A Multi-Mission Catalogue of Ultraluminous X-ray Source Candidates

D. J. Walton\textsuperscript{1,2}\textsuperscript{*}, A. D. A. MacKenzie\textsuperscript{3}, H. Gully\textsuperscript{4}, N. R. Patel\textsuperscript{5}, T. P. Roberts\textsuperscript{3}, H. P. Earnshaw\textsuperscript{6}, S. Mateos\textsuperscript{7}

\textsuperscript{1}Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
\textsuperscript{2}Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
\textsuperscript{3}Centre for Extragalactic Astronomy & Department of Physics, Durham University, Department of Physics, South Road, Durham DH1 3LE, UK
\textsuperscript{4}School of Physics, Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, UK
\textsuperscript{5}Department of Physics and Astronomy, Pevensy Building, University of Sussex, Brighton BN1 9QH, UK
\textsuperscript{6}Cahill Center for Astronomy and Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
\textsuperscript{7}Instituto de Física de Cantabria (CSIC-UC), Avenida de los Castros, 39005 Santander, Spain

\textbf{ABSTRACT}

We present a new, multi-mission catalogue of ultraluminous X-ray source (ULX) candidates, based on recent data releases from each of the XMM-Newton, Swift and Chandra observatories (the 4XMM-DR10, 2SXPS and CSC2 catalogues, respectively). This has been compiled by cross-correlating each of these X-ray archives with a large sample of galaxies primarily drawn from the HyperLEDA archive. Significant efforts have been made to clean the sample of known non-ULX contaminants (e.g. foreground stars, background AGN, supernovae), and also to identify ULX candidates that are common to the different X-ray catalogues utilized, allowing us to produce a combined ‘master’ list of unique sources. Our sample contains 1843 ULX candidates associated with 951 different host galaxies, making it the largest ULX catalogue compiled to date. Of these, 689 sources are catalogued as ULX candidates for the first time. Our primary motivation is to identify new sources of interest for detailed follow-up studies, and within our catalogue we have already found one new extreme ULX candidate that has high S/N data in the archive: NGC 3044 ULX1. This source has a peak luminosity of $L_{\text{peak}} \sim 10^{40}$ erg s\(^{-1}\), and the XMM-Newton spectrum of the source while at this peak flux is very similar to other, better-studied extreme ULXs that are now understood to be local examples of super-Eddington accretion. This likely indicates that NGC 3044 ULX1 is another source accreting at super-Eddington rates. We expect that this catalogue will be a valuable resource for planning future observations of ULXs – both with our current and future X-ray facilities – to further improve our understanding of this enigmatic population.

\textbf{Key words:} X-rays: Binaries – X-rays: Individual (NGC 3044 ULX1)

1 INTRODUCTION

Our understanding of ultraluminous X-ray sources (ULXs) – off-nuclear X-ray sources with luminosities in excess of $10^{39}$ erg s\(^{-1}\) – has evolved significantly over the past few years. Historically, the debate regarding the nature of these sources has focused on whether they represent a population of sub-Eddington ‘intermediate mass’ black holes (IMBHs with $M_{\text{BH}} \sim 10^{2−5}$ $M_{\odot}$; e.g. Colbert & Mushotzky 1999; Miller et al. 2004; Strohmayer & Mushotzky 2009) or a population of super-Eddington but otherwise normal stellar remnants (e.g. King et al. 2001; Poutanen et al. 2007; Middleton et al. 2015) for a recent review. Although evidence for large black holes is now being seen by LIGO, most notably the recent detection of a BH–BH merger resulting in a $\sim 150 M_{\odot}$ remnant; Abbott et al. (2020), the general consensus is now that the majority of ULXs represent a population of super-Eddington accretors, thanks in particular to the broadband spectral and timing studies possible in the NuSTAR era (Harrison et al. 2013) and the high-resolution spectra provided by XMM-Newton (Jansen et al. 2001).

The broadband spectra obtained early in the NuSTAR mission demonstrated that ULX spectra are clearly distinct from standard modes of sub-Eddington accretion (e.g. Bachetti et al. 2013; Walton et al. 2013, 2014, 2015; Rana et al. 2015; Mukherjee et al. 2015), confirming prior indications from XMM-Newton (e.g. Stobbart et al. 2006; Gladstone et al. 2009), and instead revealed high-energy spectra consistent with broad expectations for super-Eddington accretion (i.e. spectra that appear to show a strong contribution from hot, luminous accretion discs, e.g. Shakura & Sunyaev 1973; Abramowicz et al. 1988; Poutanen et al. 2007). The super-Eddington nature of at least some ULXs was then spectacularly confirmed with the discovery that the ULX M82 X-2 ($L_{\text{peak}} \sim 2 \times 10^{40}$ erg s\(^{-1}\)) is actually powered by a highly super-Eddington neutron star, following the detection of coherent X-ray pulsations (Bachetti et al. 2014). Five more ULX pulsars have since been discovered (Fürst et al. 2016; Israel et al. 2017b,a; Carpano et al. 2018; Sathyaprakash et al. 2019; Rodríguez Castillo et al. 2020), revealing an accretion regime that extends up to $L/L_{\text{Edd}} \sim 500$. In addition to the broadband spectra and the discovery of ULX pulsars, we now

\textsuperscript{*} E-mail: dwalton@ast.cam.ac.uk

© 0000 The Authors
have evidence in ULX data for the powerful outflows ubiquitously predicted by models of super-Eddington accretion via the detection of blueshifted atomic features. These have been seen primarily in the low-energy XMM-Newton RGS data, but also in the iron K band in a couple of cases (Pinto et al. 2016, 2017, 2020; Walton et al. 2016; Kosec et al. 2018a,b). These outflows exhibit extreme velocities (~0.1–0.3c), implying they carry a significant additional energetic output from these already extreme X-ray binary systems.

Nevertheless, important questions still remain regarding the ULX population. Although it is now speculated that ULX pulsars could actually make up a significant fraction of these sources (e.g. Pintore et al. 2017; Koliopanos et al. 2017; Walton et al. 2018b), their exact contribution is still highly uncertain. Is there also a significant population of black hole ULXs, and if so could these be the progenitors of the BH–BH mergers now regularly being seen by LIGO (Inoue et al. 2016; Mondal et al. 2020)? Given the history of the field, it is easy to forget that we still do not have a single ULX with a well-constrained mass function that unambiguously requires the accretor to be a black hole. Can black hole ULXs (assuming they exist) reach the same extreme Eddington ratios as ULX pulsars, or is this somehow related to the magnetic nature of these objects (as suggested by Dall’Osso et al. 2015; Mushotzky et al. 2015)? What fraction of the total energetic output is radiative, and what fraction is kinetic (i.e. carried by winds/outflows) at these extreme accretion rates? Understanding this last issue may in turn be critical for understanding early-universe SMBH growth (and associated feedback), given that ~10^9 M☉ black holes are now being observed when the universe was only ~0.7 Gyr old (e.g. Bañados et al. 2018).

Furthermore, although the overall population is now expected to be dominated by super-Eddington accretors, there are still rare individual sources among the ULX population that remain good IMBH candidates. Most notable among these is the case of ESO 243–49 HLX1, which reaches an astonishing luminosity of \( L_{\text{X,peak}} \sim 10^{42} \text{erg s}^{-1} \) (Farrell et al. 2009). In contrast to the vast majority of the ULX population, this source does behave as expected for a scaled-up sub-Eddington X-ray binary (Servillat et al. 2011; Webb et al. 2012). Furthermore, M82 X-1 has long been thought of as an IMBH candidate because of its X-ray properties (e.g. Feng & Kaaret 2010; Pasham et al. 2014, although see Brightman et al. 2020b for caveats), and NGC 2276–3c has also been suggested as an IMBH candidate owing to its position on the radio–X-ray fundamental plane (Mezcua et al. 2015). Identifying further IMBH candidates remains of significant interest, given the scarcity of compelling cases among the ULX population.

Key to advancing all of these areas are efforts to grow the broader ULX population and provide larger samples with which to undertake statistical studies of ULXs and identify notable individual sources for follow-up study. Most previous efforts have focused on searching for ULXs in individual mission archives, using in particular ROSAT (Roberts & Warwick 2000; Colbert & Ptak 2002; Liu & Bregman 2005), Chandra (Swartz et al. 2004; Liu 2011; Gong et al. 2016; Kovač et al. 2020) and XMM-Newton (Walton et al. 2011b; Earnshaw et al. 2019b). Focusing on data from a single mission has the advantage that everything (source selection, energy bands) can be treated in a uniform manner, which is important for performing population-based studies where selection biases need to be carefully controlled. However, this comes at the expense of limiting the sky area/temporal coverage utilized relative to that available in the full, multi-mission X-ray archive, both of which are key factors in terms of identifying individual sources that may be of particular interest.

Here, we present the results of a search for new ULX candidates, combining data from all of the public archives from the major soft X-ray imaging observatories currently operational: XMM-Newton (Jansen et al. 2001), Chandra (Weisskopf et al. 2002) and the Neil Gehrels Swift Observatory (hereafter Swift; Gehrels et al. 2004). In particular, we make use of the 4XMM-DR10, CSC2 and 2XPS source catalogues (Webb et al. 2020; Evans et al. 2020a,b). Although combining the data from these facilities does formally introduce some non-uniformity to the selection, our primary aim is to compile the largest raw sample of ULX candidates to date, facilitating searches for sources that are bright enough for detailed follow-up with current and future X-ray facilities, as well as searches for sources with multi-wavelength counterparts. This is of particular interest with both XRISM (XRISM Science Team 2020) and Athena (Nandra et al. 2013) on the horizon, as well as the new facilities due to come online at longer wavelengths (e.g. thirty-metre class optical telescopes, JWST, the SKA, etc.).

The paper is structured as follows: in Section 2 we outline the galaxy sample within which we search for ULX candidates, and in Section 3 we discuss our procedure for identifying ULX candidates from the individual archives. Section 4 presents our final, merged sample of ULX candidates, and we highlight the case of NGC 3044 ULX1 – a new extreme ULX discovered here – in Section 5. Finally, we summarise our findings in Section 6.

### 2 GALAXY SAMPLE

In addition to the various X-ray archives considered here, the other major input required for this work is a catalogue of galaxies within which to search for ULXs. Here, we primarily use the HyperLEDA database (Makarov et al. 2014), initially selecting everything labelled as a galaxy. We focus on HyperLEDA because this is one of the largest homogenized compilations of known galaxies available in the literature. However, we further supplement these galaxies with the latest version of the Catalogue of Nearby Galaxies (CNG; Karachentsev et al. 2018).

