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Extragalactic panel
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The origins of extragalactic fast X-ray transients

Abstract

Fast X-ray Transients (FXRTs) are enigmatic extragalactic X-ray flares of unknown origin. Thirty have been detected to date in narrow field of view X-ray instruments implying all-sky rates of >4 million per year. However, very few have secure redshifts. A decisive differentiation between the three promising mechanisms which have been proposed for their origin (tidal disruptions, supernova shock breakouts, neutron star mergers) requires the understanding of the FXRT energetics, environments, and/or host properties. Here we propose to increase the sample of FXRTs with known redshift by 19 from 2 to a statistically useful sample of 21. We will use Baade/FourSTAR, Baade/MagE-FIRE, and MPE 2.2m/GROND observations to identify host galaxy redshifts (and luminosities), host detection and plausible offsets to host galaxies which may be expected if such mergers arise from kicked stellar populations, such as those involving the mergers of neutron stars.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
FourStar/Magellan / Baade	2 nights	2 nights	March Any	April Any
MagE/Magellan / Baade	1 nights	1 nights	June Any	July Any
FIRE/Magellan / Baade	2 hours	2 hours	June Any	July Any
GROND/MPG 2.2-m	3 hours	3 hours	May Any	July Any

CoIs

Name	Institution	e-mail	Observer?
Franz Bauer	PUC	fbauer@astro.puc.cl	False
P Jonker	OnCL	p.jonker@astro.ru.nl	False
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Andrew Levan	OnCL	a.levan@astro.ru.nl	False

Status of the project

- Past nights: 1
- Future nights: 0
- Long term: False
- Large program: False
- Thesis: True

List of Targets

ID	RA	DEC	Mag
XRT000519	12:25:31.50	13:03:57.85	r=25
XRT110103	14:08:28.95	-27:03:28.22	r>25
XRT100831	06:00:01.08	-52:42:54.04	r>24.3
XRT110919	01:03:44.54	-21:48:45.79	r>24.4
XRT140507	15:34:56.35	23:28:06.24	r>23
XRT030510	05:07:06.76	-31:52:11.28	r>23.3
XRT140327	03:01:04.14	-77:52:51.42	i>24.7
XRT170831	23:45:03.44	-42:38:41.64	r=25.5
XRT210423	13:48:56.46	26:39:44.32	r>23
XRT070618	01:37:06.05	-12:57:10.08	r>24.1
XRT040610	11:18:08.70	07:42:09.58	r>22.8
XRT080331	11:20:17.50	12:58:18.75	g=21
XRT161125	02:26:52.13	-01:04:58.68	r=23
XRT 151219	11:34:07.29	00:52:26.72	r=21.5
XRT151128	11:08:18.92	-05:04:29.82	r=20.3
XRT191126	13:49:23.32	26:35:04.02	r=23
XRT191126	13:49:23.32	26:35:04.02	r=23
XRT140105	13:56:01.11	-32:35:15.37	r=22.4
XRT140105	13:56:01.11	-32:35:15.37	r=22.4
XRT060207	13:07:20	-40:27:40	r=23
XRT060207	13:07:20	-40:27:40	r=23
XRT060207	13:07:20	-40:27:40	r=23

SCIENTIFIC AIM AND RATIONALE

In a nutshell: This proposal will measure redshifts and host galaxy properties for the still-mysterious population of extragalactic Fast X-ray Transients (FXRTs) to make decisive inroads into the nature of their progenitors. These progenitors may be a range of physical systems. Possibilities include strong sources of both high- and low-frequency gravitational waves in the form of merging neutron stars (LIGO/VIRGO sources) or white dwarf disruptions by intermediate-mass black holes (LISA sources), as well as rare examples of supernovae shock-breakout. The identification of their origin would have significant implications across several fields. For example, if they represent isotropic signatures from neutron star mergers then such signals may be the prime route to rapidly find the electromagnetic counterparts of gravitational wave sources. Should they arise from intermediate-mass black holes, they would represent a unique way to access them, determine their critical role in galaxy formation and evolution, and even probe fundamental physics.

