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Multiwavelength Observations of Ultraluminous X-Ray Sources

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Abstract Multiwavelength observations may help us understand the physical nature of the ultraluminous X-ray sources (ULXs) found in external galaxies. Enabled by the arcsecond X-ray source positions now available from Chandra, there has been significant recent progress in the identification of optical and radio counterparts to ULXs. Recent results are reviewed on the identification of optical stellar counterparts to ULXs, the relation between ULXs and regions of active star formation, the study of optical nebular counterparts to ULXs, and the estimation of the luminosity of an ULX via its influence on a surrounding nebula.

Key words: accretion, accretion disks — black hole physics — galaxies: individual: Holmberg II, NGC 5408, M82 — X-ray: galaxies — X-ray: stars

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are bright X-ray sources found in external galaxies and displaced from the galactic nucleus. Such sources were first discovered with the Einstein satellite (Fabbiano 1989) and have been studied extensively with all subsequent X-ray observatories. The definition of ULX has been somewhat vague, particularly in terms of the luminosity threshold. In the interest of concreteness, I propose to establish the definition of ULXs as irregularly variable, non-nuclear, X-ray sources with apparent bolometric luminosities (estimated from the observed flux assuming isotropic emission) exceeding the Eddington limit for a $20M_\odot$ compact object. Including only irregularly variable sources should exclude most, if not all, young supernovae and supernova remnants, leaving the accreting sources. Because the dynamically measured masses of all of the black hole candidates within our own Galaxy are below $20M_\odot$ (McClintock & Remillard (2003)), this luminosity threshold is necessary to establish ULXs as distinct objects from the black hole X-ray binaries found in the Milky Way. Placing the luminosity cutoff at a lower value would include the 'normal' black hole binaries in the Milky Way.

The physical nature of the ULXs is very poorly constrained. Fundamental questions remain, even regarding the mass of the compact objects. Some of the major questions concerning ULXs are:

– In what environments do ULX occur?
– Are there any ULXs in elliptical galaxies?
– Are there multiple classes of ULXs?

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- Are the sources isotropic or beamed emitters?
- Do ULXs produce radio emission?
- What are the mass donors of ULXs?
- What are the properties of ULX binaries?
- How are ULXs formed?

In this review, we will examine these questions and how observations at multiwavelengths can help understand the physical nature of the ultraluminous X-ray sources.

2 MODELS

The great interest in ULXs arises from the possibility that they represent a new class of black with masses intermediate between those of stellar-mass black holes and supermassive black holes. The main motivation for this is the high luminosities inferred under the assumption of isotropic emission (Colbert & Mushotzky 1999). The spectral properties of the sources measured with the ASCA satellite have been interpreted as additional evidence for intermediate masses (Makishima et al. 2000). The existence of intermediate mass black holes would be significant because such objects may require different formation mechanism than stellar-mass black holes. Madau & Rees (2002) have suggested that such objects could be the relicts of the first generation of stars, which are thought to have had very low metallicity and therefore been extremely massive. Intermediate mass black holes could also be formed by interactions in stellar clusters (Ebisuzaki et al. 2001; Portegies Zwart et al. 2004). The high stellar density within superstar clusters found in starburst galaxies are a particularly appealing location for the formation of intermediate mass black holes via multiple stellar collisions.

However, alternative interpretations of the ULXs exist. The difficulty of forming intermediate mass black holes motivated King et al. (2001) to suggest that the ULXs are, instead, mechanically beamed sources. In their specific model, the mechanical beaming is produced by super-Eddington accretion rates caused by thermal time scale mass transfer of mass off a companion star. The thermal time scale mass transfer phase is suggest to be a common, but short lived, evolutionary phase for young, high mass stars.

