photons, we extracted a single spectrum of 150 s around the burst peak, using the tool BATPHASE. We applied the necessary geometrical corrections with BATUPDATING, administered the BAT-recommended systematical error using BATPHAVERS, and generated a single response matrix by running the task BATDRMGEN.

The BAT spectrum is relatively soft, with no photons detected above \( \sim 35 \) keV (see Fig. 2). Fitting the data between 15–35 keV with XSPEC (v. 12.6) to a simple power-law continuum yields a photon index of \( \Gamma = 5.8 \pm 0.8 \) for a reduced chi-squared value of \( \chi^2 = 0.95 \) and 10 degrees of freedom (dof). Such a high spectral index is suggestive of a thermal shape. A blackbody (BBODYRAD) model fit, shown in Figure 2, results in a temperature of \( kT_{\text{bb}} = 2.45 \pm 0.40 \) keV and an emitting radius of \( R_{\text{bb}} = 6.3^{+3.0}_{-1.0} \text{ km} \). The average BAT count rate during this interval is \( 1.20 \pm 0.02 \) counts s\(^{-1}\), whereas the observed peak count rate is \( 2.34 \pm 0.02 \) counts s\(^{-1}\). We thus expect that the peak flux of the X-ray burst lies a factor of 1.95 higher, at \( F_{\text{peak}} \approx 4.5 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}\). This is similar to the peak flux measured for the X-ray burst detected from XMMU J1747 with INTEGRAL on 2005 March 22 (Del Santo et al. 2007a).

Due to the low number of counts and the large gap with the XRT follow-up observation (see Sec. 2.2), we cannot investigate whether this X-ray burst exhibited a PRE phase. However, by equating the BAT peak intensity to the luminosity typically observed from PRE X-ray bursts \( L_{\text{old}} = 3.8 \times 10^{38} \text{ erg s}^{-1}\), we can constrain the source distance to be \( D \lesssim 8.4 \) kpc. This is consistent with the value inferred from the X-ray burst of XMMU J1747 detected by INTEGRAL (Del Santo et al. 2007a). For a photosphere of solar composition rather than pure He, the Eddington luminosity is \( L_{\text{edd}} \approx 1.5 \times 10^{38} \text{ erg s}^{-1}\), which would lower the distance estimate to \( D \lesssim 5.3 \) kpc. Throughout this Letter, we have adopted a source distance of \( D = 8.4 \) kpc.

2.2 Swift/XRT

To obtain cleaned data products, we processed raw XRT data with the task XRTPipeline, using standard quality cuts and selecting event grades 0–12. Source lightcurves and spectra were extracted with XSELECT (v. 2.4). We collected source photons from a circular region with a 15-pixel radius centred around XMMU J1747. The background emission
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2.2.1 Persistent emission
We used all publicly available Swift/XRT observations of XMMU J1747 to characterize its persistent emission. This concerns a total of 10 individual exposures, varying between 1 and 4 ks in length, and spanning the time between 2007 May 13 and 2010 November 2. The total exposure time is \( \sim 20.5 \text{ ks} \). XMMU J1747 is detected at an average count rate of \( 2.53 \times 10^{-2} \text{ counts s}^{-1} \), varying by a factor \( \sim 2 \). Most pointings did not collect sufficient photons to fit each spectrum individually, so we summed all observations.

The composite X-ray spectrum, displayed in Figure 2, can be described by an absorbed powerlaw model with the photon counting (pc) mode. In the 0.3–10 keV XRT image, shown in Figure 3, XMMU J1747 is the only X-ray point source located within the \( \sim 2.4' \) BAT position uncertainty. A second X-ray point source is visible, which lies \( \sim 3.4' \) from the BAT coordinates at a position that is consistent with \( V^4 \) BN Sgr, an eclipsing binary of Algol type. However, we show below that it was likely XMMU J1747 that caused the BAT trigger, as was also suggested by Gelbord (2010).

The spectrum of XMMU J1747 obtained during this observation, displayed in Figure 2, can be fit with an absorbed powerlaw model with a spectral index \( \Gamma = 3.2 \pm 0.5 \), yielding \( \chi^2 = 0.92 \) (8 dof), for a fixed hydrogen column density of \( N_H = 8.6 \times 10^{22} \text{ cm}^{-2} \) (see Sec. 2.2.1). The photon index is softer than obtained for other XRT observations of XMMU J1747 (\( \Gamma = 2.2 \pm 0.5 \); see Sec. 2.2.1), and suggests that the spectrum rather has a thermal shape. For an absorbed blackbody model, we obtain \( kT_{\text{bb}} = 0.78 \pm 0.09 \text{ keV} \) and \( R_{\text{bb}} = 3.9^{+1.3}_{-0.8} \text{ km} \) (\( \chi^2 = 0.6 \) for 8 dof). The inferred blackbody temperature is consistent with the tail of an X-ray burst (e.g., Linares et al. 2009; Degenaar et al. 2010).

