THE NATURE OF ULTRALUMINOUS X-RAY SOURCES IN NEARBY GALAXIES

T.P. Roberts$^1$, M.R. Goad$^{1,2}$, M.J. Ward$^1$, R.S. Warwick$^1$, and P. Lira$^1$

$^1$Department of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UNITED KINGDOM
$^2$Department of Physics & Astronomy, University of Southampton, Highfield, Southampton, Hants, SO17 1BJ, UK

Abstract

The advanced capabilities of the Chandra and XMM-Newton observatories mean that, for the first time, the detailed study of the brightest point-like X-ray sources in nearby galaxies outside of the local group is a realistic aim. Here, we present the results of a Chandra ACIS-S study of two of the nearest and brightest sources in the rare ultraluminous ($L_X > 10^{39}$ erg s$^{-1}$) X-ray source class, NGC 5204 X-1 and NGC 4559 X-1. When considered with new optical integral field spectroscopy data this provides powerful diagnostics as to the nature of these sources, in particular suggesting that NGC 5204 X-1 is a high-mass X-ray binary, and showing new evidence linking it to the Galactic microquasar phenomenon. We also find that both ULX appear to be located in cavities in emission-line gas nebulae that surround the sources. In addition, we present the results of a Chandra observation of the interacting galaxies NGC 4485/NGC 4490, a pair of late-type spiral galaxies that, remarkably, contain a total of six ULX. We identify one as a supernovae, and the remainder as plausible black hole X-ray binaries. All six are located in star formation regions, underlining the emerging link between ULX and active star formation activity.

Key words: Missions: Chandra – X-rays: galaxies

1. Motivation

EINSTEIN imaging observations were the first to reveal that the X-ray emission of a subset of spiral galaxies is dominated by one or more very luminous ($L_X \sim 10^{39-40}$ erg s$^{-1}$) discrete X-ray sources located outside the nucleus of the galaxy (Fabbiano 1989 and references therein). ROSAT and ASCA observations have since confirmed the presence of many of these “ultraluminous X-ray sources” (ULX) in nearby galaxies. A first indication of the statistical incidence of ULX in the nearby universe came from the ROSAT HRI survey of bright, nearby galaxies (Roberts & Warwick 2000) where we catalogued 28 sources with $L_X > 10^{39}$ erg s$^{-1}$ (0.1 - 2.4 keV) in the outer regions of a sample of 83 galaxies, with only one in five of the galaxies surveyed hosting one or more ULX. This clearly underlines the rarity of this source class.

Given the high luminosities of this class of objects, which appear intermediate between classic X-ray binaries ($L_X \sim 10^{36-38}$ erg s$^{-1}$) and active galactic nuclei ($L_X \sim 10^{42}$ erg s$^{-1}$), and their extra-nuclear locations, their physical nature is far from obvious. Determining this nature is therefore a compelling challenge. In this paper we review the progress made towards this end through recent ROSAT, ASCA and Chandra studies, and present new Chandra observations including an X-ray/optical study of two bright ULX, and an observation of the ULX-rich galaxy pair NGC 4485/90. We conclude with a summary of how recent results are advancing our understanding of the nature of ULX in nearby galaxies.

