Extragalactic fast X-ray transient candidates discovered by *Chandra* (2000–2014)

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**ABSTRACT**

*Context.* Extragalactic fast X-ray transients (FXRTs) are short flashes of X-ray photons of unknown origin that last a few seconds to hours.

*Aims.* Our ignorance about their physical mechanisms and progenitor systems is due in part to the lack of clear multiwavelength counterparts in most cases, because FXRTs have only been identified serendipitously.

*Methods.* We develop a systematic search for FXRTs in the *Chandra* Source Catalog (Data Release 2.0; 169.6 Ms over 592.4 deg2, using only observations with |b| > 10° and before 2015), using a straightforward X-ray flare search algorithm and incorporating various multiwavelength constraints to rule out Galactic contamination and characterize the candidates.

*Results.* We report the detection of 14 FXRT candidates from a parent sample of 214 701 sources. Candidates have peak 0.5–7 keV fluxes between 1 × 10−13 and 2 × 10−10 erg cm−2 s−1 and T90 values from 4 to 48 ks. The sample can be subdivided into two groups: six "nearby" FXRTs that occurred within d ≤ 100 Mpc and eight "distant" FXRTs with likely redshifts ≥ 0.1. Three distant FXRT candidates exhibit light curves with a plateau (~1–3 ks duration) followed by a power-law decay and X-ray spectral softening, similar to what was observed for the previously reported FXRT CDF-S XT2, a proposed magnetar-powered binary neutron star merger event. After applying completeness corrections, we calculate event rates for the nearby and distant samples of 53.7 +12.6 −13.1 and 28.2 +9.8 −9.6 deg−2 yr−1, respectively.

*Conclusions.* This novel sample of *Chandra*-detected extragalactic FXRT candidates, although modest in size, breaks new ground in terms of characterizing the diverse properties, nature, and possible progenitors of these enigmatic events.

**Key words.** X-rays: general – X-rays: bursts

1. Introduction

The *Chandra*, *Swift*, and X-ray Multi-mirror Mission Newton (*XMM-Newton*) observatories have accumulated sensitive 0.5–7 keV imaging observations over the past two decades that cover a sizeable fraction of the sky despite their relatively narrow fields of view. This has enabled the serendipitous discovery and characterization of several novel faint extragalactic transients (e.g., Soderberg et al. 2008; Jonker et al. 2013; Glennie et al. 2015; Irwin et al. 2016; Bauer et al. 2017; Lin et al. 2018, 2019, 2020, 2021, 2022; Xue et al. 2019; Alp & Larsson 2020; Novara et al. 2020; Ide et al. 2020; Pastor-Marazuela et al. 2020; Sazonov et al. 2021). The high angular resolution afforded by these space observatories has been critical for associating counterparts (or lack thereof) and host galaxies with these transients, and hence elucidating their astrophysical nature.

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1 We use the term “counterpart” throughout to denote the multiwave-length detection of emission from the transient.
In general, fast X-ray transients (FXRTs) produce short flashes of X-ray emission with durations from a few minutes to hours. Among the few extragalactic FXRTs that have been identified to date (mainly from systematic searches of serendipitous detections), in only one case, X-ray transient (XRT) 080109/SN 2008D (Mazzali et al. 2008; Soderberg et al. 2008; Modjaz et al. 2009), has it been possible to identify a mult iwavelength counterpart after the initial detection. The most stringent limits come from deep optical Very Large Telescope imaging serendipitously acquired 80 min after the onset of XRT 141001 ($m_g > 25.7$ AB mag; Bauer et al. 2017). Moreover, only a few FXRTs have had clear host-galaxy associations, and even fewer have firm distance constraints (e.g., Soderberg et al. 2008; Irwin et al. 2016; Bauer et al. 2017; Xue et al. 2019). Hence, it is not trivial to discern their energetics and distance scale or, by extension, their physical origin.

Several scenarios could explain the X-ray flares of extra-galactic FXRTs, including the following four. First, in nearby galaxies, X-ray binaries (XRBs) – which includes ultraluminous X-ray sources (ULXs) and quasi-periodic oscillations – soft gamma repeaters (SGRs), quasi-periodic eruptions, and anomalous X-ray pulsars (AXPs) – are possible explanations of FXRTs with $L_{X,peak} \lesssim 10^{42}$ erg s$^{-1}$ (Colbert & Mushotzky 1999; Kaaret et al. 2006; Woods & Thompson 2006; Miniutti et al. 2019; and references therein).

A second scenario involves shock breakouts (SBOs; $L_{X,peak} \approx 10^{42} \text{ to } 10^{47}$ erg s$^{-1}$) from a core-collapse supernova (CC-SN), whereby the X-ray emission is generated from the breakout of the supernova explosion shock once it crosses the surface of an evolved star (e.g., Soderberg et al. 2008; Nakar & Sari 2010; Waxman et al. 2017; Novara et al. 2020; Alp & Larsson 2020). Third are tidal disruption events (TDEs; $L_{X,peak} \approx 10^{42} \text{ to } 10^{50}$ erg s$^{-1}$ considering jetted emission) that involve a white dwarf (WD) and an intermediate-mass black hole (IMBH), whereby X-rays are produced by the tidal disruption and subsequent accretion of the compact WD in the gravitational field of the IMBH (e.g., Jonker et al. 2013; Glennie et al. 2015). The fourth is mergers of binary neutron stars (BNSs; $L_{X,peak} \approx 10^{47} \text{ to } 10^{51}$ erg s$^{-1}$ considering jetted emission; e.g., Dai et al. 2018; Jonker et al. 2013; Song et al. 2015; Bauer et al. 2017; Xue et al. 2019), whereby the X-rays are created by the accretion of fallback material onto the remnant magnetar or black hole (BH).

It has been argued that some of these FXRTs can be related to either long or short gamma-ray bursts (LGRBs or SGRBs, respectively) observed off-axis (e.g., Jonker et al. 2013; Bauer et al. 2017; Xue et al. 2019; Alp & Larsson 2020). Zhang (2013) proposed a type of XRT associated with the merger product of a BNS, a rapidly spinning magnetar, where our line of sight is offset from the jet of an SGRB. Soon thereafter, Luo et al. (2014) and Zheng et al. (2017) identified two new unusual FXRTs in the 7 Ms Chandra Deep Field-South (CDF-S) data set, XRT 141001 and XRT 150321, denoted “CDF-S XT1” and “CDF-S XT2”. These two FXRTs were studied later in detail by Bauer et al. (2017) and Xue et al. (2019), respectively.

In the case of CDF-S XT2, its mult iwavelength constraints and host galaxy properties are consistent with the expected features of off-axis SGRBs (Xue et al. 2019), although other possibilities cannot be completely ruled out (e.g., a TDE origin; Peng et al. 2019). CDF-S XT2 is particularly intriguing because it exhibits a flat, extended X-ray light curve that suggests a magnetar wind origin (Sun et al. 2019; Xiao et al. 2019; Lü et al. 2019), similar to GRB 160821B (Troja et al. 2019) and others and in line with the aforementioned predictions of Zhang (2013). The X-ray afterglows of gamma-ray bursts (GRBs) also show similar plateaus in their light curves (e.g., Lyons et al. 2010; Rowlinson et al. 2013; Yi et al. 2014), suggestive of a central engine related to a magnetar wind or an accreting BH (Troja et al. 2007; Li et al. 2018).

On the other hand, CDF-S XT1 could be associated with a few possible scenarios: (i) an “orphan” X-ray afterglow from an off-axis SGRB with weak optical emission (Bauer et al. 2017; Sarin et al. 2021), (ii) a low-luminosity GRB at high redshift with no prompt gamma-ray emission below ~20 keV rest frame (Bauer et al. 2017), or (iii) a highly beamed IMBH–WD TDE (Bauer et al. 2017; Peng et al. 2019). More recently, Sun et al. (2019) proposed a possible origin as a magnetar remnant of a neutron star merger, viewed at a larger off-axis angle than CDF-S XT2 and strongly obscured by ejecta material at early times. While none of these scenarios completely explain all observed properties, the large redshift uncertainty makes it difficult to discard them outright. Notably, the event rate of CDF-S XT1-like events is comparable to those of orphan and low-luminosity GRBs, as well as TDEs, implying an untapped regime for a known transient class or a new type of variable phenomenon (Bauer et al. 2017).

In order to understand if, and if so how, FXRTs, GRBs, and gravitational wave (GW) events (such as GW 170817; Abbott et al. 2017a; Nakar 2020; Margutti & Chornock 2021; Hajela et al. 2022) are related, we need to enlarge the sample of FXRTs. To this end, Yang et al. (2019) conducted a systematic search for CDF-S XT1- and CDF-S XT2-like objects in ~19 Ms of Chandra blank-field survey data with good ancillary imaging. They constrained the event rate systematically but unfortunately found no new FXRTs. The discovery, confirmation, and characterization of more FXRTs and stricter limits on their number density can place valuable constraints on the unknown electromagnetic (EM) properties of several families of astronomical transients.

In this paper we extend the efforts of Yang et al. (2019) with a search of the entire Chandra Source Catalog 2.0 (CSC2; Evans et al. 2010), identifying 14 extragalactic FXRTs, of which at least three share similar properties to CDF-S XT2 and may be related with off-axis GRBs. We recover five events previously identified and classified as FXRTs by Jonker et al. (2013), Glennie et al. (2015), Bauer et al. (2017), and Lin et al. (2019, 2022).

This manuscript is organized as follows. We explain the methodology and selection criteria in Sect. 2. We present the results of the search and the cross-match with other catalogs in Sect. 2.6, a spectral and timing analysis of our final candidates in Sect. 3, and the properties of the identified potential host galaxies in Sect. 4. In Sect. 5 we discuss possible interpretations of some FXRTs and provide a comparison with other transients. We derive local and volumetric rates for the FXRTs in Sect. 6 and the expected number in current and future X-ray missions. Finally, we present final comments and conclusions in Sect. 7.

Throughout the paper, a concordance cosmology with parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.30$, and $\Omega_{\Lambda} = 0.70$ is adopted. All magnitudes are quoted in the AB system.

2. Methodology and sample selection

We describe below our search algorithm for FXRT candidates in individual Chandra exposures (Sect. 2.1), CSC2 data...
2.1. Algorithm for transient-candidate selection

We adopt the algorithm presented in Yang et al. (2019, see their Sect. 2.2.1), taking into account their timing and spectral properties (power-law with photon index of $\Gamma = 1.7$), a conversion between $F_{\text{peak}}$ and total net counts of $N_{\text{net}} \approx 1.6 \times 10^{14} F_{\text{peak}}$ cts, aperture background count rates of $5.6 \times 10^{-5}$, $2.5 \times 10^{-4}$, and $7.0 \times 10^{-4}$ cts $^{-1}$ for 50, 80 and 110$^\circ$, respectively, and $\log(F_{\text{peak}})$ from $-13.0$ to $-12.6$. The ratio of aperture background count rates at 50', 80' and 110' instrumental off-axis angles are $\approx 9.5, 42$, and 119 times larger than at 0', respectively, highlighting the importance of defining the algorithm’s effectiveness at different locations across Chandra’s field-of-view (FoV). For all simulations, we adopt as the background count rate the median value from the Chandra Deep Field North/South surveys (Xue et al. 2016; Luo et al. 2017; Yang et al. 2019).

Figure 1, left panel, shows the detection probability $P_{\text{det}}$ as a function of $T_{\text{exp}}$, assuming instrumental off-axis angles of 50' (solid lines, representative of ~20th–30th percentile), 80' (dashed lines, representative of ~50th–70th percentile), and 110' (dotted lines, representative of worst case ~100th percentile). It is clear that $P_{\text{det}}$ decreases substantially for events at 80' (by 20–50%) and 110' (by 50–100%) at $\log(F_{\text{peak}}) \lesssim -12.7$ (for reference $\log(F_{\text{peak}}) \lesssim -12.7$ equates to $\approx 32$ counts for a CDF-S XT1-like event), especially at $T_{\text{exp}} \gtrsim 30$ ks. Thus, candidates with large instrumental off-axis angles, which incur higher background levels, subsequently have worse flux sensitivity limits using this algorithm.

To mitigate this problem, we chop each light curve into segments of 20 ks ($T_{\text{window}} = 20$ ks), and carry out Passes 1 and 2 separately on each window. This reduces the integrated number of background counts and thus enables identification of fainter events at larger instrumental off-axis angles. To maintain efficient selection of transients across the gaps between windows, we sequence through the entire light curve in three iterations: a forward division into 20 ks windows plus a remainder window, a backward division into 20 ks windows plus a remainder, and finally a forward division after a 10 ks shift into 20 ks windows plus a remainder window and the initial 10 ks window. As an example, for a 45 ks exposure, we divide it as follows: one iteration with windows of $T_{\text{exp}} = 20, 20, 5$ ks; another iteration with windows of $T_{\text{exp}} = 5, 20$, and 20 ks, and a final iteration with windows of $T_{\text{exp}} = 10, 20, 15$ ks. Then for each separate window of ~20 ks duration, we apply Passes 1 and 2. This window time is well matched to the expected durations for CDF-S XT1 and CDF-S XT2, which have $T_{\text{90}}$ of 5.0$^{+2.3}_{-0.3}$ and 11.1$^{+0.4}_{-0.6}$ ks, respectively; here, $T_{\text{90}}$ measures the time over which the event emits the central 90% (i.e., from 5% to 95%) of the total measured number of counts (Bauer et al. 2017; Xue et al. 2019). We explored how $P_{\text{det}}$ changes considering two other window sizes, $T_{\text{window}} = 10$ and 25 ks. In the case of $T_{\text{exp}} = 10$ ks, $P_{\text{det}}$ decreases by $\approx 30\%$ at $T_{\text{exp}} = 10$ ks, since the window size starts to become comparable to or smaller than the $T_{\text{90}}$ values of the simulated light curves. For $T_{\text{window}} = 25$ ks, $P_{\text{det}}$ does not change dramatically.

This additional modification to the algorithm of Yang et al. (2019, they only chopped observations with exposures longer than 50 ks) is crucial because it allows instrumental off-axis FXRTs to be detected to fainter flux limits and across Chandra’s entire FoV. Indeed, FXRTs previously published by Jonker et al. (2013) and Glennie et al. (2015) were identified at large instrumental off-axis angles (130'). Figure 1, right panel, shows the detection probability $P_{\text{det}}$ considering $T_{\text{window}} = 20$ ks (but otherwise the same conditions as in the previous simula-

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The detection probability ($P_{\text{det}}$) clearly improves by up to several tens of percent, especially for events fainter than $\log(F_{\text{peak}}) \approx -12.7$ and $T_{\text{exp}} \geq 20$–30 ks. We note that Yang et al. (2019) adopted limits of $\log(F_{\text{peak}}) \approx -12.6$, instrumental off-axis angles $\leq 8^\circ$, and $T_{\text{window}} \leq 50$ ks. With the above modification, we increase the chance to recover new FXRTs even at large instrumental off-axis (or high background levels), albeit at lower sensitivity and completeness thresholds.

We confirmed that our algorithm detects FXRTs with different light-curve shapes such as XRT 110103 (where the flux-to-counts conversion factor for this transient is $N_{\text{net}} \approx 3.2 \times 10^{32} F_{\text{peak}}$ cts; Yang et al. 2019). For instance, those of CDF-S XT1 and CDF-S XT2, with main peak durations of $\approx 5$–11 ks, are quite distinct from the events found by Jonker et al. (2013) and Glennie et al. (2015) with peak emission durations of only $\approx 0.1$–0.2 ks. Importantly, our algorithm successfully recovered all these events, and thus is flexible enough to recognize FXRTs with different light-curve shapes. We stress that this is a key advantage compared to matched filter techniques that assume an underlying model profile.

In this work, the false rate of spurious detections is inherited from the CSC2, which serves as our input catalog. The CSC2 includes real X-ray sources detected with flux estimates that are at least 3 times their estimated $1\sigma$ uncertainties in at least one energy band (between 0.2–7.0 keV), while maintaining the number of spurious sources at a level of $\approx 1$ false source per field for a 100 ks observation (Evans et al. 2010, 2019, 2020a). Although this number seems small, spurious events could be an important source of contamination, especially for events without a clear optical or near-infrared (NIR) association. To avoid this problem, we adopt a more restrictive $3\sigma$ cut, which should serve to remove all truly spurious sources (see above). Moreover, we make a final visual inspection to reject potential spurious FXRTs that appear “constant” and associated with known diffuse/extended sources, or vary in the same way that the background varies with time (see Sect. 2.5.5). To summarize, our strict cuts and visual review should produce a final sample that is largely free from spurious contamination.

2.2. Data selection

To extend previous efforts to search for FXRTs, we conducted a search through the CSC2 which provides uniformly extracted properties for 317 167 unique compact and extended X-ray sources (928 280 individual observation detections) identified in 10 382 Chandra Advanced CCD Imaging Spectrometer (ACIS) and High Resolution Camera (HRC-I) imaging observations released publicly through the end of 2014. The sensitivity limit for compact sources in CSC2 is $\approx 5$ net counts (a factor of $\geq 2$ better than the previous catalog release). For uniformity, we consider only ACIS observations in the energy range 0.5–7.0 keV, noting that HRC-I observations comprise only a few percent of the overall observations and have a poorer and softer response and limited energy resolution compared with the ACIS detectors.

The CSC2 database includes a wide variety of astrophysical objects, from galaxy clusters to stellar objects, although the CSC2 does not provide detailed source classifications. To this end, we apply the criteria explained in Sect. 2.1 to select FXRT candidates, while the criteria explained below (Sect. 2.5) are chosen in order to discard objects that are considered contamination to our search. Given the extragalactic nature of the FXRTs CDF-S XT1 and CDF-S XT2 and the high contamination rate from flaring stars (e.g., Yang et al. 2019 recovered CDF-S XT1/XT2 but otherwise only found stellar flares in 19 Ms of data), we limit our initial light-curve search to CSC2 sources with Galactic latitudes $|b| > 10$ deg. A secondary benefit of considering objects with $|b| > 10$ deg is that it helps to minimize the effects of Galactic extinction in characterizing the spectral properties of our candidates. From the previous search developed by

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3 https://cxc.harvard.edu/csc/
Yang et al. (2019), the probability of detecting FXRTs such as decreasing probability of distinguishing FXRTs in short exposures. We adopt an exposure time of 8 ks as a lower bound due to the strongly high-exposure-time tail of the distribution. The vertical dashed blue line indicates the median exposure time (≈32 ks) of the total sample. We adopt an exposure time of 8 ks as a lower bound due to the strongly decreasing probability of distinguishing FXRTs in short exposures.

Yang et al. (2019), the probability of detecting FXRTs such as CDF-S XT1 or CDF-S XT2 decreases dramatically in observations with exposure times <8 ks (similar to our case, where $P_{\text{det}} \leq 0.9$ for events log($F_{\text{peak}}$) $\leq -12.7$; see Fig. 1). Therefore, we exclude such short observations from further study in order to limit uncertainties associated with large completeness corrections when estimating the event rate (see Sect. 6). The above two criteria yield a sample of 214,701 X-ray sources detected within 5303 Chandra observations, equating to ≈169.6 Ms of exposure over $\approx592.4$ deg$^2$; this is roughly nine times more than explored in Yang et al. (2019).

To facilitate our search, we use the full-field per-observation event files available from the CSC2 data products along with the detection properties provided in the CSC2 catalog (Evans et al. 2010). Figure 2 shows the cumulative and histogram distributions of the Chandra observations used in this work as a function of exposure time.

2.3. Generation of light curves

We began by downloading the Chandra full-field per-observation data products from the CSC2 for all CSC2-detected sources with $|b| > 10$ deg. These products are preprocessing following the standard methods developed by the CSC2 (Evans et al. 2010, 2019, 2020a). We use the astropy.io (Astropy Collaboration 2013, 2018) package to extract the photon information.