While the last decade has seen excellent progress understanding short-lived transients across the electromagnetic spectrum, from long- and short-duration gamma-ray bursts (GRBs) to fast radio bursts (FRBs), the nature of the FXRTs remains unknown. Our ignorance is essentially caused by the lack of clear multi-wavelength counterparts in most cases. Sometimes even when deep observations are taken in the hours after the outburst no optical counterpart is found (with an $R > 25.7$ limit just 80 minutes after the FXRT as the most extreme example; Bauer et al. 2017). However, while counterparts may be hard to find, we still expect these progenitors to form around some underlying stellar population – a host galaxy. This host galaxy provides a route to measuring the distance to the event and hence its energetics. The luminosities of different progenitor models are drastically different, with $L_{X,peak} \lesssim 10^{46}$ erg s^{-1} for mergers, $L_{X,peak} \lesssim 10^{48}$ erg s^{-1} for disruptions and $L_{X,peak} \lesssim 10^{43}$ erg s^{-1} for shock breakout. Hence, measuring the redshifts provides an immediate indication of likely progenitors. The demographics of the hosts themselves can further enhance this. For example, shock breakout should arise in galaxies with massive stars, intermediate-mass black holes should exist in compact stellar clusters, and binary neutron stars may reside at large offsets from their hosts.

More details: Extragalactic FXRTs are short flashes of X-ray photons spanning a few seconds to hours (e.g., Soderberg et al. 2008; Jonker et al. 2013; Glennie et al. 2015; Bauer et al. 2017; Xue et al. 2019; Lin et al. 2019; Alp & Larsson 2020; Novara et al. 2020; Wilms et al. 2020; Lin et al. 2021). In addition to the FXRTs given in the references above, we performed a systematic search for these extragalactic FXRTs in the *Chandra* archive (manuscript in prep). Overall, there are ≈30 extragalactic FXRTs known, discovered in the small instantaneous fields of view of *Chandra* and XMM-*Newton*. This implies high occurrence rates of $>4\times10^6$ FXRTs per year over the whole sky with peak X-ray fluxes $F_{\rm X,peak}>5\times10^{-13}$ erg cm^{-2} s^{-1}. The three most favored scenarios to explain these FXRTs are:

1: Binary Neutron star (BNS) mergers: binary neutron star mergers are predicted to produce X-ray transients not associated with short GRBs (Dai et al. 2006; Metzger et al. 2008). Xue et al. (2019) favor this scenario for the FXRT called CDF-S XT2, which is offset by ≈0.4″ from a $z_{\rm spec}$=0.74 star-forming galaxy. A recently discovered FXRT, XRT 210423 (Lin et al. 2021) has a possible host galaxy at an angular distance of ≈4.6″ from the X-ray position. Jonker et al. (2021) reported on X-Shooter spectra of this candidate host, obtaining a redshift of 1.5105, which implies an offset of 39 kpc (similar to offsets seen for short GRBs) and a peak X-ray luminosity of 5.8×10^{45} erg/s, similar to that inferred for CDF-S XT2.

2: White Dwarf Tidal Disruption by an intermediate mass black hole (IMBH): the lower mass of an IMBH, vs. super-massive black holes, combined with the compactness of white dwarfs are predicted to lead to fast X-ray flashes via tidal disruption (see Maguire et al. 2020 for a recent review on the expected properties of such tidal disruption events). For one FXRT, XRT 000519 (Jonker et al. 2013), precursor flares support this scenario (see also Strubbe & Quataert 2009; MacLeod, Trenti & Ramirez-Ruiz 2016).

3: Supernova Shock Breakout: when the radiation mediated shock from a supernova explosion crosses the surface of a star it can be observed as a so-called supernova shock breakout. For several supernova types it should appear as an X-ray flash initially and then evolve into the UV and optical bands. The FXRT 080109 (Soderberg et al. 2008) was detected in the galaxy NGC 2770, lasting $\approx$400 seconds. This FXRT was coincident with one of the arms of the spiral galaxy, about 9 kpc from the centre of the galaxy. Its peak luminosity is $\sim 6.1\times10^{43}$ erg s^{-1} and *Swift* detected an UV/optical counterpart 1.4 hours after the X-ray outburst. This counterpart later developed into a Type Ibc supernova (Soderberg et al. 2008 and references therein).

