Ultra-Luminous X-ray Source Populations in Normal Galaxies: a Preliminary Survey with Chandra

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ABSTRACT

We present results of a Chandra survey of the ultra-luminous X-ray sources (ULX) in 13 normal galaxies, in which we combine source detection with X-ray measurement. 22 ULX were detected, i.e. with $L_X > 1 \times 10^{39}$ erg s$^{-1}$ ($L_{10}$), and 39 other sources were detected with $L_X > 5 \times 10^{38}$ erg s$^{-1}$ ($L_{5}$). We also use radial intensity profiles to remove extended sources from the sample. The majority of sources are not extended, which for a typical distance constrains the emission region size to less than 50 pc. X-ray colour-colour diagrams and spectral fitting results were examined for indicators of the ULX nature. In the case of the brighter sources, spectral fitting generally requires two-component models. In only a few cases do colour-colour diagrams or spectral fitting provide evidence of black hole nature. We find no evidence of a correlation with stellar mass, however there is a strong correlation with star formation as indicated by the 60 µm flux as found in previous studies.

Key words: accretion: accretion discs – binaries: close – black hole physics – X-rays: galaxies – X-rays: stars

1 INTRODUCTION

Ultra-luminous X-ray sources (ULX) are intriguing, apparently point-like sources in external galaxies which are normally distinguished from bright central objects. Bright objects may be divided into those that exceed the Eddington limit $L_{Edd}$ for a 1.4 M$_{\odot}$ neutron star of $\sim 2.4 \times 10^{38}$ erg s$^{-1}$, and those with luminosity greater than $10^{39}$ erg s$^{-1}$, which is the normal definition of an ULX. Observations of bright spiral galaxies with Einstein revealed substantial numbers of very bright X-ray sources external to the nuclear regions, i.e. 36 super-Eddington sources of which 16 were ULX (Fabbiano 1989). A significant fraction of the X-ray emission from galaxies has long been known to originate from X-ray binaries (e.g. Fabbiano 1989; Fabbiano, Kim & Trinchieri 1994, Fabbiano et al. 2001, Blanton et al. 2001). In a survey of nearby galaxies with Rosat, Roberts & Warwick (2000) found 28 ULX outside the nuclei. Similarly, Colbert & Mushotzky (1999) investigated extra-nuclear (>2 arcmin offset) X-ray sources in 39 nearby galaxies finding 13 ULX. They suggested these were accreting black hole systems of $10^{2}$–$10^{4}$ M$_{\odot}$. The spectra of 7 ULX in nearby galaxies studied using ASCA by Makishima et al. (2000) were well-fitted by a multi-colour disc blackbody model suggesting black hole nature. Chandra observations of galaxies have revealed a large number of previously unknown ULX, the luminosities of which extend from $1 - 10 \times 10^{39}$ erg s$^{-1}$ (Fabbiano, Zezas & Murray 2001; Blanton et al. 2001), suggesting that they may be quite common. With the advent of Chandra, it becomes possible to study ULX in more detail.

The discovery of ULX naturally led to the proposal that these may be a single type of object. Explanations of this type have involved firstly, an intermediate mass black hole binary. Makishima et al. (2000) required black hole masses of between ~3 and ~80 M$_{\odot}$ for the Eddington limit not to be exceeded. In general, intermediate mass black hole models involve masses of $10^{2}$ - $10^{4}$ M$_{\odot}$, i.e. more massive than Galactic BHB such as Cyg X-1, and substantially less massive than AGN. This possibility has been invoked to explain the most luminous, variable ULX in M82 (Kaaret et al. 2001). However, King et al. (2001) discussed the difficulties of forming these, and proposed an alternative model involving mild beaming and a link with Galactic micro-quasars. It has been known that ULX occur preferentially in regions of star formation (Zezas et al. 1999; Roberts & Warwick 2000; Fabbiano et al. 2001), and the model is consistent with the
expected association of high mass X-ray binaries (HMXB) with young stellar populations. The numbers of ULX found in the Antennae galaxies (Fabbiano et al. 2001) supports the connection with recent massive star formation. ULX, e.g. Sarazin et al. (2001), which led King (2002) to the Antennae galaxies (Fabbiano et al. 2001) supports the expected association of high mass X-ray binaries (HMXB) were also detected in elliptical galaxies which do not contain HMXB, e.g. Sarazin et al. (2001), which led King (2002) to extend the model by proposing two types of ULX: persistent sources predominating in galaxies with young stellar populations, and micro-quasars with bright, prolonged outbursts occurring in elliptical galaxies.

