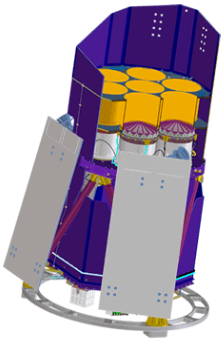

eROSITA_DE / CAASTRO
Science Project Form

Proposed Project Name:

Project Number: **Version:**

Last updated: February 2014

Title:	Professor, Dr, Mr, Mrs, Ms, Miss, (circle) or other: Dr
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1 Project Details/Science Case

- Separate document

2 Partners (from eROSITA and CAASTRO)

- eROSITA_DE
  - Arne Rau (MPE)
  - Joern Wilms (University of Erlangen-Nuremberg)
- CAASTRO
  - Paul Hancock (Curtin University)

3 External Partners

- Curtin University
  - Gemma Anderson
  - James Miller-Jones
- University of Southampton
  - Matthew Middleton
- Durham University
  - Tim Roberts

4 Data Access Requirements

From eROSITA_DE: Alerts for newly discovered tidal disruption events (TDEs) and transient ultraluminous X-ray sources (ULXs) including information about their position, brightness, temporal and spectral properties. The alerts should be available within days to weeks after the discovery to allow timely follow-up observations.

From the Australia Telescope Compact Array (ATCA): Two separate NAPA proposals to conduct ToO ATCA observations (4-hrs in duration) of 4 TDEs and 4 transient ULXs per observing semester. The targets must have a confirmed classification, and the radio follow-up selection will be based on the age and redshift/distance to the event. For both the TDE and ULXs, we aim to identify one radio-bright source for which we will request a further 4 observations (4-hrs each) per semester in-order to obtain good spectral and temporal radio coverage. This will allow us to explore the physics related to how radio jets are coupled to the accretion flow in the super-Eddington regime. (As we expect the radio emission from TDEs and ULXs to be point-like at this distance with a 6km baseline configuration, we do not require a full 12 hour ATCA observing track.)

From the Anglo-Australian Telescope (AAT): ToO access to follow-up 5 TDE candidates and 1 confirmed ULX per observing semester. AAT optical spectroscopic observations will be used to confirm the classification of the 5 TDE candidates, and also provide their redshifts. This can likely be achieved in a single night. AAT optical imaging/spectroscopy to support the ATCA radio monitoring of one radio bright ULX per semester in order to study the surrounding environment (2-4 hrs integration).

5 Resource Requirements

Resources (computing and manpower) will be provided by the institutions hosting the proposal participants. Travel support for Gemma Anderson to attend one eROSITA meeting every 1 or 2 years to report results and collaborate on this project (estimated return flight costs: $2500 AU).

6 Student involvement

- PhD students will be involved in the Near-Real-Time-Analysis (ECAP) and catalog-based transient search (MPE) and follow-up.
- PhD student at Curtin University to work on the processing and analysis of ATCA observations, combined multi-wavelength studies of individual sources and/or studies of the overall radio observed sample.
- Curtin University Honours (4th year undergraduate) and 3rd year undergraduate student projects on individual interesting sources.

7 Use of both eROSITA and CAASTRO data

The main use of the eROSITA data is to provide the triggers (i.e. the discovery of new TDEs and ULXs) to initiate the radio, optical (and X-ray) follow-up. eROSITA spectra and light curve data will also be used in the joint SED modelling.

ATCA radio data will be used to detect radio jets from the TDEs and transient ULXs. ATCA will be first used to identify the radio-bright TDEs and ULXs, providing insight into the radio populations/properties of each. Further radio monitoring of one TDE and one ULX each semester to study the physics of jet-disc coupling in the super-Eddington regime. These data will also be used in joint SED modelling of the individual sources.

AAT optical spectroscopic data will be used to confirm the classification, and obtain the redshift, of TDEs. AAT optical photometric and spectroscopic data will be used to support the ATCA observations of transient ULXs, providing information on the surrounding environment - specifically studies of the stellar population, used to discern the age of the system, and to search for any associated nebulae produced by outflows from the source or photoionisation.