The event file of full-field observations contains photon event data stored as a table, with information such as photon arrival time, energy, position on the detector, sky coordinates, and observing conditions. One advantage of using Chandra over all other X-ray satellites currently in operation is the low average number of background counts, which enables a robust detection of transient candidates with as few as $\geq10$ total counts (at $\geq99\%$ confidence; e.g., Kraft et al. 1991), allowing searches for faint FXRTs potentially in the CSC2 catalog. To construct light curves, we extract the photon arrival times in the 0.5–7.0 keV range from each event file using an aperture of $1.5 \times R_{90}$ (following the same process developed by Yang et al. 2019), where $R_{90}$ is the radius encircling 90% of the X-ray counts, which is a function of instrumental off-axis (and depends on the photon energy; for more details, see Vito et al. 2016; Hickox & Markevitch 2006). We consider this aperture ($1.5 \times R_{90}$) because, based on simulations by Yang et al. (2019), it encircles $\geq98\%$ of X-ray counts regardless of instrumental off-axis angle. Meanwhile, we calculate $N_{\text{bkg}}$ using an annulus with inner and outer aperture radii of $1.5 \times R_{90}$ and $1.5 \times R_{90} + 20$ pixels, respectively. If the background region overlaps another nearby X-ray source, we mask the nearby source (with radius of $1.5 \times R_{90}$), and do not include the masked area when estimating the background. To correct the source light curve for the effect that background photons would have, we weight $N_{\text{bkg}}$ by the source-to-background area ratio.

The typical counts of our candidates imply that we are in the Poissonian statistical regime, and therefore we adopt the distribution proposed by Kraft et al. (1991) to compute the confidence intervals of the background subtracted light curves (we use the package astropy.stats from Astropy Collaboration 2018). Figure 3 shows example light curves (black circles) detected by our method, as well as light curves for CDF-S XT1 and CDF-S XT2 (red circles) following our extraction methodology.

2.4. Initial candidate results

To summarize, we apply the FXRT detection algorithm to the 0.5–7.0 keV light curves of 214,701 CSC2 sources outside of the Galactic plane ($|b| > 10$ deg, splitting up long exposures into sub-20 ks segments), resulting in 728 FXRT candidates. This sample has total net counts, instrumental off-axis angles and time-averaged fluxes spanning $\approx6.5–42720$ (mean value of 754), $\approx0.3–20.5$ (mean value of 4.4) arcmin, and $F_X \approx 2.6 \times 10^{-16}$ $7.1 \times 10^{-12}$ (mean value of $1.2 \times 10^{-11}$) erg cm$^{-2}$ s$^{-1}$, respectively. As expected, our method selects FXRTs with a diverse range of light curve properties.

2.5. Initial purity criteria

It should be stressed that our search method does not guarantee a high-purity sample of real extragalactic FXRTs. Thus, we adopt some additional criteria based on archival X-ray data (prior and posterior X-ray detections of candidate FXRTs) and multi-wavelength counterparts (e.g., bright stars) to help differentiate real extragalactic FXRTs from Galaxy RX transients and variable among the 728 unique FXRT candidates. We explain and describe these additional criteria below. Table 1 summarizes the number and percentage, relative to the total, of events that pass criteria (column 5), as well as ignoring all previous steps (column 4). Figure 4 shows the steps to select/reject FXRTs taking into account our algorithm described in Sect. 2.1 and the additional criteria that we explain below Sects. 2.5.1–2.5.5. We discuss the completeness of our search and selection criteria in Sect. 2.5.6.

2.5.1. Criterion 1: Archival X-ray data

One important criterion to confirm the transient nature of the FXRT candidates is non-detection in prior and subsequent X-ray observations. We consider separately detections from: Chandra, based on other observations in the CSC2; XMM-Newton, based on individual observations of sources in the Serendipitous Source (4XMM-DR9; Rosen et al. 2016;
Fig. 3. X-ray light curves extracted as described in Sect. 2.3 and identified via our algorithm described in Sect. 2.1. The four light curves in black denote randomly selected sources from initial FXRTs found in the CSC2. For comparison, we show in red the FXRT sources CDF-S XT1 and CDF-S XT2. For visualization purposes, background-subtracted light curves are presented with either 1 ks or 2 ks bins with 1σ errors. In all cases, the vertical dashed gray line represents the end of the observation.

Table 1. Breakdown of FXRT candidates as a function of the selection criteria proposed in Sect. 2.5.

| Criterion                          | # Constrained | # Total removed | # Uniquely removed | # Remaining |
|------------------------------------|---------------|-----------------|--------------------|-------------|
| (1) Archival X-ray data            | 645 (†)       | 558             | 72                 | 170         |
| (2) Cross-match with stars/Gaia    | 728           | 454             | 56                 | 66          |
| (3) NED + SIMBAD + VizieR          | 728           | 525             | 31                 | 29          |
| (4) Archival images (†)            | –             | 9               | 9                  | 20          |
| (5) Instrumental effects (†)       | –             | 6               | 6                  | 14          |

Notes. Column 1: Criterion. Column 2: Number of candidates constrained by this criterion. Column 3: Number of candidates removed that would be cut at this stage if we disregard all previous stages. Column 4: Number of candidates that are solely removed by this criterion, and not any other. Column 5: Running total number of candidates that remain after applying this criterion. †Candidates with additional Chandra-ACIS, XMM-Newton, or Swift-XRT observations. Note that criteria 4 and 5 are only applied to the sources that remain after the first three criteria are applied.

Traulsen et al. 2019; Webb et al. 2020) and Slew Survey Source Catalogues (XMMML2; Saxton et al. 2008); and Swift-XRT based on individual observations in the Swift-XRT Point Source (2SXPS) catalog (Evans et al. 2014). In all cases, we require that the FXRT candidate remain undetected (consistent with zero counts) at 3σ confidence in all observations outside of the one in which the FXRT candidate is found; we convert any detection or limit from the broadest original band to an equivalent 0.5–7.0 keV flux (using PIMMS) assuming a power-law (PL) with slope Γ = 2. This requirement helps to exclude a large number of Galactic flaring sources, but may exclude FXRTs that occur in AGNs or strongly star-forming galaxies. For instance, CDF-S XT1 has 105 additional Chandra observations from the 7 Ms CDF-S survey, and its detection is >5σ higher than the limits from other observations and conforms with our adopted constraints.

The CSC2 provides uniform source extractions for all Chandra observations associated with each candidate, at least up to 2014. For 33 candidates, more recent archival observations also exist. We downloaded and manually extracted photometry for these cases, adopting consistent source and background regions and aperture corrections compared to those used for the CSC2. In total, 580 FXRT candidates were observed in multiple Chandra observation IDs, while 148 candidates have only a single Chandra visit (available in CSC2).

To recover possible XMM-Newton and Swift-XRT detections, we match to the 4XMM-DR9, XMMSL2 and 2SXPS catalogs, adopting a search radius equivalent to the 3σ combined positional errors of the Chandra detection and tentative XMM-Newton or Swift-XRT match.

We additionally search the X-ray upper limit servers FLIX5, 2SXPS6, and ULS7. The latter provides upper limits for many X-ray observatory archives (including XMM-Newton pointed observations and slew surveys; Swift pointed observations; Röntgen Satellite (ROSAT) pointed observations and all-sky survey; Einstein pointed observations), but does not necessarily use the same versions of the reduction pipeline as the first two and has somewhat different area coverage limits for the same observations. Based on visual inspections, we found that the reported detections are not always reliable, and hence

5 https://www.ledas.ac.uk/flix/flix.html
6 https://www.swift.ac.uk/2SXPS/ulserv.php
7 http://xmmuls.esac.esa.int/upperlimitserver/
we require detections to be ≥5σ. We found that: 397 candidates are observed with XMM-Newton, 4XMM-DR9, with 206 candidates detected; 590 candidates are observed with XMM-Newton XMMSSL2, with 6 candidates detected; 351 candidates are observed with Swift-XRT 2SXPS, with 31 candidates detected; 355 candidates are observed with ROSAT pointed observations, with zero candidates detected; 443 candidates are observed with Einstein pointed observations, with 1 candidate detected; finally all candidates are observed with the ROSAT All-Sky Survey, with 30 candidates detected. The upper limits from Chandra and XMM-Newton pointed observations are all comparable to or lower than our FXRT candidate peak fluxes, such that further similar transient behavior would have been detectable in such observations if present. The Swift-XRT, XMM-Newton-Slew, ROSAT, and Einstein limits are not nearly as constraining.

In total, 645 candidates have multiple hard (meaning Chandra, XMM-Newton, or Swift-XRT pointed observations) X-ray constraints, of which 580 candidates have been visited more than once by Chandra. This implies re-detected fractions of at least ≈80% among the candidate sample. On the other hand, 513 candidates have multiple soft (meaning ROSAT or Einstein pointed observations) X-ray constraints, of which 31 candidates have been detected more than once. The implied re-detection fractions are much lower, ≈4%, among the candidate sample, presumably due to the much shallower sensitivities of these past observatories. The high X-ray re-detection fraction indicates that this is a very effective criterion if additional Chandra, XMM-Newton or Swift observations are available. For the remaining 215 candidates that show no additional X-ray detections, we note that, in general, their X-ray constraints are much shallower than the detected sources, and thus we might expect a significant fraction of the data to be persistent/recurrent if observed again for similar exposure times with Chandra or XMM-Newton.

Finally, 170 candidates pass this criterion (see Table 1). Also, it is important to mention that 72 candidates are discarded by this criterion but not by the others. The left panels of Fig. 5 show the net-count and flux distributions for the 170 events that pass this criterion. To conclude, this criterion appears to be an extremely effective means to identify persistent or repeat transients, when data are available.

2.5.2. Criterion 2: Optical detections in Gaia

As discussed in Yang et al. (2019), a large fraction of FXRT candidates are Galactic in origin, associated with relatively bright stellar sources. To identify these, we cross-match with the Gaia Early Data Release 3 (Gaia EDR3; Gaia Collaboration 2021) catalog, which contains relatively uniform photometric and astrometric constraints for more than 1.8 billion sources in the magnitude range G = 3–21 mag across the entire sky, based on observations collected during the first 34 months of its operational phase; these include parameters such as position, parallax, and proper motion in the Milky Way and throughout the Local Group (Lindegren et al. 2018; Gaia Collaboration 2018).

We employ the VizieR package (EDR3 catalog), adopting the MSC2 3σ positional uncertainty associated with each source as our search radius. In general, this search radius is sufficient small to find a unique counterpart, given Chandra’s high spatial resolution and demonstrated astrometric precision (∼0.05′′; Rots & Budavári 2011); 26 candidates show multiple Gaia sources in their cone search area, for which we adopt the nearest Gaia source.

In total, 521 candidates have cross-matched sources in Gaia EDR3. However, we only reject candidates matched to stellar Gaia EDR3 optical detections (i.e., those with significant nonzero proper motion and/or parallax detected at >3σ significance), which amounts to 454 candidates from the initial sample. These stellar counterparts span a wide range in magnitude $G = 10–20.8$ mag ($G ≈ 16.9$ mag) and proper motion $\mu = [0.05 \sim 186]$ mas yr$^{-1}$ ($\mu ≈ 13.7$ mas yr$^{-1}$). To characterize the X-ray sources classified as stars according to Criterion 2, we construct a color-magnitude diagram of their Panoramic Survey Telescope and Rapid Response System (PanSTARRS) archive and Dark Energy Camera (DECam) counterparts (see Fig. B.1) and compare to theoretical isochrones taken from the MESA Isochrones & Stellar Tracks (MIST) package (Dotter 2016; Choi et al. 2016) with different metallicities (from [Fe/H] = −3.0 to +0.5), ages ($\log(Age/yr) = 7.0, 9.0, 10.0,$ and 10.3) and attenuation ($A_V = 0.0$ and 5.0). The sample of X-ray sources classified as stars covers a wide range in the parameter space (see Fig. B.1), as expected for such an inhomogeneous sample of stars.
To identify further known Galactic and Local Group objects, we search for associated objects (counterparts or host galaxies) in several large databases using the astroquery package: the NASA/IPAC Extragalactic Database (NED; Helou et al. 1991), the Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD; Wenger et al. 2000), and VizieR (which provides the most complete library of published astronomical catalogs; Ochsenbein et al. 2000). There is non-negligible redundancy here compared to the previous two searches, as these databases have ingested previous versions of X-ray serendipitous catalogs and Gaia EDR3 in the case of VizieR. To begin, we performed a cone search per candidate considering a radius equivalent to the 3σ positional error to find associated sources. These databases integrate many catalogs across the EM spectrum, helping rule out objects of our sample that were classified previously as stars, young stellar objects (YSOs), or objects associated with globular clusters, nebulae, or high-mass X-ray binaries (HMXBs) in either our Galaxy or the Local Group. However, we should stress that these catalogs are highly heterogeneous, and we must take care to not misinterpret candidate matches. Around 212 candidates have one or more entries in the various databases when cross-correlating to a region encompassing the 3σ uncertainty of the FXRT positions. In all the cases, the multiple entries had the same source classification. We uniquely identify 31 objects in this way, either as YSOs embedded in nebulae or stars identified by other catalogs, for instance, the VISTA Hemisphere Survey (VHS), the United Kingdom InfraRed Telescope (UKIRT) Infrared Deep Sky Survey, the Sloan Digital Sky Survey (SDSS), or the catalog sources from combined the Wide-field Infrared Survey Explorer (WISE) and the near-Earth objects WISE (NEOWISE) all-sky survey data at 3.4 and 4.6 µm (CatWISE) (McMahon et al. 2013; Dye et al. 2018; Marocco et al. 2021). This step is also critical because ≈78% of the initial sample show associated sources in these databases. The right panels of Fig. 5 show the net-count and flux distribution for the 203 events that pass this criterion. Applying all criteria thus far, the sample is reduced to 29 candidates.

The central panels of Fig. 5 show the net-count and flux distributions of the 274 events that pass this criterion. Among the total sample, ≈65% are associated with bright stars, highlighting the importance of this cross-match. Moreover, this criterion discards 56 sources that the other criteria do not. Nevertheless, due to the relatively bright magnitude limit and optical window of the Gaia EDR3 objects with proper motion and parallax constraints, this criterion may not identify all persistent or recurring transient Galactic objects, as we discuss in the next subsection. As a running total, only 63 candidates successfully pass both this and the previous criterion (see Table 1).

2.5.3. Criterion 3: NED, SIMBAD, and VizieR Search

In order to rule out fainter stellar counterparts, we carried out a search of ultraviolet (UV), optical, NIR, and mid-infrared (MIR) image archives; We perform a cone search within a radius equal to the 3σ uncertainty on the Chandra error position of the respective FXRTs (see Table 2) in the following archives: the Hubble Legacy Archive\(^8\); the Pan-STARRS

\(^8\) https://hla.stsci.edu/hlaview.html
a point-like NIR counterparts, and four candidates are identified as stars in Hubble Space Telescope (HST) images. The latter have no clear nearby galaxy associations, suggesting that they are likely field stars, perhaps the fainter tail of the population probed by Gaia DR3. This reduces the number of candidates to 20.

2.5.5. Instrumental effects

As a final step, we perform additional manual and visual cross-checks to rule out false positive candidates that might arise from background flares, bad pixels or columns, or cosmic-ray afterglows. Again, we only undertake this step for the remaining candidates after Sect. 2.5.4. To rule out events that occur during strong background flaring episodes (≥3σ mean value) in the energy range 0.5–7 keV, we employ the dmextract script (excluding counts associated with X-ray sources identified by CSC2 in the Chandra FoV) to investigate the evolution of the background count rate during the observations. Using the deflare script, we identify and reject six candidate FXRTs found in a circular region with radius ≈40 around the planetary nebula (PN) NGC 246 in the Chandra observation ID 2565 that are affected by background flares, reducing the number of candidates to 14. We confirm that none of the remaining 14 sources is caused by detector artifacts (bad columns or hot pixels) or are associated with bad quality flags (confused source and background regions or saturation) in the CSC2 catalog entries. Furthermore, we confirm that the counts from all sources are detected in (many) dozens to hundreds of individual pixels tracing out portions of Chandra’s Lissajous dither

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**Table 2. Properties of the extragalactic FXRT candidates detected or discussed in this work, ordered by subsample and date.**

| FXRT | Id     | ObsId | Exp. (ks) | Date   | T_W (ks) | RA (deg) | Dec (deg) | Off. Ang. | Flux | Pos. Unc. | HR | S/N  |
|------|--------|-------|-----------|--------|----------|----------|-----------|-----------|------|-----------|----|------|
| 1    | XRT 000519 | 803   | 31.0      | 2000-05-19 | 11.6±0.9 | 186.38125 | 13.06670 | 133      | 6.4e-13 | 1±8       | -0.59±0.02 | 35.1 |
| 2    | XRT 010908 | 2025  | 61.5      | 2001-09-08 | 25.7±2.3 | 167.68792 | 55.67253 | 25       | 9.2e-15 | 1±06      | -0.21±0.13 | 6.2  |
| 3    | XRT 070350 | 8490  | 97.2      | 2007-05-30 | 29.8±1.3 | 201.24329 | -43.04060 | 4.1      | 2.6e-15 | 1±3       | -0.68±0.17 | 4.6  |
| 4    | XRT 071203 | 9546  | 31.8      | 2007-12-03 | 25.3±1.4 | 211.25113 | 53.65706 | 7        | 7.0e-15 | 1±13      | -0.59±0.14 | 5.2  |
| 5    | XRT 080331 | 5487  | 31.6      | 2008-03-31 | 32.8±2.0 | 170.07296 | 12.97189 | 0.9      | 2.0e-14 | 1±0    | -0.73±0.05 | 12.0 |
| 6    | XRT 130822 | 14904 | 22.8      | 2013-08-22 | 12.1±2.4 | 345.49250 | 15.94871 | 1.6      | 6.3e-15 | 0±29      | -0.46±0.17 | 4.6  |

**Notes.** Column 1: Shorthand identifier (FXRT #) used throughout this work. Column 2: X-ray transient identifier (XRT date), plus previous name when available. Columns 3–5: Chandra observation ID, exposure time in units of ks, and date. Column 6: T_W duration, which measures the time over which the event emits the central 90% (i.e., from 5% to 95%) of its total measured counts, in units of ks. Columns 7 and 8: Right ascension and declination in J2000 equatorial coordinates. Column 9: Instrumental o flux uncertainty, defined as HR = S, where H = 2–7 keV and S = 0.5–2 keV energy bands, using the Bayesian estimation of Park et al. (2006). Column 13: Approximate signal-to-noise ratio (S/N).

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9 http://pslimages.stsci.edu/cgi-bin/plcutouts
10 https://databib.noirlab.edu/query.php
11 https://archive.gemini.edu/searchform
12 http://archive.eso.org/scienceportal
13 http://horus.roe.ac.uk/vasa/
14 https://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/
15 http://wsa.roe.ac.uk/
pattern (appearing as a sinusoidal-like evolution of \(x\) and \(y\) detector coordinates as a function of time; see Fig. A.2) over their duration, which reinforces that they are real astrophysical sources. Therefore, we have a final sample of 14 FXRTs.

2.5.6. Completeness

Below, we explore the probability that real FXRTs might have been discarded erroneously. To estimate this, we determine the likelihood that the position of a candidate FXRT overlaps, by chance, that of another X-ray source and/or star. The probability (assuming Poisson statistics; \(P(k, \lambda)\)) of one source (\(k = 1\) being found by chance inside the \(3\sigma\) localization uncertainty region of another is

\[
P(k = 1, \lambda) = \frac{e^{-\lambda} \lambda^k}{k!},
\]

where \(\lambda\) is the source density of X-ray sources and/or stars on the sky multiplied by the \(3\sigma\) Chandra localization uncertainty area. To measure the X-ray or optical source density, we consider X-sky multiplied by the 3

\[
\lambda = \frac{\sigma}{\sin\theta}
\]

\[
\text{where } \sigma \text{ is the source density of X-ray sources and/or stars on the sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area. To measure the X-ray or optical source density, we consider X-sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area.}
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\frac{\sigma}{\sin\theta}
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\text{of one source (} k = 1\text{) being found by chance inside the } 3\sigma \text{ localization uncertainty region of another is}
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\text{where } \lambda \text{ is the source density of X-ray sources and/or stars on the sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area. To measure the X-ray or optical source density, we consider X-sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area.}
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\text{where } \lambda \text{ is the source density of X-ray sources and/or stars on the sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area. To measure the X-ray or optical source density, we consider X-sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area.}
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\frac{\sigma}{\sin\theta}
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\text{of one source (} k = 1\text{) being found by chance inside the } 3\sigma \text{ localization uncertainty region of another is}
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\[
\text{where } \lambda \text{ is the source density of X-ray sources and/or stars on the sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area. To measure the X-ray or optical source density, we consider X-sky multiplied by the } 3\sigma \text{ Chandra localization uncertainty area.}
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\frac{\sigma}{\sin\theta}
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\text{of one source (} k = 1\text{) being found by chance inside the } 3\sigma \text{ localization uncertainty region of another is}
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P(k = 1, \lambda) = \frac{e^{-\lambda} \lambda^k}{k!},
\]
Swift (red), and Chandra first photon to the end of the exposure, in units of count rate (cts s$^{-1}$). For non-detections, in units of counts (second column of Table 3). Upper limits were derived when the source was not detected in the exposure or when the exposure was not long enough to detect it. All the fluxes are reported in the 0.5–7 keV band in the observer’s frame. In the case of FXRT 4 in Col. 4, additional data points are partially blocked by the blue star.