However, there is also the possibility that ULX do not consist of a single or even two types of object. Objects generating X-ray luminosities larger than the Eddington limit for a neutron star include not only stellar mass black holes ($M < 100 M_\odot$) but very young supernova remnants (Roberts & Warwick, 2000; King et al., 2001). Some pre-Chandra ULX may have been unresolved “super-bubbles” of shock-heated HII in the ISM (e.g. Stewart & Walter 2000), typically with diameters $\sim 200-1000$ pc. With the 0.3 arcsec (on-axis) resolution of Chandra (van Speybroeck et al. 1997; van Speybroeck 1999) these objects would appear extended in nearby galaxies, for example, 0.3 arcsec corresponds to a size of 27-40 pc at the distance of the Antennae galaxies (20-30 Mpc) (Fabbiano et al. 2001). Young, compact supernova remnants, which can reach luminosities of a few $\times 10^{40}$ erg s$^{-1}$ (Immler & Lewin 2002) would not be resolved even with Chandra, except in the nearest members of the Local Group. Similarly an unresolved cluster of sub-Eddington low mass or high mass XRB may appear ultra-luminous. This could be in a globular cluster such as the two sources in the Galactic globular cluster M15, White & Angelini 2001). Since the diameter of a globular cluster is typically 10 pc, these objects also cannot be resolved, even with Chandra. Large amplitude variability would be a strong pointer that the source consists of a single object or a group of a small number of objects only (Roberts & Warwick, 2000).

In this paper, we examine systematically Chandra ACIS observations of 13 normal galaxies to detect all super-Eddington sources and so determine the prevalence of ULX depends upon galaxy morphology. One aim of the work was to examine the spectra of the brighter sources and search for any spectral property that may reveal the nature of a ULX source.

2 THE GALAXY SAMPLE

Thirteen galaxies were selected from the available Chandra observations in the public archive in the summer of 2001, that were classified by the Chandra X-ray Centre (CXC) as Normal Galaxies. These galaxies were selected on the basis that the observations were longer than $\sim 10$ ksec, and covered a range of types. While this is not a statistically complete sample, the seven spiral, four elliptical and two irregular galaxies allow us to investigate whether there is any correlation of ULX occurrence with morphology. The galaxies chosen are listed in Table 1.

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Table 1. Galaxy sample and Chandra observation log. ACIS exposures are shown, and the minimum resolvable size scale (equivalent to 0.5 arcsec) using our best distances for the sources (Table 2). We also show the line-of-sight column densities within our galaxy for the centroid of each external galaxy. (Dickey & Lockman 1990).
Table 2. Preferred values of distances of each galaxy in Mpc

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<td>Dv−σ</td>
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The techniques shown are: SBF: F-band surface brightness fluctuation; Dv−σ: isophotal diameter velocity dispersion; T-F: Tully-Fisher; BS: brightest stars in galaxies; V_vir: redshift distances with Virgocentric correction.

References: (1) Tonry et al. 2001; (2) Djorgovski & Davis 1987; (3) Prugniel & Simien 1996; (4) Shapley et al. 2001; (5) Bottinelli 1985; (6) Østlin 2000; dispersion (Dv−σ) relation. Otherwise, we adopt estimates based on the brightest star in the galaxy, or use the redshift-corrected for Virgocentric flow from LEDA. Distance errors are also shown, reflecting the uncertainty in the most reliable technique available for any galaxy. Where possible, systematic and statistical errors are combined. If no errors were quoted in the literature we adopt, if possible, typical values for the given distance method as listed in Jacoby et al. (1992). For the redshift-distances we adopt errors determined by Shapley et al. (2001) of ~30% (20% in the case of NGC 1132).

3 X-RAY SOURCE DETECTION

Data analysis was performed using the CIAO 2.1.2 software, XANADU and FTOOLS 5.0. To remove periods of high background, lightcurves were accumulated from source-free regions of the active chips and intervals having factor of two increases in count rate removed. This led to significant data loss only for IZW 18 and NGC 1291, in which ~25% and ~35% of data were removed, respectively. Net exposure times are shown in Table 1.

Searches for point sources were made using the CIAO WAVDETECT algorithm, without regard to whether detections were at the centres of galaxies or not. However, as discussed below, only a few detections coincided with galaxy centres. The spurious source detection probability was set at 10^{-8} per pixel, corresponding to 0.014 spurious detections per square arcmin. Exposure maps created with MIKEMAP at 1.7 keV were used with WAVDETECT to minimize spurious detections at the detector chip boundaries and these aspects were checked by manual inspection of the images. In two galaxies, IC 5332 and NGC 1569, no sources were detected exceeding 5×10^{-3} erg s^{-1}. Detections spanning 2, 4, 8 or 16 pixels were flagged, as these imply extended sources. Radial profiles (Sect. 3.1) confirmed possible extended sources as those significantly broader than the PSF. For a typical off-axis PSF of 1 arcsec width, a typical distance of 10 Mpc implies a size of 50 pc, so that to appear point-like in Chandra a source must have a size no larger than this. Only 10 sources eventually proved to have an extended component.