8 Schedule of milestones

The schedule of milestones will be used to monitor progress as the project is executed.

#	Milestone	Date	Person Responsible
1	Pre-launch forecast simulations or radio detectable TDEs and transient ULXs	Sept 2017 - May 2018	A. Rau, J. Wilms, G. Anderson, J. Miller-Jones
2	Verification of eROSITA alert system and event identification/classification	After launch	A. Rau, J. Wilms
3	First telescope proposals for ATCA and AAT	Dec 2017 onwards to start Apr 2018	G. Anderson, J. Miller-Jones, P. Hancock
4	First X-ray (XMM, Chandra, Swift) proposals	Dec 2017 onwards	M. Middleton, T. Roberts
5	Radio, optical and X-ray follow-up of candidates	2018, with increased efforts in 2019	G. Anderson, J. Miller-Jones, P. Hancock, M. Middleton, T. Roberts
6	Modelling of individual sources	2019 onwards	All
7	Publication on interesting individual sources - radio focused analysis, and combined radio/X-ray analysis	2019 onwards	All
8	Publication on overall samples	2021	All
9			
10			

Internal use only:

Approved by eROSITA   Approved by CAASTRO

On behalf of [Party]	**On behalf of [Party]**
Signature	***Signature***
Name (Print)	**Name (Print)**
Position: Director	**Position: Director**

Project Details and Science Case

Introduction

Black holes that accrete at rates approaching, and sometimes surpassing, the Eddington limit (X-ray luminosities $L_X \leq 1.3 \times 10^{38}(M/M_{\odot})$ erg s^{-1}), undergo X-ray outbursts that can last for months, with additional flaring activity on hourly to daily timescales (e.g. Feng & Soria, 2011; Komossa, 2015). This X-ray emission is known to be coupled to the radio emission produced by relativistic jets that are launched in response to the in-falling matter (known as jet-disc coupling; Fender et al., 2004), which applies across the full black hole mass range, from stellar to supermassive (at least when accreting at a few percent of the Eddington rate; Merloni et al., 2003). Unfortunately, given their rarity, the study of super-Eddington accreting black holes at all masses has been limited, so our current understanding of accretion physics is less complete close to the Eddington regime. An additional puzzle has also been presented by the discovery of super-Eddington accreting neutron stars (Israel et al., 2017). The eROSITA_DE data will provide us with a unique opportunity to efficiently identify super-Eddington accreting X-ray transients across half of the entire sky, as the eROSITA survey mandate means the mission will revisit each sky position at least once every 6 months. This will enable us to study a large sample of super-Eddington accreting sources over a wide range of accretor masses. In order to examine jet-disc coupling in the super-Eddington regime, we propose to perform follow-up radio and optical observations of eROSITA-detected tidal disruption events (TDEs) and transient ultra-luminous X-ray sources (ULXs), which are two types of super-Eddington accreting sources that outburst over monthly timescales.

TDEs are rare events resulting from the tidal disruption of a star that strays too close to the event horizon of a supermassive black hole at the nucleus of a galaxy (Hills, 1975). TDEs are also one of a few types of accretion events that allow us to study the jet-disc coupling of supermassive black holes on human timescales, enabling us to compare their behaviour to stellar-mass black holes. They are divided into two classes: non-thermal (relativistic outflows; e.g., Swift J1644+57; Levan et al., 2011; Bloom et al., 2011) and thermal (accretion disc dominated, usually optical/UV and/or X-ray bright; Gezari et al., 2009; van Velzen et al., 2011). It has been predicted that $\sim$1000 TDE candidates will be identified by eROSITA every 6 months (i.e. $\sim$2–3 every day within the eROSITA_DE footprint), up to $\sim 10\%$ of which are expected to be non-thermal (Khabibullin et al., 2014). Until recently, only the rare, non-thermal TDEs were detected at radio frequencies, demonstrating the existence of relativistic radio jets (e.g. Zauderer et al., 2011). The non-detection of radio jets from thermal TDEs was a cause for concern as it called into question our current understanding that the radio jet behaviour is linked to the geometry of the accretion flow (van Velzen et al., 2013). Now radio emission has been detected from a small number of thermal TDEs (for example ASASSN 14li; van Velzen et al., 2016; Alexander et al., 2016), illustrating that they are much fainter than their non-thermal counterparts (3 orders of magnitude; van Velzen et al., 2013), and that they are only detectable if they are nearby and early in their evolution.