FXRT 12) where we could only derive upper limits to the presence of a host or counterpart in moderate-depth imaging; typical limits we derive are $m_r > 23.7$ and $m_i > 22.4$ AB mag. Note that the fields of FXRT 1 and FXRT 14 have been observed by Jonker et al. (2013) and Bauer et al. (2017), respectively. In Table 3 we list the position, angular offset, and magnitudes of the candidate optical/NIR counterparts or host galaxies when available, and upper limits when not. We briefly describe the counterpart or host galaxy constraints for each FXRT below.

FXRT 1/XRT 000519 (identified previously by Jonker et al. 2013) is located in the outskirts of the galaxy M86 ($m_R = 8.6$ AB mag.)
Fig. 6. continued.

mag; \(\approx 17\) Mpc) in the Virgo cluster, at an angular (projected) distance of 12/2 (\(\approx 60\) kpc). This association is still under debate; the Poisson probability of a chance alignment is \(3.6 \times 10^{-6}\) based on its angular offset and the space density of \(m_g < 9\) mag galaxies (using the GLADE catalog; Dálya et al. 2018), implying a possible association; however, the binomial probability that this FXRT is a background source is \(\approx 0.3\), indicating that the association with M86 is weak (see Sect. 3.5 for more details). The transient was previously reported by Jonker et al. (2013) to have two tentative counterparts with \(m_i = 24.3\) AB mag (with an offset of 0'8) and \(m_g = 26.8\) AB mag (with an offset of 1'2) in deeper images taken by the Isaac Newton Telescope (INT) and the Canada France Hawaii Telescope (CFHT), respectively (Jonker et al. 2013).

FXRT 2/FXRT 010908 (cataloged as an X-ray source by Wang et al. 2016; Liu 2011; and Mineo et al. 2012, although never classified as an FXRT), a local FXRT, is located in the disk of the edge-on SB(s)cd galaxy M108 (also known as NGC 3556; \(m_R = 9.2\) AB mag and \(\approx 9.0\) Mpc; Dálya et al. 2018; Tully et al. 2013), at an angular (projected) distance of 0'4 (\(\approx 1.1\) kpc). The probability of a chance alignment is \(3.2 \times 10^{-6}\) based on its angular offset and the space density of \(m_R < 9.2\) AB mag galaxies (using the GLADE catalog; Dálya et al. 2018), thus implying a highly probable association; the binomial probability
that this FXRT is a background source is $8.4 \times 10^{-7}$, reinforcing an association with M108 (see Sect. 3.5 for more details). FXRT 2 appears to lie at the edge and intersection of two extended star-forming regions (see Fig. 7, sources #1 and #2 in the northeast and southwest directions, respectively), with several potential, unresolved, optical/NIR candidate counterparts in the HST F606W image inside the Chandra 3σ error circle. The estimated magnitudes of sources #1 and #2 are $m_{F606W} = 18.4$ and 18.2 AB mag (i.e., $M_{F606W} \simeq -11.4$ and $-11.6$ AB mag), respectively (taken from the HSCv3; Whitmore et al. 2016). As such, FXRT 2 is likely associated with a region of enhanced high-mass star formation.

FXRT 3/XRT 070530 (cataloged as an X-ray source by Liu 2011 and Wang et al. 2016, although never classified as an FXRT) is located in the S0 peculiar galaxy NGC 5128 (Cen A; $m_R \approx 6.3$ AB mag; $\approx 3.1$ Mpc), at an angular (projected) distance of 5.5′ ($\approx 5.0$ kpc). The probability of this association occurring by chance is $3.6 \times 10^{-5}$ based on the FXRT–galaxy offset and the space density of $m_R < 12$ AB mag galaxies, thus implying a highly probable association; the binomial probability that this FXRT is a background source is $1.7 \times 10^{-2}$, reinforcing an association with NGC 5128 (see Sect. 3.5 for more details). There are several dozen possible faint counterpart candidates within the 3σ X-ray error region in the HST F606W and F814W images.
(typically $m_{F606W}$ and $m_{F814W} \geq 25$ AB mag; see Fig. 7), of which one very red object stands out near the center (source #1 in Fig. 7) with $m_{F606W} = 25.4$ and $m_{F814W} = 22.1$ AB mag ($M_{F606W} = -2.1$ and $M_{F814W} = -5.4$ AB mag, respectively; taken from the HSCv3; Whitmore et al. 2016) or from DECam $m_z = 22.3$ and $m_y = 21.7$ AB mag ($M_z = -5.2$ and $M_y = -5.7$ AB mag), which might be typical of either a small globular cluster or a red supergiant star. Based on the lack of young stars in the local host environment, we associate FXRT 3 with the former.

FXRT 4/XRT 071203 (cataloged as an X-ray source by Mineo et al. 2012 and Wang et al. 2016, although never classified as an FXRT) is located in the SA(s)cd peculiar dwarf galaxy NGC 5474 ($m_R = 10.8$ AB mag; $\approx 5.9$ Mpc), at an angular (projected) distance of 0′.4 ($\approx 0.7$ kpc). NGC 5474 is a highly asymmetric late-type peculiar dwarf galaxy in the M101 group, thought to be interacting with M101. The probability of this occurring by chance is $1.9 \times 10^{-6}$ based on its angular offset and the space density of $m_R < 10.8$ AB mag galaxies, thus implying a highly probable association; the binomial probability that this FXRT is a background source is $\approx 9.9 \times 10^{-4}$, reinforcing an association with NGC 5474 (see Sect. 3.5 for more details). The FXRT candidate appears to lie at the center of a resolved blue star cluster with a spatial extent of $\approx 40$ pc, with $\approx 10$ candidate unresolved optical/NIR counterparts in HST imaging inside the Chandra 3σ error circle (Fig. 7 shows the four most obvious optical and NIR counterparts). The majority of the candidate counterparts have blue colors, with brightness
Table 3. Host and/or counterpart’s photometric data or upper limits of FXRT candidates.

| FXRT | ID   | $m_B$ | $m_V$ | $m_R$ | $m_J$ | $m_H$ | $m_K$ | $W_1$ | $W_2$ |
|------|------|-------|-------|-------|-------|-------|-------|-------|-------|
|      | (1)  | (2)   | (3)   | (4)   | (5)   | (6)   | (7)   | (8)   | (9)   |
|      |      |       |       |       |       |       |       |       |       |
|      |      |       |       |       |       |       |       |       |       |
|      |      |       |       |       |       |       |       |       |       |

**Notes.** All magnitudes are converted to the AB magnitude system using González-Fernández et al. (2018) for VHS and 2MASS data, Hewett et al. (2006) for UKIDSS data, and Wright et al. (2010) for unWISE data. If an optical/NIR counterpart candidate is detected, we list its magnitude and 1σ error, otherwise we provide 3σ limits from several catalogs: Pan-STARRS-D2 (Flewelling 2018), UKIDSS-DR11 (Warren et al. 2007), unWISE (Schlafly et al. 2019), DES-D2 (Abbot et al. 2021a), NSC-DR2p (Nidever et al. 2021), 2MASS (Skrutskie et al. 2006), VHS-D5 (McMahon et al. 2013), SDSS-DR16 (Ahuadat et al. 2020), INT/CHFT (Jonker et al. 2013), CANDELS (nearest HST/Spitzer bands substituted: $g = F435W$, $r = F606W$, $i = F814W$, $z = F850LP$, $Y = F105W$, $J = F125W$, $H = F160W$, $W1 = ch1$, $W2 = ch2$; Guo et al. 2013). We omit entries for FXRTs 4 and 5, as both candidates have up to 10 potential counterparts in HST images. (1) Photometric data of FXRTs with counterpart(s) (S=# means the source number). (1) Obtained using a photometric aperture of 3.7 pixels.

peaking in F275W and F606W with $m_{F275W} \approx 21.6-23.0$ and $m_{F606W} \approx 22.2-22.9$ AB mag (i.e., $M_{F275W} \approx -5.9$ to $-7.3$ and $M_{F606W} \approx -6.0$ to $-6.7$ AB mag, and hence consistent with O stars), while source #3 is redder, peaking between F814W and F160W, with $m_{F606W} \approx 22.3$ and $m_{F814W} \approx 22.1$ AB mag (i.e., $M_{F606W} \approx -6.5$ and $M_{F814W} \approx -6.7$ AB mag, respectively, typical of a massive red supergiant star). The photometric data are taken from the HSC3 (Whitmore et al. 2016). As such, FXRT 4 is likely associated with a region of enhanced high-mass star formation.

FXRT 5/XRT 080331 (cataloged as an X-ray source by Wang et al. 2016 and Sazouno & Khabibullin 2017, although never classified as an FXRT) is located in the disk of the SAB(s)b galaxy M66 ($m_B = 9.6$ AB mag, $\approx 11$ Mpc), at an angular (projected) distance of 1′′ ($\approx 4.3$ kpc). M66 is a barred spiral galaxy in the Leo group. The probability of this occurring by chance is 2.8 × 10^{-6} based on its offset and the space density of $m_g < 9.6$ AB mag galaxies, implying a highly probable association; the binomial probability that this FXRT is a background source is $\approx 3.9 \times 10^{-3}$, reinforcing an association with M66 (see Sect. 3.5 for more details). The FXRT candidate error region is located in a high extinction region of the disk, at the edge of the bar, with very few optical counterpart candidates ($\approx 10$ sources). However, the X-ray centroid is notably well aligned with two knots of strong Hα emission (sources 1 and 2 in the HST/ACS-F658N image of Fig. 7) with $m_{658N} \approx 21.0$ AB mag (or $M_{658N} \approx -9.2$ AB mag). This suggests a link with a high-mass star formation region, while the 3σ error circle encompasses at least ten fainter, unresolved candidate counterparts in the F110W and F160W images ($m_{160W} \approx 22.5$ or $M_{160W} \approx -7.7$ AB mag).

FXRT 6/XRT 130822 (cataloged as an X-ray source by Wang et al. 2016, although never classified as an FXRT) is situated in the outskirts of the galaxy NGC 7465 ($m_B = 12.0$ AB mag; $\approx 27$ Mpc), which is part of the merging NGC 7448 group, at an angular (projected) distance of 1′′ (9.4 kpc). The probability of this occurring by chance is $1.5 \times 10^{-4}$ based on its offset and the space density of $m_B \approx 12$ AB mag galaxies, thus implying a probable association; the binomial probability that this FXRT is a background source is $\approx 1.5 \times 10^{-2}$, reinforcing an association with NGC 7465 (see Sect. 3.5 for more details). The FXRT position overlaps with a blue spiral arm and lies between two diffuse blue candidate sources in DECam images (see Fig. 7, sources #1 and #2 in g- and r-band images). These have offsets of $\approx 1′′$ to the northwest and $\approx 1′$ to the northeast, respectively, which lie just slightly outside of the 3σ X-ray error region, but their proximity suggests that FXRT 6 is likely associated with a region of high-mass star formation.

For FXRT 7/XRT 030511 (identified previously by Lin et al. 2019, 2022), no optical and NIR sources are detected within the 3σ X-ray error region of this event in the DECam, VISTA, or unWISE images (see Fig. 7). Upper limits are given in Table 3.

FXRT 8/XRT 041230 lies close to a $m_B = 33.1$ AB mag source, at an angular distance of 0′′7, detected in DECam and VISTA images (see Fig. 7, source #1). The probability of a false match (adapting the formalism developed by Bloom et al. 2002) is $P < 0.003$ for such offsets from similar or brighter objects. We analyze the properties of this extended optical/NIR source in detail in Sect. 4.

FXRT 9/XRT 080819 lies close to a $m_B = 21.1$ AB mag source, at an angular distance of 0′′5, detected in DECam, VISTA, and unWISE images (see Fig. 7, source #1). The probability of a false match is $P < 0.0004$ for such offsets from similar or brighter objects. We analyze the properties of this extended optical/NIR source in detail in Sect. 4.

Regarding FXRT 10/XRT 100831, no optical/NIR sources are detected within the 3σ X-ray error region of this event in the DECam or 2MASS images; upper limits are given in Table 3.

There is a moderately bright, marginal DECam object, at an angular distance of 2′′6, just outside the 3σ error region to the northeast (see Fig. 7, source #1 in the i-band DECam image).

Regarding FXRT 11/XRT 110103 (identified previously by Glennie et al. 2015), no optical/NIR sources are detected within the 3σ X-ray error region of this event in the DECam, Pan-STARRS, or VISTA imaging (see Fig. 7); upper limits are given in Table 3. This FXRT was discovered in an observation of the galaxy cluster Abell 3581 (at a distance of 94.9 Mpc; Johnstone et al. 2005; Glennie et al. 2015), where
the nearest known member of the cluster, LEDA 760651 (\(m_J \approx 16.7\) AB mag), is 27′ (\(\approx 71.4\) kpc) from the Chandra transient position (Glennie et al. 2015). The probability of this occurring by chance is 0.15 based on its offset and the space density of \(m_J < 16.7\) AB mag galaxies, thus implying a low probability of association; the binomial probability that this FXRT is a background source is \(\approx 7.8 \times 10^{-2}\), reinforcing an unlikely association with LEDA 760651 (see Sect. 3.5 for more details).

Regarding FXRT 12/XRT 110919 (identified previously by Lin et al. 2019, 2022), no significant optical and NIR sources are detected within the 3σ X-ray error region of this event in the DECam, VISTA or unWISE imaging (see Fig. 7) and catalogs, although we note that a marginal source (\(\lesssim 2\sigma\)) appears in red filters (DECam z-band and VISTA K-band); upper limits are given in Table 3.

FXRT 13/XRT 140327 lies close to a faint, \(m_I \approx 24.7\) AB mag source (see Fig. 7, source #1), at an angular distance of 1′.5, detected in DECam i-band and marginally visible in r-band imaging. The probability of a false match is \(P < 0.004\) for such offsets from similar or brighter objects.

Finally, FXRT 14/XRT 141001/CDF-S XT1 (identified previously by Bauer et al. 2017) lies close to a faint \((m_R = 27.2\) and \(m_I = 27.1\) AB mag) or \(M_R = 19.0\) and \(M_I = 19.1\) AB mag, respectively, assuming \(z_{\text{phot}} = 2.23\), extended (\(r_{\text{core}} = 0′.56\)) optical and NIR source in HST imaging (see Fig. 7), with an angular offset of 0′.13.

Overall, we find that six of the 14 FXRT candidates (FXRT 1–6) have high probabilities of being associated with nearby galaxies (<30 Mpc; FXRTs 2–5 show clear potential counterparts and FXRT 6 lies on top of faint optical emission, while FXRT 1 is still under consideration to be a distant event; Eppchen et al. 2022)\(^\#\) Among the other eight candidates, three (FXRTs 8, 9, and 13) are coincident with moderately bright extended sources within the 3σ position error, FXRT 14/CDF-S XT1 is coincident with a faint extended source, and for three (FXRTs 7, 10, and 12) no optical or IR emission is detected to moderate-depth limits (\(m_I \approx 24.5\) AB mag). In the case of FXRT 11, we do not discard its association with nearby galaxies completely (~94.9 Mpc); however, a relation with a background source could be more likely. Finally, based on arguments given in Sect. 3.4, FXRTs 7, 10, 11, and 12 are highly likely to be extragalactic and have relatively distant and faint optical or NIR hosts similar to or fainter than CDF-S XT1.

2.6.2. Higher energy counterparts

To investigate if the sky locations of the FXRTs are covered by hard X-ray and γ-ray observations, we performed a cone search in the Swift-Burst Alert Telescope (Swift-BAT; Sakamoto et al. 2008), International Gamma-Ray Astrophysics Laboratory (INTEGRAL; Rau et al. 2005), High Energy Transient Explorer 2 (HETE-2; Hurley et al. 2011), InterPlanetary Network (Ajello et al. 2019), and Fermi (von Kienlin et al. 2014; Narayana Bhat et al. 2016) archives. We adopt a 10′ search radius for the INTEGRAL, Swift-BAT, HETE-2 and InterPlanetary Network Gamma-Ray Bursts catalogs, while for the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT) Fermi Burst catalogs we take a search radius of 4 deg (which represents typical source positional uncertainties at the \(\approx 68\%\) confidence level for those detectors; Connaughton et al. 2015). We find no hard X-ray or γ-ray counterparts associated with INTEGRAL, Swift-BAT, HETE-2, and InterPlanetary Network catalogs. Some of the nearby (FXRTs 3, 4, and 6) and distant (FXRTs 7, 8, and 9) candidates have a potential gamma-ray association in the GBM Fermi Burst catalog; however, we rule out their association for FXRTs 3, 4, 6, 7, and 8 because of a large difference in time between the FXRT and gamma-ray detection (>4 years).

In the case of FXRT 9, it has a GBM Fermi GRB detection (called GRB 080812 at \(\alpha = 11^h46^m48^s\), \(\delta = -33^\circ12'\)) seven days before the Chandra trigger, with an offset of \(\approx 1.9\) deg, positional uncertainty of 4.1 deg, and \(T_{\text{90}}\approx 15\) s (Narayana Bhat et al. 2016). In an on-axis scenario, the beamed X-ray emission should be detected effectively concurrently with the GRB; this is inconsistent with the observed light curve shown in Fig. 6. For an off-axis scenario, a delay between the gamma-ray trigger and its peak X-ray afterglow depends on both intrinsic (e.g., the off-axis angle and the deceleration timescale of the outflow) and extrinsic (e.g., the low densities density of the BNS environment and the observer location) properties (e.g., Granot et al. 2002, 2018a,b; Troja et al. 2020; Lamb et al. 2021), effectively spanning all timescales. Strong X-ray flares have been known to occur on top of X-ray afterglow emission, but these typically occur during the early phase of the afterglow (\(\lesssim 10^{-2}\)–\(10^{-4}\) s; e.g., Yi et al. 2016). As such, an association between GRB 080812 and FXRT 9 seems unlikely.

In summary, none of our FXRT candidates has an associated detection at hard X-ray or gamma-ray wavelengths.

2.6.3. Radio counterparts

To search for possible radio counterparts to our FXRT candidates, we utilize the RADIO–Master Radio Catalog, which is a periodically revised master catalog that contains selected parameters from a number of the HEASARC database tables that hold information on radio sources from 34 MHz to 857 GHz. This catalog contains inputs from several telescopes and surveys such as the Australia Telescope Compact Array, the Very Large Array, the Very Long Baseline Array, and the Wilkinson Microwave Anisotropy Probe. Given the relatively poor angular resolution of some of these radio telescopes, we perform an initial cone search for radio sources within 60′. Only FXRTs 2, 4, and 5, all of which are associated with hosts at \(\lesssim 10\) Mpc, have radio sources within 60′. Following this initial 60′ cut, we refine our search using limiting radii consistent with the combined radio + X-ray 3σ positional errors, which yields no matches. Due to their mutual association with nearby galaxies, we cannot rule out a chance association, as the radio emission could easily arise from other mechanisms within the host galaxies. Therefore, we conclude that none of the FXRTs is unambiguously detected at radio wavelengths.

3. Spatial, temporal, and X-ray spectral properties

We investigate the spatial distribution of the final sample of FXRT candidates in Sect. 3.1. Furthermore, the X-ray temporal and spectral properties can provide essential information about the origin and physical processes behind the FXRT candidates, and thus we describe these in Sects. 3.2 and 3.3, respectively. With these in hand, we revisit whether any of the remaining FXRT candidates could be Galactic stellar flares in Sect. 3.4. Finally, we explore the robustness of the existence of two populations of FXRTs in Sect. 3.5.