We selected the point sources lying within the B-band 25th magnitude isophotes derived from RC3, which are thus likely to be associated with the galaxy. For these, spectra, lightcurves and instrument response functions were generated. Background data were extracted from annuli centred upon the source region and lying entirely within the same CCD node. The annuli were chosen to cover an area at least 8 times larger than the source extraction region and containing at least 20 photons (although such regions frequently exceeded this limit). To prevent contamination of the background spectra by photons from bright point sources, all photons detected within a region six times larger than the 1-σ encircled-energy ellipse of every source, and centred on that source were removed prior to background accumulation. Such a large masking region was adopted since with a 3-σ region, a few per cent of a source’s intensity will remain.

The total count from a given detection varied between ~100 and 1000 (Table 4). Thus to plot light curves in the normal way to achieve Poisson errors of 10%, say, would allow a very small number of bins, and searching for variability by χ^2 testing would not be sensible in most cases. We thus applied a Kolmogorov-Smirnov test to the arrival times of photons and the numbers of photons that arrive by a particular time are compared with those expected for constant intensity. This test strictly requires unbinned data, and so we used the primitive binning of the ACIS data of 3.24 s, although binning does not bias the test provided there are many primitive bins. This revealed only one source in galaxy NGC 253 which displayed variability at the 99% significance level, this source having a luminosity of 2.5×10^{38} erg s^{-1}, located at α = 0^h 47^m 30.9, δ = -25° 18' 26" (2000). Other sources exhibited no evidence for variability, however the Kolmogorov-Smirnov test does not provide upper limits for non-detections. We carried out simple χ^2 testing which indicated that other sources were not variable at a confidence of at least 90%. We adopt the procedure (below) of considering only sources brighter than 5×10^{38} erg s^{-1}, so that no bright sources detected (shown in Tables 3 – 5) displayed significant variability. Thus, none of the sources in the sample examined provided evidence in this way that the object was not a superposition of sources.

Radial brightness profiles were derived for each point source detected, which allowed extended sources to be clearly identified by comparing the profiles with the PSF derived for each position (see Sect. 3.1). Ten sources found using WAVDETECT were rejected as being clearly extended, and 2 more sources found to have point source and extended components are discussed in Sect. 3.1.

Spectral fitting (Sect. 3.3) provided best-fit models from which fluxes were derived. Then, using the preferred distances of Table 2, luminosities were calculated in the band 0.3–7.0 keV. In the case of the weaker sources, which do not permit sensible fitting to discriminate between models, an absorbed power law was fitted with a fixed power law photon index of 2.0 (typical of fit results in other cases) and column density fixed at the line-of-sight Galactic value (Dickey & Lockman 1990; see Table 1). After removal of
extended sources, in this band, 258 sources were found
with $L_x > 1 \times 10^{38}$ erg s$^{-1}$ ($L_1$), of which 158 ($N_2$) had
$L_x > 2 \times 10^{38}$ erg s$^{-1}$ ($L_2$), 61 ($N_3$) had $L_x > 5 \times 10^{38}$
ergs$^{-1}$ ($L_5$), and 22 ($N_{10}$) had $L_x > 1 \times 10^{39}$ erg s$^{-1}$ ($L_{10}$).

In Table 3 we show the number of sources detected in each
galaxy, $N_2$, $N_5$ and $N_{10}$. $N_2$ varied from 2 in NGC 1132
to 72 in NGC 1399. The numbers detected have error values
calculated using the errors in luminosity from spectral fitting
combined with the distance uncertainties. In Fig. 1, Digi-
tal Sky Survey images of each galaxy are shown with 25th
magnitude ($D_{25}$) $B$-band isophotes from RC3 superimposed.

To estimate how many background objects may have been
detected as ULX, the log $N$($>$S) - log S relations in the
Chandra Deep Field South (Giacconi et al. 2001) in the
energy bands 0.3–2.0 keV and 2.0–7.0 keV were used to ob-
tain the expected number of background objects within each
galaxy (i.e. within the 25th magnitude isophote). Data in
these bands were combined into a single plot for the total
band, approximately, by using the spectral form of Gia-
cconi et al. (2001) to relate the total flux in the 0.3–7.0 keV
band to the fluxes in the sub-bands. It was assumed that
soft sources were also detected in the hard band, and so the
conversion factor was made using $N$ values from the hard band
and correcting $S$ values to the flux in the total band. The number of
background objects detected within each galaxy is shown in Table 3. For the 13 galaxies, 17 spurious sources are ex-
pected with apparent luminosities $> 5 \times 10^{38}$ erg s$^{-1}$, and 8
with $L_x > 1 \times 10^{39}$ erg s$^{-1}$. Hence 62±7% of the ULX sources are
true members of their host galaxies (Table 3). To esti-
rate the errors of the numbers of sources in each luminosity-
band, the errors in distance and flux must be combined,
bearing in mind that the distance errors do not affect each
source independently. A simple Monte-Carlo method was
adopted with 10000 simulations for each galaxy. Each sim-
ulation consisted first of taking a random distance to the
galaxy, normally distributed about the measured value, with
a standard deviation equal to the 1-$\sigma$ distance uncertain-
ties in Table 2. From this distance, appropriate flux limits
for each luminosity-band were computed. A similar pro-
dure was adopted taking a random flux for each detection
distributed about its measured value, and the number of
sources exceeding each flux limit were counted. We adopted
the standard deviation of these numbers, accumulated over
all the simulations, as the error estimate.

