

# A superburst candidate in EXO 1745–248 as a challenge to thermonuclear ignition models

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Accepted 2012 July 23. Received 2012 July 18; in original form 2012 June 13

## ABSTRACT

We report on *Chandra*, *Rossi X-ray Timing Explorer (RXTE)*, *Swift/Burst Alert Telescope (BAT)* and *MAXI* observations of an X-ray flare of  $\sim 1$  d and subsequent outburst of a transient X-ray source observed in 2011 October–November in the globular cluster Terzan 5. We show that the source is the same as the transient that was active in 2000, i.e. the neutron star low-mass X-ray binary EXO 1745–248. For the X-ray flare we estimate a 6–11 h exponential decay time and a radiated energy of  $2\text{--}9 \times 10^{42}$  erg. These properties, together with strong evidence of decreasing blackbody temperature during the flare decay, are fully consistent with what is expected for a thermonuclear superburst. We use the most recent superburst models and estimate an ignition column depth of  $\approx 10^{12}$  g cm<sup>-2</sup> and an energy release between  $0.1 \times 10^{18}$  and  $2 \times 10^{18}$  erg g<sup>-1</sup>, also consistent with expected superburst values. We conclude therefore that the flare was most probably a superburst. We discuss our results in the context of theoretical models and find that even when assuming a few days of low-level accretion before the superburst onset (which is more than what is suggested by the data), the observations of this superburst are very challenging for current superburst ignition models.

**Key words:** accretion, accretion discs – binaries: close – stars: individual: EXO 1745–248 – stars: neutron – X-rays: binaries – X-rays: stars.

## 1 INTRODUCTION

Thermonuclear Type-I X-ray bursts are caused by unstable burning of a several metres thick layer of accreted H/He on the surface of neutron stars (NSs) in low-mass X-ray binary (LMXB) systems (e.g. Lewin, van Paradijs & Taam 1993). Manifesting themselves as a sudden (seconds) increase in the X-ray luminosity and reaching levels that can be many times brighter than the persistent (accretion) luminosity, typical bursts emit about  $10^{39}\text{--}10^{40}$  erg, last seconds to minutes and have light curves that are well described by a fast-rise exponential-decay profile. Their spectra are generally consistent with a blackbody temperature  $T_{\text{bb}} = 2\text{--}3$  keV, where  $T_{\text{bb}}$  increases until the burst peak, and then decreases exponentially. This is nat-

urally interpreted as heating resulting from the initial fuel ignition, followed by cooling of the ashes (and additional hydrogen burning through a series of rapid proton captures and  $\beta$ -decays; e.g. Schatz et al. 2001) once the main available fuel is exhausted. Type-I X-ray bursts are a common phenomenon in NS LMXBs. They have been observed in about 100 sources and, depending on the conditions (e.g. accretion rate, composition of the fuel, etc.) can have recurrence times between minutes and weeks (e.g. Galloway et al. 2008; Linares et al. 2012).

Superbursts are a class of extremely long duration bursts which are attributed to the unstable thermonuclear burning of an  $\sim 100$  m thick carbon-rich layer, formed from the ashes of normal Type-I X-ray bursts (Cumming & Bildsten 2001). Superbursts tend to quench the regular Type-I bursts for weeks afterwards, probably because the cooling flux from the superburst temporarily stabilizes the H/He burning (Cumming & Bildsten 2001; Cumming &

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Macbeth 2004; Keek, Heger & in't Zand 2012). The difference in fuel composition between Type-I X-ray bursts and superbursts leads to a clear difference in time-scales, recurrence times and energetics, where superbursts last for a few hours, recur every one to a few years and emit  $10^{41}$ – $10^{42}$  erg. With such long recurrence times superbursts are difficult to catch. While thousands of Type-I X-ray bursts have been observed (e.g. Galloway et al. 2008), to date only about 22 (candidate) superbursts have been observed from 13 sources (see e.g. Wijnands 2001; Kuulkers et al. 2004; Altamirano et al. 2011b; Asada et al. 2011; Chenevez et al. 2011; Keek & Heger 2011; Mihara et al. 2011, and references therein).

Terzan 5 is a globular cluster containing 50 known X-ray sources, of which  $\sim 12$  are likely LMXBs containing NSs (e.g. Heinke et al. 2006). During 2011 we monitored Terzan 5 on a weekly basis with *Rossi X-ray Timing Explorer (RXTE)* observations to search for transient X-ray flares and/or outbursts. At 4:57 UT, 2011 October 26, an *RXTE*-pointed observation measured a 2–16 keV intensity of  $\sim 8$  mCrab, significantly above the typical quiescent intensity of  $\sim 2$  mCrab (Altamirano et al. 2011a). Approximately 8 h earlier, *INTEGRAL* monitoring observations of Terzan 5 did not detect any enhanced activity, with a  $5\sigma$  upper limit of 6 mCrab in the 3–10 keV energy band (Vovk et al. 2011). The *RXTE* detection was confirmed by the *Swift/Burst Alert Telescope (BAT)* daily-averaged flux measurements (Altamirano et al. 2011a), as well as by a *Swift/X-ray telescope (XRT)* pointed observation performed  $\sim 11$  h after the *RXTE* one (Altamirano et al. 2011b). The position of the source from these *Swift/XRT* data was consistent (Altamirano et al. 2011b; Evans et al. 2011) with that of the transient NS LMXB that was active in 2000 (which we refer to as EXO 1745–248, though it is not necessarily the *EXOSAT* source; see Markwardt et al. 2000; Wijnands et al. 2005). This result was later confirmed by a preliminary analysis of a pointed *Chandra* observation (Pooley et al. 2011).