\(^\#\) We caution that the probabilities calculated above could be overestimated, depending on the targeting biases among the Chandra observations.
3.1. Spatial properties

If the FXRT candidates are extragalactic, and given the isotropy of the universe on large scales, we expect the FXRT spatial distribution to be randomly distributed on the sky (see Fig. 8). First, we investigate the sky distribution of all the Chandra observations considered in this work using the nonparametric Kolmogorov–Smirnov (K–S) test (Kolmogorov 1933; Massey 1951; Ishak 2017). We generate 5303 points (equal to the total number of observations in the CSC2 at \( |b| > 10 \) deg) randomly distributed (in Galactic coordinates), and we compare the generated random distributions and the real Chandra observations using a 2D K–S test following Peacock (1983) and Fasano & Franceschini (1987). We performed this process 10 000 times. As a result, we found that the null hypothesis \( NH \) that the random sample and the real data come from the same distribution is rejected in \( \approx 20\% \) of the draws (rejection of \( NH \) occurs when \( P < 0.05 \)). This is not surprising, since the Chandra pointings are not completely random and some sky regions are observed much more often than others (e.g., Magellanic clouds, Chandra Deep Field South/North; Tananbaum et al. 2014; Wilkes & Tucker 2019).

Next, we investigate whether the spatial distribution of the sample of FXRT candidates is random. Here we simulate 10 000 samples of 214701 random sources (i.e., the number of X-ray sources analyzed in this work) distributed over the sky, taking as a prior distribution the CSC2 sky positions (which are functions of the pointings and exposures). Out of these 214701 source we randomly select 14 sources, which we compare to the spatial distribution of the 14 FXRT candidates. We can reject the null hypothesis that these sources are drawn from the same (random) distribution only in \( \approx 0.25\% \) of the draws. Therefore, we conclude that the sample of 14 FXRT candidates are randomly distributed over the Chandra CSC2 observations of the sky.

3.2. Temporal properties

We characterize the X-ray light curves of the candidate FXRTs using single PL and broken power-law (BPL) models, and measure the break times and light-curve slopes. Both models describe the majority of the X-ray light curves well, although FXRTs 1, 4, 5, and 11 have more complex light curves and are not well described by these simple models. Nevertheless, in what follows we describe the most important results of these fits. The PL model is given by

\[
F_{\text{PL}}(t) = F_0 \times t^{-\alpha},
\]

where \( \alpha \) and \( F_0 \) are the PL index and normalization, respectively. Moreover, the BPL model takes the form

\[
F_{\text{BPL}}(t) = F_0 \times \left( \frac{t_2}{t_1} \right)^{-\alpha} \quad \text{for } t \leq t_{\text{break}},
\]

\[
F_{\text{BPL}}(t) = F_0 \times \left( \frac{t_2}{t_1} \right)^{-\alpha} \quad \text{for } t > t_{\text{break}},
\]

where \( t_{\text{break}} \), \( t_1 \), \( t_2 \), and \( F_0 \) are the break time, the PL slope before and after the break, and normalization, respectively. The best-fit model parameters and statistics are given in Table 4, while the light curves (in flux units; light curves have five counts per bin, except FXRT 1, which has ten counts per bin) and best-fit models are shown in Fig. 9. We used the Bayesian information criterion (BIC)\(^\text{17} \) to determine which of the two models describes the data best.

For events where the adopted model does not provide a statistically good fit (because of the complex light curve shape), we only explain their main characteristics. We define the light curve zero point \((T = 0 \) s\) as the time when the count rate is 3\( \sigma \) higher than the Poisson background level\(^{18} \). The light curves and the fits (where applicable) are shown in Fig. 9, while the model fit results are given in Table 4 for all the FXRTs. We briefly describe the timing properties for each candidate.

The light curve of FXRT 1/XRT 000519 exhibits a strong flare at \( \approx 9.6 \) ks into the observation. It has some faint precursor emission (not shown in Fig. 9) during the \( \sim 4 \) ks

\(^{17} \) BIC = \( -2 \ln L + k \ln N \), where \( L \) is the maximum value of the data likelihood, \( k \) is the number of model parameters, and \( N \) is the number of data points (Ivezić et al. 2014).

\(^{18} \) It is important to note that the light curve parameters (slopes and break time) can change considering different zero points, especially for FXRTs with high background levels and/or high offset angles. For instance, in Bauer et al. (2017) and Xue et al. (2019), the zero point is arbitrarily set to be 10 seconds before the arrival of the first photon. This is consistent with our method and does not change interpretations because of the low background level of both observations.
Table 4. Best-fit parameters obtained using a broken power-law (BPL) and a power-law (PL) model fit to the X-ray light curves.

| FXRT   | ID   | $T_0$(UTC) | Model   | $T_{\text{break}}$(ks) | $\tau_1$ | $\tau_2$ | $F_0$ (erg cm$^{-2}$ s$^{-1}$) | $\ln{L}$ (d.o.f.) | BIC   |
|--------|------|------------|---------|------------------------|---------|---------|-------------------------------|------------------|-------|
|        |      |            |         |                        |         |         |                               |                  |       |
| 1      | XRT 000519 | 2005-05-19 10:39:36.30 | BPL     | 5.9 ± 0.1              | 0.0 ± 0.1 | 1.7 ± 0.3 | (3.6 ± 0.7) × 10$^{14}$ | 177.1/8          | 344.2 |
|        |      |            | PL      | –                      | –        | –        | –                            | –                | –     |
| 2      | XRT 010908 | 2001-09-08 14:34:53.43 | BPL     | 15.1 ± 0.1             | –0.1 ± 0.1 | 0.8 ± 0.2 | (1.9 ± 0.7) × 10$^{14}$ | 108.3/3           | 212.2 |
|        |      |            | PL      | –                      | –0.2 ± 0.1 | –        | (2.5 ± 1.5) × 10$^{14}$ | –                | –     |
| 3      | XRT 070530 | 2007-05-30 06:15:13.58 | BPL     | 8.1 ± 0.1              | 1.0 ± 0.1 | 3.0 ± 0.2 | (1.1 ± 0.1) × 10$^{15}$ | 94.9/9            | 186.3 |
|        |      |            | PL      | –                      | –        | –        | –                            | –                | –     |
| 4      | XRT 071203 | 2007-12-03 08:49:55.59 | BPL     | 12.3 ± 1.2             | 0.2 ± 0.1 | 4.1 ± 0.1 | (6.1 ± 0.8) × 10$^{15}$ | 109.3/3           | 210.8 |
|        |      |            | PL      | –                      | 0.3 ± 0.1 | –        | (4.8 ± 2.9) × 10$^{14}$ | –                | –     |
| 5      | XRT 080331 | 2008-03-31 17:05:54.64 | BPL     | 15.1 ± 0.1             | 0.2 ± 0.1 | 4.1 ± 0.1 | (6.1 ± 0.8) × 10$^{15}$ | 107.4/5           | 210.8 |
|        |      |            | PL      | –                      | –        | –        | –                            | –                | –     |
| 6      | XRT 130822 | 2013-08-22 16:27:24.82 | BPL     | 13.5 ± 0.1             | 0.2 ± 0.1 | 4.1 ± 0.1 | (6.1 ± 0.8) × 10$^{15}$ | 107.4/5           | 210.8 |
|        |      |            | PL      | –                      | 0.3 ± 0.1 | –        | (4.8 ± 2.9) × 10$^{14}$ | –                | –     |

**Notes.** Columns 1 and 2: FXRT# and ID of the candidate, respectively. Column 3: Time when the count rate is $3\sigma$ above the Poisson background level. Column 4: Model used. Column 5: Break time for the BPL model. Columns 6 and 7: Slope(s) for the BPL or PL model. Column 8: Normalization for the BPL or PL model. Columns 9 and 10: Log-likelihood (L)(degrees-of-freedom (d.o.f.)) and Bayesian information criterion (BIC) of the fit, respectively. Errors are quoted at the 1σ confidence level.

Prior to the flare at flux levels of $\approx 2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, followed by a sudden increase (in $\approx 20$ s) reaching a peak flux of $\approx 1.0 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. Using a bin-width of 10 s, the main flare is resolved into two peaks, as was also reported by Jonker et al. (2013). From there, the flux decreases rapidly for $\approx 100$ s, followed by a slow decline around $\approx 1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for the next $\approx 15$ ks (with an index of $-0.3 \pm 0.1$; Jonker et al. 2013) until the end of the observation.

The broken power law in the flux $T_{\text{break}} \approx 6.0$ ks and $\approx 5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, respectively, followed by a PL decay with an index of $\approx -1.7$.

The light curve of FXRT 3/XRT 070530 is well described by a BPL model, with the ΔBIC is only $\approx 2$ with respect to the PL fit. Initially, the light curve increases slightly with an index of $\approx -0.1$ until $T_{\text{break}} \approx 1.5$ ks, reaching a flux of $\approx 2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. After $T_{\text{break}}$, the light curve decays slowly with a slope of $\approx 0.8$.

The light curve of FXRT 4/XRT 071203 shows three counts during the first $\approx 9$–10 ks (equivalent to a flux of $\approx 2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$), before its flux increases to $\approx 4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ around $\approx 20$–24 ks, for a duration of $\approx 12$–14 ks.

The light curve of FXRT 5/XRT 080331 shows multiple peaks. In the first $\approx 20$ ks prior to the bright flares, the flux is around $\approx 2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. However, the main flares appear at $\approx 20$ and 40 ks after the start of the Chandra observation, reaching fluxes of $\approx 1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Between both flares, there is a quiescent epoch where the flux diminishes by a factor of $\approx 7$, with large errors, with respect to the main flares.

The light curve of FXRT 6/XRT 130822 is well described by a PL model with an index of $\approx 0.3$, although at $\approx 10$ ks into the event, a slight enhancement in flux beyond that expected for a PL decay occurs.

The light curve of FXRT 7/XRT 030519 is described well by a BPL model (ΔBIC = $-208.3$). The flux duration of the plateau phase until the break is $T_{\text{break}} \approx 1.1$ ks with a rough flux of $\approx 1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, followed by a PL decay with an index of $\approx 1.6$.

The light curve of FXRT 8/XRT 041230 is described slightly better by a BPL than by a PL model (although ΔBIC = 2.2). The source flux is consistent with being constant at a value of $\approx 2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for about $\approx 10$ ks, then it rises.

The light curve of FXRT 9/XRT 080819 is relatively symmetric in time, and hence not perfectly described by a BPL model (ΔBIC = $-1.6$), with a flux rising from $\approx 5 \times 10^{-14}$ to
Fig. 9. Light curves, the evolution of the HR over time, and the best fitting models of the FXRT sample. Top panels: observed 0.5–7.0 keV X-ray light curves in cgs units (blue points), starting at $T = 20$ s. For FXRTs 1 and 11, we only show the main event. For ten FXRT candidates, we also plot the best-fit BPL or simple PL model (red solid lines), while for the remaining four FXRT candidates we do not because they are not well described by either model. The light curves contain five counts per bin (except that of FXRT 1, which has 20 counts per bin). Bottom panels: HR evolution (the soft and hard energy bands are 0.5–2.0 keV and 2.0–7.0 keV, respectively), following the Bayesian method of Park et al. (2006). The dashed red line denotes an HR equal to zero. For XRT 000519/FXRT 1 and XRT 110103/FXRT 11, we show close-ups of the main flare to highlight in more detail their spectral behavior. Here, $T_0 = 0$ s is defined as the time when the count rate is 3σ higher than the Poisson background level.

$\approx 1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. After 10 ks into the observation, the flux decreases to $\approx 1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ with a PL index of $\approx 2.8$ for $\approx 5$ ks.

The light curve of FXRT 10/XRT 100831 is well fitted by a BPL model (ABIC = −8.3), with a clear plateau and a subsequent PL decay. The plateau duration is $T_{\text{break}} \approx 2.7$ ks, with a flux of $\approx 2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. The decay has an index of $\approx 1.9$.

The light curve of FXRT 11/XRT 110103 is similar to that of FXRT 1/XRT 000519. The flux is $\lesssim 1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ until a sudden increase to a flux of $\approx 1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The main burst lasts just a few hundred seconds (but without a double-peak structure as in FXRT 1/XRT 000519) followed by a slow PL decay over the remainder of the observation (Glennie et al. 2015).

The light curve of FXRT 12/XRT 110919 is well fitted by a BPL model, with a plateau phase duration of $T_{\text{break}} \approx 1.8$ ks and flux of $\approx 2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The decays follows a PL index of $\approx 1.9$. 

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The light curve of FXRT 13/XRT 140327 is similar to that of FXRT 6/XRT 130822 (i.e., a PL describes the data well). The decay index is $\approx 0.2$.

The light curve of FXRT 14/XRT 141001/CDF-S XT1 is well described by a BPL model, although there is no plateau phase. The flux rises rapidly until $T_{\text{break}} \approx 100–200$ s., reaching a flux of $\approx 3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The flux subsequently decreases following a PL slope of index $\approx 1.6$ until $T \approx 20$ ks, after which no counts are detected. These values agree with the $1\sigma$ confidence level with the values reported by Bauer et al. (2017).

In summary, the light curves of two nearby (FXRTs 2 and 3) and four distant (FXRTs 7, 10, 12, 14/CDF-S XT1) extragalactic FXRTs are well described by BPL models, with mean PL indexes of $\tau_2 \approx 0.1$ and $\tau_3 \approx 1.7$ before and after the break, respectively. Among these, all except FXRT 14/CDF-S XT1 show a few ks plateau phase. On the other hand, FXRTs 8 and 9 are not well described by BPL (see Table 4). Meanwhile, the light curves of FXRTs 6 and 13 follow pure PL decays, with mean PL indexes of $\tau_3 \approx 0.3$. The slow decay until the end of the Chandra observation after the main flare for FXRTs 1 and 11 (previously reported by Jonker et al. 2013 and Glennie et al. 2015, respectively) is not seen in any of the other candidate FXRTs. Finally, the light curve of FXRT 5 shows clear multiple flares, while weaker events like FXRTs 4 and 6 show marginal hints of multiple-flare structure.

### 3.3. Spectral properties

In this section we describe the spectral properties of the sample of FXRT candidates using some basic models, as well as their HR and photon index evolution with time.

#### 3.3.1. Spectral parameters

We generate X-ray spectra and response matrices following standard procedures for point-like sources using CIAO with the specextract script. The source and background regions are the same as those for generating the light curves (see Sect. 2.3). Due to the low number of counts per bin, we adopt maximum likelihood statistics for a Poisson distribution, the so-called Cash-statistics (C-stat, with $C = -2 \ln L_{\text{Poisson}} + \text{const}$; Cash 1979) to find the best-fit model. Although C-stat is not distributed like $\chi^2$, meaning that the standard goodness-of-fit is not applicable (Buchner et al. 2014; Kaarstra 2017). Thus, to evaluate if there are differences in the goodness-of-fit between models, we use the Bayesian X-ray Astronomy (BXA) package (Buchner et al. 2014), which joins the Monte Carlo nested sampling algorithm MultiNest (Feroz et al. 2009) with the fitting environment of XSPEC (Arnaud 1996). BXA computes the integrals over parameter space, called the evidence ($\Omega$), which is maximized for the best-fit model. For BXA, we assume uniform model priors.

We consider three simple continuum models: (i) an absorbed PL model (phabs*zphabs*po, hereafter the PO model); (ii) an absorbed thermal Bremsstrahlung model (phabs*zphabs*bremss, hereafter the BR model); and (iii) an absorbed black-body model (phabs*zphabs*bb, hereafter the BB model). The PO model is typically thought to be produced by a nonthermal electron distribution, while the other two models have a thermal origin. We chose these models because we do not know the origin and the processes behind the spectral properties of FXRTs, while the limited numbers of counts do not warrant more complex models. The spectral components phabs and zphabs represent the Galactic and intrinsic contribution to the total absorption, respectively. The Galactic absorption ($N_{\text{H,gal}}$) was fixed at the values of Kalberla et al. (2005) and Kalberla & Haud (2015) during the fit, while for the intrinsic redshifted absorption, we adopt $z = 0$, which provides a strict lower bound.

The best fitting spectral models (and residuals) and their parameters are provided in Fig. 10 and Table 5, respectively, while Fig. 11 shows the histograms of the best-fit intrinsic neutral hydrogen column densities in addition to the Galactic value ($N_H$; top panels) and photon index ($\Gamma$; bottom panels) for nearby (left panels) and distant (right panels) extragalactic FXRT candidates. The $N_H$ covers ranges for nearby (distant) candidates of $N_{\text{H,PO}} = 0.3–8.1(1.1–9.4)$, $N_{\text{H,BR}} = 0.1–3.5(0.5–3.9)$, and $N_{\text{H,BB}} = 0.1–2.7(0.2–3.7) \times 10^{21}$ cm$^{-2}$, and mean values of $N_{\text{H,PO}} = 4.1(4.2)$, $N_{\text{H,BR}} = 1.5(1.4)$, and $N_{\text{H,BB}} = 1.2(1.2) \times 10^{21}$ cm$^{-2}$, respectively. Furthermore, we compare the best-fit $N_{\text{L,PO}}$ with the HI constraints from Kalberla et al. (2005) and Kalbera & Haud (2015) and note that in all cases aside from FXRT 1 and FXRT 3, the bulk of the measured $N_{\text{L,PO}}$ are higher than $N_{\text{L,Gal}}$ (a factor of $\approx 2–15$ higher).

The best-fit PL photon index ranges between $\Gamma = 2.1–5.9$ (1.9–3.7) for the nearby (distant) candidate FXRTs, with mean values of $\Gamma = 3.4$ (2.7). According to Lin et al. (2012) (which classified sources detected by XMM-Newton), the photon index covers a wide range for different types of sources such as stars, AGNs or compact objects, however, only stars and compact objects have photon indices as high as $\Gamma > 6$. For BR models, the best-fit temperatures range from $kT_{\text{BB}} = 1.1–36.2(4.1–39.0)$ keV for nearby (distant) candidates, while BB temperatures span $kT_{\text{BB}} = 0.2–0.8$ (0.4–53.2) keV for nearby (distant) candidate FXRTs. The events with BR temperatures $kT_{\text{BB}} > 10$ keV are FXRTs 2, 4, 8, 9, 10, 13, and 14, while with BB temperatures $kT_{\text{BB}} > 5$ keV are FXRTs 8, and 10. Both temperatures (especially $kT_{\text{BB}}$) are important to eventually analyze a possible association with SBOs ($kT_{\text{SBO}} = 0.03–3.0$ keV, based on the progenitor star; Matzner & McKee 1999; Nakar & Sari 2010; Sapir et al. 2013).

#### 3.3.2. Hardness ratio and photon index evolution

The HR can be used to classify X-ray sources and study their spectral evolution, particularly when low number statistics prevail (e.g., Lin et al. 2012; Peretz & Behar 2018). Below, we investigate the HR for the population of FXRTs, compare these to candidates previously classified as “stars”, and look at the evolution of the HR and photon indices over the duration of the flare. The HR is defined as

$$HR = \frac{H - S}{S + H},$$

where $H$ and $S$ are the number of X-ray photons in the soft and hard energy bands, defined as the 0.5–2.0 and 2.0–7.0 keV bands, respectively. For each candidate, we calculate the HR using the Bayesian code BEHR (Park et al. 2006), which we list in Table 2, column 13, and plot in Fig. 12 (top panel).

Notably, Yang et al. (2019) found differences between stellar objects and the FXRT CDF-S XT1/XT2 (see their Fig. 5), where the latter has an average HR $\approx 0.16$. Taking into account the 472 objects identified as stars according to Criterion 2 in Sect. 2.5.2, we compare the HRs of these objects (see Fig. 12, middle panel, cyan histogram) to the final sample of nearby and distant FXRTs (black and orange histograms). Stars typically have very soft X-ray spectra (Güdel & Nazé 2009), with some notable exceptions like Be stars (e.g., Be star HD 110432
has an HR $\gtrsim 0.0$; Lopes de Oliveira et al. 2007). We find that the HR distribution of “star” candidates also strongly skews toward softer HRs, but demonstrates that stars associated with X-ray flares cover essentially all HRs, ranging from $-0.99$ to $+0.97$ (see Fig. 12, middle panel). Importantly, there is a smooth, non-negligible tail to harder values, with $\sim20\%$ of stars having HR $\gtrsim 0.0$ (possibly related to magnetic cataclysmic variables). Given this, we conclude that the X-ray HR is not a useful discriminator on its own.

Next, we analyze if, and if so how, the HR and PL index of the X-ray spectrum evolve with time. To start, we compute the HR for each bin of the light curves using the BEHR code of Park et al. (2006), which we show in the lower panels of Fig. 9. For light curves that are well fit by a BPL model, we additionally split the event files at $T_{\text{break}}$ and extract “before” and “after” spectra to compute the spectral slopes ($\Gamma_{\text{before}}$ and $\Gamma_{\text{after}}$, respectively; see Table 6) using the best-fit PO model (see Table 5). We fit both intervals together assuming fixed constant $N_{\text{H,gal}}$ and $N_{\text{H}}$ (taken from Table 5).