Transient ULXs are a flavour of low-mass X-ray binary where the stellar mass black hole (or possibly neutron star) undergoes an outburst that reaches super-Eddington X-ray luminosities (King, 2002; Middleton et al., 2012). While we regularly observe stellar mass X-ray binaries outbursting within the Milky Way, only a handful reach the regime where they would appear as a transient ULX for an extragalactic observer (for example GRS1915+105 and V404 Cyg; King, 2002; Grimm et al., 2002; Radhika et al., 2016). Of the few extragalactic examples, one of the three known transient ULXs in M31 was observed to have an associated luminous and highly compact radio source, constraining the radio emitting region to within 5 AU (Middleton et al., 2013). It also exhibited the canonical 'hard' and 'soft' X-ray spectral states during its rise and decay phases, confirming that at least some transient ULXs are analogous to Galactic black hole X-ray binaries. Such an event would be easily detectable with eROSITA as the X-ray flare remained bright for several months, spending $\sim$40 days at super-Eddington luminosities. It is also worth noting that eROSITA may also detect ultraluminous X-ray pulsars (ULPs), which are a newly identified class of ULXs that show pulsations, and must therefore harbour a neutron star (e.g. Bachetti et al., 2014). An additional advantage to studying extragalactic transient ULXs is that they do not suffer from the large absorbing column that shrouds emission from similar sources in the Galactic Plane (Revnivtsev et al., 2002). Based on these results, and those obtained by a radio-monitoring campaign on nearby galaxies (Anderson et al., in prep), we may expect one transient ULX outburst per galaxy per year.

Targeting the multi-wavelength properties of these two source populations will allow us to simultaneously study super-Eddington accretion in two different accretor mass regimes, supermassive and stellar. Studying the radio emission from these sources will be crucial for studying the link between accretion and jet production (jet-disc coupling) in the super-Eddington regime, the mechanisms leading to these outbursting events, the nature of the accretor, and the properties of the surrounding environment. The Australian members of this proposal are experts in the study of jet-disc coupling (e.g. Miller-Jones et al., 2015; van Velzen et al., 2016; Plotkin et al., 2017; Rushton et al., 2016, 2017), and can provide valuable insight into interpreting eROSITA accreting transients through observations with the Australia Telescope Compact Array (ATCA), Australia's premier multi-frequency, full-polarisation radio interferometer. Additionally, transient candidate confirmation can be provided through optical spectroscopic follow-up with the Anglo-Australian Telescope (AAT).

Science Objectives

1. Radio studies of eROSITA TDE candidates – the supermassive analogues of super-Eddington accreting black hole X-ray binaries.

   i Systematic follow-up of eROSITA TDE candidates with ATCA holds the promise of dramatically increasing the sample size of radio-detected TDEs, allowing us to probe the origin of the radio emission (jet or wind), and the link between thermal and non-thermal events (e.g. van Velzen et al., 2016; Alexander et al., 2016).

ii Investigate what types of thermal TDEs have radio emission and whether this depends on properties such as the black hole mass, the host environment, the type of star tidally disrupted, and the black hole spin. In order to explore these parameters, the ATCA observations will be combined with targeted follow-up X-ray observations from *XMM*, *Chandra*, and the *Swift* X-ray Telescope (XRT), proposals for which will be led by M. Middleton and T. Roberts (both eROSITA_DE external collaborators).

iii Probe whether there are multiple jetted outbursts produced by a TDE (either thermal or non-thermal) as the mass is fed onto the black hole at each periastron passage of the debris.

iv Study the temporal behavior of the broadband spectral energy distribution including X-ray, optical/near-IR (e.g., from the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND) on the 2.2 m MPG telescope on La Silla, or AAT) and radio, to constrain the properties of the circum-nuclear medium from its interaction with the jet.

v Support the identification of TDE candidates and constrain their redshifts with AAT spectroscopy.