Another interpretation of the ULXs is that they may be relativistically beamed jet sources, “micro-blazars”, suggested to exist in external galaxies after the discovery of microquasars in our own Galaxy (Mirabel & Rodríguez 1999). Relativistic jets from microquasars have been observed to produce X-ray as well as radio emission (Corbel et al. 2002). Körding et al. (2001) suggest that beaming can produce the intense X-ray fluxes observed from ULXs. One possible mechanism which have been studied in some detail is inverse-Compton interactions of photons from a high mass companion star with the energetic particles in a relativistic jet (Georganopoulos, Aharonian, Kirk 2002).

Another possibility is that the sources are not beamed, but super-Eddington radiators. Begelman (2001) has suggested the potential existence of accretion flows in which the Eddington limit is significantly violated. The basic mechanism is that radiation-pressure dominated disks are highly inhomogeneous due to photon bubbles, and, therefore, may be able to radiate at rates higher than predicted in standard accretion disk theory – rates up to 10–100 times the Eddington luminosity.

Each of these different models leads to different predictions for the beaming factor of the X-ray emission and therefore the underlying number of sources required to produce the observed ULX population, for the mass of the black hole and the evolutionary state of the companion star and therefore the formation mechanism of the black hole and binary and the nature of the stellar populations where ULXs should be found, and for the duty cycle of the X-ray emission.

3 MULTIWAVELEGTH OBSERVATIONS

The motivation for performing multiwavelength observations comes from the history of X-ray astronomy and the realization that, with the possible exception of X-ray pulsars, the identification and study of counterparts to X-ray sources at other wavelengths has been necessary to understand the physical nature of all known classes of X-ray sources. Multiwavelength observations should help distinguish between the models described in the previous section. Specifically,

- The study of the stellar environments of ULXs will allow us to determine what types of stars are their progenitors (i.e. young or old) and determine if any specific conditions are required for the occurrence of ULXs (low metallicity, high star formation density, ...). This knowledge will help constrain models of the formation mechanisms of ULXs.
- Identification of stellar companions and determination of the spectral types of the companions will directly constrain the evolutionary history of the binaries containing ULXs. Some of the models described above make very specific predictions concerning the type of the companion star which can be tested.
- Spectroscopy of companion stars could enable measurement of radial velocity curves which would provide direct constraints on the compact object mass. This possibility is very exciting and could lead to definitive evidence for or against the interpretation of ULXs as intermediate-mass black holes.
- Determining whether some, all, or none of the ULXs produce radio emission should help determine whether or not relativistic beamed jet models for the ULXs are viable. Radio emission is an essential feature of relativistic jets and should be present if the ULXs are, indeed, micro-blazars.
- The identification and study of nebula associated with ULXs may enable us to probe the origin of the ULXs, if the nebula are associated with the birth event in a manner similar to supernova remnants, or enable us to determine the total radiation and particle fluxes from the ULXs. Study of these nebula will help constrain the formation mechanisms and the total energetics of ULXs.

The multiwavelength study of ULXs is a field which is just now blooming because of the accurate X-ray positions provided by the Chandra X-ray Observatory. The precise astrometry possible with Chandra has enable, for the first time, the unique identification of optical counterparts to ULXs. In the next several sections, we present a review of some recent results in multiwavelength observations of ULXs.

4 OPTICAL COUNTERPARTS IN STAR-FORMING GALAXIES

ULXs are found preferentially in actively star-forming galaxies and the ULXs in star-forming galaxies include the brightest and most highly variable members of the class. The ULXs in star-forming galaxies tend to be spatially coincident with the regions of active star formation, a trend which is discussed quantitatively below. This trend also makes the identification of unique optical counterparts difficult because ULX fields are crowded when imaged in the optical.

Pre-Chandra, progress in identification of optical counterparts was minimal because of the large number of stars in each Rosat error circle (the best available at the time). With Chandra, the situation has improved greatly, but remains difficult. An illustrative example is given by the ULX in NGC 5204. Goad et al. (2002) analyzed an HST image of the field of the ULX and considered objects found in the relative HST/Chandra error circle. The size of the error circle was dominated by the absolute astrometric accuracy of Chandra. Unfortunately, they found three potential counterparts. Measuring the magnitudes and colors of the counterparts, they found a range of objects including a single F2-F5 supergiant, 2-3 A2 supergiants, 2-3 B5 supergiants, or a small and young stellar cluster. There are more possibilities than counterparts because the magnitudes and colors of some of the counterparts could be interpreted in multiple ways.