The resulting evolution of the HRs and the PL spectral indices are shown in Figs. 9 and 12 (bottom panel), respectively. FXRTs 1 and 11 show significant early softening in their HR evolution (Figs. 9) during the $\sim50\,$s following their main peaks (consistent with Glennie et al. 2015), while FXRTs 2, 7, and 12
Table 5. Results of the 0.5–7 keV X-ray spectral fits for the CSC2 FXRT candidates.

| FXRT | ID      | Model            | $N_{H,GAL}$ | $N_H (\approx 0.0)$ | $\Gamma$ | $kT$ | log Norm | Flux | C-stat (d.o.f.) | $\ln Z$ |
|------|---------|------------------|-------------|---------------------|---------|------|----------|------|-----------------|---------|
| (1)  | (2)     | (3)              | (4)         | (5)                 | (6)     | (7)  | (8)      | (9)  | (10)           | (11)    |
| 1    | XRT 000519 | phabs*zphabs*po | 1.0 ± 0.1   | 2.7 ± 0.1           | 3.5 ± 0.03 | 90.5 ± 1.8 | 95.3 (122) | 63.4 ± 0.02 |
|      |         | phabs*zphabs*bremss | 1.0 ± 0.1 | 2.7 ± 0.1           | 3.5 ± 0.03 | 84.2 ± 2.2 | 117.0 (122) | 77.9 ± 0.02 |
|      |         | phabs*zphabs*bb   | 1.0 ± 0.1   | 2.7 ± 0.1           | 3.5 ± 0.03 | 60.9 ± 1.5 | 402.1 (122) | 223.2 ± 0.02 |
| 2    | XRT 010908 | phabs*zphabs*po  | 3.0 ± 3.6    | 2.1 ± 0.6           | 0.5 ± 0.02 | 5.1 ± 0.02 | 60.9 ± 1.5 | 88.4 ± 0.03 |
|      |         | phabs*zphabs*bremss | 3.0 ± 3.6 | 2.1 ± 0.6           | 0.5 ± 0.02 | 60.9 ± 1.5 | 402.1 (122) | 223.2 ± 0.02 |
|      |         | phabs*zphabs*bb   | 3.0 ± 3.6   | 2.1 ± 0.6           | 0.5 ± 0.02 | 60.9 ± 1.5 | 402.1 (122) | 223.2 ± 0.02 |
| 3    | XRT 070530 | phabs*zphabs*po  | 5.0 ± 2.7   | 5.9 ± 1.6           | 5.2 ± 0.04 | 0.2 ± 0.1 | 17.7 (65) | 17.4 ± 0.02 |
|      |         | phabs*zphabs*bremss | 5.0 ± 2.7 | 5.9 ± 1.6           | 5.2 ± 0.04 | 0.2 ± 0.1 | 17.7 (65) | 17.4 ± 0.02 |
|      |         | phabs*zphabs*bb   | 5.0 ± 2.7   | 5.9 ± 1.6           | 5.2 ± 0.04 | 0.2 ± 0.1 | 17.7 (65) | 17.4 ± 0.02 |
| 4    | XRT 071203 | phabs*zphabs*po  | 0.6 ± 0.6   | 1.1 ± 0.2           | 3.4 ± 0.07 | 0.2 ± 0.1 | 11.8 (7) | 13.9 ± 0.02 |
|      |         | phabs*zphabs*bremss | 0.6 ± 0.6 | 1.1 ± 0.2           | 3.4 ± 0.07 | 0.2 ± 0.1 | 11.8 (7) | 13.9 ± 0.02 |
|      |         | phabs*zphabs*bb   | 0.6 ± 0.6   | 1.1 ± 0.2           | 3.4 ± 0.07 | 0.2 ± 0.1 | 11.8 (7) | 13.9 ± 0.02 |
| 5    | XRT 080331 | phabs*zphabs*po  | 0.6 ± 3.5   | 3.6 ± 0.9           | 5.6 ± 0.02 | 0.2 ± 0.1 | 18.9 (40) | 21.0 ± 0.02 |
|      |         | phabs*zphabs*bremss | 0.6 ± 3.5 | 3.6 ± 0.9           | 5.6 ± 0.02 | 0.2 ± 0.1 | 18.9 (40) | 21.0 ± 0.02 |
|      |         | phabs*zphabs*bb   | 0.6 ± 3.5   | 3.6 ± 0.9           | 5.6 ± 0.02 | 0.2 ± 0.1 | 18.9 (40) | 21.0 ± 0.02 |
| 6    | XRT 130822 | phabs*zphabs*po  | 0.4 ± 3.4   | 1.6 ± 3.9           | 13.5 ± 0.07 | 0.2 ± 0.1 | 13.4 (7) | 15.7 ± 0.02 |
|      |         | phabs*zphabs*bremss | 0.4 ± 3.4 | 1.6 ± 3.9           | 13.5 ± 0.07 | 0.2 ± 0.1 | 13.4 (7) | 15.7 ± 0.02 |
|      |         | phabs*zphabs*bb   | 0.4 ± 3.4   | 1.6 ± 3.9           | 13.5 ± 0.07 | 0.2 ± 0.1 | 13.4 (7) | 15.7 ± 0.02 |

**Nearby extragalactic FXRT Candidates from CSC2**

**Distant extragalactic FXRT Candidates from CSC2**

**Notes.** Column 1: Number of the candidate. Column 2: Transient ID used in this work. Column 3: Spectral model considered. Columns 4 and 5: Galactic and intrinsic column density absorption ($\times 10^{22}$), respectively, in units of cm$^{-2}$. The former is kept fixed during the fit. Column 6: Photon index from the PL model. Column 7: Temperature in units of keV from the BR or BB models. Column 8: Normalization parameter (in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$). Column 9: Absorbed fluxes ($\times 10^{-15}$) in units of erg cm$^{-2}$ s$^{-1}$ (0.5–7.0 keV). Column 10: C-stat value and the number of degrees of freedom. Column 11: Log-evidence ($\ln Z$) values for each model. Errors are quoted at the 1σ confidence level.

show marginal (~90% confidence) spectral softening after the plateau stage, like CDF-S XT2 trends, and FXRT 8 appears to soften marginally (~90% confidence) throughout its light curve. None of the other FXRTs show any evidence of spectral evolution.

### 3.4. Galactic origin

FXRTs 2, 3, 4, 5, 6, 8, 9, and 14 can be associated with extended host galaxies, proving and/or strengthening their extragalactic origin (see Sect. 2.6 for more details). FXRTs 1 and 11 are located near the outskirts of M86 and Abell 3581 (Jonker et al. 2013; Glennie et al. 2015), respectively, which, while suggestive of an extragalactic nature, is not definitive. Below, we investigate whether some FXRTs could still be associated with Galactic M- or brown-dwarf flares.

Magnetically active dwarfs (which comprise around 30% of M dwarfs and 5% of brown dwarfs) are known to exhibit flares on timescales of minutes to hours, with flux increases (not only in X-ray) by one or two orders of magnitude (Schmitt & Liefke 2004; Mitra-Kraev et al. 2005; Berger 2006; Welsh et al. 2007). The coldest object observed to flare in X-rays.
is an L1 dwarf (De Luca et al. 2020). Flares can be classified in two groups according to a time–luminosity relation (following previous efforts by Bauer et al. 2017): (i) short “compact” flares ($L \lesssim 10^{30}$ erg s$^{-1}$ and $\Delta t \lesssim 1$ h), and (ii) “long” flares ($L \lesssim 10^{35}$ erg s$^{-1}$ and $\Delta t \gtrsim 1$ h). The flaring episodes often occur recurrently on timescales from hours to years. The flares typically have thermal spectra with temperatures of $kT \sim 0.5–1$ keV.

M-dwarf stars have optical and NIR absolute magnitudes in the range of $M_{\text{bol}} \sim 8–13$ mag (Hawley et al. 2002) and $M_{K} \sim 3–10$ mag (Avenhaus et al. 2012), respectively, while brown dwarfs have $M_{\text{bol}} \sim 13–18$ mag (Hawley et al. 2002) and $M_{J} \sim 15–25$ mag (Tinney et al. 2014), respectively. In the case of X-ray emission, M dwarfs show flares in the range of $F_{X}^{	ext{M-dwarf}} \sim 10^{28–10^{32}}$ erg s$^{-1}$ (Pallavicini et al. 1990; Pandey & Singh 2008; Pye et al. 2015), while brown dwarf flares span $F_{X}^{	ext{L-dwarf}} \approx 10^{27–10^{30}}$ erg s$^{-1}$ (Berger 2006; Robrade et al. 2010). Furthermore, cold M dwarfs and L dwarfs typically exhibit ratios no larger than $\log(L_{X}/L_{\text{bol}}) \lesssim 0.0$ and $\lesssim 3.0$ (the dwarf star flare saturation limit), respectively, where $L_{X}$ and $L_{\text{bol}}$ are the X-ray flare and average (non-flare) bolometric luminosities, respectively (e.g., García-Alvarez et al. 2008; De Luca et al. 2020).

Thus, it is possible to discard a stellar flare explanation for FXRTs using their optical and NIR detections and/or upper limits compared to the expected absolute magnitudes in these bands (see above), as well as the ratio $\log(L_{X}/L_{\text{bol}}) = \log(F_{X}/F_{\text{bol}}) \lesssim -3.0$ (García-Alvarez et al. 2008)$^{19}$.

We derive a lower limit to the distance for each source using the expected $z$-band absolute magnitude ranges for M-dwarf and brown dwarf stellar flares listed above. We subsequently convert the X-ray flux to a lower limit on the luminosity using these distance limits. If this lower limit is above the maximum luminosity

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$^{19}$ To compute the ratio $\log(L_{X}/L_{\text{bol}})$, we normalize stellar synthetic models of dwarf stars (taken from Phillips et al. 2020, $1000 \lesssim T_{\text{eff}} \lesssim 3000$ K and $2.5 \gtrsim \log g \gtrsim 5.5$) to the deepest photometric upper limits and/or detections (as listed in Table 3), and compute bolometric fluxes by integrating the normalized models at optical/NIR wavelengths.
Luminosities are the 90% confidence level.

Table 6. Spectral slope computed “before” and “after” the $T_{\text{break}}$.

| FXRT | ID      | $\Gamma_{\text{before}}(T < T_{\text{break}})$ | $\Gamma_{\text{after}}(T \geq T_{\text{break}})$ |
|------|---------|---------------------------------------------|---------------------------------------------|
|      |         | (1)                          | (2)                          |
|      |         | (3)                          | (4)                          |
| Nearby extragalactic FXRT Candidates from CSC2 |
| 2    | XRT010908 | 1.8 ± 0.7                    | 2.1 ± 0.7                    |
| 3    | XRT070530 | 6.2 ± 2.6                    | 5.9 ± 1.6                    |
| Distant extragalactic FXRT Candidates from CSC2 |
| 7    | XRT030511 | 1.8 ± 0.3                    | 2.4 ± 0.2                    |
| 8    | XRT041230 | 2.6 ± 1.2                    | 3.6 ± 3.5                    |
| 9    | XRT080819 | 2.4 ± 1.2                    | 5.9 ± 2.2                    |
| 10   | XRT100831 | 3.7 ± 1.0                    | 2.7 ± 1.7                    |
| 12   | XRT110919 | 1.8 ± 0.9                    | 2.8 ± 1.1                    |
| 14   | XRT141001 | 1.7 ± 0.8                    | 1.7 ± 0.3                    |

Notes. Columns 1 and 2: FXRT# and ID of the candidate, respectively. Columns 3 and 4: Spectrum photon index computed before and after the $T_{\text{break}}$ for light curves that are well fit with a BPL. Errors are quoted at the 90% confidence level.

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4. Host galaxy features

The host galaxy or host environment of an FXRT can provide important information on its nature. Five nearby FXRTs (2, 3, 4, 5, and 6) and three distant FXRTs (8, 9, and 14) have been classified as extended sources (galaxies) by the VHS catalog (McMahon et al. 2013), but their properties have not been analyzed previously. We used photometric data of their putative host galaxies to constrain the host properties through spectral energy distribution (SED) model fitting.

We initially explored the spectral nature of FXRTs 8, 9, and 14 based on their $i-K_s$ versus $g-i$ colors in Fig. 14. FXRTs 8, 9, and 14 were compared to the counterparts of the X-ray sources classified as stars according to Criterion 2 (gray points; see Sect. 2.5.2) and the expected parameter space for stars (orange region) with different ages (log(Age/yr) = 7.0–10.3), metallicities (from [Fe/H] = –3.0–0.5), and attenuations ($A_V = 0.0–5.0$ mag) from theoretical stellar isochrones (MIST; Dotter 2016; Choi et al. 2016). The bulk of the stellar X-ray variables form a much tighter sequence than what is conceivably allowed by the full range of isochrones. The stellar X-ray sources that appear as outliers are identified as PNe, YSOs (e.g., eruptive variable stars, T Tauri stars), or emission-line stars. The FXRTs generally lie outside of or at the edge of the stellar region, away from the tight stellar locus, although the large error bars or limits in the NIR photometry preclude any definitive statements here. We conclude that the SED by itself is not a clear-cut discriminator and thus the spatially resolved nature of the counterparts remains vital to their confirmation.

Next, we employ the code BAGPIES (Bayesian Analysis of Galaxies for Physical Inference and Parameter Estimation; Carnall et al. 2018), which fits stellar-population models taking star-formation history and the transmission function of neutral/ionized ISM into account to broadband photometry and spectra using the MultiNest nested sampling algorithm (Feroz & Hobson 2008; Feroz et al. 2009), to derive constraints on the host-galaxy properties. BAGPIES gives the posterior distributions for the host-galaxy redshift ($z$), age, extinction by dust ($A_V$), SFR, metallicity ($Z$), stellar mass ($M_*$), specific star formation rate. To account for dust attenuation in the SEDs, we use the parameterization developed by Calzetti et al. (2000), where $A_V$ is a free parameter within the range 0.0 to 3.0 mag.

We assume an exponentially declining star formation history function parametrized by the star formation timescale (free parameter). Table 8 provides the best-fit parameters obtained with BAGPIES for the hosts of FXRTs 8 and 9, while Fig. 15 shows the 16th to 84th percentile range for the posterior spectrum and photometry. The posterior distribution for the fitted parameters is shown in the bottom panels. We have confirmed

4.2. Distant extragalactic FXRT sample

The optical/NIR hosts of the distant events FXRTs 8 and 9 are classified as extended sources (galaxies) by the VHS catalog (McMahon et al. 2013), but their properties have not been analyzed previously. We used photometric data of their putative host galaxies to constrain the host properties through spectral energy distribution (SED) model fitting.

We initially explored the spectral nature of FXRTs 8, 9, and 14 based on their $i-K_s$ versus $g-i$ colors in Fig. 14. FXRTs 8, 9, and 14 were compared to the counterparts of the X-ray sources classified as stars according to Criterion 2 (gray points; see Sect. 2.5.2) and the expected parameter space for stars (orange region) with different ages (log(Age/yr) = 7.0–10.3), metallicities (from [Fe/H] = –3.0–0.5), and attenuations ($A_V = 0.0–5.0$ mag) from theoretical stellar isochrones (MIST; Dotter 2016; Choi et al. 2016). The bulk of the stellar X-ray variables form a much tighter sequence than what is conceivably allowed by the full range of isochrones. The stellar X-ray sources that appear as outliers are identified as PNe, YSOs (e.g., eruptive variable stars, T Tauri stars), or emission-line stars. The FXRTs generally lie outside of or at the edge of the stellar region, away from the tight stellar locus, although the large error bars or limits in the NIR photometry preclude any definitive statements here. We conclude that the SED by itself is not a clear-cut discriminator and thus the spatially resolved nature of the counterparts remains vital to their confirmation.

Next, we employ the code BAGPIES (Bayesian Analysis of Galaxies for Physical Inference and Parameter Estimation; Carnall et al. 2018), which fits stellar-population models taking star-formation history and the transmission function of neutral/ionized ISM into account to broadband photometry and spectra using the MultiNest nested sampling algorithm (Feroz & Hobson 2008; Feroz et al. 2009), to derive constraints on the host-galaxy properties. BAGPIES gives the posterior distributions for the host-galaxy redshift ($z$), age, extinction by dust ($A_V$), SFR, metallicity ($Z$), stellar mass ($M_*$), specific star formation rate. To account for dust attenuation in the SEDs, we use the parameterization developed by Calzetti et al. (2000), where $A_V$ is a free parameter within the range 0.0 to 3.0 mag.

We assume an exponentially declining star formation history function parametrized by the star formation timescale (free parameter). Table 8 provides the best-fit parameters obtained with BAGPIES for the hosts of FXRTs 8 and 9, while Fig. 15 shows the 16th to 84th percentile range for the posterior spectrum and photometry. The posterior distribution for the fitted parameters is shown in the bottom panels. We have confirmed
Table 8. Parameters obtained from the literature and by our SED fitting to archival photometric data using the BAGPIPES package (Carnall et al. 2018).

| FXRT | ID | RA (deg) | Dec (deg) | Offset | $z$ or d/Mpc | Log(Age/yr) | Log($M_r$/$M_\odot$) | Log(SFR($M_\odot$/yr)) | $A_V$ (mag) | References |
|------|----|---------|----------|--------|-------------|-------------|-----------------|-----------------|-------------|------------|
| 1    | XRT 000519 | 186.54893 | 12.94622 | 12.2 | 16.4 | – | 11.89 | –2.0 | 0.081 | 1.15 |
| 2    | XRT 010908 | 167.87904 | 55.67411 | 0.4 | 9.3 | – | 11.11 | 0.34 | 0.046 | 2.13,14 |
| 3    | XRT 070530 | 201.26506 | 83.01911 | 5.5 | 4.04 | – | 10.83 | –1.5 | 0.315 | 4.5,13,16 |
| 4    | XRT 071203 | 211.25671 | 53.66222 | 0.4 | 6.9 | – | 8.27 | –1.15 | 0.029 | 6.1,13,17 |
| 5    | XRT 080331 | 170.06235 | 12.99154 | 1/3 | 8.1 | – | 10.80 | 0.51 | 0.091 | 8.9,13,14 |
| 6    | XRT 130823 | 345.50403 | 15.96478 | 1/2 | 29.3 | – | 10.40 | 0.14 | 0.211 | 10.11,13 |
| 14   | XRT 141001 | 53.16158 | –27.85938 | 0/13 | 2.23 | – | 7.99 | 0.06 | 0.021 | 12.18 |

Notes: Column 1: FXRT candidate number. Column 2: Candidate ID. Column 3 and 4: Right ascension and declination of the host galaxies.

References. (1) Rhode et al. (2007), (2) Wiegert et al. (2015), (3) Rhode et al. (2007), (4) Espada et al. (2019), (5) Rejkuba et al. (2011), (6) Drozdovsky & Karachentsev (2000), (7) Lanz et al. (2013), (8) Buta et al. (2015), (9) Beuther et al. (2017), (10) Cappellari et al. (2011), (11) Davis et al. (2014), (12) Bauer et al. (2017), (13) Helou et al. (1991), (14) Sorce et al. (2014), (15) Jonker et al. (2013), (16) Crooijmans et al. (2016), (17) Tully et al. (2015), (18) Schally & Finkbeiner (2011).

The obtained photometric redshifts of 0.61$^{+0.13}_{-0.17}$ and 0.7$^{+0.04}_{-0.10}$ for FXRTs 8 and 9 with our 2D spectra taken by X-Shooter (PIs: Quirola and Bauer, program ID: 105.20HY.001). A detailed analysis of the spectral data will be presented in future work.

FXRT 13 only has a single $i$-band DECam source associated with it. The non-detections in other bands may suggest that the $i$-band DECam image ($z=6948–8645\,\angstrom$) includes a dominant flux contribution from a high equivalent width emission line. Considering this shortest interval. Next, to convert the peak-count rates to fluxes, we multiply the flux from the time-averaged Spectral fits by the ratio $F_{\text{peak}}$ to $F_{\text{peak,corr}}$.

To understand the origin of our sample of FXRTs, we compare them with other well-known transient sources. We split our discussion into nearby (Sect. 5.1) and distant (Sect. 5.2) samples. The former have well-established distances, and therefore we can compare their light curves in luminosity units. As we do not know the redshift of several distant FXRTs, we compare their X-ray light curves in luminosity units assuming nominal distances. Given the uncertainty in the associations for FXRTs 1 and 11, we discuss them under both the nearby and distant extragalactic scenarios.