For our work here, we need to be able to define the sky area subtended by the galaxy (in order to positionally match X-ray sources) as well as the distance to the galaxy (in order to compute source luminosities). For the galaxy areas, we assume the extent of each galaxy is determined by the elliptical region defined by its D25 isophote (i.e. the best elliptical fit to the area over which B-band surface brightness of the galaxy exceeds 25 mag arcsec^-2), which is given in HyperLEDA (where this information is available). However, CNG uses the Holmberg radius to define the semi-major axis of the galaxy ellipse instead, which corresponds to a surface brightness of 26.5 mag arcsec^-2. For the subset of galaxies included in both HyperLEDA and CNG, we therefore calculate an empirical correction between the D25 semi-major axes \( R_{\text{D25}} \) and the Holmberg radii \( R_{\text{Holm}} \), and then apply this to any remaining galaxies that are only included in CNG in an attempt to normalise these to the D25 definition. On average, we find \( R_{\text{Holm}} = (1.26 \pm 0.02)R_{\text{D25}} \) (where the uncertainty quoted here is the 1σ standard error on the mean). Although the full set of D25 information (semi-major axis, semi-minor axis, position angle) is obviously required to search the full sky area subtended by the galaxy, in cases where the position angle is missing it is still possible to search for ULX candidates within a circular region defined by the semi-minor axis, as this will always be within the galaxy area regardless of the orientation of its full elliptical region. We therefore also retain these galaxies in our input sample. However, any galaxies in the HyperLEDA/CNG catalogues
that do not have sufficient information that we can compute at least their D25 semi-minor axes are discarded.

For the majority of the galaxies considered, we compute distances based on their measured redshifts ($z$) assuming they adhere to the Hubble flow. However, where redshift-independent distance estimates are available, we prioritise these measurements. HyperLEDA and CNG both include these based on a variety of different methods (via e.g. Cepheid variables, the tip of the red giant branch, the Tully-Fischer relationship), and we further supplement these with distance measurements from the latest version of the Cosmicflows galaxy catalogue (Tully et al. 2016). Such measurements are particularly critical for very nearby galaxies (recession velocities $cz < 1000 \text{ km s}^{-1}$), where peculiar motions can dominate over the Hubble flow. For these galaxies, we therefore also collected further redshift-independent distance from the NASA Extragalactic Database where such measurements were not available in any of the HyperLEDA/CNG/Cosmicflows catalogues. Where there are multiple distance estimates available among these catalogues, we prioritise them in the following order: Cosmicflows > CNG > Hyperleda > NED > Hubble flow, but we stress that in the majority of cases there is generally good agreement between the different catalogues regarding the redshift-independent distance estimates. However, since a reasonably reliable distance estimate is in turn critical for a reliable luminosity calculation, we therefore discard galaxies with recession velocities $cz < 1000 \text{ km s}^{-1}$ where there is no redshift-independent distance estimate available in any of the above (similar to both Walton et al. 2011b and Earnshaw et al. 2019b).

The final galaxy sample utilized here consists of 966,010 entries, after accounting for the requirements outlined above, the vast majority of which come from HyperLEDA (only 215 of these galaxies are found in CNG but not HyperLEDA). Just under half of these galaxies have morphology estimates available in the form of the Hubble type, $T$. Following Walton et al. (2011b), for these galaxies we make the distinction between spiral galaxies ($T \geq 1$, including irregular galaxies) and elliptical galaxies ($T < 1$, including lenticular galaxies). We show the distance distributions for the full galaxy sample utilized here, as well as some of these subsets, in Figure 1. The majority of the galaxies considered are within a Gpc, although the galaxies for which morphology information is not available do have larger distances on average than those where the morphology has been identified.

3 SELECTION OF ULX CANDIDATES

3.1 Basic Approach

We take the same basic approach to selecting ULXs for each of the three X-ray source catalogues utilized here (4XMM-DR10, 2SXPS and CSC2). Our initial analysis of these individual archives can be broadly summarised into 5 main steps, as described below. Many of the specific details differ for the different catalogues utilized, owing to the differences between the different X-ray observatories they are derived from and the different formats in which the data are provided; these details are discussed in Section 3.2.

Step 1 – positional match: First, we perform a positional cross-match between our input galaxy list and each X-ray catalogue; as noted above, for galaxies where the full set of spatial information is available (both the major and minor axes, and the position angle) we perform a standard elliptical match around the position of the galaxy (i.e. utilizing the full sky area it subtends), while for galaxies where the position angle is missing we perform a circular match within the radius set by the semi-minor axis (and thus potentially only utilize a fraction of its sky area). Where relevant, only X-ray sources listed as being point-like are retained (both CSC2 and 4XMM-DR10 also contain extended sources, while in principle 2SXPS only includes point sources).

There are inevitably a small subset of X-ray sources that are consistent with being associated with more than one galaxy in our initial matched source lists. In these cases, we make sure to retain only one of the repeat entries in order to avoid individual X-ray sources/detections appearing more than once. To do so, we initially associate the X-ray source with the galaxy for which it is closest to the centre. This is because we expect the majority of these cases to be interacting galaxies, which by definition will be at essentially the same distance, and on average the density of ULXs is known to increase as you approach the galaxy centre (Swartz et al. 2011). However, we re-visit this assumption at the end of our analysis of the individual archives (i.e. after step 5), and assess whether the different galaxy distances really are similar for any remaining sources that are potentially associated with more than one galaxy. Here, we treat galaxies with distances that differ by <15% as having similar distances. Where this is not the case, such that the potential host galaxies appear to be un-associated galaxies that happen to overlap when viewed in projection, we switch the association of the X-ray source to the less distant galaxy. This is both a conservative approach, resulting in lower X-ray luminosities, and also probably a more realistic assumption in these situations, as the enhanced absorption by gas and dust in the foreground galaxy would mean sources in

![Figure 1. Distance distributions for the full galaxy sample utilized here (top panel), galaxies identified as spiral ($T \geq 1$) and elliptical ($T < 1$) galaxies (upper-middle and lower-middle panels, respectively), and for galaxies where morphology information is not available (bottom panel).](image-url)
the background galaxy are less likely to be seen as ULXs based on their observed luminosities. For any sources where the association is changed at this stage, the luminosities are re-evaluated (see step 2), and any sources that no longer meet the ULX criterion are excluded.

**Step 2 – luminosity cut:** With our positionally matched source lists, we then compute X-ray luminosities using our preferred galaxy distance. Here, we use the full band fluxes available in each of the individual X-ray catalogues (see Section 3.2). These bandpasses are not precisely identical, but are sufficiently similar that we consider this a reasonable compromise for the sake of simplicity, particularly in light of the simple spectral forms assumed when estimating these fluxes (see Section 3.2). Attempting to correct all of the fluxes to have a common treatment is non-trivial, particularly given the time-dependent nature of the Chandra instrumental responses (owing to the long-term build-up of the ACIS contamination layer; Plucinsky et al. 2018). With the luminosities in hand, we retain only sources with a full band luminosity that exceeds $10^{39}$ erg s$^{-1}$, the standard definition of a ULX. In particular, we select sources that have exhibited luminosities in excess of $10^{39}$ erg s$^{-1}$ during any individual observation of the source, allowing us to select both persistent and transient/highly variable ULXs. This is a key consideration here, since the latter are now being detected in increasing numbers as our X-ray archives continue to grow (e.g. Soria et al. 2012; Middleton et al. 2012, 2013; Pintore et al. 2018, 2020; Earnshaw et al. 2019a, 2020; van Haften et al. 2019; Brightman et al. 2020a; Walton et al. 2021), and may be of particular interest in the context of identifying good ULX pulsar candidates (e.g. Tsygankov et al. 2016; Earnshaw et al. 2018; Song et al. 2020).

**Step 3 – quality flag cut:** Each of the X-ray catalogues utilized here contain a variety of information that relate to the robustness of the X-ray detection included and the source properties derived. In each case, we make use of this information to ensure that we only consider sources for which the available X-ray information is reliable, further discarding sources where there are concerns that this may not be the case. The approach taken here is necessarily specific to each of the individual catalogues considered, and is detailed below for each in turn (Section 3.2).

**Step 4 – nuclear exclusion:** By definition, ULXs are off-nuclear sources, and so we attempt to exclude sources that may be associated with the nuclei of their host galaxies. However, this is made challenging by the fact that low-luminosity AGN can exhibit similar luminosities to ULXs (Ghosh et al. 2008; Zhang et al. 2009). We therefore exclude potential AGN through their position relative to the centre of the galaxy instead, following the approach taken in Earnshaw et al. (2019b). In brief, for each X-ray source we compute the minimum separation from the central galaxy position, $R_{\text{min}}$, based on its $3\sigma$ positional uncertainty (i.e. we define $R_{\text{min}} = \text{ nuclear separation} − 3\sigma$ position error). We then select sources with $L_X > 10^{42}$ erg s$^{-1}$, as these sources are almost certainly AGN (only one ULX, ESO243–49 HLX1, has exhibited such luminosities to date; Farrell et al. 2009), and calculate the cumulative distribution of their $R_{\text{min}}$ values. Unsurprisingly, these typically exhibit very small minimum nuclear separations, and we determine the value of $R_{\text{min}}$ that contains $>99\%$ of these sources, which we take to be our exclusion criterion for nuclear sources, $R_{\text{min, excl}}$ (see Section 3.2). All sources with $R_{\text{min}} < R_{\text{min, excl}}$ are subsequently excluded from our analysis. We repeat the assessment of $R_{\text{min}}$ with both our input galaxy catalogue, where we have a requirement for a minimum amount of information regarding the extent of the galaxy (Section 2), and also with the full HyperLEDA/CNG/Cosmicflows galaxy catalogues (as for this stage, only the position of the galaxy is required), such that sources with $R_{\text{min}} < R_{\text{min, excl}}$ for any galaxy included in these databases are excluded from our source lists. This empirical approach allows us to conservatively account for the uncertainty associated with the fact that for some galaxies it can be difficult to precisely identify its central/nuclear position (e.g. irregular or merging galaxies, and/or offset nuclei).

**Step 5 – removal of other known contaminants:** In addition to the nuclei of the apparent host galaxies for our sources, we also attempt to remove other known contaminants. At this stage, we particularly focus on background AGN and foreground stars that coincidentally appear to be associated with a host galaxy in projection. We therefore positionally match our remaining source lists against lists of known stars and quasars. For the former, we use the Tycho2 catalogue (Hog et al. 2000) while for the latter we use the GAIAwise quasar catalogue (Shu et al. 2019) and the quasar catalogue of Véron-Cetty & Véron (2010). The search radii we use vary depending on the X-ray archive, as detailed in Section 3.2. Any source that matches with either a known star or a known quasar is excluded from our analysis.

### 3.2 Specific Catalogue Details

#### 3.2.1 4XMM-DR10

The 4XMM catalogue (Webb et al. 2020) is formatted such that every row entry represents a unique detection of an X-ray source by the EPIC detectors (pn, MOS1, MOS2; Strüder et al. 2001; Turner et al. 2001), meaning that the observation-by-observation information needed to determine the peak flux for sources that have been observed on multiple occasions is already incorporated. For the initial position match (step 1), we specifically use the RA$_{SC}$ and DEC$_{SC}$ columns in the 4XMM catalogue for the X-ray position, which give the catalogue-averaged position for sources that have been detected on multiple occasions. 4XMM includes both point sources and extended sources, and we exclude observations in which the detection is marked as extended\(^{1}\). When computing detection luminosities (step 2), we use the full band flux provided in the catalogue (i.e. 4XMM band 8, spanning 0.2–12.0 keV); these fluxes are computed by summing the fluxes of the 4XMM sub bands, which are themselves computed assuming a standard spectral shape (an absorbed powerlaw continuum with $\Gamma = 1.7$ and $N_H = 3 \times 10^{20}$ cm$^{-2}$).