Just before the *INTEGRAL* non-detection, *MAXI* and *Swift/BAT* light curves of Terzan 5 revealed an X-ray flare that lasted less than a day. We identified this flare as a possible superburst based on its duration, shape of its light curve and estimated radiated energy of  $\sim 10^{42}$  erg (Altamirano et al. 2011b). Our speculations were supported by the results of Mihara et al. (2011) who used the *MAXI* data and showed that (i) the spectra of the flare were well modelled with a blackbody component at  $\sim 2$ – $3$  keV and that (ii) there was an apparent decrease of the blackbody temperature, which is usually interpreted as the cooling of the NS surface after a thermonuclear burst (see e.g. Lewin et al. 1996). Very recently, Serino et al. (2012) have presented a detailed analysis of the *MAXI* data supporting the superburst identification.

The occurrence of a superburst in the transient NS LMXB 4U 1608–522 after 55 d of low ( $\lesssim 10$  per cent Eddington) accretion rate has challenged superburst theory, as it is difficult to explain carbon ignition at the observed depths when the NS surface is still cool (Keek et al. 2008), i.e. when accretion has not yet been able to ‘warm up’ the NS. The superburst candidate in Terzan 5 is even more challenging for theoretical models, as the NS is very cool (Wijnands et al. 2005; Degenaar & Wijnands 2012) and the superburst onset was coincident with a period of only low-level accretion or no accretion at all.

## 2 OBSERVATIONS AND DATA ANALYSIS

In this paper we make use of data from the *MAXI* (Matsuoka et al. 2009), *Swift/BAT* (Barthelmy et al. 2005), *Chandra* (Garmire et al. 2003), *INTEGRAL* (Winkler et al. 2003) and *RXTE* (Jahoda

et al. 1996) missions. Most data presented here were obtained during 2011 October–November. However, as we explain below, we also used archival data sets from different periods to put our results in a long-term context.

We used the processed *MAXI* data as provided by the *MAXI* team: four light curves are available (corresponding to the 2–4, 4–10, 10–20 and 2–20 keV energy bands), which are given in either 1-d or 1-orbit bins.<sup>1</sup> We also used data from the *Swift/BAT* transient monitor.<sup>2</sup> These 15–50 keV data are provided by the *Swift/BAT* team after being processed, corrected for systematic errors and binned in both daily and orbital bins.

To identify the active source in Terzan 5, we obtained a 9.8-ks *Chandra* observation (ObsID 12454, 2011 November 3 at 5:05:57 UTC) taken with the Advanced CCD Imaging Spectrometer S3 chip in imaging mode. We also used other available *Chandra* observations of Terzan 5 (e.g. Wijnands et al. 2005; Heinke et al. 2006; Pooley et al. 2010). All images were reprocessed with CIAO 4.3 following standard recipes.<sup>3</sup>

We used 18 pointed observations of the *RXTE* Proportional Counter Array (PCA; for instrument information see Zhang et al. 1993; Jahoda et al. 2006) that sampled the 2011 outburst in Terzan 5. We use the 16-s time resolution Standard 2 mode data to calculate the Crab-normalized 2.0–16.0 keV intensity as described in Altamirano et al. (2008). For the timing analysis we used Event mode E\_125us\_64M\_0\_1s or the Good Xenon data. Power spectra were generated following Altamirano et al. (2008) using data segments of 128 and 1/8192 s time bins. To fit the power spectra, we used a multi-Lorentzian function. We only include those Lorentzians in the fits whose single trial significance exceeds  $3\sigma$  based on the error in the power integrated from 0 to  $\infty$ , and we give their frequency in terms of characteristic frequency (Belloni, Psaltis & van der Klis 2002). The quoted errors use  $\Delta\chi^2 = 1.0$  corresponding to a 68 per cent confidence level.

Recent estimates of the distance to the globular cluster Terzan 5 range between 4.6 and 8.7 kpc (Cohn et al. 2002; Ortolani et al. 2007; Lanzoni et al. 2010). The large distance range to this globular cluster is mainly due to an ongoing discussion on how to identify the horizontal branch in the Hertzsprung–Russell diagram of Terzan 5 and the assumed reddening factor in the direction of this globular cluster. We refer the reader to the discussion reported in Ortolani et al. (2007). Following these authors’ discussion, in this paper we use a distance of  $5.5 \pm 0.9$  kpc which falls in between the different estimates and comes from the *Hubble Space Telescope* photometry of Terzan 5 (Ortolani et al. 2007).

## 3 RESULTS

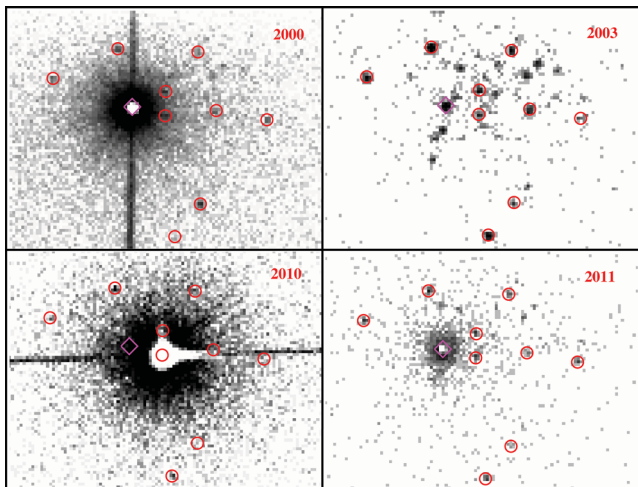
### 3.1 Identification of the source in Terzan 5