First, from the best-fit PL spectral model, we compute the X-ray peak flux (corrected for Galactic and intrinsic absorption; $F_{\text{peak}}$), the associated intrinsic X-ray peak luminosity ($L_{\text{X,peak}}$), and the Eddington mass (defined as $M_{\text{Edd}} = 7.5 \times 10^{39} L_{\text{X,peak}}$ in solar mass units). We report these values in Table 9 in the energy range 0.3–10 keV.

5.1. Nearby extragalactic FXRT sample

The nearby FXRTs 2, 3, 4, 5, and 6 have peak isotropic X-ray luminosities in the range of $L_{\text{X,peak}} \approx 10^{38}–10^{40} \,\text{erg s}^{-1}$ (see Table 9). This appears inconsistent with origins as SBOs ($L_{\text{SBO,peak}} \approx 10^{42}–10^{47} \,\text{erg s}^{-1}$; Ennsman & Burrows 1992; Soderberg et al. 2008; Modjaz et al. 2009; Waxman et al. 2017; Alp & Larsson 2020), TDEs ($L_{\text{TDE,peak}} \approx 10^{42}–10^{50} \,\text{erg s}^{-1}$; Rees 1988; MacLeod et al. 2014; Maguire et al. 2020; Saxton et al. 2021, considering a jetted emission), or on-axis GRBs ($L_{\text{GRB,peak}} \approx 10^{47}–10^{51} \,\text{erg s}^{-1}$; Berger 2014; Bauer et al. 2017, considering a jetted emission).

These lower luminosities fall into the realm of ULXs (extragalactic X-ray emitters located off-center of their host galaxy and with luminosities in excess of $L_{\text{ULX}} \approx 10^{39} \,\text{erg s}^{-1}$; if the emission is isotropic, well above the Eddington limit for neutron stars; Bachetti et al. 2014; Kaaret et al. 2017) and Galactic XRBs (X-ray emitters where a compact object accretes mass from a companion star with $L_{\text{XRB}} \lesssim 10^{39} \,\text{erg s}^{-1}$; Remillard & McClintock 2006; van den Eijnden et al. 2018). Most ULXs are semi-persistent X-ray emitters for years to decades (Kaaret et al. 2017), and in extreme cases can reach high luminosities such as NGC 5907 ULX1 ($\approx 5 \times 10^{40} \,\text{erg s}^{-1}$; Walton et al. 2016). The much shorter and stronger variability of $F_{\text{peak}}$ due to the lack of a standardized method to estimate the $F_{\text{peak}}$, we consider the following. First, we find the shortest time interval during which 25% of the counts are detected, and we compute a count rate during this shortest interval. Next, to convert the peak and time-averaged Spectral fits by the ratio between the peak and the time-averaged count rates (i.e., we assume no spectral evolution).
our FXRTs compared to ULXs implies that they are caused by a different phenomenon.

Another alternative could be XRBs. Figure 16 shows the X-ray light curves of FXRTs 1, 2, 3, 4, 5, 6, and 11 one per panel, compared to several well-known XRB flaring episodes. XRBs in the Milky Way exhibit pronounced variability whereby the X-ray flux changes from quiescent to flare states on timescales of weeks to months (Remillard & McClintock 2006). Particularly, FXRTs 2 and 4 reach peak luminosities ($L_{X,\text{peak}} \approx 10^{38} - 10^{39}$ erg s$^{-1}$) similar to some XRBs’ flares (e.g., the flare luminosity of GX339-4 of $\approx 4 \times 10^{38}$ erg s$^{-1}$), which suggests that these FXRTs could be related with the tip of longer flares. Nevertheless, they are not in agreement with the duration (in the order of weeks) and timescale evolution (following a slow PL decay $F_X \propto t^{-0.3}$) of XRBs flares. Thus, FXRTs 2, 3, 4 are unlikely to be related with XRBs. Meanwhile, FXRTs 1, 3, 5, 6, and 11 are not related with XRBs because of their high luminosity ($L_{X,\text{peak}} \geq 10^{39}$ erg s$^{-1}$).

Next, we compare the FXRTs to SGRs and AXPs, which are both believed to be related to young, highly magnetic neutron stars (Woods & Thompson 2006). Soft gamma repeaters and AXPs are very faint in quiescence but can flare by factors of hundreds to thousands on timescales of tens of ms to seconds ($\approx 4 \times 10^{38}$ erg s$^{-1}$), which suggests that these FXRTs could be related with the tip of longer flares. Nevertheless, they are not in agreement with the duration (in the order of weeks) and timescale evolution (following a slow PL decay $F_X \propto t^{-0.3}$) of XRBs flares. Thus, FXRTs 2, 3, 4 are unlikely to be related with XRBs. Meanwhile, FXRTs 1, 3, 5, 6, and 11 are not related with XRBs because of their high luminosity ($L_{X,\text{peak}} \geq 10^{39}$ erg s$^{-1}$).
At the distances of our nearby FXRTs, we would presumably only see the most luminous portions of these rare giant bursts (a few seconds at most) and not be sensitive to the fainter bursts or quiescent emission. They should be quite spectrally hard (e.g., SGR 1900+14 has a photon index range $\Gamma \approx 1.0-2.0$; Tamba et al. 2019) and given the relation to young, highly magnetic neutron stars, seen to be originating from young star clusters and HII regions (Woods & Thompson 2006). In this sense, FXRTs 2, 4, 5, and 6 share some similarities with the SGR and AXP phenomena. For instance, they seem related to star-formation galaxies (see Fig. 13), although their spectra remain relatively soft and their light curve lengths last thousands of seconds. In the case of FXRT 5, we see multiple flares over $\approx 35$ ks. On the other hand, FXRTs 1, 3, and 11 are not associated with young star clusters, and thus seem far less likely to be explained by an SGR/AXP origin.

A final point of comparison is with the FXRTs discovered in NGC 4636 and NGC 5128 (Cen A) by Irwin et al. (2016) and NGC 4627 by Shivakoff et al. (2005). All exhibit rapid ($\approx 50-100$ s) flares with peak luminosities of $\approx 10^{39}-10^{40}$ erg s$^{-1}$, but remain detectable by Chandra in quiescence. In two cases, multiple flares are observed across multiple observations, while two transients are spatially associated with globular clusters in their host galaxies (similar to FXRT 3, which intriguingly is also associated with NGC 5128). Overall, while the luminosities are comparable, the faster timescales, multiple outbursts, and quiescent detections are unlike the behavior seen among the nearby sample of FXRTs, although it could be the case that (some) FXRTs have quiescent fluxes well below the sensitivity of Chandra and XMM-Newton and/or have not been observed frequently enough to see multiple outbursts (e.g., FXRT 6 has not been observed again by Chandra or XMM-Newton; see Fig. 6).

In the case of FXRTs 1 and 11, their origin remains unclear. For FXRT 1, assuming the association with M86 ($\approx 16.4$ Mpc; Jonker et al. 2013), it is characterized by a peak luminosity of $\approx 6 \times 10^{42}$ erg s$^{-1}$ (see Table 9). According Jonker et al. (2013), this X-ray flash (XRF) could have been caused by the disruption of a compact WD by a $4.9 \times 10^4$ M$_\odot$ BH. Nevertheless, other scenarios such as a highly off-axis GRB (Dado & Dar 2019) cannot be discarded because of distance uncertainties. For FXRT 11, assuming the association with the galaxy cluster Abell 3581 ($\approx 94.9$ Mpc; Glennie et al. 2015), a (9.9 $\times 10^4$ M$_\odot$) BH. Nevertheless, other scenarios such as a highly off-axis GRB (Dado & Dar 2019) cannot be discarded because of distance uncertainties. For FXRT 11, assuming the association with the galaxy cluster Abell 3581 ($\approx 94.9$ Mpc; Glennie et al. 2015), its peak luminosity and Eddington mass are $\approx 2 \times 10^{39}$ erg s$^{-1}$ and $\approx 1.9 \times 10^4$ M$_\odot$ (see Table 9). Glennie et al. (2015) suggest that FXRT 11 could be consistent with the early X-ray emission typically seen in GRB light curves; however, its similarities with FXRT 1 also suggest that both events share the same origin.

Overall, the behavior of the nearby FXRTs appears to represent a genuinely new phase space of transient phenomena. The wide variety of observed properties strongly suggests that multiple physical origins may be at work.

### Table 9. Energetics of the FXRT sample (fluxes are corrected for Galactic and intrinsic absorption, and calculated over the energy range 0.3–10 keV).

| FXRT   | $F_{\text{peak}}$ (erg cm$^{-2}$ s$^{-1}$) | $L_{\text{peak}}$ (erg s$^{-1}$) | $\text{M}_{\text{Edd}}$ (M$_\odot$) |
|--------|------------------------------------------|---------------------------------|-------------------------------------|
| Nearby sample |                                          |                                 |                                     |
| 1      | XRT 000519 (1, 2) (3) (4) (5) | $(1.9 \pm 0.1) \times 10^{40}$ | $(6.1 \pm 0.3) \times 10^{40}$ | $(4.9 \pm 0.3) \times 10^{40}$ |
| 2      | XRT 019096 (1, 2) (3) (4) (5) | $(1.7 \pm 0.5) \times 10^{40}$ | $(1.8 \pm 0.5) \times 10^{40}$ | $3.9 \pm 1.4$ |
| 3      | XRT 070530 (1, 2) (3) (4) (5) | $(2.7 \pm 1.1) \times 10^{40}$ | $(3.5 \pm 1.1) \times 10^{40}$ | $4.1 \pm 1.7$ |
| 4      | XRT 071203 (1, 2) (3) (4) (5) | $(6.4 \pm 2.5) \times 10^{40}$ | $(3.6 \pm 1.4) \times 10^{40}$ | $2.9 \pm 1.1$ |
| 5      | XRT 080331 (1, 2) (3) (4) (5) | $(1.7 \pm 0.3) \times 10^{40}$ | $(1.3 \pm 0.2) \times 10^{40}$ | $1.0 \pm 0.7$ |
| 6      | XRT 130822 (1, 2) (3) (4) (5) | $(2.3 \pm 0.9) \times 10^{40}$ | $(2.4 \pm 0.9) \times 10^{40}$ | $187.5 \pm 73.4$ |
| Distant sample |                                          |                                 |                                     |
| 7      | XRT 00511 (1, 2) (3) (4) (5) | $(2.3 \pm 0.3) \times 10^{40}$ | $(1.3 \pm 0.2) \times 10^{40}$ | $9.9 \pm 1.3$ |
| 8      | XRT 041230 (1, 2) (3) (4) (5) | $(6.9 \pm 3.4) \times 10^{40}$ | $(1.1 \pm 0.5) \times 10^{40}$ | $8.8 \pm 4.3$ |
| 9      | XRT 080189 (1, 2) (3) (4) (5) | $(6.5 \pm 2.9) \times 10^{40}$ | $(1.5 \pm 0.7) \times 10^{40}$ | $(1.2 \pm 0.5) \times 10^{40}$ |
| 10     | XRT 100831 (1, 2) (3) (4) (5) | $(8.9 \pm 3.4) \times 10^{40}$ | $(4.8 \pm 1.8) \times 10^{40}$ | $(3.8 \pm 1.5) \times 10^{40}$ |
| 11     | XRT 110103 (1, 2) (3) (4) (5) | $(2.2 \pm 0.2) \times 10^{40}$ | $(2.4 \pm 0.2) \times 10^{40}$ | $(1.9 \pm 0.2) \times 10^{40}$ |
| 12     | XRT 110919 (1, 2) (3) (4) (5) | $(5.6 \pm 1.3) \times 10^{40}$ | $(3.0 \pm 0.7) \times 10^{40}$ | $(2.4 \pm 0.6) \times 10^{40}$ |
| 13     | XRT 140327 (1, 2) (3) (4) (5) | $(1.2 \pm 0.5) \times 10^{40}$ | $(6.3 \pm 2.8) \times 10^{40}$ | $(4.9 \pm 2.3) \times 10^{40}$ |
| 14     | XRT 141001 (1, 2) (3) (4) (5) | $(4.3 \pm 1.1) \times 10^{40}$ | $(1.7 \pm 0.4) \times 10^{40}$ | $(1.3 \pm 0.3) \times 10^{40}$ |

Notes. Column 1: FXRT candidate number. Column 2: Candidate ID. Column 3 and 4: X-ray peak flux and isotropic luminosity in cgs units (corrected for Galactic and intrinsic absorption). Column 5: Eddington mass (defined as $M_{\text{Edd}} = 7.7 \times 10^{30} L_{\text{peak}}$, in solar mass units (M$_\odot$)).

(1) Assuming an association with Abell 3581 at 94.9 Mpc (Glennie et al. 2015). (2) Assuming a mean redshift of $z = 2.23$ (Bauer et al. 2017). (3) Assuming a redshift of $z = 1$. (4) The distance or redshift is taken from Table 8.

5.2. Distant extragalactic FXRT sample

For the moment, we split the discussion of FXRTs into those with fairly secure hosts and reasonable distance estimates (see Sect. 5.2.1) versus those with less certain or no clear hosts (see Sect. 5.2.2). Here we analyze the scenario where the FXRTs 1 and 11 are related to distant extragalactic objects (see Sect. 5.2.2).

#### 5.2.1. FXRTs with known distances

Using the photometric host redshifts calculated in Sect. 4, FXRTs 8 and 9 reach peak X-ray luminosities of $L_{X,\text{peak}} \approx 1.5 \times 10^{44}$ and $1.3 \times 10^{45}$ erg s$^{-1}$, respectively (see Table 9 and Fig. 17 for a light curve comparison). The FXRTs have an isotropic fluence of $F_X \approx 2.2 \times 10^{47}$ and $3.9 \times 10^{47}$ erg, respectively.
Such luminosities fall with the ranges predicted or detected for SBO models ($L_{X,\text{peak}}^{\text{SBO}} \approx 10^{42} - 10^{47} \text{ erg s}^{-1}$; Soderberg et al. 2008; Modjaz et al. 2009; Waxman et al. 2017; Alp & Larsson 2020), although both FXRTs exhibit energy released that are at least one to two orders of magnitude higher than the energy predicted by SBO models (e.g., Waxman et al. 2017) or detected from the enigmatic SBO XRT 080109/SN 2008D ($E_X \approx 2 \times 10^{46} \text{ erg}$; Soderberg et al. 2008). As such, we rule out an SBO interpretation for FXRTs 8 and 9.

Considering an on-axis GRB origin, we note that no gamma-ray signals detected near the time of discovery were associated with FXRTs 8 or 9, and neither exhibits a characteristic PL decay phase ($F_X^{\text{FXRTs/9}} \propto t^{-2.9} - 2.8$ associated with GRB afterglows $F_{\gamma}^{\text{GRBs}} \propto t^{-1.2}$; Evans et al. 2009; Racusin et al. 2009), although some GRBs show strong X-ray flaring in the tail of the X-ray afterglow distribution that could mimic the observed temporal behavior (Barthelmy et al. 2005; Campana et al. 2006; Chincarini et al. 2010; Margutti et al. 2011). Critically, Fig. 17 demonstrates that the X-ray light curves of both FXRTs are fainter than almost any known on-axis GRB X-ray afterglow over the same timescale, with (prompt) initial luminosities $> 3–4 \text{ dex}$ below the luminosity ranges observed for GRBs ($L_{X,\text{peak}} \approx 10^{47} \text{ erg s}^{-1}$). Based on their best-fit X-ray spectral slopes of $\Gamma_{\text{FXRTs/8,9}} \approx 2.7/3.0$, they formally lie at the edge of the standard afterglow distribution ($\Gamma_{\text{GRBs}} = 1.5–3.0$; Berger 2014; Wang et al. 2015; Bauer et al. 2017) overlapping at the 1σ confidence level. In terms of their host-galaxy properties (see Fig 13 and Table 8), FXRT 8’s host has a low-SFR ($=0.5 M_\odot \text{ yr}^{-1}$) and old stellar population ($\geq 1 \text{ Gyr}$). It is classified as a quiescent galaxy according to the criteria from Moustakas et al. (2013), and is thus a potential host for an SGRB. Nevertheless, an association with low-luminosity LGRBs (LL-LGRBs) could be discarded due to the high stellar mass of its host galaxy.

FXRT 9’s galaxy is a massive blue starburst galaxy ($=120 M_\odot \text{ yr}^{-1}$) with a young stellar population ($=0.15 \text{ Gyr}$). Hence, FXRT 9 might be related to an LGRB origin, although an association with SGRBs cannot be discarded. On the other hand, an association with LL-LGRBs could be ruled out because of the high stellar mass of its host galaxy relative to LL-LGRBs’ hosts (higher than one order of magnitude; see Fig 13). Unfortunately, the low angular resolution of the current archival images does not permit us to compute the offset from the host center.

Alternatively, these FXRTs could be related to ultra-long duration GRBs. Several ultra-long GRBs (longer than thousands of seconds) have been detected (Thöne et al. 2011; Campana et al. 2011; Gendre et al. 2013; Virgili et al. 2013; Stratta et al. 2013). Their nature still unclear. Gendre et al. (2013) and Levan et al. (2014) argue that the long duration of this population of GRBs may be explained by engine driven explosions of stars of much larger radii than typical LGRB progenitors (which are thought to have compact Wolf-Rayet progenitor stars). Figure 17 shows a comparison of both FXRTs and the ultra-long GRB 111209A. At early times their luminosities are $\approx 6–7 \text{ dex}$ lower than that of GRB 111209A. Nevertheless, we cannot discard an association with this population of GRBs because of the uncertainty in the zero point of our FXRTs, which when changed could match well with the temporal decay ($F_X \propto t^{-1.4(±0.5)}$) and spectral trend ($Γ \approx 2.4$ at $t > 40 \text{ ks}$) of this GRB.

The possibility of an off-axis orphan GRB origin still remains plausible, given the lack of an initial gamma-ray detection and lower luminosity. Here we compare to the light curves of XRF 060218/SN 2006aj (Campana et al. 2006), XRF 100316D/SN 2010bh (Starling et al. 2011), and SN 2020bvc (Izzo et al. 2020), which have all been argued to be potential off-axis LGRBs, as well as GRB 170817A (Nynka et al. 2018; D’Avanzo et al. 2018; Troja et al. 2020) and CDF-S XT2 (Xue et al. 2019), and thus possible off-axis SGRBs (see Fig. 17). We note in particular that the plateau phases of FXRTs 8 and 9 are $\approx 1–3 \text{ dex}$ lower than those of XRF 060218, XRF 100316D, and CDF-S XT2, although the break and late-time light curves (to the extent that they can be quantified) appear to match reasonably well. By extension, SN 2020bvc and GRB 170817A appear to be even weaker, and join with the faint declining tails of the XRFs at very late times. We speculate that perhaps FXRTs 8 and 9 could be weaker or higher inclination versions of off-axis SGRB and LGRBs (e.g., Granot et al. 2002), respectively, somewhere
Fig. 16. 0.3–10 keV light curves of the five local CSC2 FXRTs, plus FXRTs 1 and 11, in luminosity units. The 0.3–10 keV light curves are obtained by multiplying the 0.3–7 keV light curves by the factor derived from extrapolating the best-fit PO model flux to the 0.5–7.0 keV spectrum to the 0.3–10 keV band and correcting it for the effects of Galactic plus intrinsic absorption. For comparison, we overplot flaring episodes for several individual well-known Galactic XRBs: GX339−4 (9 kpc, green line; Heida et al. 2017), Swift J1357.2−0933 (8 kpc, magenta line; Mata Sánchez et al. 2015), MAXI J1543−564 (5 kpc, gray line; Stiele et al. 2012), and MAXI J1659−152 (6 kpc, blue line; Jonker et al. 2012b). The light curves of the comparison sources are taken from the 2SXPS catalog (Evans et al. 2020b).

intermediate between the XRFs and SN 2020bvc/GRB 170817A along the possible viewable parameter space of such events. Unfortunately, the poor count statistics (to constrain any spectral evolution) and the lack of additional EM counterparts do not permit us to analyze this picture in detail.