For the quality flags (step 3), we largely follow the approach taken in Earnshaw et al. (2019b). In brief, detections with a summary flag $\geq 2$ are excluded to reduce spurious detections in general, and sources with the out-of-time event flag (Flag 10) set and a total count rate $< 0.05$ ct s$^{-1}$ are also excluded as these are likely to be artefacts of out-of-time events that are associated with a nearby bright source. However, in addition to these cuts, we also filter out entries where the MASKFRACTION flag (Flag 1) is set to be true for each of the EPIC detectors that registered the detection. This helps to further limit spurious detections seen at chip edges, and also spurious ‘new’ detections at the edge of the field-of-view (FoV) that are really associated with known bright sources just outside the FoV. When filtering out sources consistent with being the nuclei of the host galaxies...
ies (step 4) and identifying likely matches with known foreground stars/background quasars, we again make sure to use the RA,SC and DEC,SC columns for the X-ray positions. For the former, we find $R_{\text{min,excl}} = 9''$ following the empirical approach described above. This is a pretty conservative cut, compared to previous works involving XMM-Newton data (Walton et al. 2011b; Earnshaw et al. 2019b).

In the latter case, since we are simply matching point-source positions, we use a matching radius for the various star/quasar catalogues of 5″, roughly corresponding to the typical $3\sigma$ positional accuracy for point sources in 4XMM-DR10 (Webb et al. 2020).

### 3.2.2 2SXPS

By definition the 2SXPS catalogue (Evans et al. 2020b) only includes point sources detected by the XRT (Burrows et al. 2005), and the main table of the catalogue is formatted such that every row entry represents a unique X-ray source, with the observation-by-observation detection information contained in a separate table. However, the primary source table includes information on the peak flux seen by the XRT for each source included, and so we mainly use this table for our analysis. As such, for the initial position match (step 1), we are naturally using the best-fit position determined from all of the available observations of a given source. When computing the relevant source luminosity (step 2), we primarily select sources based on the peak flux given for each source in the full XRT band (spanning $0.3\text{–}10.0\text{ keV}$) assuming again an absorbed powerlaw continuum (fluxes for various potential spectral models are provided, but of these the absorbed powerlaw is the most appropriate choice for ULXs below 10 keV). Here, the powerlaw parameters adopted when computing the catalogued fluxes are either fit directly, derived from the 2SXPS hardness ratios, or a photon index of $\Gamma = 1.7$ and the Galactic column in the direction of the source are assumed (see Evans et al. 2020b for details).

In contrast to both XMM-Newton and Chandra, typical Swift observations are very short exposures ($\sim 1\text{-}2\text{ ks}$). Furthermore, these observations themselves are often split up into several shorter ‘snapshots’, and the peak flux included in the catalogue can in principle be drawn from the count rate seen during one of these snapshots instead of the full observation. As such, the peak flux often has large uncertainties, being based on only a handful of counts. For sources where the peak luminosity has a fractional error of $\geq 40\%$ (averaging the positive and negative errors quoted), corresponding to a detection with $\sim 10$ counts based on the approximation for the Poisson distribution presented in Gehrels (1986), we therefore also require that the source meet at least one of three additional criterion for inclusion. Either: 1) the average luminosity is also consistent with the ULX regime, assuming that the average and peak luminosities are not identical, or 2) there are two or more independent detections of the source in the ULX regime, based on the observation-by-observation data, or 3) the source has also previously been detected in the ULX regime by some other facility (i.e. the detection is spatially consistent with an entry in one of the archival ULX catalogues we compare our new dataset against; see Section 4.1 for further discussion). For the quality flag cut (step 3), we exclude sources with the summary flag set to $\geq 1$ (i.e. the “clean” criterion defined by the Swift team). When filtering out sources consistent with being the host galaxy nuclei (step 4), we also find $R_{\text{min,excl}} = 9''$, similar to our analysis of 4XMM. Finally, when identifying likely matches with known foreground stars/background quasars (step 5), we use a matching radius of $10''$ for the Swift data, again corresponding to the typical $3\sigma$ positional accuracy for sources in 2SXPS (Evans et al. 2020b).

### 3.2.3 CSC2

Similar to 2SXPS, the main table of the CSC2 catalogue (Evans et al. 2020a) is formatted such that every row entry represents a unique X-ray source, with the observation-by-observation detection information presented in a separate table, and similar to 4XMM both point-like and extended sources are included. We therefore use the primary source table when performing the initial position match with our galaxy catalogue (step 1), such that we are again using the best-fit position determined from all of the available observations of a given source, but we then compile the observation-by-observation information for each matched source from the secondary table so that we can be sure to account for the peak flux seen by Chandra for each source in our analysis. Sources listed as being extended are discarded. When computing detection luminosities (step 2), we use the broadband CSC2 fluxes, i.e. ‘broad’ fluxes for the ACIS detectors (Garmire et al. 2003), spanning $0.5\text{–}8.0\text{ keV}$, or ‘wide’ fluxes for the HRC (Zombeck et al. 1995), spanning $0.2\text{–}10.0\text{ keV}$. Where possible we again use fluxes derived assuming a powerlaw spectral form (as with 2SXPS, fluxes for a variety of spectral models are provided, see the CSC2 documentation for details). Here the catalogued powerlaw fluxes we use are computed assuming $\Gamma = 2$ and the appropriate Galactic column. However, if this powerlaw flux is not available then we use the raw aperture flux instead. For the quality flag cut, we only consider sources which are flagged as ‘true’ detections in the primary source table (i.e. sources flagged as ‘marginal’ detections are excluded), and we also exclude source detections at the observation level for which the ‘streak’ flag is set.

In addition to the standard filtering steps outlined above, one further issue that is of relevance for the observation-by-observation Chandra data is the fact that the Chandra PSF degrades rapidly with off-axis angle (in a relative sense, much more severely than is the case for either XMM-Newton or Swift). As such, the typical extraction radii used in CSC2 also increase with increasing off-axis angle; for example, sources with off-axis angles of $\sim 8'$ often have extraction radii of $\sim 9\text{–}10''$, significantly larger than the on-axis PSF. Unfortunately, for point sources that are either in crowded regions or are embedded in extended regions of diffuse emission, this can result in spurious fluxes for any significantly off-axis observations, as these off-axis detections can occasionally be blends of multiple point sources, and/or include significant diffuse flux not actually associated with the point source in question. This is particularly an issue for observations of nearby giant elliptical galaxies; Chandra has undertaken significant programs tiling a number of these galaxies (e.g. M87) resulting in a combination of on- and off-axis observations of the same crowded fields. As such, there are a number of sources in these galaxies which have very modest luminosities when viewed on-axis ($L_X < 10^{38}\text{ erg s}^{-1}$) but which all appear to share the same ULX-level off-axis detection. Although some ULXs can be highly variable, as noted above, in many of these cases the ULX-level detections are unfortunately spurious. We therefore manually inspect cases where the only ULX-level detection is taken significantly off-axis, and there is also an on-axis observation that shows the source to have a significantly lower luminosity. Where these are clearly cases relating to source confusion, we exclude these sources from our analysis. We also exclude cases in which the size of the aperture increases to the point where it covers the nominal position of the galaxy centre. In cases where the higher flux could plausibly be due to variability (i.e. the on-axis observations show no evidence for large numbers of sources or diffuse emission whose integrated flux could explain that seen in the off-axis observation) we retain these detections, but stress that they should be considered high-priority for...
further (triggered) follow-up to confirm their nature. We also retain cases in which the aperture marginally overlaps with the edge of the nuclear exclusion zone (but not the nominal nuclear position).

When filtering out sources consistent with being the host galaxy nuclei (step 4), we find $R_{\text{min, excl}} = 6.1''$ for CSC2, smaller than the equivalent value for both 4XMM and 2SXPS. Although in a qualitative sense this is not surprising, given the superior imaging capabilities, it is still worth noting that this value is still significantly larger than the Chandra point spread function. This likely reflects the fact that for more complex galaxy morphologies it can be difficult to accurately identify the position of the true galaxy centre. Finally, when identifying likely matches with known foreground stars/background quasars (step 5), we use a matching radius of 3''.

3.3 Merging and Further Filtering

Once all of the individual catalogues of ULX candidates from each of the 4XMM-DR10, CSC2 and 2SXPS archives have been produced, we merge them all into a final ‘master’ ULX catalogue. To do so, we sequentially match our individual XMM-Newton, Swift and Chandra catalogues of ULX candidates by position. We begin by matching the XMM-Newton and Swift catalogues. As Swift is typically the limiting factor regarding position uncertainties, we match the two within a radius of $10''$, corresponding to the typical $3\sigma$ 2SXPS position uncertainty. There are three main outcomes from this initial match: sources with only XMM-Newton data, sources with only Swift data, and matched sources with both. Each of these lists are then matched with the Chandra catalogue. For the sources with only Swift data, we again use a matching radius of $10''$ here, and for the sources with only XMM-Newton data we use a matching radius of $5''$ (again, the typical $3\sigma$ 4XMM-DR10 position error, as XMM-Newton is the limiting factor regarding position uncertainties here). For sources with both XMM-Newton and Swift data, we assume the XMM-Newton position to be more accurate, and so use this to match to the Chandra catalogue, again using a matching radius of $5''$.

At each of these matching stages, there is the possibility that there are multiple matches for the same source. This is particularly the case when matching either the XMM-Newton or the Swift data with Chandra, given the potential for source confusion and the superior imaging capabilities of the latter; a famous example is the case of NGC 2276, in which a source perceived to be an extremely luminous ULX by XMM-Newton is actually resolved into three distinct point sources by Chandra (Sutton et al. 2012). In that case, all of the resolved sources are themselves ULXs, but it is also possible that a source that appears as a ULX to XMM-Newton or Swift will actually be resolved into multiple sub-ULX sources (this is conceptually similar to the issue regarding the degradation of the off-axis Chandra PSF discussed in Section 3.2.3). In addition to matching them against our Chandra catalogue of ULX candidates, we therefore also match our XMM-Newton and Swift ULX candidates against the set of Chandra sources that did not make our luminosity cut, and again manually inspect all cases of multiple matches in order to identify sources that only appear to be ULXs because of a detection that is actually likely the blend of several point sources, artificially inflating its apparent flux. As before, these sources are removed from our analysis. We note, however, that we still retain cases where e.g. Chandra resolves an XMM-Newton detection into two discrete sources, but that the XMM-Newton data imply that at least one of these must have varied into the ULX regime (for example, a scenario in which Chandra sees two sources at $L_X \sim 10^{38}$ erg s$^{-1}$, but the XMM-Newton/Swift detection that is consistent with both of these sources implies $L_X \sim 2 \times 10^{39}$ erg s$^{-1}$, meaning that at least one of these sources must have been in the ULX regime during the XMM-Newton/Swift observation). In these cases, we add a flag to the final version of the master catalogue noting that this issue exists (a separate flag is added for each of the matched catalogue pairs, see Table 1 for the definitions of the different values these flags can take).