Our main objectives are to 1) identify faint hosts and establish host offsets 2) determine the redshifts and thereby the peak X-ray luminosities, and 3) characterize bright hosts for a statistically meaningful sample of 19 of the 30 FXRTs (all those accessible from Chile; 6 *XMM-Newton* and 13 *Chandra* FXRTs; see Table 1, and two examples in Fig. 1). To achieve this, we request the following: *i*) FourSTAR (Baade) *J*-band imaging for 9 host-less and 4 faint/ambiguous FXRTs (all have $\log(F_{X,peak}/F_{bol}) \gtrsim -3$, excluding a Galactic stellar flare origin; Garcia-Alvarez et al. 2008); *ii*) MagE optical or FIRE NIR spectroscopy (Baade) to determine redshifts for 8 host counterparts, and thus constrain the X-ray luminosity and host properties; *iii*) GROND (MPE 2.2m) multi-band photometry for 3 bright hosts, which lack a full complement of high signal-to-noise optical and NIR host detections for size/shape/SED modeling. In this way, we hope to characterize the novel sample of FXRTs detected by *XMM-Newton* and *Chandra*. Although the sample is modest in size, it represents two decades of accumulated X-ray data and represents a huge jump in both quality and quantity of constraints compared to past one-off (e.g., Jonker et al. 2013, Bauer et al. 2017, Xue et al. 2019) or small sample studies (only Alp & Larsson 2020 to date).

References

[1] Alp & Larsson, 2020, ApJ, 896, 39
[2] Bauer et al. 2017, MNRAS, 467, 4841
[3] Dai et al. 2013, ApJ, 775, L9
[4] Garcia-Alvarez et al. 2008, ApJ, 679, 1509
[5] Glennie et al. 2015, MNRAS, 450, 3765
[6] Jonker et al. 2013, ApJ, 779, 14
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[15] Strubbe, & Quataert 2009,MNRAS, 400(4), 2070-2084
[16] Wilms et al. 2020, ATel #13416
[17] Xue et al. 2019, Nature, 568, 198

#	Id	T_{90} (ks)	Flux (cgs)	Pos. Unc.	Host offset	m (AB mag)	Pho	Spec
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
		FXRTs sample from *XMM-Newton* (Alp & Larsson 2020)						
1	XRT 040610	≈25	1.2e-14	1.5	—	m_r>22.8	FourSTAR	—
2	XRT 050925	≈4	2.4e-14	2.0	1.5	m_z=21.9	GROND	FIRE
3	XRT 060207	≈0.2	1e-12	1.8		m_r=23.0	GROND, FourSTAR	MagE
4	XRT 070618	≈0.15	3.2e-12	1.4	—	m_r>24.1	FourSTAR	—
5	XRT 151128	≈5	2.7e-14	2.0	3.5	m_r=20.3	—	MagE
6	XRT 151219	≈0.8	2.3e-13	1.6	2.9	m_r=21.5	—	MagE
		FXRTs sample from *Chandra* (Quirola–Vásquez et al. in prep)						
7	XRT 000519	11.6	6.4-13	0.9	—	m_r≈25	FourSTAR	—
8	XRT 030510	7	1.1e-13	0.78	—	m_r>23.3	FourSTAR	—
9	XRT 080331†	21	2.0e-14	0.5	78	m_g=21.0	—	MagE
10	XRT 100831	4	3.9e-15	0.58	—	m_r>24.3	FourSTAR	—
11	XRT 110103	40.1	6.2e-14	1.3	—	m_r>25	FourSTAR	—
12	XRT 110919	4	2.1e-15	0.55	—	m_r>24.4	FourSTAR	—
13	XRT 140105	≈35.0	3.7e-14	0.58	0.65	m_r=22.4	GROND	MagE
14	XRT 140327	16	5.1e-15	0.88	—	m_i>24.7	FourSTAR	—
15	XRT 140507	≈9.6	5.9e-15	0.18	—	m_r>23.0	FourSTAR	—
16	XRT 161125	≈6.0	1.58e-13	1.62	1.79	m_r=23.0	—	MagE
17	XRT 170831	4	3.2e-14	0.1	0.5	m_r=25.5	FourSTAR	—
18	XRT 191126	≈0.5	2.4e-14	0.46	—	m_r∼23.0	FourSTAR	MagE
19	XRT 210423	≈4.1	4.0e-13	0.5	—	m_r>23.0	FourSTAR	—