Finally, in the TDE scenario, if we interpret the peak luminosities as the Eddington luminosity, we derive masses of \( \gtrsim 1.2 \times 10^6 \) and \( 1.0 \times 10^7 \) \( M_\odot \) for FXRT 8 and FXRT 9, respectively. These masses are the total stellar mass of the host galaxies as derived in Sect. 4.2 is associated with a spheroid component, could be approximately consistent with the stellar velocity dispersion (\( \sigma \)) of a galaxy bulge and the mass of the SMBH (\( M_{\text{BH}} \)) at its center (\( M_{\text{BH}} - \sigma \) relation; e.g., Ferrarese & Merritt 2000). These luminosities are in rough agreement with the recent sample of TDEs published by Saxton et al. (2021).

Alternatively, these FXRTs could be related with an IMBH–WD or IMBH–MS TDEs (which could occur in dwarf galaxies and stellar systems such as globular clusters; Jonker et al. 2012a; Reines et al. 2013), assuming the observed luminosities are super-Eddington or due to relativistic beaming. The FXRTs are offset from the nuclei of their associated optical and NIR sources by only 0′.5 and 0′.7 (or projected physical distances of 3 and 3.5 kpc), respectively, and hence remain consistent with both on-axis and off-axis scenarios within the positional uncertainties (see Fig. 7).

Saxton et al. (2021) review the observed and theoretical X-ray properties of TDE candidates. Among confirmed SMBH–MS TDEs detected to date, several exhibit peak luminosities similar to those of FXRTs 8 and 9. However, the X-ray spectra of SMBH–MS TDEs are generally softer and none exhibit short-term X-ray variability comparable to what see from the FXRTs, but instead show much slower declines over timescales of months to years. For this reason, we disfavor such an explanation, but cannot completely rule out a possible detection bias here, given the limited sensitivity of current all-sky instruments. One intriguing possibility for generating higher luminosities, faster variability, and harder spectra is relativistic beaming from jetted TDEs such as Swift J1644+57 (Bloom et al. 2011; Levan et al. 2011). This could also significantly relax the mass and/or accretion rate limits quoted above. In the case of Swift J1644+57, shown in Fig. 17, it has a peak luminosity of \( \approx 10^{48} \) erg s\(^{-1}\) and time-averaged photon index of \( \Gamma = 1.6–1.8 \) (Levan et al. 2011), although the photon index increases and softens with decreasing flux (Bloom et al. 2011). Clearly FXRTs 8 and 9 remain \(<3\) dex fainter, but otherwise have potentially consistent spectral and temporal properties. As neither has multiple X-ray observations, we cannot say anything about their long-term evolution. We can also compare the timing and spectral properties of the 0.3–7 keV light curves of the five local CSC2 FXRTs, plus FXRTs 1 and 11, in luminosity units. The 0.3–10 keV light curves are obtained by multiplying the 0.3–7 keV light curves by the factor derived from extrapolating the best-fit PO model flux to the 0.5–7.0 keV spectrum to the 0.3–10 keV band and correcting it for the effects of Galactic plus intrinsic absorption. For comparison, we overplot flaring episodes for several individual well-known Galactic XRBs: GX339−4 (9 kpc, green line; Heida et al. 2017), Swift J1357.2−0933 (8 kpc, magenta line; Mata Sánchez et al. 2015), MAXI J1543−564 (5 kpc, gray line; Stiele et al. 2012), and MAXI J1659−152 (6 kpc, blue line; Jonker et al. 2012b). The light curves of the comparison sources are taken from the 2SXPS catalog (Evans et al. 2020b).

\[ L_X \text{(erg s}^{-1}) = 4 \times 10^{45} \]
Fig. 17. 0.3–10 keV light curves of the nine CSC2 FXRTs in luminosity units (as in Fig. 16, 0.3–10 keV light curves were converted from 0.5–7 keV ones). The X-ray afterglow light curves of 64 LGRBs plus 32 SGRBs (taken from Bernardini et al. 2012; Lü et al. 2015) are shown as a 2D histogram, as are the X-ray afterglows of GRB 170817A (off-axis SGRB, solid dark green line; Nynka et al. 2018; D’Avanzo et al. 2018; Troja et al. 2020, 2022), SN 2020bvc (the first off-axis LGRB candidate, solid light green line; Izzo et al. 2020), and the ultra-long duration GRB 111209A (solid magenta line, $z = 0.677$; Levan et al. 2014). Additionally, several individual transients are overplotted: the low-luminosity supernova SBO SN 2006aj (solid blue lines, 145 Mpc;), XRF 100316D (solid orange lines, 263 Mpc; Barniol Duran et al. 2015; Starling et al. 2011; Modjaz et al. 2009; Evans et al. 2007, 2009; Soderberg et al. 2008; Campana et al. 2006), the relativistically beamed TDE Swift J1644+57 (solid black lines, $z = 0.3543$; Bloom et al. 2011; Levan et al. 2011), the non-beamed TDE J2150-05 (solid pink line, $z = 0.055$; Lin et al. 2018), and CDF-S XT2 (solid indigo lines; Xue et al. 2019). For FXRTs 1, 7, 10, 11, 12, and 13 (open symbols), we assume $z = 1.0$, we adopt $\zeta_{\text{photo}} = 2.23$ for FXRT 14 from Bauer et al. (2017), and for FXRTs 8 and 9 we consider the values from Table 8.

Unlike the other events, FXRT 14 has been constrained by multiwavelength counterparts (Bauer et al. 2017). The available data are consistent with expectations for off-axis SGRBs, although other possibilities might not be ruled out. For instance, Peng et al. (2019) argue for an IMBH–WD TDE, Sun et al. (2019) explain the X-ray emission considering a magnetar remnant after a BNS merger observer at an off-axis viewing angle, while Sarin et al. (2021) discuss an association with an off-axis afterglow of a BNS merger, without discarding that its X-ray spectrum is $F_{\text{X}} \propto t^{-5/3}$ during $\gtrsim 14$ yr (see Fig. 17), and ultrasoft X-ray spectra with $kT \lesssim 0.25$ keV, which soften with time (Lin et al. 2018, 2020). This lies in stark contrast with FXRTs 8 and 9, which show a short and fast timescale variability, and somewhat hotter/harder X-ray spectra. In summary, FXRTs 8 and 9 do not conform to the “traditional” expectations of TDEs, in terms of slow temporal evolution or ultrasoft X-ray spectra, but relativistically beamed emission from an IMBH–TDE scenario cannot be discarded.
properties could be related to compact object such as an asteroid hitting an isolated foreground neutron star (Colgate & Petschek 1981; van Buren 1981; Campana et al. 2011). It is important to mention that FXRT 14/CDF-S XT1 and XT2 seem to fall in the same host’s properties parameter space as the LL-LGRBs and SGRBs at lower stellar masses (≤10^3 M⊙; see Fig. 13). This reinforces the likely association with SGRBs.

5.2.2. FXRTs with unknown distances

FXRTs 7, 10, 12, and 13 do not have clear host associations as yet, and hence have wildly uncertain distances. Based on their typical optical and NIR upper limits (e.g., m_r ≥ 23.3 and m_z ≥ 22 AB mag), and considering distances of other FXRT host galaxies such as FXRTs 8 and 9 (zFXRT host galaxies such as FXRTs 8 and 9 (zFXRT host galaxies such as FXRTs 8 and 9 (zFXRT host galaxies such as FXRTs 8 and 9 (zA168, page 32 of 43 and zA168, page 32 of 43 on their typical optical and NIR upper limits (e.g., m_tions as yet, and hence have wildly uncertain distances. Based on their typical optical and NIR upper limits (e.g., m_r ≥ 23.3 and m_z ≥ 22 AB mag), and considering distances of other FXRT host galaxies such as FXRTs 8 and 9 (zFXRT host galaxies such as FXRTs 8 and 9 (zFXRT host galaxies such as FXRTs 8 and 9 (zFXRT host galaxies such as FXRTs 8 and 9 (zA168, page 32 of 43 and spectrometer (z_photo ≈ 0.7), FXRT 14 (m^FXT14 = 27.5 AB mag and z^photoFXT14 = 0.39–3.21; Bauer et al. 2017), and CDF-S XT2 (m^XT2 = 25.35 AB mag and z^spectroscopyXT2 = 0.738; Xue et al. 2019), we adopt a nominal redshift of z = 1 for these sources. Figure 17 (open markers) compares FXRTs 7, 10, 12 and 13 (at z = 1.0) to several classes of transients.

We note that FXRTs 7, 10, and 12 have light curves that exhibit plateau phases of ≳1–3 ks, followed by PL decays (F_X ∝ t^{-2.4±1.6}) that are accompanied by possible softening of the spectra for FXRTs 7 and 12 (see Table 6). Spectral softening has been seen previously in SBOs (e.g., XRF080109/SN 2008D), GRBs afterglows, TDEs (e.g., MacLeod et al. 2014; Malvani et al. 2019), and CDF-S XT2 (Xue et al. 2019). FXRTs 7, 10 and 12 have photon indices (see Table 5) similar to the SBO XRF080109/SN 2008D (Γ ≈ 2.3; Soderberg et al. 2008) and GRB afterglows (Γ ≈ 1.5–3.0; Berger et al. 2014; Wang et al. 2015) at a 1σ confidence level. If these events lie at z ≳ 0.5, we can discard the SBO scenario, however, due to their high X-ray luminosities (L_X,peak ≳ 10^{44} erg s^{-1}); an SBO association would only be expected at low redshifts (z ≤ 0.5). The light curves (at z = 1.0) also appear inconsistent with on-axis GRBs. Although they share similar luminosities and PL decays beyond ~10^3 s, the early plateau phases of FXRTs are inconsistent with the typical PL or BPL decays of on-axis GRBs and afterglows. A subset of SGRBs exhibit plateau phases (Rowlinson et al. 2010, 2013), although these generally have plateau luminosities ≥10^{46} erg s^{-1} (although if no redshift is known the mean X-ray luminosities (L_X,peak ≳ 10^{44} erg s^{-1}); an SBO association would only be expected at low redshifts (z ≤ 0.5), which could be discarded by the non-detection of hosts. Furthermore, Fig. 17 shows a comparison of these FXRTs with the ultra-long GRB 111209A. Assuming z = 1.0, at early times their luminosities are orders of magnitude lower than GRB 111209A.

On the other hand, the luminosities and light curve shapes of FXRTs 7, 10, and 12 share remarkable similarities to X-ray flashes XRF060218/SN 2006aj and XRF100316D/SN 2010bh (which may be related to shock breakout from choked GRB jets; Campana et al. 2006; Bromberg et al. 2012; Nakar & Sari 2012), as well as CDF-S XT2 (which is consistent with being powered by a millisecond magnetar; Xue et al. 2019; Sun et al. 2019). The light curves of FXRTs 7, 10, and 12 follow the expected shape for IMBH–WD TDEs (e.g., see MacLeod et al. 2014; Malvani et al. 2019). For instance, the photon index and flux PL decay of these FXRTs are similar to the IMBH TDE candidate TDE121505G (Γ ≤ 4.8 and F_X ∝ t^{-3.3}; Lin et al. 2018). Assuming z = 1, only FXRT 7 reaches a luminosity close to the beamed TDE Swift J1644+57 (L_X,peak ≳ 10^{46}–10^{47} erg s^{-1}; see Fig. 17; Bloom et al. 2011; Levan et al. 2011), but without flaring episodes. Again, the poor count statistics (to constrain any spectral evolution) and the lack of host or additional EM counterparts do not permit us to analyze this picture in detail.

FXRT 13 exhibits a single PL light curve with a slow decay (F_X ∝ t^{-0.5}). This seems to exclude a SBO nature for this FXRT. There is a faint optical source likely associated with this FXRT, only visible in i-band DECam images (m_i ≈ 24.7 AB mag), which does not constrain its origin significantly.

Finally, assuming FXRTs 1 and 11 are actually foreground objects that randomly overlap with nearby sources, we find that their light curves remain unique. Given the uncertain distances in their histories, we adopt nominal redshifts of z = 1 as above (see Fig. 17). Their X-ray luminosities of reach values L_X,peak ≳ 10^{47} erg s^{-1}, respectively, ruling out an association with SBOs but falling in the range of XRFs (e.g., XRF060218/SN 2006aj and XRF100316D/SN 2010bh; Campana et al. 2006; Bromberg et al. 2012; Nakar & Sari 2012) and beamed TDEs (e.g., TDE J1644+57; see Fig. 17). The duration and shapes do not appear consistent with XRFs, but do resemble individual flares seen from TDE J1644+57.

Unfortunately, the unknown distances of these FXRTs do not permit better constraints on their origin.

6. Rates

We computed the event rates of FXRTs and compared them with those for other transients to explore possible associations and interpretations. We derived the event rates (deg^{-2} yr^{-1}; Sect. 6.1), the volumetric rate for nearby and distant samples (yr^{-1} Gpc^{-3}; Sect. 6.2), the local density rate (Sec. 6.3), and the expected number of events for current and future X-ray missions (Sec. 6.4).

6.1. Event-rate estimation

We found 14 FXRTs (including XRT000519, XRT110103 and CDF-S XT1; Jonker et al. 2013; Glennie et al. 2015; Bauer et al. 2017) within 160.96 Ms of CSC2 data. For a set of Chandra observations, the number of transients can be written as

\[ N = \sum_i R_i \epsilon_i \Omega_i t_i, \]

where R_i is the event rate, \( \Omega_i \) and t_i are the FoV and exposure time, respectively, and \( \epsilon_i \) is an area correction factor, with the subscript i denoting each Chandra observation.

The area correction factor, \( \epsilon_i \), is important for the faintest FXRTs and captures the changes in sensitivity over the Chandra detector. \( \epsilon_i \) is defined as the area within which we expect successful FXRT detections (S/N ≥ 3.0) normalized by the total detection area. To determine \( \epsilon_i \), we simulate 1,000 fake instances of each FXRT, randomly distributed in position (using MARX and simulate_psff scripts taking into account the particular features per Chandra observation) within Chandra’s FoV for each individual observation. We compute the S/N for fake FXRTs in the energy range of 0.3–10 keV. Thus, \( \epsilon_i \) falls in the range \( \epsilon_i \in [0.0, 1.0] \). For the brightest FXRTs, \( \epsilon_i \approx 1.0 \), meaning that they are detectable across the entire detector FoV, while for fainter FXRTs, \( \epsilon_i \leq 1.0 \), such that only a portion of the detector is sensitive to them.
We assume that \( R_0 \) is constant (such that \( R_0 = R \)), because the universe is isotropic on large scales and we are focusing on extragalactic sources \(^1\text{Yang et al. 2019}^\). \( \Omega \) depends on which chips of the detector are turned on; due to the degradation of the PSF at higher instrumental off-axis angles, we consider only chips I0–I3 for ACIS-I and chips S1–S4 for ACIS-S, respectively. Therefore, the expected number of events depends on \( \Omega_i, t_i \), and \( e_i \) per observation as
\[
N = R \sum_i e_i \Omega_i t_i, \tag{6}
\]
such that the event rate, \( R \), is
\[
R = \frac{N}{\sum_i e_i \Omega_i t_i}. \tag{7}
\]

We derive the rate of our sample considering two cases: (i) five nearby events (seven if we include FXRT 1/2 XRT 11/12 XRT 11/210103, which have unequal associations with M86 and the galaxy cluster Abell 3581, respectively; called Case I), and (ii) seven distant events (nine if we include FXRT 1/2 XRT 11/12 XRT 11/210103; called Case II). Because our algorithm does not have good efficiency in detecting objects in observations with exposure times \( \leq 8 \text{ks} \) (in fact, we do not detect any candidates for such exposures), we do not consider such observations to derive the rates. Another consideration when estimating the event rates for both FXRT samples is to identify and isolate the fraction of observations that target nearby galaxies. While distant FXRTs can be detected in any Chandra observation (i.e., in the background of nearby galaxy observations), nearby FXRTs can only be detected if nearby galaxies lie within the Chandra FoV. Thus for Case II, we consider just Chandra observations that target non-neighbouring galaxies, while for Case I, we only consider the fraction of Chandra observations that target nearby galaxies at \( <100 \text{ Mpc} \) (\( \approx 21\% \) of the total sample; see Sect. 3.5).

Therefore, we estimate the event-rates (fully accounting for the ambiguity of FXRTs 1 and 11 in the errors) of nearby FXRTs to be \( R_{\text{Case I}} = 53.7^{+22.6}_{-15.1} \text{deg}^{-2} \text{yr}^{-1} \); while for distant FXRTs it is \( R_{\text{Case II}} = 28.2^{+9.6}_{-6.0} \text{deg}^{-2} \text{yr}^{-1} \). The distant rate is consistent with the rate of \( R_{\text{range+19}} = 59^{+38}_{-27} \text{deg}^{-2} \text{yr}^{-1} \) at the Poisson 1\(\sigma\) confidence level, as derived by Yang et al. (2019), but is \( \approx 0.9 \text{dex} \) higher than the rate of \( \approx 3.4 \text{deg}^{-2} \text{yr}^{-1} \) derived by Glennie et al. (2015). The latter discrepancy is not surprising, however, since Glennie et al. (2015) calculated the rate for a much higher peak flux of \( F_{\text{peak}} \approx 10^{-10} \text{erg cm}^{-2} \text{ s}^{-1} \).

It is essential to mention again that FXRTs previously discovered as CDF-S X2 (XRT 150321; Xue et al. 2019), XRT 170831 (Lin et al. 2019) and XRT 210423 (Lin et al. 2021) are not part of this work because of the data cut-off of CSC2. As we showed in Sect. 2.5.6, the number of FXRTs that is removed from our sample by our selection criteria erroneously is probably less than 1. Therefore, the estimated event rates are robust results for FXRT candidates brighter than \( \log(F_{\text{peak}}) > -12.6 \) for Chandra observations with \( T_{\text{exp}} > 8 \text{ ks} \).

The event rate (event rate per dex of flux) behaves as a PL function as \( \propto F_{\text{peak}}^{-\gamma} \), where \( \gamma \) is a positive value. In Fig. 18, we plot the observed cumulative \( N \)–log \( S \) distribution for our entire sample, which appears to follow \( \gamma \approx 0.5 \) (red line). We also plot the extrapolation of the best-fit slope, \( \gamma = 1.0 \), based on the estimates of FXRTs at bright fluxes (\( \geq 10^{-10} \text{erg cm}^{-2} \text{ s}^{-1} \)) from Arefiev et al. (2003). We caution that Arefiev et al. (2003) do not specify an exact energy band and make no distinction between various potential Galactic and extragalactic classes, although it is noteworthy that the sky distribution at these bright fluxes is also isotropic. We see that the brightest sources in our CSC2 sample are consistent with this bright-end extrapolation, while the fainter sources fall well below it by \( \approx 1 \text{dex} \), implying a potential break around a flux of \( 3 \times 10^{-8} \text{erg cm}^{-2} \) to our best-fit slope.

6.2. Volumetric rate estimate

In addition to the event rate on the sky (deg\(^{-2}\)), we compute the volumetric density rate \( \rho(z) \), in units of yr\(^{-1}\) Gpc\(^{-3}\), to compare with other known transient classes (GRBs, SBOs, or TDEs). Following Zhang (2018), the number of FXRTs, \( N \), identified per unit (observing) time, \( dT \), per unit redshift bin, \( dz \), can be written as
\[
dN = \rho(z) dV(z) dz, \tag{8}
\]
where \( dV(z)/dz \) is the derivative of the volume with regards to \( z \). Integrating the previous equation by \( dz \) and \( dV \), we can estimate the density rate at a particular redshift \( z \) as
\[
\rho(z) = \frac{4\pi N(1+z)}{\Omega TV_{z,\text{max}}}, \tag{9}
\]
where \( V_{z,\text{max}} \) is the maximum co-moving volume (at the maximum co-moving distance \( D_{z,\text{max}} \)), while \( \Omega \) and \( T \) are the FoV and the exposure time used in this work (corrected by \( e_i \); see Sect. 6.1), respectively.

For Case I (between five and seven local FXRTs), the density rate at \( \approx 100 \text{ Mpc} \) is \( \rho_{\text{Case I}} = (5.9^{+29}_{-26}) \times 10^{-7} \text{ yr}^{-1} \text{ Mpc}^{-3} \), at
a 1σ confidence level. Due to the small distance of these FXRTs, we can approximate this result at z = 0, also called the local density rate (denoting as \( \rho_0 \)), that is, \( \rho_{\text{case}} \approx \rho_0 \text{Case 1} \). This value is consistent with previously derived rates for ULXs, taking ULX M82 as an example (1.75 \( \times 10^{-2} \) yr\(^{-1} \) Mpc\(^{-3} \); Kaaret et al. 2006; Swartz et al. 2011; Pradhan et al. 2020).