On occasion, where there are multiple matches it is possible to determine with reasonable confidence which of the resolved sources the unresolved detection is actually associated with (for example, cases where Chandra sees two sources, one with $L_X \sim 10^{38}$ erg s$^{-1}$ and one with $L_X \sim 10^{40}$ erg s$^{-1}$ and XMM-Newton/Swift sees one source that also has $L_X \sim 10^{40}$ erg s$^{-1}$, or alternatively cases in which the position of the first Chandra source is in outstanding agreement with the position of the XMM-Newton/Swift detection, while the second Chandra source is right at the edge of the $3\sigma$ uncertainty range). In these cases, we make a judgement call ourselves and assign the unresolved detection to the resolved source we feel is most appropriate. Where we feel unable to make a judgement, but there are multiple ULX candidates among the resolved sources (similar to the case of NGC 2276 highlighted above), we retain all of the potential resolved matches within the master catalogue. Both of these scenarios are also indicated by the matching flags highlighted above (again, see Table 1).

Having merged the XMM-Newton, Swift and Chandra data as best we can, we now address the presence of one more class of known contaminant, X-ray transients associated with one-off explosive events (i.e. supernovae). Although certainly not all do, these events can reach ULX luminosities, and would then be selected by our process (given our interest in genuinely transient ULXs) even though they are clearly not accretion-powered X-ray binaries. This is particularly relevant here given our use of Swift data, since one of Swift’s main focuses is rapid follow-up of transient events. We therefore correlate our master catalogue with the positions of known supernovae recorded in the Open Supernova Catalogue (Guillochon et al. 2017; note that this includes both supernovae that have occurred since XMM-Newton, Chandra and Swift have been observing and more historic supernovae). To do so, we prioritise X-ray source positions from Chandra, XMM-Newton and Swift in that order (i.e. in cases where a source is detected by all three observatories, we use the Chandra position for this match), and perform the match using search radii of $3''$, $5''$ and $10''$ for Chandra, XMM-Newton and Swift positions, respectively. However, in order to determine whether the X-ray source is really associated with the transient in question we

| Value | Description |
|-------|-------------|
| NULL | No match between the catalogues |
| 0 | Unique match between ULX candidates |
| 1 | Formally more than one potential match between ULX candidates, but one is clearly preferred and assumed to be the correct match; only this match is reported |
| 2 | Formally more than one potential match between ULX candidates, and it is unclear which is the correct association; all potential matches are given |
| 3 | ULX detection consistent with several lower luminosity sources seen by the other mission in question, but their combined flux is not sufficient to explain that seen of the ULX detection, so the source is still retained |
Figure 2. X-ray (left) and accompanying optical (right) images for three example galaxies that demonstrate some of the main stages of our source selection. For the X-ray images, from top to bottom, we show an XMM-Newton EPIC image of NGC 6946 (OBSID 0691570101), the integrated Swift XRT image of NGC 1097 (generated with the standard online XRT pipeline; Evans et al. 2009) and a Chandra ACIS image of NGC 720 (stack ID acisfJ0153056m134345). All are smoothed with a Gaussian of width 3 pixels. The optical images are from the Digitized Sky Survey. In all panels, the D25 extent of the galaxy in question is indicated with the blue dashed ellipse, and the nuclear position with a cross (note that in the case of NGC 1097, the small companion galaxy NGC 1097A is also shown). ‘Field’ sources (i.e. outside of the D25 extent) are shown with squares, point sources within the D25 extent that do not qualify as ULX candidates with circles, and finally sources selected as ULX candidates are shown with diamonds, respectively; all markers are shown in either black or white simply so that they can most easily be seen against the background images, there is no further significance to the choice of colour. The XMM-Newton and Chandra images represent the deepest observation/stack of NGC 6946 and NGC 720 that are included in 4XMM-DR10 and CSC2, respectively. However, owing to the variable nature of the ULX population (see e.g. Earnshaw et al. 2019a for NGC 6946 in particular), not all sources identified as ULX candidates are necessarily visible in these X-ray images.
also examine the relative timing of the event and the first detection of the X-ray source (hence our decision to only apply this filter to the merged dataset, where we can most robustly determine when the source was first detected). X-ray sources that are positionally coincident with supernovae, but which were detected as ULXs significantly before the event occurred are deemed to be unrelated to the supernova and retained in our sample. However, sources positionally coincident with known transients that have only been detected after the event occurred are assumed to be associated with the supernova, and so are excluded from our final sample.

We also match our remaining sample against both the NED and SIMBAD databases in order to identify and remove any further non-ULX contaminants that have been identified in the literature ( uncatalogued AGN, stars, supernovae). We adopt the same spatial matching procedure as for the Open Supernova Catalogue, prioritising Chandra, XMM-Newton and Swift positions in that order and using matching radii of 3″, 5″ and 10″. For any further supernovae identified, we also again consider the date of the first X-ray detection when deciding whether the X-ray source should be removed. We then remove any remaining sources obviously associated with the host-galaxy AGN that have been missed by our nuclear cut (e.g. sources with \( L_X \geq 10^{42} \text{ erg s}^{-1} \) that lie just outside our nuclear exclusion radii or, in the case of Centaurus A, are located in the X-ray emission from the AGN jet; Hardcastle et al. 2007) as well as a number of sources for which we are aware of follow-up studies that have previously found the ULX candidate to be an uncatalogued background quasar/foreground star (Dadina et al. 2013; Heida et al. 2013; Sutton et al. 2015; Guo et al. 2016).

Finally, after all of the above steps, we find that the remaining sample contains a number of highly clustered sources which only appear in 2SXPS and actually seem to be associated with the bright diffuse emission known to be present in the M82 galaxy (e.g. Griffiths et al. 2000; Lopez et al. 2020), even though 2SXPS is intended to be a dedicated point source catalogue. This is likely related to the typical snapshot nature of Swift XRT observations; with such short exposures random Poisson fluctuations from the diffuse emission may more easily be mistaken as point sources. 2SXPS notes all of the potential aliases for each entry, and many of these M82 sources are listed as potentially being aliased with each other. We therefore also manually inspect X-ray images – both the images integrated over the duration of the Swift mission and specifically taken from the observation corresponding to the reported best detection for the XRT, and, where available, any CSC2 Chandra images as well – for all of the 2SXPS sources which have not also been identified as a ULX candidate in either of our 4XMM-DR10 or CSC2 sub-samples and are listed as having other potential 2SXPS aliases. Any sources which we judge to be likely associated with diffuse emission (similar to the M82 case) are removed from the final sample. During this process, if a source is aliased with another genuine point source (as opposed to being part of a cluster of sources associated with extended emission), we also make a judgement over whether these are likely the same source, and retain only one entry in these cases.

### 4 THE FINAL SAMPLE

Our final sample of ULX candidates consists of 1843 individual sources residing in 951 host galaxies. The catalogue will be made available to the public, and will be comprised of four tables. The first is a ‘master’ list formatted to have one row entry per source, summarising some key information and detailing which combination of XMM-Newton, Swift and Chandra have reported the source as a ULX. We stress that we are focused only on the detections of these sources that meet the ULX luminosity threshold here (i.e. \( L_X \geq 10^{40} \text{ erg s}^{-1} \)); if an XMM-Newton ULX candidate does not have a Chandra counterpart reported, for example, this does not necessarily mean that Chandra has not detected that source, only that Chandra has not seen it at a flux that would correspond to the ULX regime. The other three tables provide the full details of the 4XMM-DR10, 2SXPS and CSC2 entries for the ULX-level detections of these sources. These follow the formats of the data used to compile these subsamples of ULX candidates in the first place (i.e. the XMM-Newton and Chandra tables have one row entry per observation of a ULX candidate, while the Swift table just has one row entry per ULX candidate).

Some statistics for the full sample and the individual 4XMM-DR10, 2SXPS and CSC2 sub-samples are given in Table 2, and we show examples of our source selection in Figure 2 for each of the XMM-Newton, Swift and Chandra observatories. By number, the CSC2 component contributes the most sources to our final sample, followed by 4XMM-DR10 and then 2SXPS. The latter still makes a very significant contribution though. There is obviously notable overlap between the individual subsamples (i.e. some sources are detected as ULXs by multiple missions), as also detailed in Table 2 and in the master table provided. Of our 1843 individual sources, 50 are detected at ULX luminosities in all three of our contributing source catalogues.

As expected, given the known connection between ULXs and recent star formation (Swartz et al. 2009; Mineo et al. 2012; Lehmer et al. 2019), the majority of our ULX host galaxies with...
morphism information available are spiral galaxies (~60%, using the T-type ranges defined above). We also plot the distribution of host galaxy distances in Figure 3 for the full sample and each of the individual catalogue subsamples. There is significant overlap in the individual distributions, but typical host galaxy distances are lowest for the 2SXPS subsample, and largest for the CSC2 subsample, as the latter has the best sensitivity to faint point sources among the X-ray catalogues considered owing to both the low background and superior imaging capabilities of Chandra. This allows Chandra to more easily detect ULX candidates out to larger distances than either XMM-Newton or Swift, and thus the CSC2 subsample ends up making the largest contribution to our final sample.

Of our 951 host galaxies, 333 are found to host multiple ULX candidates. As our primary interest is focused on individual sources, and our sample selection is highly non-uniform, we do not make any attempt to correct for (in)completeness in any galaxies observed with insufficient depth to reach luminosities of $10^{39}$ erg s$^{-1}$, so this should likely be considered a lower limit for ULX multiplicity in these hosts. The most extreme example is NGC 2207 – one half of an interacting galaxy pair (the other being IC 2163; Eskridge et al. 2002) – which appears to host an astonishing 34 ULX candidates, the majority of which (31) are contributed by the CSC2 catalogue. This is notably larger than the 21 ULXs reported to reside in NGC 2207/IC 2163 by Mineo et al. (2013), likely due to additional Chandra observations being included in CSC2 and our explicit consideration of long-term variability in selecting our ULX sample. Owing to the interacting nature of these galaxies, it is not surprising that there should be a large number of ULXs. It is nevertheless worth noting that there seems to be some disagreement over the distance to NGC 2207 in the literature. The distance we have adopted here is $D = 36.4$ Mpc, which is based on the recession velocity reported in HyperLEDA. This distance is very similar to that reported based on the supernova SN1975A which occurred in NGC 2207 ($D = 39.6$ Mpc; Arnett 1982), which is adopted by Mineo et al. (2013). However, the more recent estimates from the Tully-Fisher method typically seem to imply a distance of $D \sim 17$ Mpc (Russell 2002; Theureau et al. 2007). Should this be correct, only 7 of our sources in NGC 2207 would still be considered ULXs. However, our assumption is that the supernova-based distance is the most reliable here, and so our luminosity estimates should be reasonable.