2. A new class of black holes?

A reasonable assumption to make is that ULX are powered by accretion. If we then consider a ULX emitting isotropically in the X-ray regime with a luminosity of $\sim 5 \times 10^{39}$ erg s$^{-1}$, a simple Eddington luminosity limit argument implies that the mass of the compact accreting object is at least $25 M_\odot$. If the accretion is occurring at lower rates, this implies that the compact object mass is even higher, potentially placing it anywhere in the $10^2 - 10^5 M_\odot$ regime (dependent upon the accretion rate). This is at odds with previous theoretical and observational studies of black holes which have found evidence for two main types, the remnants of massive stars (with $M_{BH} \leq 10 M_\odot$), and the “super-massive” black holes residing in the nuclei of galaxies ($M_{BH} \geq 10^6 M_\odot$). It is very unlikely that ULX contain the latter super-massive flavour, as these object would sink to the centre of the host galaxy through the action of dynamical friction in less than a Hubble time (c.f. Tremaine et al. 1979), and the Eddington limit argument rules out the stellar remnant black holes as insufficiently massive. It has therefore been suggested that ULX may represent a hitherto unrecognised $10^2 - 10^5 M_\odot$ intermediate-mass class of black holes (e.g. Colbert & Mushotzky 1999).
The evidence that a large fraction of ULX may indeed be powered by accretion onto a black hole is compelling. Variability studies of ULX are very informative; both ROSAT and ASCA studies have detected short-term variations (~1000 s of seconds) consistent with accretion processes in the lightcurves of ULX (e.g. Zzas et al. 1999; Okada et al. 1998). Other ASCA studies have observed long-term spectral transitions between soft/high and hard/low states, very similar to the state changes observed in Galactic black hole binaries (La Parola et al. 2001; Kubota et al. 2001; Mizuno et al. 2001). Additionally, the first suggestion of X-ray periodicity were recently discovered in a deep ASCA observation of a ULX in IC 342, indicative of it residing in a stellar binary system (P ~ 30 – 40 hours, Sugihro et al. 2001). ASCA spectroscopy has also provided important evidence towards a black hole interpretation for ULX, with the spectra of many examples being well-fit by the “multi-colour disc black-body” (MCDBB) emission model characteristic of an optically thick accretion disc around a black hole (Makishima et al. 2000; Colbert & Mushotzky 1999). Intriguingly, this spectrum is also found to provide a good spectral fit to several Galactic microquasars. However, the ULX spectral fits are problematic, as the derived inner-disc temperatures are too high for the massive black holes expected in these systems. Makishima et al. (2000) explain this by inferring the presence of a rapidly-rotating Kerr black hole, which allows the inner-edge of the accretion disc to move closer to the black hole and thus heat up. An alternate scenario that predicts the high temperatures observed in ULX, whilst retaining an intermediate-mass black hole, is the “slim disc” accretion regime (Watarai et al. 2001). In this scenario near Eddington-rate accretion is occuring and the X-ray emission is dominated by a compact region located very close to (within three Schwarzschild radii of) the black hole, which is not required to be rotating.

However, none of the ASCA data make an overwhelming case for the presence of a 10² – 10⁵ M☉ black hole. This is in a large part due to the uncertainty introduced by the source confusion inherent in the > 90⁰ spatial resolution of ASCA, which may lead to overestimates of the source luminosities. The best evidence for intermediate-mass black holes comes from recent high spatial resolution Chandra observations. The starburst galaxies M82 and NGC 3628 are both observed to host a near-nuclear, point-like ULX which is seen to be highly variable in observations spanning periods of several years, and display a peak luminosity of well over 10⁴⁰ erg s⁻¹ (e.g. Kaaret et al. 2001; Brickland et al. 2001). This implies black holes with masses in excess of several hundred M☉ in each ULX.

Recent results have, however, called into question the presence of an intermediate-mass black hole in many ULX. Chandra observations have revealed that large numbers of ULX are present in very active starburst galaxies with, for example, about ten found in each of the Antennae and NGC 3256 systems (Fabbiano et al. 2001; Lira et al. 2002). Other ULX, such as those in M82 and NGC 3628 mentioned above, also appear in star forming regions. This implies that a large proportion of the ULX population is intrinsically linked to active star formation. This may be inconsistent with the presence of an intermediate-mass black hole, with the strongest objection being that most formation scenarios, such as their creation from the hierachal merging of black holes in the centre of a globular cluster, require considerably longer than the ~ 10⁸ year lifetime of a starburst event. Also, this model would locate the sources very close to the nucleus of the galaxy where the potential well is deep enough to retain the stellar mass black holes within the cluster (see King et al. 2001 and references therein for further discussion). We must therefore consider alternative origins for the ULX phenomenon.

One possibility is that a reasonable proportion of the ULX population is composed of recent supernovae, which are known to reach X-ray luminosities of up to 10⁴¹ erg s⁻¹ if they explode in dense environments (e.g. SN 1988Z, Fabian & Terlevich 1996). Of the 28 ULX catalogued by Roberts & Warwick (2000), 3 – 4 are indeed identifiable with recent supernovae. However, given the spectral and variability characteristics of ULX described above it is unlikely that a much larger fraction have this origin. Instead, it may be that a large proportion of ULX are mildly-beamed X-ray binaries, as suggested by King et al. (2001). Crucially, if ULX emit anisotropically then this removes the necessity for an intermediate-mass black hole. It does however imply large numbers of ULX, as only a small fraction of a beamed population will direct their emission along our line of sight at any one time. This problem is solved if the beaming originates in “ordinary” black hole and/or neutron star intermediate- and high-mass X-ray binaries. This scenario produces a viable solution to the problem of associating ULX with ongoing star formation, as the short lifetime of high-mass X-ray binaries is well matched to the lifetime of the starburst. Hence this is a promising candidate for explaining the nature of a large proportion of ULX.