2. Radio studies of transient ULXs – super-Eddington X-ray outbursts from extragalactic stellar mass black hole or neutron star X-ray binaries.

   i Once a transient ULX is identified in the eROSITA_DE data, coordinated radio and X-ray observations provided by ATCA, *XMM*, *Chandra* and *Swift*-XRT will allow us to probe jet-disc coupling in stellar-mass black holes and neutron stars in the Eddington and super-Eddington regimes. This will further our understanding gained to date through studies of Galactic sources (e.g. Grimm et al., 2002), and the radio detected transient ULX in M31 (Middleton et al., 2013).

   ii Determine if radio emission is associated with ULPs.

   iii The detection of short-term radio variability can be used to constrain the size of the radio emitting region, which can be used to measure the brightness temperature, the corresponding beaming factor of the ejecta, and therefore constrain the inclination angle required to generate that level of beaming (e.g. Middleton et al., 2013).

   iv ATCA also has full polarisation capabilities, allowing us to probe jet orientation (e.g. Curran et al., 2015).

   v Look for associated radio synchrotron nebulae (bubbles) produced by ULX outflows interacting with the interstellar medium, which can be used to calculate the contribution of relativistic particles to the total energy output by the system (see Kaaret et al., 2017, and references therein).

   vi Determine how common these sources are using statistics gained from nearby, face-on galaxies, which are not limited by Galactic absorption.

   vii Use AAT photometric and spectroscopic data to explore the surrounding stellar population, estimate the age of the system, and search for optical nebulae that can be created from outflows or photoionsiation, and thus probe the kinematics or total energy budge of the system (see Kaaret et al., 2017, and references therein).

3. Pre-launch activities

   i Transient rate forecasting simulations.

   ii Verification of eROSITA transient alert system.

   iii Submit telescope proposals for radio, optical, and X-ray follow-up at the latest deadlines prior to the eROSITA launch date in-order to treat the early eROSITA, post-launch phase as a pilot study for our proposed multi-wavelength campaign.

eROSITA transient alert and classification system

eROSITA's all-sky survey scan strategy will provide access to transient and variable X-ray sources over a wide range of cadences (from seconds to years) and fluxes.

The brightest sources, e.g. luminous Galactic X-ray binaries, but also the most extreme TDEs and ULXs, will be discovered in the Near-Real-Time-Analysis (NRTA) pipeline developed at ECAP. The NRTA will reveal sources with rapid flux changes in data from a single telemetry downlink and between individual and/or subsequent erodays (one full rotation of the spacecraft) by analysing the integrated rates over the eROSITA field of view at a given time. As this method does not rely on complete data sets, including the attitude information, sources can be discovered within minutes after the telemetry downlink. Alert information shall be distributed quickly to enable rapid follow-up. In the first phase of the mission (exact timeline still TBD), this will be limited to members of the eROSITA_DE consortium and external collaborators.

The majority of TDEs and ULXs will likely be too faint for a discovery in the NRTA. Instead they are expected to be uncovered in dedicated explorations of the products of the eROSITA Science Analysis Software System (eSASS). A PhD thesis project at MPE (supervisor A. Rau) will focus on the development of an intelligent algorithm to localise and classify fainter transients in catalog space combining eROSITA and multi-wavelength information. Initial candidates are expected from a comparison of the first eROSITA survey with the ROSAT All-Sky survey and/or the XMM Slew survey. Subsequent comparisons of individual eROSITA surveys will also provide access to fainter transients. Events shall be discovered within a few days after the data have been taken, and alerts will initially be limited to the eROSITA_DE consortium and its external collaborators.

Instruments for eROSITA transient multi-wavelength follow-up

Australia Telescope Compact Array (ATCA)

ATCA is a radio interferometer composed of six 22-m dishes with a maximum baseline length of 6 km. The 4-cm receiver is capable of conducting simultaneous observations at central frequencies of 5.5 and 9 GHz, each with an instantaneous bandwidth of 2048 MHz. The synthesised beam in this band is $1-3$ arcsec when the array is in one of its most extended 6-km configurations. This instrument is therefore ideal for targeting the synchrotron emission from TDEs and transient ULXs, which peak both brighter and earlier at higher frequencies. This, along with the wider bandwidth and lower system temperature, makes ATCA more competitive for this project when compared to the Australian Square Kilometre Array Pathfinder (ASKAP), which will be limited to a tunable range of $0.7-1.8$ GHz with a 300 MHz bandwidth.