To extrapolate the fit to the 0.01–100 keV energy range, we can estimate an absorbed bolometric flux of \( F_{\text{bol}}^{XRT} = 8.7^{+3.4}_{-1.9} \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \).

In order to investigate whether the data exhibits the characteristic spectral softening of X-ray bursts, we split the XRT observation into two separate intervals of similar length. We extracted spectra for the two data segments and fitted these to an absorbed blackbody model. The hydrogen column density was fixed at \( N_H = 8.6 \times 10^{22} \text{ cm}^{-2} \), and the emitting area was assumed to remain constant. This yielded blackbody temperatures of \( kT_{\text{bb}} = 0.88 \pm 0.09 \) and \( 0.80 \pm 0.08 \text{ keV} \) for the first and second interval, respectively. Although the errors are substantial due to the low number of counts in the spectra (\( \sim 150 \) per interval), it is suggestive of cooling along the decay. This further strengthens the idea that XMMU J1747 was exhibiting an X-ray burst.

During the XRT observation of 2010 August 13, XMMU J1747 was detected at an average count rate of \( \sim 0.1 \text{ counts s}^{-1} \), which is a factor \( \sim 5 - 10 \) elevated above its typical emission level (see Sec. 2.2.1). As shown in Figure 4, XMMU J1747 shows a clear decay in count rate during the 2.2-ks long XRT exposure. We fitted the lightcurve, binned by 150-s, to a powerlaw decay, which resulted in an index of \( -1.8 \pm 0.4 \) and a normalization of \( \sim 4 \times 10^5 \text{ counts s}^{-1} \) (\( \chi^2 = 1.10 \) for 13 dof). The value of the decay index is consistent with the theoretical prediction for the cooling tail of a long X-ray burst (Cumming & Macbeth 2004), and similar to observational results of intermediate- and long X-ray bursts from other sources (e.g., Falanga et al. 2008; Linares et al. 2009; Degenaar et al. 2010).

The total length of the X-ray burst can be determined by extrapolating the above described powerlaw decay down to the persistent emission level. This suggests a duration of \( t_{\text{burst}} \approx 10500 \text{ s} \) (\( \approx 2.9 \text{ h} \); see Fig. 4). To estimate the fluence in the X-ray burst tail, we integrate the powerlaw decay function from \( t = 150 \text{ s} \) (the time at which the burst

Figure 2. Spectra of the X-ray burst seen by BAT (right) and XRT (top left), as well as the persistent emission of XMMU J1747 (bottom left). The solid lines indicate the model fits (see text).
peak disappeared from the BAT lightcurve; see Fig. 11 till $t = 10500$ s after the BAT trigger. By applying a count rate to flux conversion factor inferred from fitting the XRT spectrum of the X-ray burst, we find a bolometric fluence of $f_{\text{XRT}} \simeq 7.3 \times 10^{-6}$ erg cm$^{-2}$. Adding this to the BAT result (see Sec. 2.1), the total estimated bolometric fluence of the X-ray burst becomes $F_{\text{burst}} \simeq 1.1 \times 10^{-5}$ erg cm$^{-2}$. For a distance of $D = 8.4$ kpc, this implies a radiated energy of $E_{\text{burst}} \simeq 9.1 \times 10^{49}$ erg. The ignition column depth of an X-ray burst is given by $y = E_{\text{burst}} (1 + z) / 4 \pi R^2 Q_{\text{nuc}}$, where $z$ is gravitational redshift, $R$ is the neutron star radius and $Q_{\text{nuc}} = 1.6 + 4 \times 10^8$ MeV nucleon$^{-1}$, the nuclear energy release given a H-fraction $X$ at ignition (e.g., Galloway et al. 2008). For a neutron star with $M = 1.4 M_\odot$ and $R = 10$ km ($z = 0.31$), we find $y \simeq 6.2 \times 10^9$ g cm$^{-2}$ for pure He ($X = 0$), or $y \simeq 2.3 \times 10^9$ g cm$^{-2}$ for solar abundances ($X = 0.7$).

