An *XMM-Newton* and *Chandra* study of a small sample of the most luminous ULXs

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Abstract

We present a sample of 10 extreme-luminosity candidate ultraluminous X-ray sources ($L_x > 5\times10^{40}$ erg s^{-1}), all located within 100 Mpc, identified from a cross-correlation of the RC3 catalogue of galaxies with the 2XMM catalogue. Five of the sample have also been observed by *Chandra*. Of the 10 sources, seven reside in the disc or arms of spiral galaxies, and the remaining three are close to large elliptical galaxies. Unlike many less luminous ULXs, high levels of temporal variability on short (ks) and long (year) timescales are observed. Long term spectral variability is also evident in some sources. In one case, we use archival Chandra data to demonstrate that a hyperluminous X-ray source candidate identified by XMM-Newton is actually resolved into multiple point sources at high spatial resolution, but note that the other candidates remain unresolved under *Chandra's* intense scrutiny.

Imaging

Four out of the five 2XMM ULX candidates imaged by *Chandra* remain point-like in appearance at higher spatial resolution; however the HLX candidate of Davis & Mushotzky (2004), NGC 2276 ULX-1, is resolved into multiple point sources (Fig. 1). If at the distance of NGC 2276, all three sources are luminous enough to be candidate ULXs, although their total flux is less than that previously observed for the unresolved source by *XMM-Newton*. Clearly at least one of these sources was substantially more luminous during the earlier observation. The fact that short-term variability was detected in the unresolved source (cf. Fig.4) suggests that it's flux was dominated by a single source. The remaining 4 sources observed by *Chandra* remain point like in appearance.

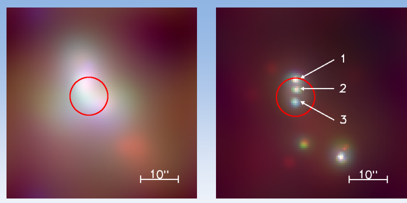

Figure 1. *XMM-Newton* EPIC PN (left) and *Chandra* ACIS-S (*right*) images of the position of NGC 2276 ULX-1. Clearly multiple sources are resolved by *Chandra*.

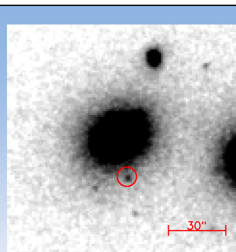

Figure 2. DSS2 blue image centred on NGC 4065. The 90% *XMM-Newton* error region of the HLX candidate 2XMM J120405.8+201345 coincides with the position of SDSS J120405.84+201345.1.

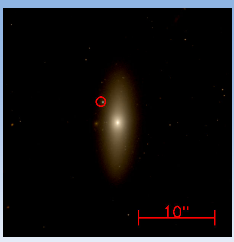

Figure 3. *Hubble* ACS/WFC two colour image centred on SDSS J125939.65+275714.0, a satellite galaxy of NGC 4874. The 90% *Chandra* position of a HLX candidate is circled.

Initial estimates from combining sensitivity maps of each 2XMM field, the area of each RC3 galaxy falling within 2XMM fields and the log*N*-log*S* curves of Moretti et al. (2003) were for at most ~ 1 in 4 candidates to be background sources. Possible counterparts were identified for two sources, implying that they are likely background contaminants. Both were initially associated with elliptical galaxies and were amongst the highest implied luminosity sources in our sample. The ULX candidate 2XMMJ134404.1-271410, in the elliptical galaxy IC 4320, remains as the most luminous detection and only object in an elliptical.

The XMM-Newton error region of 2XMM J120405.8+201345, the HLX candidate initially identified as being associated with NGC 4065 was shown to be coincident with SDSS J120405.84+201345.1 (Fig. 2). We tentatively identify this HLX candidate as a contaminant AGN, although *Chandra* data is required to confirm this. The HLX candidate 2XMM J125939.8+275718 was initially identified with NGC 4874. The *XMM-Newton* error region showed it may instead be associated with the smaller satellite galaxy SDSS J125939.65+275714.0. This was confirmed by the later *Chandra* observation, and its location ~3 arcsecs from the centre of the satellite galaxy maintained it as a good HLX candidate. However, an optical point source was identified, using *Hubble* ACS/WFC archived data, at the position of the HLX candidate (Fig. 3). The source was therefore conservatively excluded as a possible contaminant, awaiting further examination of the Hubble data.

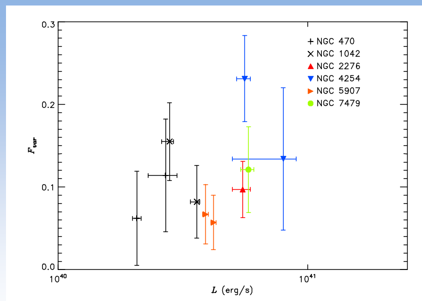

Figure 4. Excess variability of ULX candidates in which variability was detected at greater than 1σ significance.

Short-term variability

A characteristic of ULXs as a class is that they show little short-term variability – for example Swartz et al. (2004) found that ~ 5-15% of ULX candidates displayed detectable variability, and Heil et al. (2009) showed that variability is suppressed in a number of high quality ULX datasets. For our sample of the most luminous ULX candidates, variability was examined on timescales such that ~25 counts were required per element of temporal resolution, resulting in 10 detections of variability (6 sources out of 8 remaining) (Fig. 4). Similar levels of variability could not be ruled out in the remaining two sources. If variability is common amongst these most extreme ULXs, we could be observing the high luminosity end of a linear rms variability – flux relation for ULXs as a class (cf. Heil & Vaughan 2010).