Inspection of the 2011 *Chandra* data reveals a bright transient (which suffers from pile-up) and a few low-luminosity X-ray sources that are also seen in deeper *Chandra* observations in quiescence, such as the 2003 observation shown in Fig. 1. We match 10 of the brighter 2011 sources with sources in the 2003 observation, allowing us to confidently identify (within 0.2 arcsec) the 2011 X-ray transient in Terzan 5 with CXOG1b J174805.2–244647 [CX3 in Heinke et al. 2006, at J2000 coordinates 17:48:05.236

<sup>1</sup> <http://maxi.riken.jp/top/>

<sup>2</sup> <http://swift.gsfc.nasa.gov/docs/swift/results/transients/>

<sup>3</sup> <http://cxc.harvard.edu/ciao/threads/>



**Figure 1.**  $39 \times 52 \text{ arcsec}^2$  *Chandra* images of Terzan 5 from different epochs show the 2011 outburst source is EXO 1745–248. The upper-left panel shows the combined image of two observations (2000 July 24 and 29, ObsIDs 655 and 644, respectively) for a total time of 47 ks (see Heinke et al. 2003). The upper-right panel shows a 35-ks observation on 2003 July 13 (ObsID 3798; see Wijnands et al. 2005; Heinke et al. 2006). The lower-left panel is a 10-ks observation on 2010 October 24 (ObsID 11051; Pooley et al. 2010), and the lower-right panel is our 9.8-ks observation on 2011 November 3 (ObsID 12454; Pooley et al. 2011). All images were extracted in the 1–3 keV energy range (chosen to try to maximize S/N in the 2011 image). 10 X-ray sources from Heinke et al. (2006) are marked with red circles (2 pixel to 0.984 arcsec radius). Diamonds mark the position of EXO 1745–248 as detected in its 2000 outburst. The active source in the 2010 observation (Pooley et al. 2010) was the 11-Hz pulsar IGR J17480–2446 (Strohmayer & Markwardt 2010; Papitto et al. 2011).

(0.002),  $-24:46:47.38$  (0.02)]. In Fig. 1 we show *Chandra* images of Terzan 5 from different epochs including that of 2011. Given that the 2000 outburst was identified with EXO 1745–248 (Markwardt et al. 2000; Wijnands et al. 2005), in the rest of this paper we refer to the source as EXO 1745–248.

### 3.2 Long-term light curves

In the left-hand panel of Fig. 2 we show the 2–20 keV *MAXI* light curve (upper panel), 15–50 keV *Swift*/BAT light curve (middle panel) and 2–16 keV *RXTE* light curve (lower panel). In the lower panel we also show the *INTEGRAL* upper limits; in the upper panel we mark the time of the *Chandra* observation. Right-hand panels show a zoom-in to the moment of the initial X-ray flare. Due to the low statistics of both the *MAXI* and *Swift*/BAT orbital data, we used an adaptive binning method which (i) has been fixed to start around the beginning of the flare (MJD 55859.5) and (ii) bins observations until finding a  $3\sigma$  detection within a day, or calculates a  $3\sigma$  upper limit for 1 d of data. Fig. 2 shows that the peak of the X-ray flare as seen by *MAXI* occurs approximately half a day before that of *Swift*/BAT. Other binning methods led to similar results. Fig. 2 also shows that both *MAXI* and *Swift*/BAT appear to have detected the source before the peak of the flare in the *MAXI* data. In a period of  $\sim 250$  d before the flare we find five similarly significant detections in the *MAXI* light curve and two in the *Swift*/BAT light curve. These events did not occur simultaneously in *MAXI* and *Swift*/BAT and even if real, cannot be unambiguously identified with EXO 1745–248 due to the large number of X-ray sources in Terzan 5 (e.g. Heinke et al. 2006). The fact that we find simultaneous excesses in the *MAXI* and the *Swift*/BAT data is suggestive of a real

increase of flux before the flare; however, given the lack of further information we decided to take these detections only as marginally significant given the systematic errors and possible background issues which we are unable to account for.

The last *RXTE*/PCA observation was performed on 2011 November 19, after which the source was not visible anymore due to visibility constraints. The lower-left panel of Fig. 2 shows that the outburst lasted at least 25 d (still ongoing at the moment of the last pointed observation), but that the source was brighter than 10 mCrab for only about 4 d.

Terzan 5 was not visible to X-ray instruments (due to Sun constraints) for the next couple of months. The next pointed observation of Terzan 5 was on 2012 February 9, for 972 s with *Swift*/XRT, which showed a count rate of  $0.015 \text{ count s}^{-1}$ , translating to a total  $L_X \sim 6 \times 10^{33} \text{ erg s}^{-1}$ . As this is consistent with the typical integrated X-ray luminosity of the cluster sources in quiescence, we conclude that the outburst was finished by then, having lasted between 25 and 106 d.

### 3.3 Type-I X-ray bursts and superbursts

We searched all *RXTE* observations of Terzan 5 that were taken in 2011 (up until November 19) for Type-I X-ray bursts, but none was found. Lower limits on X-ray burst recurrence times are unconstrained, as our data set consists of about 27 h of data in about 15 d, i.e. at an average of less than 2 h a day. The *MAXI* data consist of about 100 orbital data sets with an average length of less than a minute each. None of these pointings shows evidence for an X-ray burst (see also Serino et al. 2012).