The recurrence time that corresponds to a certain ignition depth is $t_{\text{rec}} \simeq y (1 + z) / \dot{m}$, where $\dot{m}$ is the accretion rate onto the neutron star surface per unit area. The bolometric persistent luminosity of XMMU J1747 is $L_{\text{bol}}^\text{pers} \simeq 1.6 \times 10^{35}$ $(D/8.4$ kpc)$^2$ erg s$^{-1}$ (see Sec. 2.2.1), which yields a mass-accretion rate of $\dot{M} \simeq R J_{\text{bol}}^\text{pers} / GM \simeq 1.4 \times 10^{-11} M_\odot$ yr$^{-1}$ ($\simeq 0.05\%$ of Eddington). If the emission is isotropic, this corresponds to a local accretion rate of $\dot{m} \simeq 68$ g cm$^{-2}$ s$^{-1}$. We can thus roughly estimate that the time required to build up the layer that caused the X-ray burst is $t_{\text{rec}} \simeq 3.8$ yr ($X = 0$) or $t_{\text{rec}} \simeq 1.4$ yr ($X = 0.7$).

3 DISCUSSION

In this Letter, we analyzed the Swift/XRT data of BAT trigger 431582, which occurred on 2010 August 13. The BAT spectrum fits to a blackbody model with a temperature of $kT_{\text{bb}} \simeq 2.5$ keV and an emitting radius of $R_{\text{bb}} \simeq 6.3$ km, suggesting that this was a thermonuclear event. Follow-up observations with Swift/XRT, performed $\simeq 1$ h after the BAT trigger, reveal that the known X-ray burster XMMU J174716.1–281048 was the only X-ray point source located with the $\simeq 2.5'$ BAT error circle. Analysis of the XRT data shows that the intensity of XMMU J1747 was elevated above its persistent level by a factor of $\simeq 5$–10, while the source lightcurve displayed a clear decaying trend that fits to a powerlaw with index $-1.8$. This provides strong evidence pointing towards XMMU J1747 as the source of the BAT trigger. The fact that the XRT spectrum can be described by a blackbody model with a temperature of $kT_{\text{bb}} \simeq 0.8$ keV, and shows indications of cooling during the decay, further strengthens the idea that the BAT trigger on an X-ray burst from XMMU J1747.

From the observed BAT peak flux, we derive an upper limit on the distance towards XMMU J1747 of $D \lesssim 8.4$ kpc. A location near the Galactic centre is consistent with the large hydrogen column density inferred from fitting the persistent X-ray spectrum ($N_H \simeq 9 \times 10^{22}$ cm$^{-2}$). The total radiated energy of $E_{\text{burst}} \simeq 9 \times 10^{49}$ erg, classifies this event as an intermediate long X-ray burst (e.g., Falanga et al. 2003; in’t Zand et al. 2008; Degenaar et al. 2010). The fact that the X-ray burst could be observed for a very long time ($\simeq 1.5$ h) and extrapolated to a duration of $\simeq 2.9$ h, can be attributed to the low persistent emission level of the source, combined with the sensitivity and low X-ray background of the Swift/XRT. This provides the unique possibility to follow the tails of X-ray bursts down to very low temperatures below $\sim 1$ keV. The inferred column depth ($y \simeq 2 \times 10^9$ g cm$^{-2}$) requires that XMMU J1747 accreted for $\sim 1$–4 years to be able to power this X-ray burst.

Investigation of Swift/XRT data obtained between 2007 May and 2010 November, reveals that XMMU J1747 was likely continuously active, displaying a 2–10 keV luminosity of $L_X \simeq 5 \times 10^{34}$ $(D/8.4$ kpc)$^2$ erg s$^{-1}$. Similar intensities were measured with XMM-Newton in 2003 March and 2005 February (Del Santo et al. 2007), and with Chandra in 2007 May (Degenaar et al. 2007). This supports the suggestion of Del Santo et al. (2007) that the system exhibits a very long accretion outburst. The detection history suggests that the outburst started between 2001 July 16 and 2003 March 12. This sets the counter on the outburst duration to 7–9 years. The mass-accretion rate ($\simeq 0.05\%$ of Eddington) is amongst the lowest encountered for currently known neutron star LMXBs.