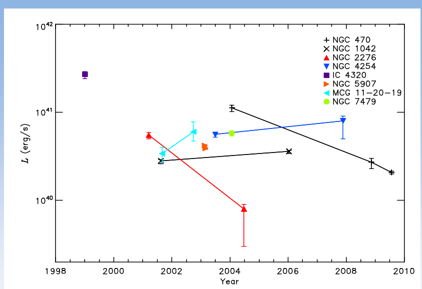

Figure 5. Long term luminosity variability of all ULX candidates (excepting those that have been excluded as background objects) for observations with > 100 counts. For the later observation of the HLX candidate associated with NGC 2276 the most luminous of the resolved point sources is plotted.

Long-term variability

A number of the ULX candidates were observed to vary in luminosity, by factors ~ 1.4 – 7. Interestingly, in a number of sources with multiple observations, the peak luminosity is not sustained (Fig. 5).

Spectral analysis

Absorbed power-law and multi-colour disc blackbody (diskBB in XSPEC) spectral models were fitted to data with sufficient counts. Two absorption components were included, one fixed to the Galactic foreground column density, the other free. A power-law model provided the best fit to the majority of observations, with typical intrinsic absorption columns of ~ 0.1-1×10^{22} cm^{-2} and generally fairly hard spectral indexes of 1.5-2.2. For perspective, typical spectral parameters derived from ULX samples over a more complete luminosity range are: (*XMM-Newton*) N_H ~ 0.09-0.57×10^{22} cm^{-2}, Γ ~ 1.6-3.3 (Gladstone et al. 2009) ; (*Chandra*) N_H ~ 0.02-3×10^{22} cm^{-2}, Γ ~ 0.8-4 (Berghea et al. 2008); $\langle\Gamma\rangle$ = 1.74 ± 0.03, with ~ 20 out of 130 sources having $\Gamma \geq 3$ (Swartz et al. 2004). Hence the brightest ULXs are interesting in that they don't appear to show the minority of very soft spectra evident elsewhere in the ULX population.

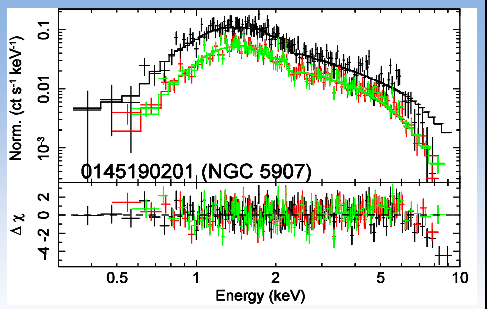

Figure 6 Power-law fit to *XMM-Newton* EPIC detection of 2XMM J151558.6+561810, a ULX candidate in spiral galaxy NGC 5907. A spectral turn-over at ~ 6 keV is clearly visible.

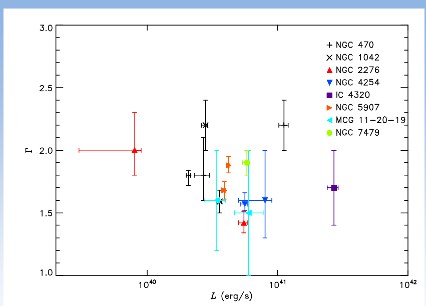

Figure 7. Power-law photon index plotted against luminosity for ULX candidate observations with greater than 100 counts. 90% errors are shown for the spectral index.

Thermal (disc-dominated) spectra were statistically preferred in the most luminous observation of NGC 470 HLX-1, in 2 of the 3 resolved sources in the later observation of NGC 2276 ULX-1 and the later observation of the ULX candidate identified in NGC 5907. Disc temperatures varied between ~1.0-1.6 keV, similar to the thermal dominated state. However, at these extreme luminosities it is possible that a disc-like spectral fit to moderate quality X-ray data may indicate an ultraluminous state spectrum (Gladstone & Roberts 2009).

Observations of the ULX candidate in NGC 5907 – with clearly the best X-ray data in the sample – contain significant evidence of a high energy spectral break (Fig. 6). When the 2-10 keV spectrum was fitted with both a standard and a broken power-law, the broken power-law gives a significant improvement in both observations (*F*-test probabilities of 1×10^{-12} and 4×10^{-8}), an observational signature of the ultraluminous state (Gladstone et al. 2009). Thus it appears the ultraluminous state (i.e. super-Eddington accretion) is still present in ULXs exceeding 5 × 10^{40} erg s^{-1}.

Motivated by the fact that these most luminous of ULX candidates tend to be rather hard sources, the effect of luminosity on observed spectral index was studied (Fig. 7). The sample appears to possess heterogeneous behaviours. The spectra of NGC 470 HLX-1 and the ULX candidate in NGC 5907 are softer at increased luminosities, whereas that of NGC 1042 ULX-1 and NGC 2276 ULX-1 clearly harden at higher luminosities (the brightest resolved source at the position of NGC 2276 ULX-1 is plotted, although the same is true for all 3 resolved sources). This variety of behaviours is redolent of what we know of lower-luminosity ULXs (cf. Kajava & Poutanen 2009).

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