We also note that among the 1843 ULX candidates, our catalogue contains 71 ‘hyperluminous’ X-ray source (HLX) candidates. These are the most extreme members of the ULX population, exhibiting luminosities of $L_X \geq 10^{41}$ erg s$^{-1}$. Owing to their astonishing luminosities, such sources are often considered the best candidates for IMBH accretors. Indeed, two of the sources discussed as the leading IMBH candidates in the literature, M82 X-1 and ESO 243–49 ULX1, are found among this population. However, it is also worth noting that one of the known ULX pulsars, NGC 5907 ULX1, also reaches luminosities of $L_X \sim 10^{41}$ erg s$^{-1}$ (Israel et al. 2017a; Fürst et al. 2017), despite being powered by a neutron star. Nevertheless, these sources are still of particular interest, and our new HLX candidates will be discussed in more detail in future work (A. D. Mackenzie, in prep.).

### Table 2. The final sample of ULX candidates compiled from the 4XMM-DR10, 2SXPS and CSC2 catalogues

| Number of ULX Candidates | 4XMM-DR10 | 2SXPS | CSC2 | Combined Sample |
|--------------------------|-----------|-------|------|-----------------|
| (with multiple ULX detections in the parent catalogue) | 641 | 501 | 1031 | 1843 |
| (seen as a ULX by multiple observatories) | 177 | 291 | 246 | 702 |
| (HLX candidates) | 241 | 173 | 209 | 293 |
| Host Galaxies (average distance, Mpc) | 403 | 269 | 548 | 951 |
| (containing multiple ULX candidates) | 130 | 89 | 190 | 333 |

4.1 Comparison with Other ULX Catalogues

The first major effort to search for ULXs among any of the X-ray source catalogues considered here was presented by Kovlakas et al. (2020), who also searched CSC2 for ULX candidates. Although both the approach taken and the input galaxy sample used are quite similar in both cases, there are also a couple of notable differences. First and foremost, we have considered the Chandra data down to the observation-by-observation level, in order to select sources based on their peak flux and specifically include transient ULXs in our sample, while Kovlakas et al. (2020) base their luminosity selection on the flux recorded in the longest uninterrupted segment of Chandra data (which is not necessarily the peak flux exhibited by the source). Second, we have taken a much more conservative approach to excluding potential nuclear sources associated with our host galaxies. Kovlakas et al. (2020) flag a source as ‘nuclear’ if it is within 3″ of the nominal galaxy centre, while we both consider the position error on the X-ray detection and utilize a much larger minimum exclusion radius (6.1″). This is based on our empirical assessment of the separation between the nominal centre of the host galaxies and sources that we consider likely to be their AGN (those that appear to have $L_X \geq 10^{42}$ erg s$^{-1}$). Our more conservative approach does mean that our catalogue is likely cleaner with regards to any remaining contamination from AGN in our host galaxies, but this will come at the cost of excluding a larger number of bona fide ULXs from our sample, particularly given that the spatial density of ULXs is seen to increase towards the galaxy centres (Swartz et al. 2011; Wang et al. 2016; Kovlakas et al. 2020). Nevertheless, this is a more appropriate approach given that our primary motivation is to find individual sources that are of interest for follow-up studies; detailed follow-up procedure, such that if the peak luminosity is not well constrained (average fractional uncertainty of >40%) then the source has to either have a better-constrained average luminosity that is also in the HLX regime, or at least two separate XRT observations that place it in the HLX regime.
of ULXs within a few arcseconds of the nuclear position will not realistically be feasible for the majority of our current and planned X-ray facilities if the nuclear black hole is even reasonably active. Despite these differences, though, there is naturally a fairly significant degree of overlap (754 sources) between our sample and sources that would qualify as ULXs in Kovlakas et al. (2020).

More recently, Inoue et al. (2021) have also searched for CSC2 for ULX candidates. However, a major difference between these works is that Inoue et al. (2021) have used a much smaller catalogue of input galaxies than that used here, derived by combining IRAS galaxies with the CNG catalogue. Furthermore, while they do consider the observation-by-observation data provided in CSC2, they use the flux from the longest individual observation when computing luminosities, which again is not necessarily the peak flux exhibited by the sources in question (which is what we are interested in here), and we have again been more conservative in our treatment of nuclear sources. Although their work primarily focuses on CSC2, the final catalogue does also include sources selected from 4XMM-DR9 and 2SXPS, and so is therefore conceptually similar to our multi-mission approach. There is not a lot of specific detail provided for these latter analyses, unfortunately, but the approach is stated to be broadly similar to that used for CSC2, and so similar differences between the two works are presumably present here too. In addition, another key difference with regard to the 2SXPS analysis is that they appear to have only made use of the average fluxes from Swift, while we have considered the peak flux (where this is considered reliable). Furthermore, we have used an even more recent release of the 4XMM survey here. Nevertheless, despite these differences, there is again some notable overlap of 357 sources in total (251, 107 and 149 from Chandra, XMM-Newton and Swift, respectively).

Finally, Barrows et al. (2019) also utilize CSC2, but only search specifically for HLXs within the SDSS-DR7 galaxy sample. However, the spatial offsets relative to the central galaxy positions would result in the majority of their HLX candidates being considered as nuclear sources with our more empirical approach to this stage of the catalogue production. Only one of our sources is also present in the Barrows et al. (2019) catalogue, 2CXX155910.3+204619, and we have assigned this to a different (and closer) host galaxy, giving it a much more modest luminosity of \( L_X \approx 2.5 \times 10^{39} \text{ erg s}^{-1} \). As such, our sample of HLX candidates differs entirely to that presented by Barrows et al. (2019).

In addition to these more recent works, we also match our new catalogue against a series of other archival ULX catalogues, which have been derived using previous generations of X-ray surveys. In these cases we match by position, as they are not drawn from any of the exact X-ray catalogues used here (and thus do not have identical naming conventions). Similar to our final matching against the NED and SIMBAD for remaining contaminants, we split our ULX catalogue into sources where the best position comes from Chandra, from XMM-Newton and from Swift, and then individually match these sub-sections against each of the archival ULX catalogues in turn. The matching radius used for each comparison depends on the origins of the data being compared, and always corresponds to the larger of the typical positional uncertainties associated with the two input tables. As before, positions from Chandra, XMM-Newton, Swift and ROSAT are considered to have typical uncertainties of 3″, 5″ and 10″, respectively, and ROSAT positions are considered to have a typical uncertainty of 20″. For example, when comparing the subset of our catalogue with Chandra positions against another catalogue derived from Chandra data, we would use a matching radius of 3″, but comparing the same subset against a catalogue derived from ROSAT observations, we would use a matching radius of 20″.

| Catalogue | Primary Source & Notes |
|-----------|------------------------|
| Colbert & Prak (2002) | ROSAT |
| Swartz et al. (2004) | Chandra |
| Liu & Bregman (2005) | ROSAT |
| Liu & Mirabel (2005) | Literature (incl. ROSAT, so positions treated as having ROSAT accuracy) |
| Liu (2011) | Chandra |
| Swartz et al. (2011) | Chandra |
| Walton et al. (2011b) | XMM-Newton (specifically 2XMM) |
| Gong et al. (2016) | Chandra (only \( L_X \geq 3 \times 10^{40} \text{ erg s}^{-1} \)) |
| Earnshaw et al. (2019b) | XMM-Newton (specifically 3XMM-DR4) |
| Barrows et al. (2019) | Chandra (specifically CSC2 HLXs) |
| Kovlakas et al. (2020) | Chandra (specifically CSC2) |
| Inoue et al. (2021) | Mainly Chandra (specifically CSC2), but also includes XMM-Newton and Swift (specifically 4XMM-DR9 and 2SXPS) |

For this analysis, we simply note all potential matches. The catalogues we match against are listed in Table 3.

Based on all of these matches, we find that 689 of the ULX candidates presented here are completely new, i.e. do not seem to appear in any of the other ULX catalogues considered, and 1318 have only recently been catalogue as a ULX, i.e. they only appear in catalogues based on the latest generation of X-ray source catalogues (this work, Barrows et al. 2019, Kovlakas et al. 2020 and Inoue et al. 2021). Of these ‘new’ and ‘recent’ ULX candidates, 48 and 59, respectively, are HLX candidates. We stress that even if a source is considered ‘new’ in this respect, this does not necessarily mean the sources are completely unknown, only that it has not been formally catalogued as a ULX previously. For example, NGC 300 ULX1 is considered ‘new’ here, even though this source is one of the few known ULX pulsars (Carpano et al. 2018), and as such has received significant individual attention (Walton et al. 2018a; Kosec et al. 2018b; Vasilopoulos et al. 2018, 2019; Heida et al. 2019).

4.2 Estimation of Unknown Contaminants

Although we have taken significant measures to try and remove known contaminants, these processes can never be perfect, and so we stress that there will still be a significant contribution of sources that are not actually ULXs in our final sample of ULX candidates. By far the majority of these will be foreground/background sources that coincidentally appear to be associated with the host galaxies in question in projection, but have just not been formally identified/catalogued as such in the databases we have utilized (and thus have not been removed by our effort to identify and exclude these sources). Although we cannot remove these sources, it is still important to quantify their likely contribution.

In order to do so, we broadly follow the approach taken in Walton et al. (2011b), and subsequently Sutton et al. (2012) and Earnshaw et al. (2019b). This involves a calculation of the total expected number of sources that would be resolved from the cosmic X-ray background (CXB) given our selection criterion, the sensitivity of the observations from which the 4XMM, 2SXPS and CSC2 X-ray catalogues have been generated, and the full set of galaxies in our catalogue that have been covered by the observations that con-
tribute to these X-ray catalogues (not just those galaxies that have ULX detections). These estimates are then compared to the number of sources remaining in our catalogue, after accounting for the number of identified foreground/background sources that have already been filtered out, in order to estimate the remaining fractional contribution from these contaminants.

In order to estimate the total expected number of contaminants, we make use of empirically determined forms of the $N(S)$ curves which quantify the number of sources per square degree ($N$) resolved from the CXB as a function of flux sensitivity ($S$). These are combined with observational sensitivity maps in order to estimate the number of background sources each galaxy in our input sample that has been observed should contribute. Sensitivity maps for the observations from which the 4XMM and CSC2 catalogues are compiled are provided as part of these data releases, but are not available for the 2SXPS catalogue at the time of writing. We therefore focus our calculations on the 4XMM and CSC2 data, performing this calculation for each dataset separately; as will be clear below, the expected level of contamination for these datasets are very similar, and so we still expect these results to hold overall.

For CSC2, since the initial source detection is performed using ‘stacks’ of observations (a stack is defined as a group of observations for which the aimpoints are all within 1 arcminute; see the CSC2 documentation), we use the sensitivity maps generated for these stacks in our analysis. These are provided for all of the energy bands considered in the CSC2 catalogue. However, as noted by Walton et al. (2011b), owing to absorption in the apparent host galaxies (which lie between us and any background AGN) these calculations are most robust at higher energies, and so we limit ourselves to the hard band (2–7 keV) ACIS maps that correspond to the ‘true’ detection threshold to match our data selection (the HRC makes a negligible overall contribution here). We also make use of the $N(S)$ curves recently published by Masini et al. (2020), who present an expression for the same 2–7 keV band.