Table 1: Properties of our extragalactic FXRT candidate sample, ordered by sub-sample and date. *Col. 1:* FXRT number. *Col. 2:* X-ray transient identifier (XRT date). *Col. 3:* T_{90} duration (i.e., time over which central 90% of emission occurs). *Col. 4:* average 0.5–7.0 flux in cgs units, calculated using the full observational exposure. *Col. 5:* estimated 1-σ X-ray positional uncertainty, in arcseconds. *Col. 6:* Angular offset between X-ray and optical/NIR host positions, in arcseconds. *Col. 7:* observed (or deepest upper limit) magnitudes. *Col. 8 and 9:* requested instrument(s) for photometry or spectroscopy, respectively, in this proposal. † FXRTs possibly related to local galaxy (d<17 Mpc).

Figures

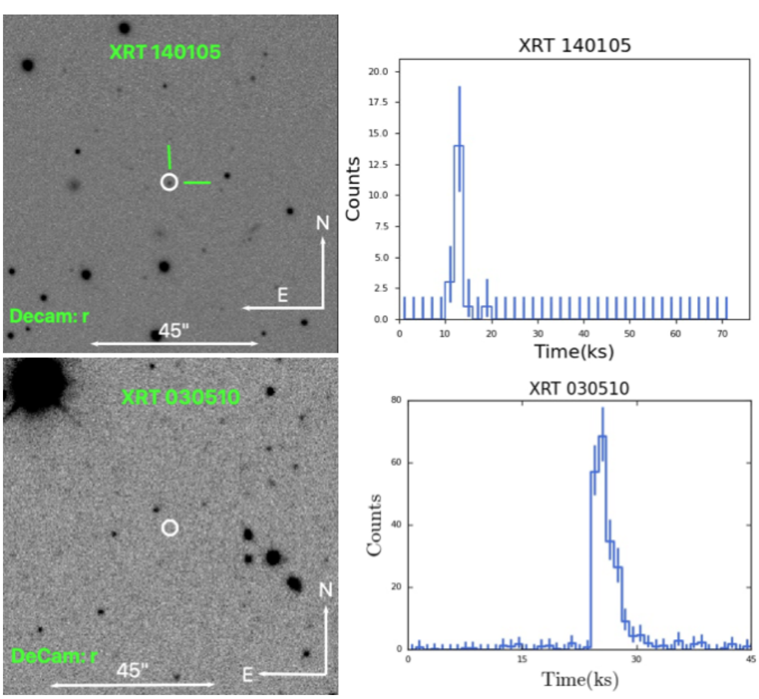

Figure 1: DECam r-band images centered on the positions of FXRTs 140105 and 030510 (left panels) and their respective X-ray light curves (in the 0.3–10 keV band; right panels). FXRT 140105 is an example of an FXRT with a bright host, while the FXRT 030510 appears hostless. The white circles represent the 2-σ X-ray positional uncertainty.

CURRENT STATUS OF THE PROJECT

This proposal's main goals are to identify faint host galaxies for the remainder of known FXRTs which lack clear associations in current imaging, characterize optical/NIR SEDs for FXRTs with bright hosts which lack imaging in hand, and measure redshifts for all accessible/feasible host counterparts to derive their distances and assess FXRT and host properties. The FXRT sample comes from systematic searches through the serendipitous catalogs of the *Chandra* and *XMM-Newton* telescopes.