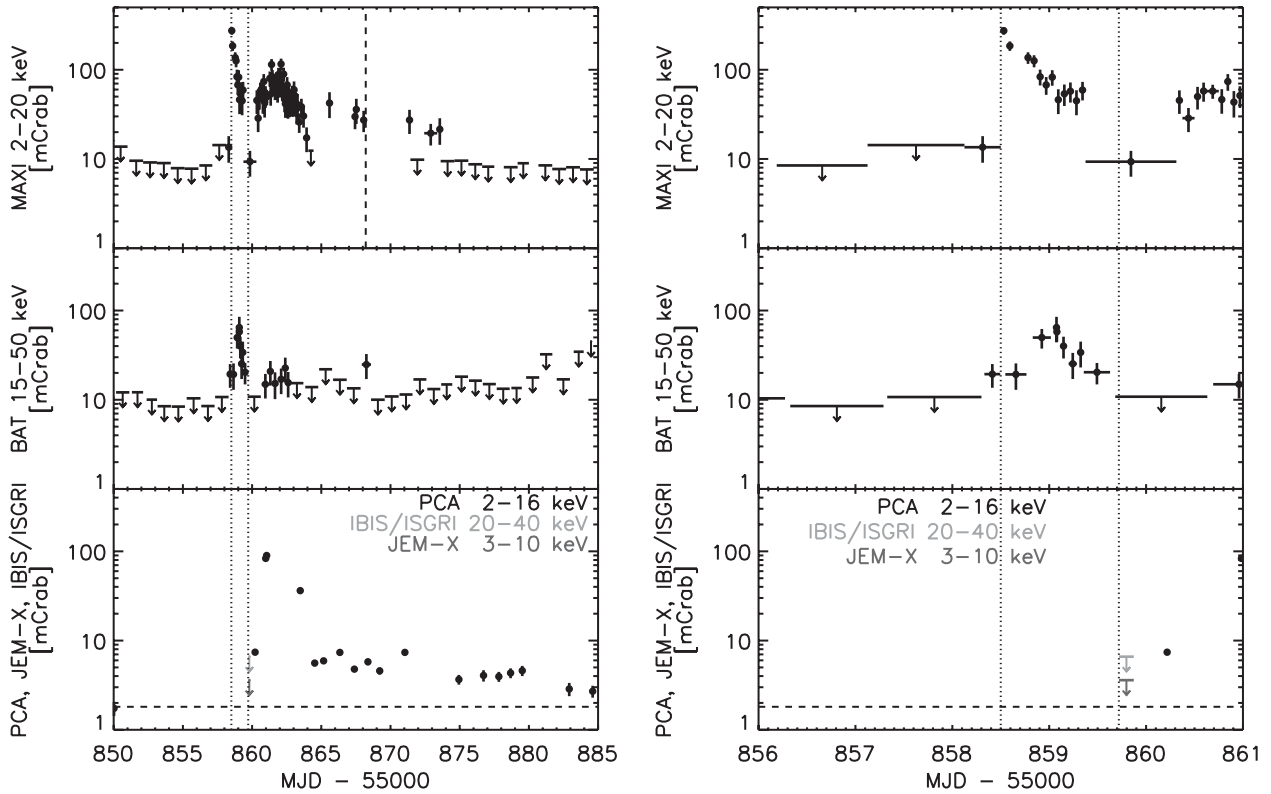
To calculate the bolometric luminosity, radiated energy and e-folding time-scale of the flare, we used the background-corrected 2–4 keV *MAXI* data during the period MJD 55858.5–55859.5. (We did not use the 2–20 keV light curve to avoid systematics related to the flux conversions between a 2-keV blackbody and a 2.1-index power law as in the Crab nebula spectra.) We estimated the *RXTE* Crab flux in the 2–4 keV range to be  $1.0326 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ . For the 2–4 keV *MAXI* light curve,<sup>4</sup> 1 Crab equals  $1.87 \text{ photon cm}^{-2} \text{ s}^{-1}$ . With the above values we transformed the 2–4 keV intensity ( $\text{photon cm}^{-2} \text{ s}^{-1}$ ) into flux. We then followed Mihara et al. (2011)<sup>5</sup> and approximated blackbody colour temperatures from the 4–10/2–4 keV colour hardness. Then we used PIMMS,<sup>6</sup> the absorbed flux and colour temperatures estimated above to approximate the unabsorbed (assuming Galactic  $N_H = 1.2 \times 10^{22} \text{ cm}^{-2}$ ; Altamirano et al. 2011b) bolometric flux of a blackbody in the 0.01–200 keV range. We finally converted our values to bolometric luminosities assuming a distance of 5.5 kpc (Ortolani et al. 2007). The bolometric luminosity of the superburst as a function of time is shown in Fig. 3.

Due to (i) all of the assumptions made to calculate the bolometric luminosity, (ii) the fact that the *MAXI* data do not sample the beginning of the flare (which could have happened at any time in the 90 min between orbits) and (iii) the fact that under the hypothesis that the flare is from a thermonuclear origin, we assume

<sup>4</sup> See <http://http://maxi.riken.jp/top/>.

<sup>5</sup> The method used by Mihara et al. (2011) is instrument-dependent and consists of the estimation of hardness ratios for given  $kT$  parameters through simulated energy spectra using the *MAXI* energy response. The energy ranges used in this paper and in Mihara et al. (2011) allow estimates of the temperature  $kT$  from the hardness ratios (M. Serino, private communication). Similar methods have been used for *RXTE* (e.g. fig. 1 in Belloni et al. 2000).