The situation can be significantly improved if objects, other than the ULX, can be identified in both HST and Chandra images. In this case, the uncertainty in relative astrometry can be greatly decreased as compared with the uncertainty in the absolute astrometry of Chandra or

Table 1 Optical stellar counterparts to ULXs. The table includes the ULX name, the spectral type of the optical counterpart, and the publication were the optical identification was reported.

Source	Counterpart	Reference
M81 X-6	O8V	Liu et al. 2002
NGC 1313 X-2	early O V, O-B I	Zampieri et al. 2004
Holmberg II	O4V to B3 Ib	Kaaret et al. 2004b
NGC 5204	B0 Ib	Liu et al. 2004

HST. However, the number of cases where this has been possible as small. The major hurdle at this point is the low number of X-ray sources in the subset of the Chandra fields overlapping the HST field. Liu et al. (2002) used SN 1993J to align HST and Chandra images of M81 and obtain relative astrometry accurate to $0.2''$ and identify a unique optical counterpart to the ULX NGC 3031 X-11. Zampieri et al. (2004) used SN 1987K in NGC 1313 for relative astrometry to identify counterpart to NGC1313 X-2. Liu et al. (2004) used the coincidence of an optical bright object with a Chandra source to improve on the astrometry for NGC 5204 and unique identify the ULX with one of three possible counterparts found by Goad et al. (2002). The fourth unique optical counter part identification was made for the ULX in Holmberg II where the presence of a bright HeII nebula and a relatively uncrowded field made a unique counterpart identification possible without highly accurate relative astrometry (Kaaret et al. 2004b).

The current full set of unique optical counterpart identifications for ULXs is given in Table 1. There are only four. The colors and magnitudes of all of the counterparts are consistent with young, massive stars, in particular O or B stars. This suggests that the ULXs are very young objects. However, care must be taken in interpretation of the optical spectral types because reprocessed disk emission may contribute to optical light. The optical colors of low-mass X-ray binaries in the Milky Way where the optical light is dominated by reprocessed emission from the accretion disk are similar to those found for the ULXs.

Optical spectroscopy of the counterparts should enable detailed understanding of their nature. The first step has been taken by Liu et al. (2004) who obtained an HST/STIS far-ultraviolet spectrum of the counterpart of the NGC 5204 ULX. The line spectrum bolsters their identification of the star as B0 Ib. The spectrum also shows a NV emission line. This is a very high ionization line which is not seen in B star spectra, but is seen in X-ray illuminated accretion disks and coronae. Detection of this line is strong evidence that the correct companion to the ULX has been identified. Liu et al. (2004) suggest that the B0 star fills it Roche lobe and that mass transfer proceeds via Roche lobe overflow. This mode of mass transfer differs from the wind-fed accretion typical of high-mass X-ray binaries in the Milky Way and was first suggested by Kaaret et al. (2004) as necessary in order to produce the high luminosities seen from ULXs. The detection of spectral lines from the optical companion to a ULX raises the exciting possibility that it may be possible to obtain a radial velocity curve and therefore dynamical constrains on the compact object mass.

5 ULX AND SUPER STAR CLUSTERS

ULXs preferentially occur in starburst galaxies and the most luminous ULXs are often found near sites of active star formation (Zezas & Fabbiano 2002). In starburst galaxies, a substantial fraction of young stars are found in "super star clusters" – luminous, compact, clusters containing up to $10^6 M_\odot$ of stars within a radius of a few parsecs (Meurer et al. 1995). Stellar encounters in such dense clusters may lead to enhanced production of binaries, particularly binaries containing compact objects (Portegies Zwart et al. 2004).