For Case II (distant FXRTs), redshift and cosmological effects become important. Currently, we only have photometric redshifts for FXRT 8 and FXRT 9 (\( z_{\text{phot}} \approx 0.7 \)), and suspect that FXRT 13 must have a similarly redshift range (\( z \approx 0.2–1.1 \) and \( \tau \approx 0.7 \); see Sect. 4). Thus we only compute the cosmological rate for these FXRTs. Using Eq. (9) and assuming that FXRT 8, 9, and 13 occurred at \( m \text{bol} \) rate for these FXRTs. Using Eq. (9) and assuming.

\[ \rho_{\text{cosmological rate}} = \frac{\rho_{\text{case}}}{1 + (1 + \frac{z}{z_0})^{1+n}} \]

Moreover, the TDE local density rate of FXRTs 8, 9, and 13 is consistent with previously derived rates for LGRBs (normalized to \( z = 0 \)). Therefore, it is possible to determine the local density rate if \( f(z) \) is known.

We adopted \( \rho_{\text{cosmological rate}} = \rho_0 f(z) \) where \( f(z) \) is a function that describes the density rate evolution (normalized to \( z = 0 \)) and \( \rho_0 \) is the density rate at \( z = 0 \). Therefore, it is possible to determine the local density rate if \( f(z) \) is known. We adopted \( \rho_{\text{cosmological rate}} = \rho_0 f(z) \) where \( f(z) \) is a function that describes the density rate evolution (normalized to \( z = 0 \)). Therefore, it is possible to determine the local density rate if \( f(z) \) is known.

\[ \rho(f(z)) = \rho_0 f(z) \]

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\[ \rho(f(z)) = \rho_0 f(z) \]

Finally, five potential distant FXRTs (FXRTs 1, 7, 10, 11, and 12) lack redshift constraints of any kind. To constrain their contribution to the density rate, we compute upper limits assuming that they all lie in a single redshift bin of \( \Delta z \approx 0.5 \). Figure 19, left panel, shows the resulting upper limits (black triangles) on the rate of these FXRTs. These limits are consistent with the density rate computed for FXRTs 8, 9, and 13, CDF-S XT1, and CDF-S XT2 (Xue et al. 2019), but are inconsistent with CC-SNe beyond \( z \approx 0.5 \). Clearly, with firmer distance constraints on these objects, we will be able to pin down the density rates with higher precision.

6.3. Local density rate

Additionally, we extrapolate the density rates of FXRTs 8, 9, and 13 and CDF-S XT1 to the local universe (i.e., \( z = 0 \)) and compare them to other transients. The density rate of any transient evolves through redshift following Sun et al. (2015),

\[ \rho(z) = \rho_0 f(z) \]

where \( f(z) \) is a function that describes the density rate evolution (normalized to \( z = 0 \)) and \( \rho_0 \) is the density rate at \( z = 0 \). Therefore, it is possible to determine the local density rate if \( f(z) \) is known. We adopted \( \rho_{\text{cosmological rate}} = \rho_0 f(z) \) where \( f(z) \) is a function that describes the density rate evolution (normalized to \( z = 0 \)). Therefore, it is possible to determine the local density rate if \( f(z) \) is known.

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\[ \rho(f(z)) = \rho_0 f(z) \]
6.4. Expected events in current and future missions

Taking the computed rates from Sect. 6.1, we examine the prospects for detecting FXRTs in other ongoing and future X-ray missions. The expected rate of a new mission (called $N_{\text{New}}$) regarding our results using CSC2 is

$$N_{\text{New}} = \Omega_{\text{New}} T_{\text{New}} R_{\text{New}} = \Omega_{\text{New}} T_{\text{New}} \left( \frac{F_{\text{New,lim}}}{F_{\text{CSC2,lim}}} \right)^\gamma R_{\text{CSC2}},$$

(12)

where $\Omega_{\text{New}}$ and $T_{\text{New}}$ are the FoV and the operational time of a new mission, respectively. It is important to realize that Eq. (12) takes into account the ratio between the new mission ($F_{\text{New,lim}}$) and Chandra (the limit imposed by our method $F_{\text{CSC2,lim}} = 1.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$) X-ray flux limits, respectively, which is a correction factor between both instruments.

Given the low-count statistics, we quote estimates incorporating the Poisson 1$\sigma$ errors.

Current operating observatories such as XMM-Newton, Swift–XRT, and eROSITA have sufficient sensitivity and/or history in orbit to detect similar FXRTs to those found here.

The European Photon Imaging Camera (EPIC; pn plus Metal Oxide Semi-conductor CCD arrays) on board the XMM-Newton telescope have an instantaneous FoV of $0.25$ deg$^2$, flux sensitivity of $\sim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the energy range of $0.15$–$12$ keV, and have an archive of roughly $\approx 476$ Ms total exposure time during $\approx 20$ years in orbit (mean value between pn and MOS cameras; Ehle et al. 2003). Adopting a spectral slope of $\Gamma = 1.7$, typical of FXRTs (e.g., CDF-S XT1), a correction factor to account for the contribution of background flares (assuming that 30–40% of exposure time is affected by them) and a flux cutoff of $F_{\text{XMM,lim}} \sim 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (to avoid effects from Poisson noise), we predict up to $\approx 68$–135 Case I and $\approx 37$–68 Case II FXRTs, respectively.

Similarly, Swift–XRT has a FoV of $\approx 0.15$ deg$^2$, a flux sensitivity of $\approx 8 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the energy band of $0.2$–$10$ keV, and has accumulated $\approx 315.4$ Ms of archival data over $\approx 14$ years operational time (Hill et al. 2000; Burrows et al. 2003). Adopting a flux limit of $F_{\text{XRT,lim}} \sim 8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (again, to avoid Poisson noise effects), the expected number of FXRTs are $\approx 27$–$55$ Case I and $\approx 15$–$27$ Case II events.
The above implies that there should be a substantial number of FXRTs hidden within the XMM-Newton and Swift–XRT archives and catalogs. The X-ray transient and variable sky (EXTras) project (De Luca et al. 2021) and systematic searches such as Alp & Larsson (2020) have reported 136 and a dozen candidates to date, respectively, which presents a lower bound to the total numbers estimated above. Also, in the systematic search developed by the EPIC-pn XMM-Newton Outburst Detector (EXOD) search project (Pastor-Marazuela et al. 2020), 2536 potential XRTs have been identified, but this large number is dominated by stellar flares, cataclysmic variables, type I X-ray bursts, supergiant FXRTs, SBOs, AGNs, and more.

Finally, the Spectrum-Roentgen-Gamma (SRG)–eROSITA mission, launched in July 2019, is scanning the entire sky in the X-ray band (0.2–10 keV) with a FoV $\approx 0.833$ deg$^2$ during SRG–eROSITA’s official 4-year survey phase. This should provide roughly equivalent coverage in sky area per time to the current XMM-Newton archive. The SRG–eROSITA all sky survey is expected to yield flux limits of $\approx 10^{-14}$ and $\approx 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5–2 and 2–10 keV energy bands, respectively. Avoiding Poisson noise effects as above, we adopt an SRG–eROSITA 0.5–2 keV flux limit for FXRTs of $F_{\text{lim}} \approx 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Thus, during the 4-year survey, the expected number of FXRTs detected by SRG–eROSITA (in the 0.5–2 keV band) should be $\approx 50$–100 and 27–50 events for Case I and Case II, respectively.

Concerning future missions, the Advanced Telescope for High ENergy Astrophysics (Athena) has been selected by European Space Agency to characterize the hot and energetic universe, with an anticipated launch in the mid 2030s. It is projected to have an effective area of 0.25–2.0 m$^2$, energy range of 0.3–12 keV, and a nominal lifetime of five years, although consumables (such as fuel) have been rated for 10 years in the case of a mission extension (Nandra et al. 2013; Barret et al. 2013). The Wide Field Imager (WFI) is one of two detectors on board Athena, with a spectral resolution of $\Delta E < 170$ eV at 7 keV, spatial resolution of $\leq 10$ arcsec PSF on-axis, and FoV of 0.44 deg$^2$ (Rau et al. 2016). To estimate the number of extragalactic FXRTs, we conservatively assume a flux threshold 10 times higher than the nominal 60 ks (longer than the expected duration of the FXRTs) flux limit due to Poisson fluctuations of $F_{\text{lim}} \approx 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (where the point source detection limit is $\approx 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ for the WFI deep fields). This flux limit is a factor of 100 deeper than the SRG–eROSITA sky survey flux limit. Thus, during a 4–year mission, adopting $\gamma \approx 0.5$ for the faint-end slope extrapolation the expected number of FXRTs detected by Athena will $\approx 130$–270 and 72–130 events for Case I and Case II, respectively. This sample size of bright and fainter events can be used to probe the multicolor properties with coordinated campaigns. Assuming that the WFI observations will be spread evenly during the mission and that those observations will also be performed during the Athena ground contact, approximately one-sixth of the events ($\approx 9$ and 16) could have Athena alerts with latencies $< 4$ h.

We also consider the Einstein Probe (EP), which aims to monitor high-energy transient and variable phenomena in 0.5–4.0 keV band (Yuan et al. 2015, 2017). The EP is scheduled for launch by the end of 2023, with a 3-year operational lifetime and 5-year goal (Yuan et al. 2017). EP will carry two scientific instruments, the Wide-field X-ray Telescope (WXT) with a large instantaneous FoV of 3600 deg$^2$ and a narrow-field Follow-up X-ray Telescope, as well as a fast alert downlink system (Yuan et al. 2015). To estimate the expected number of FXRTs, we consider just the WXT instrument, which has a threshold sensitivity of $F_{\text{WXT}} \approx 5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ at 1 ks, that is, $\approx 500$ times higher than our flux limit and $\gamma \approx 1.0$.

Thus, during the $\approx 3$ year mission, the expected number of FXRTs detected by EP should be $\approx 69$–138 and 38–69 events for Case I and Case II, respectively.

7. Conclusions and future work

In this work we search for extragalactic FXRTs hidden in CSC2. We have applied a modified version of the algorithm developed by Yang et al. (2019) to 214,701 X-ray sources identified in the CSC2 with $|b| > 10$ deg (i.e., 5303 Chandra observations, totaling $\approx 169.6$ Ms and 592 deg$^2$). Considering additional criteria (analyzing further X-ray observations taken by Chandra, XMM-Newton, Swift–XRT, Einstein, and ROSAT) and other astronomical catalogs (Gaia, NED, SIMBAD, VHS, DES, Pan-STARRS, and others), we identify 14 FXRTs that remain consistent with an extragalactic origin. We rediscovers all (five) previously reported Chandra events covered by CSC2: XRT 000519 (previously identified by Jonker et al. 2013), XRT 110103 (previously identified by Glennie et al. 2015), XRT 030511 and XRT 110919 (previously identified by Lin et al. 2019, 2022), and XRT 141001/CDF-S XT1 (previously identified by Bauer et al. 2017).

Candidates have peak 0.5–7 keV fluxes between $\approx 10^{-13}$ and $2 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ and $T_{90}$ values from $\approx 4$ to 40 ks. None of the FXRTs are detected in gamma rays near the time of the detection of the transient X-ray light. Based on multiwavelength constraints, we rule out a Galactic origin (e.g., as Galactic M or brown-dwarf stellar flares) in all but two cases (for these, existing data cannot yet rule out extreme stellar X-ray flares). The origin of the extragalactic FXRT sample appears to be diverse: five events are robustly associated with local galaxies ($\lesssim 100$ Mpc; called the local sample); seven are likely distant events ($\gtrsim 100$ Mpc; called the distant sample); and two events, XRT 000519 and XRT 110103, have nearby associations that remain somewhat ambiguous. Among the distant FXRTs, we identify hosts for four FXRTs, which span a wide range of magnitudes ($m_i \approx 20.6$–27.0 AB mag), while we can only place upper limits on five FXRTs.

We have studied the spectral and timing properties of the FXRTs. The X-ray spectra can be well fitted by PLs with a median slope of $\Gamma = 2.5$ and an overall range $\Gamma \approx 1.7$–4.0. Furthermore, we observe potential spectral softening for six FXRTs with time (for XRT 000519 and XRT 110103, the softening is highly significant and occurs during the main flare; Glennie et al. 2015). In the case of timing properties, five FXRTs show plateaus in their X-ray light curves, similar to CDF-S XT2 (Xue et al. 2019), with durations of $\approx 2$–10 ks followed by PL decays with slopes ranging from $\approx 1.2$ to 2.6. For three FXRTs we see, simultaneously with the plateau and decay, possible spectral softening (at 90% confidence), similar to CDF-S XT2 (Xue et al. 2019).

The five local FXRTs have projected physical offsets between $\approx 0.7$ and 9.4 kpc, with four being co-spatial with apparent star-forming regions or young star clusters. Adopting their host distances, these local events have peak isotropic X-ray luminosities of $L_{\text{X,peak}} \approx 10^{38}$–$10^{40}$ erg s$^{-1}$, well below expectations for GRBs, TDEs, XRFs, and supernova SBOs. Such luminosities are comparable to those of ULXs and Galactic XRBs, although the durations and time variability properties of the local FXRTs are quite distinct. As such, we speculate that several may represent a new type of X-ray phenomenon related to massive stars.

Among the distant FXRT sample, two are associated with relatively bright optical and NIR extended sources, allowing...
us to derive galaxy properties using photometric archival data. The other two host associations are very faint extended sources; one is detected only in a single band, and hence lacks physical constraints, while the other is fortuitously observed by the HST but has only weak constraints on its properties. Both bright hosts have similar redshifts ($z_{\text{host}} \approx 0.5$–0.7) and stellar masses ($M_\star \approx 3 \times 10^{10} M_\odot$), but starkly different SFRs ($SFR \approx 0.5$ vs. $\approx 125 M_\odot \text{yr}^{-1}$), and the faint HST host has an uncertain redshift ($z_{\text{host}} = 0.4$–3.2) and associated host properties (Bauer et al. 2017). Adopting $z = 0.7$ for all four events, the peak luminosities, energetics, and spectro-temporal properties robustly rule out an SBO origin but potentially remain consistent with origins as on-axis GRBs, and even off-axis GRBs in the tail of the X-ray afterglow, or TDEs involving an IMBH and a WD.

For the three FXRTs that lack optical and NIR host detections, interpretations are broader. An association with SBOs remains possible at low redshifts ($z \leq 0.5$), as long as potential hosts are low-mass, low-SFR dwarf galaxies. An off-axis GRB afterglow scenario is also viable, except perhaps for very low redshifts ($z \leq 0.1$), where the lack of any association with a host becomes problematic. Finally, a TDE scenario remains possible across a broad redshift range, although the lack of a detectable host requires strong beaming, for instance, similar to Swift J1644+57.

We compute the event rates of local (Case I) and distant (Case II) FXRTs of $R_{\text{Case I}} = 53.7^{+22.6}_{-15.1}$ and $R_{\text{Case II}} = 28.2^{+9.8}_{-6.9}$ deg$^{-2}$ yr$^{-1}$, respectively. Additionally, for three distant FXRTs (assuming $z = 0.7$), we derive a volumetric rate (in units of yr$^{-1}$ Gpc$^{-3}$) of $\rho_{\text{FXRT}} = 8/13 (4.8^{+4.7}_{-2.6}) \times 10^3$ yr$^{-1}$ Gpc$^{-3}$ at $z_{\text{max}} = 2.1$. This value is in good agreement with the value derived by Xue et al. (2019) at a similar redshift ($z_{\text{max}} = 1.9$), as well as with other transient classes such as LGRBs, SGRBs, and TDEs. Nevertheless, this rate is $\approx 2$ order of magnitude lower than that of CC-SNe.

Our investigation of 14 Chandra-detected extragalactic FXRT candidates breaks new ground in terms of characterizing their diverse properties and nature, although the lack of firm distances and host properties for the distant subset clearly leaves much to speculation. The Chandra sample provides the most accurate positions among existing X-ray missions, which is critical for pinpointing potential host galaxies and potential physical offsets. Given the low numbers of distant FXRTs (both found here and predicted in other archives) and the diverse range of host redshifts and properties, it will be critical to identify and follow up their associated host galaxies with dedicated spectroscopy and/or deep multiwavelength imaging in order to place extragalactic FXRTs in a proper physical and cosmological context. The contemporaneous multiwavelength nature of FXRTs remains completely unknown. Given the short duration of these events, progress here will crucially hinge upon the ability of current and future X-ray observatories to carry out efficient strategies for (onboard) detection and alert generation to trigger follow-up campaigns while the FXRTs are still active in X-rays and, presumably, at other wavelengths. The launch of narrow- and wide-field observatories such as Athena and EP should provide a watershed moment for expanding samples.

As future work, we plan to characterize this new sample of FXRTs using recent optical and NIR observations to catch their host galaxies and thus constrain their energetics. Also, we plan to extend our search to Chandra data not considered in the CSC2 to identify new FXRTs and thus better understand their elusive nature.
Appendix A: Spatial location and duration of X-ray events

To estimate the duration of the final sample of FXRTs, we computed the $T_{90}$ duration parameter. $T_{90}$ measures the time over which the event emits from 5% to 95% of its total measured counts (in the 0.5–7.0 keV band in our case). Figure A.1 shows the $T_{90}$ duration (orange region) for each event, as well as their light curves (with a bin time of 1 ks) in unit of counts.

Furthermore, Fig. A.2 confirms that the final sample of FXRT candidates are real celestial sources in the sky rather than detector artifacts. Due to Chandra’s Lissajous dither pattern, executed during observation, the X-ray photons of the FXRTs are distributed over dozens to hundreds of individual pixels on the detector. The first column of the figure shows the light curves, color-coded by the phase in the light curve evolution. The second column shows the spatial location in x and y chip detector coordinates, also color-coded by time, tracing out a sinusoidal-like evolution in x and y coordinates over time. The third and fourth columns show the x and y position changes (in blue and purple, respectively, over time, with the light curve superimposed in dark gray.

![Fig. A.1. Light curves for each FXRT candidate in units of counts and the region covering the $T_{90}$ (which measures the time over which the event emits from 5% to 95% of its total measured counts; orange region) The light curves have a bin width of 1 ks.](image-url)
Fig. A.2. Lissajous dither pattern in detector coordinates. First column: FXRT 0.5–7.0 keV light curves in count units, color-coded as a function of time. Second column: Chandra 0.5–7.0 keV images in detector coordinates, with the same color-coding as a function of time, demonstrating the temporal movement of the source on the detector in response to the Lissajous dither pattern. A flaring pixel would appear as a point on these plots. Third and fourth columns: x (blue) and y (purple) detector coordinates, respectively, of the detected X-ray photons from the FXRTs as a function of time, with the candidate light curves superimposed as solid dark gray lines.
Fig. A.2. (continued)
Appendix B: Color-magnitude diagram of stellar matches

To further demonstrate the stellar-like nature of the star candidates (beyond identification by Gaia), we show an example $M_g$ versus $g - i$ color-magnitude diagram (see Fig. B.1) considering all Pan-STARRS and DECam counterparts of X-ray sources classified as stars according to Criterion 2 (see Sect. 2.5.2). Isochrones with different ages (from $\log($Age$) = 7.0 - 10.0$) taken from the MIST package (Dotter 2016; Choi et al. 2016) are overplotted, with each panel representing different metallicities (from $[\text{Fe/H}] = -3.0$ to $+0.5$). Solid and dashed lines denote isochrones with attenuations of $A_V = 0.0$ and 5.0, respectively. The vast majority of the stars fall on these tracks. According to SIMBAD, the outliers are identified as PNe, YSOs, or emission-line stars. We additionally stress that the Pan-STARRS and DECam colors are not necessarily taken in a purely simultaneous manner; in the case of Pan-STARRS, they are averaged over the duration of the survey, while for DECam they come from only a few disjoint epochs.

Fig. B.1. Color-magnitude diagrams, considering only Pan-STARRS and DECam counterparts (gray background points) of X-ray sources classified as stars according to Criterion 2 (see Sect. 2.5.2). As a comparison, we overplot isochrones with different ages (from $\log($Age$) = 7.0 - 10.0$) taken from the MIST package (Dotter 2016; Choi et al. 2016). Each panel represents different metallicities (from $[\text{Fe/H}] = -3.0$ to $+0.5$), while solid and dashed lines are isochrones with attenuations of $A_V = 0.0$ and 5.0, respectively.