<sup>6</sup> <http://heasarc.nasa.gov/Tools/w3pimms.html>



**Figure 2.** X-ray light curves of EXO 1745–248 in Terzan 5 as sampled with *MAXI* (upper panels), *Swift*/BAT (middle panels) and *RXTE* pointed observations (lower panels). For *MAXI* we subtracted an average background of  $0.05 \text{ counts s}^{-1}$  before converting to Crab. *MAXI* and *Swift*/BAT data points are either a  $3\sigma$  detection or a  $3\sigma$  upper limit (see Section 3.2 for more details). The dashed line in the upper-left panel marks the time of the *Chandra* observation (MJD 55868). The arrows in the lower panels mark the time of the *INTEGRAL* 2–10 keV 6-mCrab upper limits (with IBIS/ISGRI upper limit higher than JEM-X), while the circles mark the average per observation *RXTE* 2–16 keV intensity. The horizontal dashed line in the lower panels marks the average background emission as estimated from 10 months of *RXTE* non-detections before the 2011 outburst in Terzan 5. These values can be taken as upper limits to the intensity. Vertical lines mark the approximate region between the onset and end time of the superburst. Right-hand panels show zoom-ins to this region.

the contribution from the accretion disc to be negligible, it is not possible to get tight constraints on the characteristics of the flare. Since the first *MAXI* data point sampling the flare is at  $\sim 6 \times 10^{37} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$ , the flare peak was probably brighter. The flare duration is about a day; an exponential fit to the bolometric luminosity light curve gives e-folding times between 6 and 11 h depending on the assumed onset time. Exponential fits to the raw 2–20 keV *MAXI* data give consistent results. Integrating this exponential curve during a 1-d period gives a radiated energy in the  $2\text{--}9 \times 10^{42} \text{ erg}$  range. More than 85 per cent of the contribution comes from the first 5 h. All of these values are within the ranges expected for superbursts, although this one appears to be one of the longest such bursts (see e.g. Keek & in't Zand 2008). Our results, together with the fact that the *MAXI* spectra of the flare are consistent with blackbody spectra at  $\sim 2\text{--}3 \text{ keV}$  that cool as the intensity decreases (Mihara et al. 2011; Serino et al. 2012), strongly suggest that the observed X-ray flare is most probably a superburst.

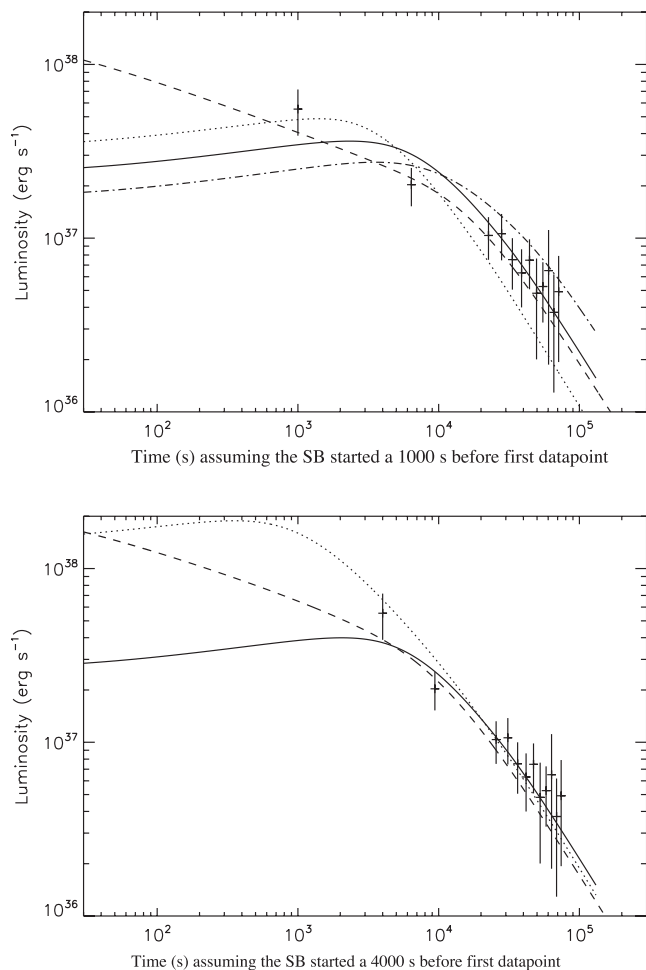
We note that recently Serino et al. (2012) reported on the spectral modelling of the same *MAXI* data used in this work. Their spectral results are binned into five intervals (A–E) of different time lengths to improve the signal-to-noise ratio (S/N) of their energy spectra. The method used in this paper to estimate the blackbody temperature and flux is more rudimentary, but has the advantage of giving more points for fitting the thermal evolution of a superburst (see Section 3.4). Given that the values of bolometric luminosity and radiated energy Serino et al. (2012) obtain are consistent with ours within errors (after correcting for the fact that they estimated

the fluence in the 2–20 keV range and used 8.7 kpc as the distance to Terzan 5), in the following sections we use the values for the bolometric luminosity as we calculated above.

### 3.4 Ignition depth and energy release

Cumming & Macbeth (2004) modelled the thermal evolution of the surface layers as they cool after a superburst onset, assuming that the fuel is burned locally and instantly. These authors showed that simultaneous modelling of superburst light curves and quenching times could be used to constrain both the thickness of the fuel layer and the energy deposited in the NS envelope. Cumming et al. (2006) applied the Cumming & Macbeth (2004) models to the observations of several superbursts and found that their fits implied ignition column depths in the range  $(0.5\text{--}3) \times 10^{12} \text{ g cm}^{-2}$ , energy releases of the order of  $\approx 2 \times 10^{17} \text{ erg g}^{-1}$  and total radiated energies of the order of  $10^{42} \text{ erg}$ , very similar to the observed superburst characteristics.