The X-ray burst observed from XMMU J1747 with Swift is only the second one ever reported from this source. The first X-ray burst was detected with INTEGRAL on 2005 March 22, and reached a peak flux of $F_{\text{peak}} \simeq 5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (Del Santo et al. 2007a), similar to our result for the Swift event. The INTEGRAL X-ray burst was detected with the IBIS/ISGRI in the 18–26 energy band for $\simeq 100$ s (Del Santo et al. 2007b), comparable with the visibility in the 15–35 BAT lightcurve. In the 3–6 keV band, JEM-X detected the X-ray burst for $\simeq 200$ s, i.e., much shorter than observed with Swift/XRT. However, JEM-X has a lower sensitivity and no energy coverage below $\simeq 3$ keV, where the tail of the X-ray burst emission lies. The total radiated energy of the INTEGRAL event, $E_{\text{burst}} \simeq 2 \times 10^{49}$ erg (Del Santo et al. 2007a), suggests that this was likely an intermediately long X-ray burst as well. From the energy budget of the Swift X-ray burst, we estimate a recurrence time of $\sim 1$–4 years, depending on the photospheric composition. For pure He, this is roughly consistent with the time elapsed since the INTEGRAL X-ray burst (5 years). However, additional X-ray bursts might have been missed.

There are two scenarios for which intermittently long X-ray bursts may occur. First, in ultra-compact X-ray binaries (UCXBs), the mass donor is H-poor, so that the neu-

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Swift/XRT image (0.3–10 keV) obtained $\simeq 1$ h after the BAT trigger. The 2.4' BAT error circle is indicated.}
\end{figure}
tron star is accreting nearly pure He. In absence of heating from H-burning, the temperature in the ignition layer is low. As a consequence, a thick layer of He can build up before it ignites, giving rise to a long and energetic X-ray burst (Cumming et al. 2006). Second, some sources accrete matter from a H-rich companion at such a low rate that H burns unstably. For these very-faint LMXBs, successive weak H-flashes can result in the production of a large reservoir of H that also causes an intermittently long X-ray burst upon ignition (Cooper & Narayan 2007; Peng et al. 2007). There are observational examples for both scenarios (e.g., in’t Zand et al. 2005; Chenevez et al. 2007; Falanga et al. 2008, 2009; Degenaar et al. 2010; Kuulkers et al. 2010).

Without a direct measurement of the orbital period, clues to the ultra-compact nature of an X-ray binary may come from a comparison of the X-ray and optical flux (e.g., Bassa et al. 2006), or abundance patterns revealed through optical spectroscopy (e.g., Nelemans & Jonker 2001). However, the inferred large hydrogen column density of XMMU J1747 ($N_H \approx 9 \times 10^{22} \text{ cm}^{-2}$) implies a visual extinction of $\approx 50$ mag (Predehl & Schmitt 1995), rendering searches for an optical counterpart basically impossible. Although XMMU J1747 is a confirmed transient system, it appears able to keep the accretion ongoing for many years. This suggests the possibility of a relatively small orbit, and UCXB nature, since small accretion disks are easier to be kept fully ionized so that the accretion can be sustained (in’t Zand et al. 2007). However, the neutron star LMXB 1RXJ 173523.7-354013 is likely persistently accreting at $P_{\text{bol}} \approx 4 \times 10^{35} \text{ erg s}^{-1}$, but shows a strong Hα emission line that indicates a H-rich donor (Degenaar et al. 2010).

Intermittently long X-ray bursts that are likely triggered by unstable H-burning have been observed at mass-accretion rates of $\approx 0.1 - 1\%$ of Eddington (e.g., Degenaar et al. 2010; Linares et al. 2009; in’t Zand et al. 2008). Initial calculations predict that these should occur only for a narrow regime spanning a factor $\approx 3$ in mass-accretion rate (Cooper & Narayan 2007; Peng et al. 2007). In contrast, if XMMU J1747 (accreting at $\approx 0.05\%$ Eddington) fits into this framework, the observations would span a factor $\approx 20$ in mass-accretion rate. However, the theoretically allowed range relaxes if the heat flux coming from the neutron star crust varies between the different sources (Cooper & Narayan 2007), and this is indeed expected to depend on the mass-accretion rate onto the neutron star (Cumming & Bildsten 2006; Brown 2004). So far, it thus remains unclear which of the two possibilities sketched above apply to the intermittently long X-ray burst observed from XMMU J1747 with Swift.

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Figure 4. Swift/XRT lightcurve of XMMU J1747 observed on 2010 August 13, at 150-s time resolution (0.3–10 keV). The dashed line indicates the persistent emission level and the solid line represents a fit to a powerlaw decay with index $-1.8$. 

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