King et al. (2001) also postulate that the ULX phase is associated with a short-lived but common epoch of thermal-timescale mass transfer, which is inevitable in intermediate- and high-mass X-ray binaries. This in turn provides a potential physical link to the Galactic microquasars. The possibility of this physical similarity is further discussed by Georganopoulos et al. (2002), who conclude that ULX are likely to be microquasars located in nearby galaxies that are observed with their jet oriented into our line-of-sight (a phenomenon that may also referred to as “microb-lazars”; see Mirabel & Rodriguez 1999). Hence we now have a viable alternative to the intermediate-mass black hole scenario which may be tested observationally by looking for further similarities between the ULX and Galactic microquasar phenomena.
3. AN X-RAY/OPTICAL STUDY OF TWO ULX

The ULX phenomenon is comparatively poorly studied, mainly as result of their moderate observable X-ray fluxes (\(\sim 10^{-13} - 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\) for the limited number of ULX within 10 Mpc) and the small X-ray collecting areas of previous missions. ULX are also particularly poorly understood in a multi-wavelength context, with little or no evidence for discrete counterparts previously reported in the literature. However, the increased effective areas and better spectral and spatial resolution of Chandra and XMM-Newton now provide us with a first opportunity to study many of these objects in detail.

For our study we adopted a two-pronged approach, obtaining Chandra X-ray data and William Herschel Telescope/INTEGRAL optical data. The Chandra ACIS-S data\(^2\) were obtained to provide the best indication of whether the ULX are truly point-like at the highest currently available X-ray spatial resolution, and to provide the subarcsecond astrometry critical to follow-up the X-ray sources with multi-wavelength studies. The data were obtained in two epochs, separated by several months, to provide an initial study of the X-ray characteristics of the ULX, and their gross variability. Optical data were obtained with the “INTEGRAL” integral field unit on the William Herschel Telescope, La Palma. This provided 189 separate optical spectra covering a 16\(^{\prime}\) x 12\(^{\prime}\) field of view, over which images can be reconstructed (utilising the relative fibre positions) in any narrow-band within the \(\sim 4500 - 7500\) Å wavelength coverage of the observations. Here, we detail the results of this study for two of the nearest and brightest ULX catalogued by Roberts & Warwick (2000).

3.1. NGC 4559 X-1

This ULX was first identified by Vogler et al. (1997), who inferred from ROSAT PSPC data that it was likely to be a several hundred year old buried supernova remnant on the outskirts of NGC 4559 (note that they catalogue it as NGC 4559 X-7, but we use the nomenclature of Roberts & Warwick 2000). Its position is shown in Figure 1, where it appears coincident with an anomalous group of HII regions on the outskirts of the galaxy (see also Pakull & Mirioni 2002, and below). Its X-ray profile is entirely consistent with a point-like X-ray source, and it is very luminous: the Chandra ACIS-S data measure a luminosity of \(\sim 10^{40}\) erg s\(^{-1}\) in both observation epochs. There is no significant short-term X-ray variability observable in either epoch, though a long-term lightcurve based on ROSAT data and the current observations suggests a gradual (though not linear) reduction in the flux level over the last 10 years (see Figure 2). The analysis of the X-ray spectra of the ULX proved problematic, with no simple models provid-

\(^2\) Note that the ACIS-S data for the two observations discussed below were obtained in a sub-array mode to mitigate the effects of detector pile-up.

Figure 1. The position of NGC 4559 X-1 relative to its host galaxy. The optical greyscale image is DSS-2 blue data. Overlaid onto the image are Chandra ACIS-S X-ray contours (in red), the coverage of the Chandra ACIS-S sub-array (green) and the field-of-view of the INTEGRAL instrument (orange). The nucleus of NGC 4559 is marked by an asterisk, and hosts a discrete X-ray source.

Figure 2. Long-term X-ray variability of NGC 4559 X-1. ROSAT PSPC data points are shown in blue; ROSAT HRI in magenta; and Chandra ACIS-S in red. The lightcurve is derived in the 0.5 - 2 keV band as this range is common to all three instruments.
In Figure 3 we show the INTEGRAL data for the region containing NGC 4559 X-1. This is shown as a series of four continuum-subtracted emission-line images, in the [SII], Hα, [OIII] and Hβ bands respectively, and also red continuum (6000 – 6200 Å) and blue continuum (5100 – 5200 Å) bands for comparison. The data shows that there is no obvious optical counterpart to NGC 4559 X-1. Instead, the most interesting feature of the images is the location of NGC 4559 X-1 in the centre of an apparent cavity in a region of emission-line gas surrounding the ULX. This leads to an interesting question: is NGC 4559 X-1 responsible for the emission-line nebulae? The nebulae have previously been identified as a series of HII regions (Vogler et al. 1997), and hence assumed to be powered by young stars, which would of course fit conveniently into the emerging relationship of ULX with star formation. However, the position of the ULX in the centre of the nebulae may call this into question, as it suggests the ULX is somehow responsible for the nebulae. A study of the extent of the influence of NGC 4559 X-1 on the surrounding nebulae is beyond the scope of this paper, but it is interesting to note that while this system may possibly be another manifestation of the relationship between ULX and active star formation, this cannot be established for certain until we distinguish to what degree the nebulae are energised by the ULX, then this clearly supports the model of ULX as beamed systems.