The model has four free parameters to vary: energy release  $E_{18} \times 10^{18} \text{ erg g}^{-1}$ , ignition column depth  $y_{\text{ign}}$  (in units of  $\text{g cm}^{-2}$ ), burst start time and the power-law slope of the initial temperature profile  $T \propto y_{\text{ign}}^{\alpha}$ . The model assumes a  $1.4 M_{\odot}$  and a 10-km-radius NS. Cumming et al. (2006) assumed that the fuel burned instantaneously ‘in place’, giving an initial temperature profile with  $\alpha \sim 1/8$ . Instant burning implies that the rise of the burst is instantaneous. Here we also explore  $\alpha = 0.225$ , which is required to fit the rise of the

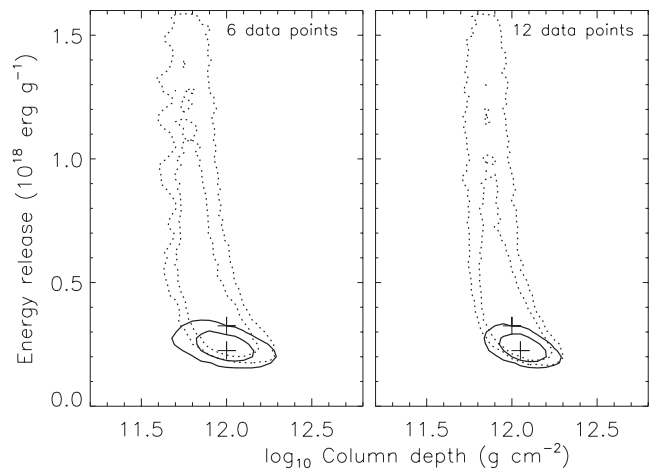


**Figure 3.** Upper and lower panels show representative fits to the first six data points assuming *MAXI* observations starting 1000 and 4000 s after superburst ignition, respectively. Upper panel: solid, dotted, dot-dashed and dashed curves correspond to  $E_{18} = 0.28, 0.28, 0.28$  and  $0.175$  and  $y_{\text{ign}} = 12.06, 11.8, 12.3$  and  $12.1$ , respectively. Bottom panel: solid, dotted and dashed curves correspond to  $E_{18} = 0.29, 0.6$  and  $0.225$  and  $y_{\text{ign}} = 12.04, 11.9$  and  $12.0$ , respectively. Solid, dotted and dot-dashed curves assume  $\alpha = 0.225$ , while the dashed curves assume  $\alpha = 1/8$ , i.e. instantaneous burning.

superburst light curve of 4U 1636–53 (this fit and its implications will be published elsewhere).

As is usually the case in the spectral analysis of Type-I X-ray bursts, it is possible that the tail of the superburst can be contaminated by the accretion disc. To understand the possible contribution, we fit all superburst data as well as data from the first 0.5 d (12 and six independent points, respectively). We assumed a distance of  $5.5 \pm 0.9$  kpc and allowed the superburst start time to vary between 0 and 5800 s before the first data point. To model the superburst light curve we used a Markov chain Monte Carlo method with 30 000 samples.

Although we find that  $y_{\text{ign}}$  is well constrained to  $\log y_{\text{ign}} = 12.0 \pm 0.3$  (including errors in the distance), our fits failed to constrain the start time and  $E_{18}$ . This is due to the fact that our data do not sample the initial rise of the superburst: as explained by Cumming & Macbeth (2004), during the first part of the superburst the energy released from the surface is mainly sensitive to  $E_{18}$  and insensitive to  $y_{\text{ign}}$ . However, as the superburst evolves, the characteristics of the cooling tail mainly depend on  $y_{\text{ign}}$ .



**Figure 4.** Contours for  $\alpha = 0.225$  when using the first six data points (left) versus 12 data points (right) of the superburst. Filled curves are for a superburst starting time of 1000 s, while dashed curves are for 4000 s. Contours are at 68 and 95 per cent confidence levels.

In the upper and lower panels of Fig. 3 we show representative fits to the first six data points of the superburst for different  $E_{18}$  and  $y_{\text{ign}}$ , assuming that the first *MAXI* observation occurred 1000 or 4000 s after the superburst ignition, respectively.

For a 1000-s start time (upper panel), our data sample the first hour of the superburst and therefore the model allows only a narrow range of  $E_{18}$ . The column depth is not as well constrained when using six points (but it is when using 12 points). For a start time of 4000 s (bottom panel), however, the first data point becomes part of the cooling tail. This means that the early part of the light curve can be very bright and  $E_{18}$  becomes poorly constrained, while  $y_{\text{ign}}$  is well constrained when using both six and 12 points. In Fig. 4 we show the relation between  $E_{18}$  and  $y_{\text{ign}}$  ( $\alpha = 0.225$ ). Left- and right-hand panels are for fits to the first six and 12 superburst data points, respectively. We note that a larger distance than that assumed in this paper would imply that the data points of the superburst move to higher luminosity. This requires a larger energy release to increase the luminosity in the early part of the superburst, and a deeper ignition depth to increase the luminosity in the cooling tail. For the largest distance estimate of 8.7 kpc, we find that the inferred energy release increases to close to  $10^{18}$  erg  $g^{-1}$  and the column depth close to  $10^{13}$  g  $cm^{-2}$ .

### 3.5 Short (subsecond) variability

Our power spectral analysis does not reveal major features. In the first observation of the outburst (MJD 55860.2) we only find a  $3.2\sigma$  (single trial)  $500 \pm 20$  Hz quasi-periodic oscillation. In the following three observations which sample the rest of the bright part of the outburst, the power spectra are well described by a combination of three zero-centred Lorentzians with  $\nu_{\text{max}}$  at  $\sim 0.002$ ,  $\sim 1$  and  $\sim 15$  Hz. After MJD 55864.5 we only detect evidence for power-law low-frequency noise. Adding all these observations to increase statistics did not reveal any additional feature.