FXRT candidates detected by *XMM-Newton* were identified by Alp & Larsson 2020 from the 3XMM-DR8 catalog, while *Chandra* candidates (Quirola-Vásquez et al. in prep) were selected from the *Chandra Source Catalog 2.0* ($\sim$192 Ms; CSC2.0, up to 2015) and the archive data beyond 2015 (data not considered in CSC2.0). Both FXRT sub-samples are chosen to have >3-σ variability within a 10-20 ks window in a portion of the observation consistent with background limits; for all proposed FXRT candidates, we require prior and subsequent X-ray observations with *Chandra*, *XMM-Newton*, and *Swift-XRT* to be non-detections.

Currently, the characterization of host galaxies has mainly leveraged existing multi-wavelength archival data (from DES, PanSTARRS, VHS, unWISE), however, not all the FXRTs have enough or uniformly deep archive observations. Deep host searches have also been undertaken for a few FXRTs. For instance, VLT/FORS2 R-band observations of XRT 000519 (Jonker et al. 2013) marginally detect (3σ) a source on the North-West side of the $\sim$1$''$ error circle of the transient XRT 000519. This possible host candidate, e.g., a (faint) globular cluster near M86, has a magnitude of R$\sim$ 25.9$\pm$0.3, which considering a likely (but unconfirmed) distance of 16 Mpc to M86 translates to an absolute magnitude of $M_R \approx -5.1$ (Eappachen et al. in prep). Another FXRT, XRT 110103 (Glennie et al. 2015), which shows similar properties to XRT 000519, seems to be associated with a galaxy cluster and has no optical counterpart down to a limit of R$>$26.0 mag (Eappachen et al. in prep). Moreover, additional follow-up campaigns have been implemented to identify and/or characterize potential host galaxies using imaging (GROND, GEMINI/GMOS, VLT/FORS2; CNTAC awarded to this project 1 GROND night) and spectroscopy (VLT/X-SHOOTER, GEMINI/GMOS) optical facilities. Nevertheless, many host galaxies have not been observed by NIR instruments, or the awarded time allocations were canceled (because of COVID-19 restrictions). The observations requested in this proposal form a crucial portion of our project to enable the study and characterization of the origin of FXRTs. It is necessary to obtain high signal-to-noise detection, spectroscopy, and multi-band photometric information.

The related experience of the authors began with the very first discovery of this class of X-ray transients. The list of relevant refereed publications detailing our involvement is summarized as follows: **Jonker et al. (2013), ApJ, 779, 14J; **Glennie et al. (2015), MNRAS, 450, 3765G; **Bauer, F. E., Treister, E., Schawinski, K., et al. (2017), MNRAS, 467, 4841-4857; **H., Li, Y., Zhang, B., et al. (2019), ApJ, 886, 2, 129; **Xue, Y. Q., Zheng, X. C., Li, Y., et al. (2019), Nature, 568, 198-201; **Yang, G., Brandt, W. N., Zhu, S. F., et al. (2019), MNRAS, 487, 4721-4736; **Jonker et al. (2021), AstroNote, 160.

STUDENT THESIS

The proposed follow-up will form critical components of two PhD projects. Particularly, this proposal is related to the PhD thesis of the PI (graduate student in a Chilean institution). His thesis started in mid-2019 and is now in the final stages of the investigation. The PI has made an extensive search for fast X-ray transients and narrowed down the candidates through existing multi-wavelength constraints. Unfortunately, this follow-up work has been delayed due to the pandemic. The current proposal for Baade FourSTAR/MagE/FIRE and MPG 2.2m GROND observations will form a critical part of his doctoral thesis.

TECHNICAL DESCRIPTION

This proposal adopts three different instrument configurations to achieve our scientific goals. The expected distances cover a wide redshift range $z\approx0.1$–1, based on: crude photometric redshifts estimated by Alp & Larsson 2020 for *XMM-Newton* FXRTs ($z_{\rm phot}\approx0.1$–1.2) the photometric redshift of CDF-S XT1 ($z_{phot}\approx0.4$–3.2; Bauer et al. 2017), the spectroscopy redshifts of CDF-S XT2 (z_{spec}=0.74; Xue et al. 2019), and the *Chandra* FXRTs 041230 and 080819 ($z_{\rm spec}$=0.7; Quirola-Vásquez et al. in prep). The technical description and conditions per setup as follows:

<u>**Baade/FourSTAR imaging**</u>: 9 FXRTs (see Table 1) remain host-less in Pan-STARRS, DECam, VISTA, UKIDSS, and unWISE images and/or catalogs. For this sub-sample, reasonable limits will be set on possible associations with faint/distant dwarf galaxies (Simon 2019) and/or globular clusters (Harris 1996). Additionally, the hosts of 4 FXRTs remain marginal and/or ambiguous, for which NIR imaging confirmation is desired. We propose deep J-band imaging with FourSTAR to $m_J<24.4$–24.5 AB mag (5-σ depth) to locate faint extragalactic hosts of FXRTs. We select the J filter due to its high efficiency and the capacity to detect red and/or high-z hosts. Based on the current optical/NIR magnitude distribution, we expect $\sim$90% of our targets to be detectable at this limit, with non-detections motivating an HST proposal. To reach this depth requires $\approx$1 hr exposures per target according to the LCO Exposure Time Calculator, adopting Moon distance=45 deg, Moon phase=0.5, and airmass=1.8. Assuming 1-hr per source, with 25% overheads (§6 of FourSTAR manual), **we request 13+3 hr ($\sim$2 nights) of FourSTAR J-band imaging. Up to 10 targets are observable in March/April, up to 10 targets in June/July.**

<u>**Baade/MagE–FIRE spectroscopy**</u>: we request spectroscopy for 8 FXRTs (see Table 1), 7 with MagE and 1 with FIRE, to identify spectral features and measure distances. The proposed MagE/FIRE observations for known candidate host galaxies (e.g., XRT 140105 in Fig. 1) will have sufficient signal-to-noise (>3–4/pix) to identify stellar absorption features (e.g., Ca H&K, or Balmer absorption), the overall shape of the continuum spectrum (e.g., the Balmer break, which provides an indication of the host-galaxy's stellar age), and the presence/absence of emission lines (e.g. O[II], O[III], Hβ, Hα, N[II]) related to star-forming systems across a large range of redshifts. To reach S/N>3–4 for hosts with $m_{\rm r}\sim$20–23, we estimate $\approx$7.5 hr of exposure for MagE (via LCO Exposure Time Calculator). For XRTs 151128, 151219, and 080331 we assume airmass=1.5, $\pm$7 days from New Moon, and seeing=1.0; meanwhile for the faintest FXRTs (XRTs 191126, 140105, 161125, and 060207) we adopt observing conditions as airmass=1.2, seeing=0.7 and low Moon luminosity. On the other hand, we require $\approx$2 hrs of exposure for FIRE spectroscopy for XRT 050925 (based on past success, we use X-SHOOTER ETC, rescaling by collecting areas). Assuming 20% overheads, **we request 9.5+2 ($\sim$1 night) hrs Baade/MagE–FIRE spectroscopy. Up to 6 targets are observable in March–April, up to 8 targets in June–July.**

For Baade we prefer 1 night in Feb/March/April (any Moon), 2 nights in June–July (1 dark, 1 any Moon). Optimally, we will split time between FourSTAR/MagE/FIRE (changes require $\sim$15 min).

<u>**MPE 2.2m/GROND multi-band photometry**</u>: due to its unique simultaneous imaging in different optical+NIR filters, GROND is highly efficient to characterize and study hosts galaxies and to measure their spectral energy distribution. We aim to constrain the host galaxy properties of three FXRTs (XRTs 050925, 060207 and 140105) which lack high S/N archive optical/NIR photometry to 5-σ depths of $g\lesssim24.0$, $i\lesssim23.5$, $z\lesssim23.2$, $J\lesssim21.6$, $H\lesssim21.1$ and $K\lesssim20.4$ AB mag. Based on the MPE exposure time tables, assuming good photometric conditions ($\pm$4 days from New Moon and airmass<1.5, with nominal La Silla extinction coefficients) under a seeing of $\sim$1.0 arcsec, we can achieve the above with 1.0 hr per target including overheads. **In total, we request $\approx$3 hrs. The targets will be visible during May–July.**