We show the ULX detected in Fig. 1 (as diagonal crosses) in each galaxy, and other super-Eddington sources ($L_x > L_5$) are shown separately. In Table 4 (upper panel), individual ULX in each galaxy are listed, and given a source name such as NGC 4636 PSX-1, the “P” indicating pointlike
nature. For each source, the total number of counts (‘count’) contained in the spectrum (discussed in Sect. 3.3), the source
count-rate, the luminosity ($L_x$) in the band 0.3–7.0 keV de-
ferred from spectral fitting using the best distance value,
with 90% confidence errors, the offset ($\Delta R$) of the source
from the nominal galaxy centre. Source names following the
Chandra-naming convention are given. In the upper panel
we include sources marked ‘+’ which would fall below $L_{10}$ at
their lower limit. The lower panel shows sources exceeding
$L_5$ which would join the ULX detections if given their upper
error limit luminosity (marked ‘+’). Table 5 similarly lists
the extended sources detected.

Next, we estimate the completeness of our source sam-
ples, for each galaxy, i.e. the probability that a source of
given luminosity will be detected by the detection algo-
rithm. This requires firstly the estimated number of counts
of the source in the image, this requiring a flux to counts
conversion factor. We chose a conservatively low factor, i.e.
an estimate erring on the low side of the counts obtained,
by adopting a simple absorbed power law model having a
photon index fixed at 1.0, i.e. a smaller value than typical
of spectral fitting results. The column density was fixed at
the average value measured in the sources detected. Aver-
ging the threshold of the “correlation parameter” used by
WAVEDETECT to identify sources in the vicinity of each of
our detections and assuming a Gaussian distribution of the
correlation parameter (Freeman et al. 2002), we can esti-
mate the fraction of the complete number of sources above
each limit that will be detected by the algorithm. This is
$>$97% for $L_5$ sources (except in NGC 1132), and $>$94% for
$L_2$ sources (except for NGC 1132, NGC 1399, NGC 1291
and IZW 18). In these objects, the number detected represents a
lower limit.

As the Eddington limit for a 1.4 $M_\odot$ neutron star is be-
 tween $2 - 4 \times 10^{38}$ erg s$^{-1}$, depending on composition, opac-
ity and gravitational redshift (Paczynski 1983), luminosities
smaller than $L_5$ do not exceed the Eddington limit substan-
tially, and may be neutron star binaries. Only a very small
number of Galactic neutron star binaries ($< 1\%$) are known
to ever exceed the Eddington limit: the bright LMXB GX 5-1
has been observed with $L_x \sim 4 - 5 \times 10^{38}$ erg s$^{-1}$ (Church &
Bahcall-Church 2001; Christian & Swank 1997). In Sco
X-1, the total luminosity often exceeds $L_{10}$. In Table 3 we
show the detections of objects brighter than various thresh-
olds. However, in the rest of the paper we concentrate on
the ULX ($L_x > L_{10}$), and do not consider at all objects
faunter than $L_5$ thus excluding most neutron star binaries.
The number of ULX detected is 22, and these exceed the
Eddington limit for a 10 $M_\odot$ black hole. There are 39 other
sources in the luminosity range $5 - 10 \times 10^{38}$ erg s$^{-1}$ which
may be expected to consist mostly of Black Hole Binaries
(BHB).

3.1 Radial intensity profiles

The excellent spatial resolution of Chandra (Weisskopf et al.
2002) makes it possible to test for spatial extension of the
ULX. Accordingly, radial intensity profiles for each detected
bright source were extracted, to search for excesses above the
point-spread function. Since the PSF width depends on the
do-axis angle and the source spectrum, PSFs were generated
for each source based on the mean detected photon energy
using the CIAO tool MKPSF. Source data were extracted in 18
logarithmically-spaced radial bins in the total band 0.3–
7.0 keV and rebinned to ensure a minimum of 20 counts per
bin, and compared with the PSF. This was done using dedi-
cated software in which it was tested whether a point source
model fits the data well. It was also possible to fit extended
source models such as a simple King model. The background
was assumed to be constant over the radial distance in the
radial profiles, and all point sources detected in the neigh-
bourhood of the source being modelled were excluded from

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