ATCA has two target-of-opportunity (ToO) modes of operation that can be accessed via the six-monthly calls for proposals on June 15 and December 15 each year. The first is the standard "Non A Priori Assignable" (NAPA) mode, which involves requesting transient follow-up observations that are then manually scheduled within a few days. The second is the "rapid-response" mode, which automatically overrides the current observing program and conducts the observations as soon as the source is visible (a strong science case is necessary to justify the need for rapid overrides).

Selection criteria for TDE follow-up

i The TDEs need to be young, preferably $\lesssim 6$ months (based on calculations conducted by van Velzen et al., 2016), unless they are extremely close (e.g. NGC 4845 at 17 Mpc, which was still detectable ~ 4 yrs following the disruption; Irwin et al., 2015; Perlman et al., 2017).

ii A radio follow-up redshift limit of $z \lesssim 0.2$ for thermal TDEs. ASASSN-14li had a peak X-ray luminosity of $L_X \sim 10^{43}$ erg s^{-1}. Assuming an eROSITA sensitivity of $F_X \sim 1\times10^{-13}$ erg s^{-1}, this limits us to a redshift of $z \lesssim 0.2$. The 5.5 and 9 GHz ATCA sensitivity for a 4-hr integration is $\sim 10\,\mu$Jy bm^{-1}. As this redshift, ATCA will detect radio emission with luminosities $L_R \gtrsim 3\times10^{38}$ erg s^{-1}, which would detect the maximum radio luminosity measured for ASASSN-14li (van Velzen et al., 2016). (As we expect the TDE radio emission to be point-like at this distance using a 6km baseline configuration, we do not require a 12-hr ATCA observing track.)

Selection criteria for transient ULX follow-up

i Within 5 MPc

- In the soft (0.5–2 keV) and hard (2–10 keV) X-ray bands, eROSITA will be sensitive to X-ray luminosities of $L_x \approx 1.3\times10^{38}$ and 2.1×10^{39} ergs s^{-1}, respectively, for a single survey scan (Merloni et al., 2012) out to 5 Mpc. eROSITA will therefore be able to detect super-Eddington outbursts from $\sim 10\ M_\odot$ black hole X-ray binaries in nearby galaxies.
- At 5 Mpc, ATCA can probe radio luminosities $L_R \gtrsim 5-8\times10^{33}$ ergs s^{-1} at 5.5 and 9 GHz, respectively, for a 4-hr integration (3σ signal-to-noise detection). This sensitivity will allow us to follow the temporal and spectral evolution of the radio emission during the brightest X-ray flaring. (Once again, we expect the radio emission to be point-like.)

Anglo-Australian Telescope (AAT)

The AAT is the largest optical telescope based in Australia (3.9 m aperture). Its instruments are primarily designed to collect simultaneous spectra of hundreds of galaxies or stars within a single field-of-view. The AAT has recently developed the ability to perform spectral follow-up of single sources, making it competitive as a ToO instrument. AAT accepts proposals for two types of ToO overrides: rapid (immediate interrupt of the current observing program) and standard (observations scheduled within a few days). Both modes of ToO are manually performed by the astronomer and are not automatic. Proposal deadlines occur on March 15 and September 15 each year.

- AAT will be primarily used to perform optical spectroscopy of candidate eROSITA TDEs to confirm their classification and redshift before investing in radio follow-up. Spectral lines may also be detectable from TDE winds.
- AAT optical imaging and/or spectroscopy will be used to study transient ULX environments such as the surrounding stellar population, which places age constraints on the binary system. The detection of an associated nebula (or bubble), created by shocks from the binary outflows or powered by photoionisation, can be used to probe system kinematics or the true X-ray luminosity of the system (see Kaaret et al., 2017, and references therein).

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