## 4 DISCUSSION

We present *Chandra*, *RXTE*, *Swift*/BAT and *MAXI* data of the X-ray flare and subsequent outburst of EXO 1745–322 in Terzan 5. We show that the active source is the same as that active in 2000 and that the characteristics of the flare are consistent with what is

expected for a superburst. We also show that the outburst may have started just before the superburst onset, although our results are not conclusive due to systematics in the data. The *Swift*/BAT peak in the superburst flux was delayed by about 0.5 d compared to the flux peak on the *MAXI* data. Similar delays between soft and hard energy bands have already been seen in Type-I X-ray bursts (of the order of seconds; see e.g. Lewin et al. 1993; Falanga et al. 2008; Chelovekov & Grebenev 2011) and in at least one superburst (about  $\sim 1000$  s in the LMXB 4U 1820–30; see e.g. in't Zand & Weinberg 2010). These delays have been interpreted as due to photospheric radius expansion (PRE) bursts, where the X-ray intensity first peaks in the low-energy band and later X-rays become visible at higher energies (see e.g. Lewin et al. 1993; in't Zand & Weinberg 2010). The  $\sim 1000$  s duration of the PRE phase in the superburst observed in the LMXB 4U 1820–30 is already at the limit of what current superburst models can explain. Irrespective of the mechanism, the delay we observed in EXO 1745–248's superburst is by far the largest. The fact that it is so much larger may raise the question of its origin being the same as that proposed for Type-I PRE X-ray bursts.

In Section 3.2 we show marginal evidence that EXO 1745–248 may have been detected before the peak of the superburst. In the rest of this section we will discuss the implications of our results on superburst theory, taking into account both the possibilities that the outburst started a few days before or approximately a day after the peak of the superburst. For a discussion on how the superburst emission may have affected the accretion disc to trigger the subsequent outburst, we refer the reader to Serino et al. (2012). We note that if the pre-superburst detections of the source are real, then the superburst most probably momentarily affected the normal outburst evolution (see e.g. Ballantyne & Strohmayer 2004, for the study of the evolution of the accretion disc around the NS system 4U 1820–30 during a superburst).

#### 4.1 Comparison to other superbursts and theoretical implications

Previously, the longest and most energetic superburst known from a hydrogen-accreting source was from 4U 1254–690 (in't Zand et al. 2003a). Unlike for that superburst, we did not observe the start of the superburst from EXO 1745–248, resulting in large uncertainties in the superburst properties. The superburst of EXO 1745–248 is *at least* of equal duration and twice as energetic (Table 1). The largest values of the bolometric radiated energy,  $E_b$ , consistent with the observations, are close to the predicted maximum radiated energy for a superburst set by neutrino emission (Keek & Heger 2011; see also Cumming et al. 2006).

The decay time,  $\tau_{\text{exp}}$ , depends on the thickness of the cooling layer, and, therefore, on the ignition column depth,  $y_{\text{ign}}$ . For 4U 1254–690 the depth was determined using the instantaneous burning model, yielding a depth comparable to the larger values in the range we derive for EXO 1745–248, which are also favoured by

**Table 1.** Comparison to the superburst of 4U 1254–690 (in't Zand et al. 2003b; Cumming et al. 2006).

	EXO 1745–248	4U 1254–690
$\tau_{\text{exp}}$ (h)	6–11	$6 \pm 0.3$
$E_b$ ( $\times 10^{42}$ erg)	2–9	$0.8 \pm 0.2$
$\log(y$ (g cm $^{-2}$ ))	$12.0 \pm 0.3$	12.4
$E_{18}$ ( $\times 10^{18}$ erg g $^{-1}$ )	$>0.1$	0.15

our fits with the same model (Cumming et al. 2006). This suggests that the ignition depths and decay times of the two superbursts likely have similar values. The larger  $E_b$  for EXO 1745–248 can be explained by the burning of more carbon-rich material, which is accommodated by the larger values in the range found for the specific energy release,  $E_{18}$ . Therefore, this is the most energetic and possibly the longest superburst observed to date.

Most superbursting sources, including 4U 1254–690, are observed to accrete continuously at a high rate of around 10 per cent of the Eddington limited rate  $\dot{M}_{\text{Edd}} = 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$  (for solar composition and a 10 km radius; e.g. Keek & in't Zand 2008). The high rate ensures a hot outer crust, forces unstable ignition of the carbon and may be necessary for the production of a mixture of carbon and heavy isotopes that is thought to be the fuel for superbursts (Cumming & Bildsten 2001; see also Cooper, Steiner & Brown 2009). Both sufficient heat and carbon are required for superburst ignition. This scenario was challenged by the observation of the superburst from the NS-transient 4U 1608–522, which occurred only 55 d after the onset of an accretion outburst. Keek et al. (2008) showed that the NS envelope does not heat up quickly enough to explain the ignition of runaway carbon burning. In the past year, three more superbursts have been detected from transient sources, including the one discussed in this paper (for the other detections, see Chenevez et al. 2011 and Asada et al. 2011). Even if we assume that EXO 1745–248 started accreting at an increased rate 0.5 d or even a few days before the superburst (but at levels undetected by *MAXI* and *Swift*/BAT), the time is much too short for the envelope at the derived ignition depths to heat up from either thermonuclear burning in the envelope or from nuclear processes in the inner crust. Therefore, sufficient heat must have been generated at the superburst ignition depth within this short time interval. Currently, there is no known process that could provide this. The case for a substantial additional heat source in the outer crust (close to the superburst ignition depth) has also been made from observations of crustal cooling after outbursts in long-duration transients (Brown & Cumming 2009). The 0.5-d time-scale that we find, however, puts strong constraints on the immediacy with which this heating process must take place.

