Individual External Collaborator Project Proposal

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WG(s) involved in the project:

Time Domain Astrophysics, *Normal Galaxies, Compact Objects*

Scientific Project description (up to two pages, all included):

We stand at a critical juncture in the study of ultraluminous X-ray sources (ULXs), those objects with X-ray luminosities in excess of 10^{39} erg s^{-1} located away from the nucleus of galaxies (Kaaret, Feng & Roberts 2017). We have recently detected pulsations from half a dozen of these objects, meaning they harbour neutron stars undergoing extreme super-Eddington accretion (e.g., Bachetti et al. 2014; Israel et al. 2017; Sathyaprakash et al. 2019). This has dramatically affected our understanding of these objects and posed many new questions about their nature. For instance, what proportion of the ULX population hosts neutron stars, rather than the previously-supposed black holes? And how does the physics of extreme accretion work for each type of compact object?

By virtue of its scanning cadence and sensitivity, *eROSITA* will provide the most complete X-ray survey ever undertaken. This is of great importance for studies of the ULX population, which we know to contain sources which evolve and can appear highly variable, even appearing transient. This proposed project will address one of the most important current questions about ULXs – the fraction of objects harbouring a neutron star – and in doing so will help maximise the science of *eROSITA*. This proposal is directly complementary to that of that of Dr Matt Middleton (University of Southampton), who will investigate the physics of extreme accretion in ULXs.

The hunt for new Pulsating ULXs

Six ULXs to-date have been identified as accreting pulsars (pulsating ULXs, or PULXs), five of which possess rotation periods of ∼1-3 s (Bachetti et al. 2014; Israel et al. 2016a,b; Fuerst et al. 2016, Rodriguez Castillo et al. 2019) including one recently identified by the proposer's team (Sathyaprakash et al. 2019). Such systems provide powerful new insights into the nature of neutron stars and extreme accretion physics in the presence of strong magnetic fields, and so finding more systems is of the utmost importance. *eROSITA*'s all-sky survey is the single best opportunity to find more ULXs in an unbiased way in the near future, and so derive statistically meaningful limits on populations. ***Critically, eROSITA will place the first meaningful lower limit on the proportion of the ULX population composed of pulsars.*** The unveiling of new members of this class will enlarge the sample of known objects and so enable more detailed studies of a variety of individual objects that will for example help constrain surface field strengths (distinguishing between magnetar-like and lower field strength neutron stars) and constrain the physics of the accretion flow, e.g. whether it contains both a geometrically thick disc outside its magnetosphere, and an optically-thick accretion curtain within it (cf. Mushtukov et al. 2019).

We have conducted extensive simulations of anticipated *eROSITA* PULX data, based on the properties of known PULXs, that show that we are unlikely to directly detect pulsations within the *eROSITA* data, excepting rare instances of high flux (>~ 10^{-11} erg cm^{-2} s^{-1}) and pulse fraction (>50%), which may occur in 1 – 2 sources per year. However, the eRASS strategy means it is ideal for detecting *candidate* PULXs via the propeller effect. In this, the putative high magnetic field of PULXs shuts off accretion when the accretion rate drops and the magnetospheric radius expands beyond its corotation radius with the accretion disc, resulting in a precipitous drop in flux, which may have already been seen in more than one PULX (e.g. Tsygankov et al. 2016). Hence, the search for highly variable ULXs (larger than an order of magnitude) provides a plausible means of searching for candidate PULXs. Indeed we have found several new PULX candidates, and confirmed that known PULXs are picked up by this method, in two pilot studies that we have conducted (Earnshaw et al. 2018; Song et al. submitted).

Methodology:

In our earlier collaboration with the TDA team we have already delivered the largest current *XMM-Newton* ULX catalogue that we developed (Earnshaw et al. 2019) as the basis for monitoring known ULXs via the NRTA and searching for new ULX detections. We are working on further ULX catalogues (e.g., based on the *Chandra* source catalog) to augment this. Updates will be regularly provided to the NRTA team. We have also delivered trigger criteria for the detection of the new, transient ULXs. **Any new, bright candidate PULX detections will be followed up with other missions (DDT/ToO proposals that we will lead) to provide a search for pulsations**; access to NRTA data will ensure this is expedited such that there is a good chance the PULX remains active and so there is a good chance of it pulsating when followed-up. The full sky survey offered by the first six months of *eROSITA* operations (eRASS1) will provide the first sensitive and complete all-sky scan of ULXs; this will allow us to refine our search criteria while at the same time providing **the first statistically meaningful lower limit on the fraction of ULXs hosting neutron stars, via the fraction with detected pulses.**

We note that PULXs will not be the only transient ULX detections – for instance, the most luminous LMXBs exceed 10^{39} erg s^{-1} (e.g. Middleton et al. 2012, 2013). These will be studied as part of a separate program to locate radio-bright transients (PI: Anderson). Using the *eROSITA* data, we can separate these source classes in two ways. First we would expect the PULXs to be spectrally harder (cf. Walton et al. 2018) than the LMXB ULXs. Second, we would expect to see a LMXB outburst only once in the 8 ERASS sweeps of the sky, as its peak luminosities would last for weeks and would be very unlikely to repeat during the 4-year ERASS period; a PULX entering and leaving propeller phases would likely spend a much larger fraction of this period active. We expect to assist in using these and other means to develop methods to separate out the LMXBs and other highly variable ULX classes from the best PULX candidates.

Required data, supporting datasets and/or tools:

Access to eRASS1, NRTA results for possible ULX, and *eROSITA* simulation software. The work will be done by T. Roberts in conjunction with a PhD student. In addition to the catalogues mentioned above, we will contribute manpower for NRTA shifts, if necessary, and work on refining the selection criteria for ULX (see also IEC proposal by M. Middleton).

The proposing team will consist of T. Roberts and one PhD student.

List of Potential Collaborators within eROSITA_DE

Arne Rau
Joern Wilms
Thomas Dauser
Stefania Carpano
Chandreyee Maitra

Expected Outcome

Any new PULXs discovered with *eROSITA* will be published as a matter of urgency in close collaboration with the *eROSITA* consortium. The incidence of PULXs as a function of the complete sample of ULXs within eRASS1 will also be the basis of a publication; this will include publishing the complete sample of ULXs for the community.

Expected duration of the project

One year. Future EC status requests are foreseen as the full science potential of this project will only be realized with access to the final, full eRASS products.