There are two limiting fluxes to consider here. The first is set by our selection of sources that appear to have $L_X \gtrsim 10^{39}$ erg s$^{-1}$. For each galaxy we work out the hard band flux that would correspond to a broadband luminosity of $10^{39}$ erg s$^{-1}$, $S_{\text{ulx}}$, based on the distance to the galaxy and the fraction of the broadband flux that would appear in the hard band. We use a coarse representation of the average spectral shape for ULXs below 10 keV (e.g. Stobbart et al. 2006; Gladstone et al. 2009; Pintore et al. 2017): an absorbed powerlaw spectrum with $\langle N_H \rangle = 3 \times 10^{21}$ cm$^{-2}$ and $\Gamma = 2.1$. The second flux is the limiting sensitivity of the stack in question, $S_{\text{obs}}$, provided by the sensitivity maps. The relevant limiting sensitivity for use with the $N(S)$ curve is then the larger of these two values, such that if an observation is sensitive enough to detect sources at lower luminosities, these are not included in our estimated number of contaminants. For each of the galaxies covered by CSC2 we use the $N(S)$ curve and the appropriate limiting sensitivity to compute maps of the number of expected background sources per pixel, and integrate these over the area of the galaxy covered by each relevant Chandra stack (excluding the typical area excised around the central galaxy location by our nuclear cut). For each of the galaxies covered by CSC2 data (again, not just those with ULX detections), we perform this calculation for every available stack. We then select the stack that would give the largest number of contaminants, and sum these values over all of the galaxies covered by CSC2 stacks to compute the total number of expected contaminants prior to the removal of any known foreground/background sources. From this, we compute the remaining fractional contamination among the CSC2 ULX candidates by comparing the expected number of remaining contaminants to the number of ULX candidates detected in the hard band for self-consistency (i.e. excluding sources that only have upper limits).

For 4XMM, the sensitivity maps are only provided for the full band (0.2–12.0 keV) and are based on the combined sensitivity for all of the EPIC detectors (see Section 9 in Webb et al. 2020). However, as stated above, it is preferable to work in the hard band here. Furthermore, suitable $N(S)$ curves are not currently available for the full XMM-Newton bandpass; aside from work focusing specifically on Chandra, $N(S)$ curves are determined almost exclusively for the 0.5–2.0 and 2–10 keV bands. It is therefore necessary to correct the results from the available broadband maps to one of these bands, and we again choose the harder band, but this is not a trivial process. To do so, we also make use of the hard band (2–12 keV) sensitivity maps computed as part of the Earnshaw et al. (2019b) ULX catalogue for the majority of observations that make up 4XMM-DR10 (specifically those that make up 3XMM-DR4). However, these are computed using a different approach (see Carrera et al. 2007 and Mateos et al. 2008), consider each of the EPIC detectors separately, and adopt a different detection threshold (the hard band maps are computed for a $\sim 4\sigma$ detection in a single detector, while the broadband maps are computed for a $\sim 3\sigma$ detection combining all the EPIC detectors), further complicating the situation.

For each galaxy covered by these earlier observations, we therefore process the available hard band sensitivity maps for each of the detectors in a similar manner as above, using the appropriate $N(S)$ curve published by Cappelluti et al. (2009) but only considering for the limiting observational sensitivity ($S_{\text{obs}}$) for the time being, and note the results for the detector that predicts the largest number of contaminants. We also process the broadband maps for the same observations by computing the fraction of the broadband flux in both the softer (0.5–2.0 keV) and harder (2–10 keV) bands using the spectral form assumed in their generation (an absorbed powerlaw with $N_H = 1.7 \times 10^{20}$ cm$^{-2}$ and $\Gamma = 1.42$, typical for CXB sources), processing these updated maps in turn using the relevant $N(S)$ curves, again only considering $S_{\text{obs}}$, and averaging the final results to obtain an estimate for the number of contaminating sources the broadband maps would imply. For each galaxy covered by these earlier observations, we then compare the results from the broadband and the hard band maps to compute an empirical correction for the former; we find this correction to be a factor of 9. We then process the full set of 4XMM-DR10 broadband sensitivity maps using this correction to produce maps of the expected number of hard band CXB sources. At this point, we also consider the number of contaminants implied by the second limiting sensitivity, $S_{\text{ulx}}$, and update the maps accordingly. Similar to before, we then integrate these maps over the galaxy area covered by every observation of that galaxy (again excluding the typical area around the central position excited by our nuclear cut, and again considering all galaxies covered by 4XMM-DR10) and pick the observation that gives the largest number of hard-band contaminants for each galaxy. We then sum these values to compute the total number of expected contaminants prior to the removal of any known foreground/background sources, and finally compute the remaining fractional contamination among the 4XMM ULX candidates (comparing the expected number of remaining contaminants against the number of ULX candidates that are detected at the $4\sigma$ level in any of the EPIC detectors for self-consistency).

Based on these approaches, and the numbers of known foreground/background contaminants already removed, we estimate fractional contaminations of $(23\pm2)\%$ and $(18\pm3)\%$ for our CSC2 and 4XMM-DR10 ULX candidates, respectively (quoted uncertain-
ties are due to counting statistics, and are 1σ. These values are sufficiently similar that, even though the relevant sensitivity maps are not yet available for 2SXPS, we still expect that an overall fractional contamination of ∼20% is relevant for the whole catalogue.

5 NGC 3044 ULX1 – A NEW EXTREME ULX

The non-uniform selection means the full ULX sample presented here is not necessarily well suited for detailed statistical studies of the ULX population similar to those presented by Kovlakas et al. (2020) and Inoue et al. (2021). Indeed, our intention in compiling this sample is to facilitate follow-up studies of interesting individual sources. As such, in order to highlight the potential of our catalogue, we instead present a case study of a new extreme ULX candidate with $L_{\text{X,peak}} \sim 10^{40}$ erg s$^{-1}$ in the edge-on spiral galaxy NGC 3044 by both Swift and XMM-Newton (see Figure 4). Although we have found several new HLX candidates in our analysis, we highlight this new source in particular both because of its luminosity is still very extreme, but also because it already has high signal-to-noise (S/N) XMM-Newton data (several thousand counts) available in the archive; as noted above, our new HLX candidates will instead be studied in future work (A. D. Mackenzie, in prep.). Hereafter we refer to this source as NGC 3044 ULX1 for simplicity, as it is the brightest ULX candidate in NGC 3044, but its catalogued 4XMM-Newton detections (see below). Background is estimated from a larger region of blank sky on the same detector as ULX1. All of the observations suffer from periods of enhanced background to some degree, and for each observation we determine the background threshold that maximises the source S/N over the full XMM-Newton band considered in our more detailed analysis (0.3–10.0 keV) following the method outlined in Picone et al. (2004). Only single and double patterned events are considered for EPIC-pn (PATTERN ≤ 4) and single to quadruple patterned events for EPIC-MOS (PATTERN ≤ 12), as recommended, and all of the necessary instrumental response files were generated using ARFGEN and RMFGEN. After performing the reduction separately for the two EPIC-MOS units, we combine their individual spectra using ADDASCASPEC.

5.1 Observations and Data Reduction

NGC 3044 has been observed on four occasions by XMM-Newton, and on five occasions by Swift. A log of these observations is given in Table 4. We primarily focus on the XMM-Newton observations here, but also process the Swift observations to provide further information on the long-term variability.

The XMM-Newton data for each observation are reduced following standard procedures using the XMM-Newton Science Analysis System (SAS v19.1.0). All of the XMM-Newton observations were taken in full frame mode. Raw observation files for the EPIC-pn and EPIC-MOS detectors are cleaned using EPCHAIN and EMCHAIN, respectively. In order to facilitate pulsation searches, the cleaned EPIC-pn event files are corrected to the solar barycentre using the DE200 solar ephemeris, as this has the best time resolution of the XMM-Newton detectors (73.4 ms in full frame mode). Source products are extracted from the cleaned event files with XMMSELECT. Given the relative proximity of supernova SN1983E (separated by ∼35″; see Figure 4), we use circular source regions of radius 15–20″, with the larger region size used for the higher flux observations (see below). Background is estimated from a larger region of blank sky on the same detector as ULX1. All of the observations suffer from periods of enhanced background to some degree, and for each observation we determine the background threshold that maximises the source S/N over the full XMM-Newton band considered in our more detailed analysis (0.3–10.0 keV) following the method outlined in Picone et al. (2004). Only single and double patterned events are considered for EPIC-pn (PATTERN ≤ 4) and single to quadruple patterned events for EPIC-MOS (PATTERN ≤ 12), as recommended, and all of the necessary instrumental response files were generated using ARFGEN and RMFGEN. After performing the reduction separately for the two EPIC-MOS units, we combine their individual spectra using ADDASCASPEC.

5.2 Spectral Analysis

Based on the 4XMM-DR10 data, the first two XMM-Newton observations (2001 and 2002) both caught NGC 3044 ULX1 in a lower flux state, while the latter two (2013 and 2016) caught the source in a higher flux state. We therefore combine the XMM-Newton spectra from these pairs of observations using ADDASCASPEC to provide the highest S/N data possible for these two flux regimes. These spectra are shown in Figure 5.

We initially begin by fitting the high-flux data with a simple absorbed powerlaw model. We use XSPEC for our spectral analysis (Arnaud 1996), and allow for both the Galactic absorption column of $N_{H,\text{Gal}} = 2.33 \times 10^{20}$ cm$^{-2}$ (HI4PI Collaboration et al. 2016) and further absorption at the redshift of NGC 3044 ($z = 0.00430$) that is free to vary in all our models. Both absorbers are modelled using TBABS, and we adopt solar abundances from Wilms et al.
(2000) and absorption cross-sections from Verner et al. (1996). We also allow for cross-normalisation constants to float between the data from the pn and MOS detectors to account for residual calibration differences; these factors are always within a few per cent of unity. Finally, the higher flux data are grouped to a minimum of 25 counts per bin to facilitate the use of $\chi^2$ minimisation. The absorbed powerlaw model returns a fairly steep continuum, with $N_{\text{H, high}} = (2.1 \pm 0.2) \times 10^{21} \text{ cm}^{-2}$ and $\Gamma_{\text{high}} = 2.41 \pm 0.07$ (uncertainties on the spectral parameters are quoted at the 90% level).

Unsurprisingly, the lower flux data have a much lower S/N (in addition to the lower flux, these data have a much lower combined exposure). We therefore group these data to just 1 count per bin, and fit them with the same model using the Cash statistic (Cash 1979). Here we find $N_{\text{H, low}} = 1.1_{-0.7}^{+0.8} \times 10^{21} \text{ cm}^{-2}$ and $\Gamma_{\text{low}} = 2.3 \pm 0.4$. Within the limitations of the available data, there is therefore little evidence for spectral variability, although the parameter constraints are not particularly tight for the lower flux data.