#### 4.2 On the carbon production

But where does the carbon fuel necessary for a superburst come from? Hydrogen-accreting superburster display a high ratio of the persistent fluence between two (Type-I X-ray) bursts to the burst fluence (in't Zand et al. 2003a), indicating that apart from during Type-I X-ray bursts, a substantial fraction of the accreted hydrogen and helium burns in a stable manner. This is thought to be a required process to produce the carbon fuel for superbursters (Schatz et al. 2003), and it is observed to occur close to an accretion rate of 10 per cent  $\dot{M}_{\text{Edd}}$ , i.e. the rate inferred for most superbursters. During the outburst in 2000, EXO 1745–248 accreted at a comparable rate of on average 17 per cent  $\dot{M}_{\text{Edd}}$  for 2 months (Degenaar & Wijnands 2012), during which there were bursts as well as periods without bursts. In fact, because the quiescent luminosity is over a factor of  $10^4$ – $10^5$  lower ( $L_X$  in quiescence is  $5$ – $7 \times 10^{32}$  erg s $^{-1}$ ; see Degenaar & Wijnands 2012), effectively all of the superburst fuel must have been created in such short outbursts. This conclusion is still valid even if we consider that at the above level of quiescent emission, EXO 1745–248's luminosity might vary by a factor of a few on time-scales of hours to years (which may indicate that the accretion does not fully switch off in quiescence, but continues at a very low rates; see e.g. Wijnands et al. 2005).

During the outburst in 2000, about 8 per cent of the inferred  $y_{\text{ign}} = 1.0 \times 10^{12} \text{ g cm}^{-2}$  was accreted. Using the shortest suggested outburst recurrence time of 11 yr (Degenaar & Wijnands 2012), a superburst recurrence time of 186 yr is inferred, but it may very well be longer (unless the outburst recurrence time is shorter, which would translate into shorter superburst recurrence times). Because of the low average luminosity, the NS is relatively cool, which reduced the carbon-burning rate at the bottom of the accreted pile to allow for sufficient carbon to remain to trigger a thermonuclear runaway after such a long recurrence time.

Of course, we cannot exclude the possibility that the superburst ignition conditions had been almost reached during the previous outburst, such that only a short accretion episode of a few days was required to set it off. Although not impossible, we find it improbable as the outer crust is expected to have reached a higher temperature by heating during the 2-month outburst in 2000 (i.e. conditions more favourable for ignition) than after a few days in 2011.

A more plausible scenario could be that the carbon fuel necessary for a superburst was created mostly during outburst, and then concentrated during the long period of quiescence, as after accretion ceases, there is time for the light and heavy elements to separate out from each other (see e.g. Brown, Bildsten & Chang 2002). An additional potentially important process is chemical separation by freezing at the interface of the ocean and the outer crust (see Medin & Cumming 2011, and references therein). After the previous outburst there was plenty of time for carbon to separate out from iron and heavier isotopes, and so substantially increasing the carbon fraction at the bottom of the accreted column. If this scenario is correct, then it is possible to explain the  $y_{\text{ign}}$  necessary in cases where superburst ignition occurs at early times of the outburst. However, it could be problematic for models, as pure carbon layers have a higher thermal conductivity and will remain colder than impure carbon layers (see Cumming & Bildsten 2001); moreover, upward transport of carbon could make it harder for the carbon to reach ignition depth. In any case, still unexplained is how the NS temperature can rise so quickly at the start of the outburst to be able to ignite the superburst.

The difficulties faced by superburst models that invoke carbon ignition may point to a different fuel for superbursts. In the analysis of bursts from the likely ultracompact X-ray binary 4U 0614+091, Kuulkers et al. (2010) pointed out that in principle helium ignition could explain many of the observed column depths of superbursts. This would require accumulation of a deep and cold layer of helium on the star. Further theoretical work on this scenario is needed, but the fact that the superburst from EXO 1745–248 appears to have one of the largest ignition column depths of known superbursts may place it too deep for helium ignition.

## ACKNOWLEDGMENTS

We thank H. Krimm for his help on the *Swift*/BAT data and J. J. M. in't Zand for insightful discussions. RW acknowledges support from a European Research Council (ERC) starting grant. LK is supported by the Joint Institute for Nuclear Astrophysics (JINA; grant PHY08-22648), a National Science Foundation Physics Frontier Center. ND is supported by NASA through Hubble Postdoctoral Fellowship grant number HST-HF-51287.01-A from the Space Telescope Science Institute. AC, GRS and COH are supported by Discovery Grants from the Natural Sciences and Engineering Research Council of Canada (NSERC). COH is also supported by an Alberta Ingenuity New Faculty Award. JH acknowledges financial support through *Chandra* award GO1-12055B. AC and LK

are members of an International Team in Space Science on Type-I X-ray bursts sponsored by the International Space Science Institute (ISSI) in Bern. DP gratefully acknowledges support provided by the National Aeronautics and Space Administration through *Chandra* Award Number GO1-12055A issued by the *Chandra* X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-03060. We thank the CXC, *RXTE* and *Swift* staff for their quick response to our ToO requests. This research has made use of the *MAXI* data provided by RIKEN, JAXA and the *MAXI* team.

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