3.2. NGC 5204 X-1

This ULX was first detected in EINSTEIN data (Fabriano et al. 1992), and has since been catalogued in several ROSAT surveys, but has never been well-studied to date. The Chandra ACIS-S data reveal NGC 5204 X-1 to lie ∼15″ away from the nucleus of its host galaxy, the Magellanic-type galaxy NGC 5204 (see Figure 4). It is also point-like at the resolution of Chandra, and has a luminosity that varies in the range 2 × 10^{39} erg s^{-1} between the two observations (an interval of four months). Again, we see no evidence of short-term variability in the data, but the long-term lightcurve shows evidence for strong variability over a baseline of 20 years (Figure 5). The X-ray spectrum is again best-fit by a powerlaw continuum model in both epochs. The best fits show that as the flux drops to ∼40% of its original value over the four months interval between observations, the spectral index of the powerlaw softens from Γ ≈ 2.4 to Γ ≈ 2.9. This is counter to the behaviour shown by other ULX and black hole X-ray binaries in general. However, this unusual behaviour may constitute the best evidence yet linking ULX to microquasars, as an anomalous soft/low state is also observed by XMM-Newton for the Galactic microquasar GRS 1758-258 (Miller et al. 2002).

Perhaps the most important discovery in this work was reported in Roberts et al. (2001), in which we revealed the...
Figure 6. INTEGRAL narrow-band images of the region containing NGC 5204 X-1, displayed similarly to Figure 3, albeit with the image intensities arbitrarily-scaled.

Figure 4. The position of NGC 5204 X-1 relative to its host galaxy. The figure is arranged similarly to Figure 1.

The detection of the first possible stellar optical counterpart to an ULX. This object is dominated by blue continuum emission, and so only appears in the continuum band images shown here in Figure 6, and is discussed below. NGC 5204 X-1 also appears to be located in the centre of a cavity evident in the continuum-subtracted emission-line images (though we note that this is not as “clean” an environment as NGC 4559 X-1, since NGC 5204 X-1 is located further within its galaxy where source confusion is a greater issue). This potential similarity to the environment of NGC 4559 X-1 raises the question of whether a large number of ULX are located in similar cavities, and implies that they may be a common feature of ULX. Further results on this phenomenon, showing it may indeed be common to ULX, are presented by Pakull & Mirioni (2002) in these proceedings.

In Roberts et al. (2001) we discussed the nature of the optical counterpart, concluding from its featureless blue continuum optical spectrum that it was likely to be an O-star, or a small O-star association, in NGC 5204 (since at $m_o = 19.7$ we require at least 5 O supergiants to be present to account for the optical flux). However, we could...
not completely rule out the scenario in which the X-ray source and its optical counterpart are actually a BL Lac object located behind the galaxy. This can now be ruled out. Firstly, newly public HST WFPC images covering the region around NGC 5204 X-1 resolve the previous counterpart into two separate, yet still point-like, optical sources at 0.1″ resolution, both of which remain blue in colour. The resolved sources are shown in Figure 7. The brighter of the sources has $m_r \sim 20.5$, and is still consistent with at least four O supergiants in NGC 5204. Secondly, new VLA radio data has placed a stringent limit of 84 $\mu$Jy on the 3.6 cm radio continuum emission at the position of NGC 5204 X-1 (Wong et al. 2002, these proceedings), which implies the radio flux is too low for the source to be identified as a BL Lac. We are therefore now confident that we are observing a good candidate ULX and optical counterpart system in NGC 5204. The O-star classification is wholly consistent with the relationship between ULX and star formation, and indeed is consistent with the King et al. (2001) scenario in which ULX are ordinary high-mass X-ray binaries with X-ray emission beamed into our line-of-sight. Furthermore, the noted similarity between the soft/low state of NGC 5204 X-1 and that observed in the Galactic microquasar GRS 1758-258 may provide some of the best evidence so far that ULX and microquasars are one and the same phenomenon.