Although the absorbed powerlaw model captures the overall shape of the spectrum in the 0.3–10.0 keV band fairly well, the high-flux data have sufficient S/N that systematic residuals to this simple model can be seen (see Figure 6), implying that a more complex continuum model is required. Indeed, the quality of fit provided by the absorbed powerlaw model for the high flux data is $\chi^2 = 353$ for 285 degrees of freedom (DoF), which is not formally an acceptable fit. This residual structure is fairly typical for extreme ULXs when fit with a single powerlaw model (e.g. Stobbart et al. 2006; Gladstone et al. 2009; Mukherjee et al. 2015), and indicates the need for distinct continuum components above and below $\sim 1$–2 keV. We therefore fit the high-flux data with a few more complex models often used to describe ULX spectra. First, we fit a model consisting of a lower energy accretion disc component, and a higher energy powerlaw continuum. We use the DISKBB model (Mitsuda et al. 1984) for the former, which implicitly assumes a thin disc profile (Shakura & Sunyaev 1973), such that the model broadly represents the classic disc–corona geometry seen in sub-Eddington X-ray binaries. This provides a significant improvement to the simpler powerlaw fit, with $\chi^2$/DoF = 284/283. The best-fit parameters are given in Table 5.

There is still a mild hint of curvature in the spectrum at higher energies though ($E > 2$ keV; Figure 6). This is seen in the majority of high S/N ULX spectra, initially implied by XMM-Newton (e.g. Gladstone et al. 2009; Walton et al. 2011a) and then unambiguously confirmed by the higher energy coverage provided by NuSTAR (e.g. Bachetti et al. 2013; Walton et al. 2014; Rana et al. 2015). These broadband observations find that ULX spectra are primarily described by two thermal components below 10 keV. We therefore also fit a second model that is often considered for ULXs, combining two accretion disc components.3 Specifically, for the higher energy emission we replace the powerlaw component with a DISKBB model (Mineshige et al. 1994). This allows for the radial temperature index ($p$) to be an additional free parameter, such that the model can mimic a thick, advection-dominated super-Eddington accretion disc (which would be expected to have $p < 0.75$ instead of the $p = 0.75$ appropriate for thin accretion discs; Abramowicz et al. 1988). The DISKBB+DISKBB does provide a moderate additional improvement in fit over the DISKBB and powerlaw combination, with $\chi^2$/DoF = 273/282 (i.e. an improvement of $\Delta \chi^2 = 11$ for one extra free parameter). As our best-fit model, we show the relative contributions of the different model components in Figure 6, and the parameter constraints are also given in Table 5.

The best-fit spectral form for NGC 3044 ULX1 differs somewhat from that used to compute the fluxes in 4XMM-DR10, so we also re-calculate the observed 0.3–10 keV fluxes for the individual XMM-Newton observations using the spectral models for the high- and low-flux states discussed above. To further examine the long-term behaviour of the source we also consider the Swift data at this stage. These observations can themselves be split into two main groups, taken in April and June 2015. We process the combined data from these two sets of observations, compute the average count rates for each of the two groups using the same 20′′ regions as for the XMM-Newton data (correcting appropriately for the point spread function), and convert these to fluxes using the spectral shape implied by the simple powerlaw fits to the XMM-Newton data. The long term lightcurve combining the XMM-Newton and Swift data is shown in Figure 7. The coverage is admittedly sparse, but the Swift fluxes are consistent with the more recent XMM-Newton measurements, and so it appears as though the higher flux state persisted throughout 2013–2016. We also still find the peak luminosity of the source to be $L_{\text{X, peak}} \sim 10^{40}$ erg s$^{-1}$, confirming the extreme luminosity implied by our analysis of 4XMM-DR10.

5.3 Timing Analysis

The longest of the available XMM-Newton observations of NGC 3044 ULX1, OBSID 0782650101, returns a total of $\sim 5000$ net source counts with the EPIC-pn detector, roughly comparable to the quality of data used to detect X-ray pulsations for some of the known ULX pulsars (e.g. Israel et al. 2017a; Rodríguez Castillo et al. 2020). We therefore also perform a search for pulsations on this dataset. We focus on the data from the EPIC-pn detector here as this has both the highest count rate and the best
Table 5. Key parameters obtained for the various continuum model fits to the high-flux data available for NGC 3044 ULX1

| Model Component | Parameter | Continuum Model |
|-----------------|-----------|-----------------|
|                 |PARAMETER | POWERLAW | DISKBB+POWERLAW | DISKBB+DISKPBB |
| TBABS           | $N_H [10^{21} \text{ cm}^{-2}]$ | 2.1 ± 0.2 | 3.5$^{+0.7}_{-0.6}$ | 3.0 ± 0.6 |
| DISKBB          | $T_{in} [\text{keV}]$ | – | 0.16 ± 0.02 | 0.19 ± 0.03 |
|                 | Norm | – | 37$^{+80}_{-25}$ | 13$^{+26}_{-7}$ |
| POWERLAW        | $\Gamma$ | 2.41 ± 0.07 | 2.2 ± 0.1 | – |
|                 | Norm [10$^{-5}$] | 6.1 ± 0.3 | 5.0$^{+0.6}_{-0.5}$ | – |
| DISKPBB         | $T_{in} [\text{keV}]$ | – | – | 1.7$^{+0.7}_{-0.4}$ |
|                 | $p$ | – | – | 0.56$^{+0.15}_{-0.05}$ |
|                 | Norm [10$^{-4}$] | – | – | 3.6$^{+5.7}_{-0.5}$ |
| $\chi^2$/DoF   | 353/285 | 284/283 | 273/282 |

Figure 6. Top panel: The relative contributions of the best-fit DISKBB+DISKPBB model to the high-flux XMM-Newton data for NGC 3044 ULX1. The total model is shown in black, the DISKBB component in blue and the DISKPBB component in red, respectively. Lower panels: The data/model ratio for a simple absorbed powerlaw continuum model, a DISKBB+POWERLAW continuum and the DISKBB+DISKPBB models, respectively. For the ratio panels, the colours have the same meanings as in Figure 5, and the data have again been rebinned for visual purposes.

Figure 7. Longtime lightcurve for NGC 3044 ULX1 based on the available X-ray data. XMM-Newton data are shown in black, and Swift in red. Note that the sets of Swift observations taken in April and in June have been combined together here (see Section 5.2).

timing resolution of the EPIC detectors (73.4 ms in the full-frame mode used for this observation).

For this analysis we use the pulsar timing tools included in the HENDRICS package (Bachetti 2018). Since the pulse period can evolve rapidly in ULX pulsars, either due to the secular spin-up driven by the extreme accretion (Fürtst et al. 2016; Israel et al. 2017a; Carpano et al. 2018; Vasilopoulos et al. 2018) or orbital motion of the neutron star (Bachetti et al. 2014; Israel et al. 2017a; Fürtst et al. 2018, 2021), we perform an ‘accelerated’ pulsation search, which considers both the frequency of the pulsations ($f$) and its first derivative ($\dot{f}$) when searching for any signals. Specifically, we use the HENZSEARCH script, which performs the $Z_n^2$ search originally outlined in Buccheri et al. (1983), and allow for $n = 2$ harmonics in our search (i.e. we use the $Z_2^2$ statistic). Based on the properties of the known ULX pulsars, we focus on the frequency range of 0.01–6.75 Hz, and the “fast” search option utilized allows for $\dot{f}$ values in the range $\pm10^{-8} \text{ Hz s}^{-1}$. Unfortunately we did not find any promising pulsation candidates in this observation.

In the absence of a robust pulsation detection, we estimate an upper limit on the pulsed fraction any undetected signal could have following the method used in Walton et al. (2021). In short, we use the HENZ2VSPF script, which simulates datasets using the same GTIs and total number of events as the real data, then uses rejection
sampling to modulate the events with an increasingly strong pulsed signal (assuming a sinusoidal pulse profile, which is appropriate for ULX pulsars), and finally calculates the $Z^2$ statistic at which the $Z^2$ statistic reaches $\sim$40. This threshold roughly corresponds to a $3\sigma$ detection, and thus indicates the equivalent upper limit on the pulsed fraction that could still be present in the real data. We find an upper limit on the pulsed fraction of $\sim$22% when considering the full XMM-Newton bandpass.

5.4 The Nature of NGC 3044 ULX1

NGC 3044 ULX1 is a new extreme ULX discovered in our analysis that already has high S/N data available in the archive. Although it has always been in the ULX regime whenever observed with our current X-ray facilities (considering XMM-Newton and Swift in combination, we have observations from 6 different epochs), sometime between 2002 and 2013 it seemed to jump up by a factor of $\sim$3–4 in luminosity from $L_X \sim 3 \times 10^{39}$ erg s$^{-1}$ to $L_X \sim 10^{40}$ erg s$^{-1}$, where it seems to have remained since (see Figure 7).

The 0.3–10.0 keV X-ray spectrum observed during this high-flux period is very similar to other extreme ULXs: the flux below 10 keV is dominated by two continuum components that primarily contribute above and below $\sim$1–2 keV and, although it is not a strong statistical detection, there is a hint of spectral curvature in the higher energy component. We note in particular that, although there is no higher energy coverage available here, the spectrum of NGC 3044 ULX1 is highly reminiscent of that seen from Holmberg II X-1 – another extreme ULX with $L_X \sim 10^{40}$ erg s$^{-1}$ – during the broadband observations performed with XMM-Newton, Suzaku and NuSTAR in 2013 (Walton et al. 2015). As noted previously, this was part of a series of broadband observations of ULXs (e.g. Bachetti et al. 2013; Walton et al. 2014; Rana et al. 2015; Mukherjee et al. 2015) that robustly confirmed earlier indications from XMM-Newton (e.g. Stobbart et al. 2006; Gladstone et al. 2009; Walton et al. 2011a) that the high-energy spectra of ULXs are distinct from those seen from sub-Eddington black holes. While the spectra from these systems are typically dominated by Comptonisation in an optically-thin ‘corona’ above $\sim$2 keV (e.g. Haardt & Maraschi 1991), the spectra of ULXs instead seem to be dominated by two thermal components below 10 keV, before falling away steeply at higher energies. Indeed, the best-fitting model for the high-flux XMM-Newton spectra from NGC 3044 ULX1 consists of two thermal accretion disc components.

The distinct broadband spectra of ULXs, along with the detection of X-ray pulsations (Bachetti et al. 2014; Först et al. 2016; Israel et al. 2017a,b; Carpano et al. 2018; Sathyaprakash et al. 2019; Rodriguez Castillo et al. 2020) and extreme outflows (Pinto et al. 2016, 2017, 2020; Walton et al. 2016; Kosec et al. 2018b) from a growing number of these systems have, together, helped clearly establish that the majority of the ULX population is dominated by super-Eddington accretors. In this context, the two continuum components seen in ULXs below 10 keV likely represent the complex thermal emission from a hot, super-Eddington accretion disc (and potentially its associated outflow; e.g. Poutanen et al. 2007; Middleton et al. 2015). Given its similarity to other, better studied ULXs that are now well accepted to be super-Eddington accretors, NGC 3044 ULX1 is therefore likely another super-Eddington system. As discussed above, these sources are of particular interest, as they may provide a local observational window into the conditions required to rapidly grow SMBHs in the early universe (e.g. Bañados et al. 2018).