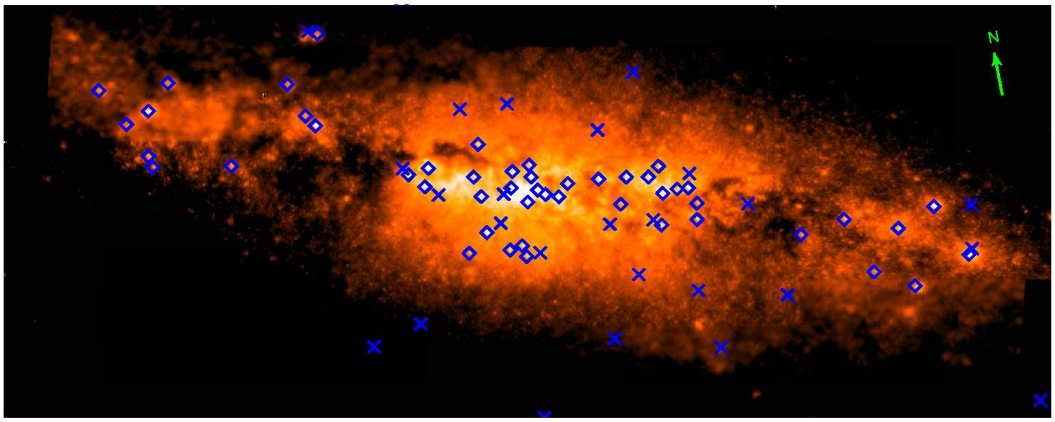

Fig. 1 Infrared image of M82 from HST/NICMOS with super star clusters are marked as diamonds and X-ray sources are marked as X's (following Kaaret et al. 2004a).

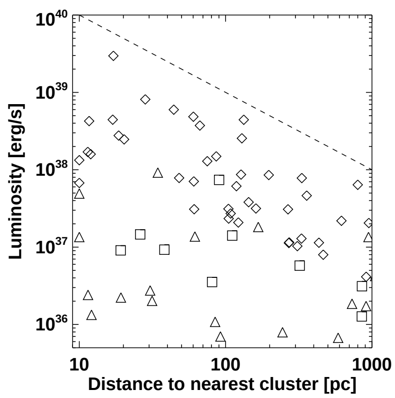

Fig. 2 Displacements of X-ray sources from the nearest super star clusters for three nearby starburst galaxies: M82 (diamonds), NGC 1569 (triangles), NGC 5253 (squares) (from Kaaret et al. 2004a). The luminosities are calculated from the flux for the 0.3–8 keV band assuming isotropic emission. The dashed line represents the equation $L_x = (1 \times 10^{41}\,\mathrm{erg\,s^{-1}})/(d/\mathrm{pc})$.

Kaaret et al. (2004a) studied the spatial offsets between super star clusters and X-ray sources (both ULXs and normal X-ray sources) in starburst galaxies, see Figures 1 and 2. The position of the X-ray sources are well correlated with, but have significant offsets from, the super star clusters. Further, the brighter X-ray sources preferentially occur closer to clusters. Because the star clusters are very good tracers of star formation activity, the good correlation of X-ray sources with super star clusters indicates that the X-ray sources are young objects associated with current star formation. This may suggest that the X-ray sources and the ULXs in particular are produced via dynamical interactions in the super star clusters (Portegies Zwart et al. 2004).

The offset of the X-ray sources from the super star clusters suggests motion of the X-ray sources. Such motions can naturally be produced by dynamical interactions within the clusters leading to ejection of X-ray binaries with speed comparable to the cluster escape velocity. The absence of very bright sources at large displacements from clusters may help constrain models of the sources. It particular, it suggests that the ULXs are not simply a subset of the normal

X-ray population viewed at particular beaming angles. Further, it suggests that the turn-on of a ULX occurs promptly and is not significantly delayed after the creation of the binary.