4. The ULX Population of NGC 4485/4490

A further, perhaps more convenient, method of studying the X-ray properties of ULX is to observe several of them at once. This is only possible in a few galaxies in the local universe, which tend to be systems undergoing very active star-formation (see Section 2). One such host is the tidally-interacting late-type galaxy pair NGC 4485/NGC 4490 which is located at a distance of only 7.8 Mpc. It was observed to host three ULX in the ROSAT HRI survey of Roberts & Warwick (2000). A 20 ks Chandra ACIS-S GTO was undertaken in November 2000, the results of which are discussed in Roberts et al. (2002). Here, we concentrate on the remarkable population of ULX unveiled by this observation.

The Chandra ACIS-S observation reveals a total of six ULX within NGC 4485/90, ranging in observed luminosity between $\sim 1$ and $4 \times 10^{39}$ erg s$^{-1}$ (0.5 - 8 keV). The positions of the ULX within the galaxies are shown in Figure 8. Note that we see all three ULX reported in Roberts & Warwick (2000), and of the three new ULX two appear due to the hard ($> 2$ keV) response of the ACIS-S (one of which was previously unknown, the other known but not luminous enough to be classified as an ULX). The third new ULX appears to be a truly transient source. An examination of the short-term variability data for each ULX shows that none are significantly variable over the duration of the Chandra observation. However, the long-term lightcurves (Figure 9) show that significant variabil-

![Figure 7. HST WFPC F606W filter image covering the region around NGC 5204 X-1. North is indicated. The error circle shown around the Chandra ACIS-S position is 1″ in radius.](image)

![Figure 8. Chandra ACIS-S X-ray source detections in the NGC 4485/90 field overlaid onto a greyscale DSS-2 blue image of the galaxies. NGC 4490 is the larger, southern galaxy and contains the majority of the X-ray source detections. The six ULX are indicated by green circles and labelled A - F. A further 24 X-ray sources are found within the optical extent of the galaxies (i.e. within each $D_{25}$ ellipse), with luminosities down to $3 \times 10^{37}$ erg s$^{-1}$, and are shown by the red circles. The circle sizes scale logarithmically with flux for each source.](image)
Figure 9. Long-term lightcurves of the six ULX in NGC 4485/90. The formatting is as per Figures 2 & 5, except for the upper limits shown by downwards-pointing arrows. The labels (A) - (F) refer to the sources as labelled in Figure 8.

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regions in NGC 4485/90 is more confirmation of the apparently strict relationship between the phenomena. Additionally, the inference that five of the six ULX are black hole X-ray binaries implies that even in very active star formation regions, the ULX phenomenon is predominantly due to accreting sources as opposed to supernovae.

5. Conclusions

Our knowledge of the properties of ULX is growing rapidly in the era of Chandra and XMM-Newton. The following themes are emerging:

- ULX are a heterogeneous class, displaying a variety of different temporal and spectral X-ray characteristics, though with broad similarities in many cases.

- A small number (10 - 20% of ULX?) are identifiable with recent supernovae, and the remainder appear to have the X-ray characteristics of black hole X-ray binaries.

- A pattern of the spatial co-location of ULX with active star formation regions is emerging, demonstrated clearly in the case of NGC 4485/90, implying a direct link between the presence of ULX and the ongoing star formation.

- A viable model for the nature of ULX that links the two preceding points is that ULX may be high-mass X-ray binaries with their X-ray emission beamed into our line-of-sight. The case of NGC 5204 X-1 presented above strongly supports this scenario, in that we have an optical counterpart that appears to be one or more O-stars, along with possible evidence that the ULX has a rare X-ray spectral state that is similar to that observed in a Galactic microquasar (which could provide a physical basis for the beaming hypothesis).

- A new phenomenon highlighted by our work is the presence of apparent cavities in emission-line gas immediately in the vicinity of the ULX NGC 5204 X-1 and NGC 4559 X-1. This immediately raises questions as to the rate of occurrence and the formation and energetics of these nebulae, which will be the subject of future work.

- Though much circumstantial evidence now points to a model of ULX as beamed high-mass X-ray binaries, it is important to remember that there is as of yet no clear and unambiguous evidence to prove that they are not intermediate-mass black holes.

It is notable that in the case of NGC 5204 X-1 the key piece of evidence in linking it to Galactic microquasars is its spectral variability. Since the majority of the ULX with established long-term lightcurves appear highly variable, it may be that their long-term behaviour between separate epochs will provide the key diagnostics for establishing their true natures. This will be tested with future observations (and re-observations!) of the nearest ULX with both Chandra and XMM-Newton. The EPIC instruments on XMM-Newton offer the best opportunity to constrain the X-ray spectral characteristics of ULX, and the simultaneous UV imaging with the Optical Monitor will allow an unprecedented view of the link between ULX and the young, hot stars associated with stellar formation regions.

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