We have searched for X-ray pulsations from NGC 3044 ULX1, which would unambiguously identify the accretor as another neutron star and confirm its nature as a highly super-Eddington system. We focused on the 2016 data, which by far have the best S/N among the available observations, and searched for pulsations over the 0.01–6.75 Hz frequency range based on the properties of the known ULX pulsars, but unfortunately we did not find a robust detection of any such variations. However, even though the available data has quite high S/N, we can only place an upper limit of $\sim$20% on the pulsed fraction of any pulsations present during this observation. Although pulsations of the strength seen in NGC 300 ULX1 can therefore be firmly excluded (pulsed fraction of $\sim$60% below 10 keV; Carpano et al. 2018), other known ULX pulsars exhibit pulsed fractions that are lower than this limit in the XMM-Newton bandpass (e.g. Sathyaprakash et al. 2019; Rodríguez Castillo et al. 2020). Furthermore, even in ULXs that are known to be pulsars the pulsations can be transient, and are not always observed even when the data should have sufficient S/N to see them (e.g. Israel et al. 2017a; Bachetti et al. 2020). As such, even though we have not seen any clear evidence for X-ray pulsations from NGC 3044 ULX1, we cannot exclude the possibility that this is another neutron star ULX.

Although the comparison with other ULXs is quite compelling, obtaining higher energy data would be of particular use in order to more robustly confirm NGC 3044 ULX1 as another super-Eddington accretor. In the known ULX pulsars the pulsed fraction is seen to increase with energy, perhaps because non-pulsed components from the accretion flow make a more significant contribution below $\sim$10 keV (e.g. Walton et al. 2018b). Higher energy coverage would therefore help to mitigate against these issues in terms of further pulsation searches, and would also allow us to extend the continuum spectroscopy above 10 keV, and further confirm that the broadband spectrum of NGC 3044 ULX1 is similar to other ULXs. Unfortunately, given both the fairly low peak flux from NGC 3044 ULX1 ($\sim 2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 3.0–10 keV band; see Figure 7) and the fairly close proximity of SN1983E (see Figure 4), meaningful observations of NGC 3044 ULX1 with NuSTAR would likely be very challenging. This may, instead, be a suitable target for a facility like the High Energy X-ray Probe (HEX-P; Madsen et al. 2018), which would have both superior sensitivity and imaging capabilities to NuSTAR.

6 SUMMARY AND OUTLOOK

We have compiled a new catalogue of ULX candidates, combining the latest data releases from each of the XMM-Newton, Swift and Chandra observatories (the 4XMM-DR10, 2SXPS and CSC2 source catalogues, respectively). Our new catalogue contains 1843 sources residing in 951 different host galaxies, making it the largest ULX catalogue compiled to date. Of these, 689 sources are catalogued as ULX candidates for the first time. Our sample also contains 71 HLX candidates, of which 48 are new catalogue entries. We have made significant efforts to clean the catalogue of known non-ULX contaminants (e.g. foreground stars, background AGN, supernovae), and estimate that the remaining contribution of unknown contaminants is $\sim$20%. Our primary motivation here is to unearth new sources of interest for detailed follow-up studies, and among this new catalogue we have already found one new extreme ULX candidate with high S/N data in the archive: NGC 3044 ULX1. This shows a factor of at least $\sim$4 variability on long timescales, based on the
available XMM-Newton and Swift data, with a peak luminosity of $L_{X, \text{peak}} \sim 10^{40} \text{ erg s}^{-1}$ to date. The XMM-Newton spectrum of the source while at this peak flux is reminiscent of other extreme ULXs (and Holmberg II X-1 in particular), and is best-fit by a model combining two thermal accretion disc components. This likely indicates that NGC 3044 ULX1 is another member of the ULX population accreting at super-Eddington rates.

We anticipate this new catalogue will be a valuable resource for planning future observational campaigns, both with our current X-ray imaging facilities (XMM-Newton, Chandra, Swift, NuSTAR) and with upcoming missions such as XRISM and, in particular, Athena. Our new catalogue should also help to facilitate further studies of ULXs at longer wavelengths, particularly in the era of the new optical, NIR and radio facilities due to come online (the thirty-metre class ground-based observatories, JWST, the SKA). Such work will be vital for determining the contribution of ULX pulsars to the broader ULX population, their accretion physics, the prevalence of extreme outflows among the ULX population and the impact of the winds launched by super-Eddington accretors, and for the hunt for the first dynamically confirmed black hole ULX. Further iterations of the XMM-Newton, Swift and Chandra serendipitous surveys, combined with the upcoming results from eROSITA (Predehl et al., 2021), will also allow us to continue expanding this ULX sample in the future.

ACKNOWLEDGEMENTS

DJW acknowledges support from the Science and Technology Facilities Council (STFC) via an Ernest Rutherford Fellowship (ST/N004027/1). TPR also acknowledges support from STFC via consolidated grant ST/000244/1. SM acknowledges financial support from the Spanish Ministry MCIU under project RTI2018-096686-B-C21 (MCIU/AEI/FEDER/UE), cofunded by FEDER funds and from the Agencia Estatal de Investigación, Unidad de Excelencia María de Maeztu, ref. MDM-2017-0765. This research has made use of data obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States, as well as public data from the Swift data archive. This work has also made use of data obtained from the Chandra Source Catalog, provided by the Chandra X-ray Center (CXC) as part of the Chandra Data Archive, as well as public data from the Swift data archive. This paper made use of the Whole Sky Database (WSDB) created by Sergey Koposov and maintained at the Institute of Astronomy, Cambridge by Sergey Koposov, Vasily Belokurov and Wyn Evans with financial support from STFC and the European Research Council (ERC), as well as the Q3C software (Koposov & Bartonov 2006). This research has also made use of the NASA/IPAC Extragalactic Database (NED), which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology, as well as the SIMBAD database, operated at CDS, Strasbourg, France, and we further acknowledge usage of the HyperLEDA database.

DATA AVAILABILITY

All of the raw data underlying this article are publicly available from ESA’s XMM-Newton Science Archive 4, NASA’s HEASARC database5 and NASA’s Chandra Data Archive 6. The primary X-ray catalogues (4XMM7, 2SXPS8 CSC29), galaxy catalogues (HyperLEDA10, CNG11 and Cosmicflows12) and general catalogues (NED13, SIMBAD14) used in this work are also all publicly available via the links provided. The final catalogues of ULX candidates produced here will also be made publicly available via the VizieR archive15 after the publication of this work.

REFERENCES

Abbott R., Abbott T. D., Abraham S., et al., 2020, Phys. Rev. Lett., 125, 10, 101102
Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Arnaud K. A., 1996, in Astronomical Data Analysis Software and Systems V, edited by G. H. Jacoby & J. Barnes, vol. 101 of Astron. Soc. Pac. Conference Series, Astron. Soc. Pac., San Francisco, 17
Arnett W. D., 1982, ApJ, 254, 1
Bañados E., Venemans B. P., Mazzucchelli C., et al., 2018, Nat, 553, 473
Bachetti M., 2018, Astrophysics Source Code Library, ascl:1805.019
Bachetti M., Harrison F. A., Walton D. J., et al., 2014, Nat, 514, 202
Bachetti M., Maccarone T. J., Brightman M., et al., 2020, ApJ, 891, 1, 44
Bachetti M., Rana V., Walton D. J., et al., 2013, ApJ, 778, 163
Barrows R. S., Mezcua M., Comerford J. M., 2019, ApJ, 882, 2, 181
Brightman M., Earnshaw H., Fürst F., et al., 2020a, ApJ, 895, 2, 127
Brightman M., Walton D. J., Xu Y., et al., 2020b, ApJ, 889, 1, 71
Buccheri R., Bennett K., Bignami G. F., et al., 1983, A&A, 128, 245
Burrows D. N., Hill J. E., Nousek J. A., et al., 2005, Space Science Reviews, 120, 165
Cappelluti N., Brusa M., Hasinger G., et al., 2009, A&A, 497, 2, 635
Carcano S., Haberl F., Maitra C., Vasilopoulos G., 2018, MNRAS, 476, L45
Carrera F. J., Ebrero J., Mateos S., et al., 2007, A&A, 469, 27
Cash W., 1979, ApJ, 228, 939
Colbert E. J. M., Mushotzky R. F., 1999, ApJ, 519, 89
Colbert E. J. M., Ptak A. F., 2002, ApJS, 143, 1, 25
Dadina M., Masetti N., Cappi M., et al., 2013, A&A, 559, A86
Dall’Osso S., Perna R., Stella L., 2015, MNRAS, 449, 2144
Earnshaw H. P., Grefenstette B. W., Brightman M., et al., 2019a, ApJ, 881, 1, 38
Earnshaw H. P., Heida M., Brightman M., et al., 2020, ApJ, 891, 2, 153
Earnshaw H. P., Roberts T. P., Middleton J. M., Walton D. J., Mateos S., 2019b, MNRAS, 483, 4, 5554
Earnshaw H. P., Roberts T. P., Sathya-prakash R., 2018, MNRAS, 476, 4272
Eskridge P. B., Frogel J. A., Pogge R. W., et al., 2002, ApJS, 143, 1, 73
Evans I. N., Primini F. A., Miller J. B., et al., 2020a, in American Astronomical Society Meeting Abstracts, American Astronomical Society Meeting Abstracts, 154.05
Evans I. N., Beardmore A. P., Page K. L., et al., 2009, MNRAS, 397, 1177
Evans I. N., Page K. L., Osborne J. P., et al., 2020b, ApJS, 247, 2, 54
Farrell S. A., Webb N. A., Barret D., Godet O., Rodrigues J. M., 2009, Nat, 460, 73
Feng H., Kaaret P., 2010, ApJ, 712, L169
Fürst F., Walton D. J., Harrison F. A., et al., 2016, ApJ, 831, L14
Fürst F., Walton D. J., Heida M., et al., 2018, A&A, 616, A186

5 https://heasarc.gsfc.nasa.gov/
6 https://cxc.harvard.edu/cda/
7 http://xmmssc.irap.omp.eu/Catalogue/4XMM-DR10/4XMM_DR10.html
8 https://www.swift.ac.uk/2SXPS/
9 https://cxc.harvard.edu/csc/
10 http://leda.univ-lyon1.fr/
11 https://www.sao.ru/lv/lvgdb/
12 http://edd.ifa.hawaii.edu/
13 https://ned.ipac.caltech.edu/
14 http://simbad.u-strasbg.fr/simbad/
15 https://vizier.u-strasbg.fr/viz-bin/VizieR
Webb N. A., Coriat M., Traulsen I., et al., 2020, A&A, 641, A136
Weisskopf M. C., Brinkman B., Canizares C., Garmire G., Murray S., Van Speybroeck L. P., 2002, PASP, 114, 1
Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914
XRISM Science Team, 2020, arXiv e-prints, arXiv:2003.04962
Zhang W. M., Soria R., Zhang S. N., Swartz D. A., Liu J. F., 2009, ApJ, 699, 281
Zombeck M. V., Chappell J. H., Kenter A. T., et al., 1995, in EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VI, edited by O. H. Siegmund, J. V. Vallerga, vol. 2518 of Proc. SPIE, 96–106