6 OPTICAL COUNTERPARTS IN NON STAR-FORMING GALAXIES

The presence of ULXs in early-type galaxies, in which there is no active star formation and the youngest stellar populations are billions of years old, is an actively pursued question. Irwin et al. (2003) showed that the numbers of seeming ULXs in early-type galaxies are consistent with expected number of background AGN. This would suggest there are no ULXs (meeting the definition above) in early-type galaxies. However, positive identifications of ULXs with globular clusters identified in the optical can exclude an AGN identification. The identification of cluster counterparts to ULXs in NGC 1399 (Angelini et al. 2001) and NGC 4565 (Wu et al. 2002) show that the total (isotropic equivalent) X-ray luminosities of some globular clusters can be as high as $5 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. However, these luminosities may represent the summed output from several different objects and no ULXs with (isotropic equivalent) luminosities exceeding $10^{40}\,\mathrm{erg\,s^{-1}}$ have been found.

Intermediate mass black holes could be formed by dynamical interactions in globular clusters, similar to the case described above for super star clusters. Such black holes could remain within the clusters and then capture a star to become active again at the current epoch. Alternative explanations for the bright X-ray emission from some globular clusters are that the Eddington limit is violated, the emission is mechanically beamed, or the emission is relativistically beamed (see section 2). Kalogera et al. (2004) suggest intermediate mass black holes will be transient, while thermal time scale mass transfer sources will be persistent. Transient behavior would then be a signature of an intermediate mass black hole. However, the time scale of the transient behavior is expected to be quite long, "far longer than an observer's lifetime" (Kalogera et al. 2004). In addition, relativistically beamed sources could also be transient, which might make the interpretation of transient behavior ambiguous.

7 NEBULAR COUNTERPARTS

Optical and radio nebulae have been found which are spatially coincidence and likely physically related to ULXs. Such nebula may have been produced in the birth of the ULXs or may be continuously powered by the ULX. The study of nebulae associated with ULXs may constrain the epoch and energetics of the origin of ULX. Study of the nebulae also may constrain the current energetics of the ULXs and help determine if the X-rays observed directly are beamed or unbeamed, The study of optical nebulae associated with ULXs has been pioneered by Manfred Pakull and much of the state of our current knowledge is summarized in Pakull & Mirioni (2002).

While the number of optical nebulae associated with ULXs is relatively small, the nebulae identified to date show some interesting similarities. Most of the nebula show emission line ratios similar to those seen in supernova remnants. This suggests that shocks power the emission. In analogy with standard supernova remnants, a natural interpretation of these nebula is in terms of expanding shells of material powered by an initial explosion. In the case of NGC 1313 X-2, high resolution spectroscopy of the emission lines provides direct evidence for expansion with a velocity of 80 km/s.

The nebula tend to be quite large, ranging in diameter from 200 pc for the nebula surrounding IC 342 X-1 (Roberts et al. 2003) to 400 pc for the nebula near NGC 1313 X-2 (Pakull & Mirioni 2002). If the nebulae are, indeed, expanding from a single initial explosion, then the large diameters require very energetic explosive events with total energies $\sim 10^{52}$erg. This is more energetic than a single supernova. Such energies can be produced via a hypernova, potentially linking the ULXs with gamma-ray bursts, or multiple supernovae. The dynamics of the nebulae, in this case, would also require very young ages for the ULXs, typically less than 1 Myr.

Table 2 X-ray and photoionization luminosities for 3 observations of Holmberg II. The X-ray luminosity is the equivalent isotropic luminosity calculated from the X-ray flux and spectrum measured using XMM-Newton on the date indicated in 2002. The photoionization luminosity is the that required to produce the observed HeII luminosity using the X-ray spectrum measured with XMM-Newton on the date indicated.

Observation	L_X [erg s^{-1}]	L_{PI} [erg s^{-1}]
10 April	16×10^{39}	5.9×10^{39}
16 April	17×10^{39}	6.1×10^{39}
19 Sept	5×10^{39}	3.7×10^{39}

An alternative interpretation of the nebulae is that they are continuously energized by jets produced by the ULX. The nebula would then be similar to that surrounding the Galactic jet source SS 433. In this case, the nebulae should reflect the total energy output of the ULX.

8 A BLACK HOLE CALORIMETER

Nebula powered by photoionization provide a potential means to measure the total energy output of a ULX in all directions. This would enable us to answer the question of whether or not the X-rays from the ULX are beamed along our line of sight.

The idea is that X-rays from the ULX will ionize the nebula. Excited atoms in the nebula will then produce line emission from high excitation states. A particularly useful emission line is the λ4686 line from fully ionized Helium. The HeII emission is proportional to the total luminosity of ionizing radiation from 54 eV, the ionization threshold of He, to about 300 eV. At most one HeII photon is produced for reach X-ray in this band.

Pakull & Mirioni (2002) discovered a HeII emission line nebula near the ULX in the galaxy Holmberg II using ground-based optical spectroscopy. Using a thermal bremsstrahlung spectrum fit to non-simultaneous Rosat and ASCA data and then folding the fitted spectrum through a photoionization code to relate the HeII luminosity to the X-ray luminosity, they found that the total X-ray luminosity required to produce the observed photoionization was in the range $L_{PI} = 3 - 13 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. The dominant uncertainty in their luminosity estimate is the HeII luminosity to X-ray luminosity conversion and is caused by the uncertainty in the X-ray spectrum.

Kaaret et al. (2004b) observed the same nebula using HST and obtained images in the optical emission lines HeII λ4686, Hβ, and [OI] λ6300. Examination of the relative morphology of the nebula in the three lines shows that the structure of nebula is consistent with that expected from photoionization. This strengthens the suggestion by Pakull & Mirioni (2002) that the nebula is photoionization powered. The total HeII luminosity from the HST data is $2.7 \times 10^{36}\,\mathrm{erg\,s^{-1}}$. Using archival XMM-Newton data, the X-ray spectrum of the ULX was fit to a Comptonization model in which the seed photons for the Comptonization are drawn from a multicolor disk black body spectrum. The use of a Comptonization model rather than a simple powerlaw is motivated because a model in which the low energy extension of the spectrum is well defined, and preferably physically motivated, is needed for the photoionization modeling. The fitted spectral model from three different XMM-Newton observations were then used an inputs to modeling of the photoionization nebula to calculate the conversion factor between HeII luminosity and X-ray luminosity. The estimated X-ray luminosity is at least $4-6 \times 10^{39}\,\mathrm{erg\,s^{-1}}$, see Table 2. The range in luminosity comes from the different spectral fits for the different XMM-Newton observations. These numbers are lower bounds on the true luminosity because the HST images reveal that the nebula only partially covers the ULX. The recombination time of HeII at the density estimated for the nebula is of order 3000 years. Therefore, these luminosities represent the average luminosity of the ULX over the past several thousand years.

If the Eddington limit holds, then the implied minimum black hole mass for the ULX is $25M_{\odot}$. This is greater than the measured mass of any stellar black hole in our Galaxy and establishes the source as truly ultraluminous (but not necessarily as an intermediate mass black hole).

9 CONCLUSIONS

Multiwavelength study of ultraluminous X-ray sources is a very active field and has led to significant new information about the nature of the objects. First, ULXs tend to be associated with young, high mass stars and, possibly in some cases with super star clusters. This clearly indicates that most ULXs are young objects. An association of ULXs with super star clusters might suggest an origin via dynamical interactions in clusters for at least part of the ULX population. While high luminosities have been observed from some globular clusters, the incidence of ULXs in early-type galaxies has not been definitively proven (strong variability from an X-ray bright cluster would do so) and the number of ULXs in early-type galaxies may be consistent with zero.

The study of optical nebulae associated with ULXs reveals unusually large nebula, compared with normal supernova remnants, which tend to show evidence for shock emission. The most natural interpretation of these nebula is as remnants of explosions. These explosions must have been significantly more powerful than standard supernovae. Alternatively, the nebula may be continuous powered by jets emitted by the ULXs. Finally, the energetics of the HeII emission line nebula in Holmberg II shows that at least one ULX is truly ultraluminous over a time scale of several thousand years.

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