RevMexAA (Serie de Conferencias), **20**, 46–49 (2004)

ULTRALUMINOUS X-RAY SOURCES: AN OBSERVATIONAL REVIEW

G. Fabbiano[1]

RESUMEN

Las fuentes ultraluminosas en rayos X (ULXs) son, como su propio nombre indica, emisores extremadamente luminosos en rayos X, además de objetos relativamente poco frecuentes en galaxias. Debido a su luminosidad, se ha sugerido que pueden ser producidos por un fenómeno de acreción a un agujero negro (BH) de unos cientos de $M_\odot$, es decir, a un agujero negro más masivo que el que se podría originar a partir del proceso de evolución estelar normal. Hay modelos alternativos que incluyen remanentes jóvenes de supernovas (SNRs), emisión dirigida en forma de haz desde un agujero negro normal perteneciente al sistema binario emisor en rayos X (XRB) y con un alto ritmo de acreción, o bien, sistemas binarios con emisión en rayos X que emiten un haz con velocidades relativistas. La evidencia observacional sugiere que, aunque la mayoría de estos objetos parecen ser objetos acrecientes compactos, no hay una evidencia clara de si estamos ante un sistema binario emisor de un haz dirigido en rayos X, o bien, ante un agujero negro acreciente muy masivo. Es posible que lo que se denomina ULXs sea una familia heterogénea de fuentes de rayos X.

ABSTRACT

Ultraluminous X-ray Sources (ULXs) are, as suggested by their name, extremely luminous and rare X-ray emitting objects found in galaxies. Because of their luminosity, it has been suggested that they may be powered by accretion onto a black hole (BH) of a few 100 $M_\odot$, more massive than what one would expect to originate from normal stellar evolution. Alternative models include young supernova remnants (SNRs), beamed emission from normal BH X-ray binaries (XRB) with high accretion rates, and relativistically beamed XRB emission. The observational evidence on ULXs suggests that while most of them are likely to be compact accreting objects, there is no clear unique evidence pointing either to the beamed XRB model or to accretion onto a very massive BH. It is possible that what we call ULXs are a heterogeneous family of X-ray sources.

Key Words: **X-RAYS: BINARIES — X-RAYS: STARS**

1. ULTRALUMINOUS X-RAY SOURCES: DEFINITION AND A BRIEF HISTORY

Although different definitions exist, my observational definition of ULX is a (*usually*, exception is e.g., the nucleus of M33, see below) non-nuclear source emitting at $\geq 10^{39}$ ergs s^{-1}, well in excess of the Eddington luminosity of a spherically accreting neutron star ($\sim 2 \times 10^{38}$ ergs s^{-1}). ULXs are also named super-Eddington sources (see Fabbiano 1989, 1995 and references therein), and intermediate luminosity X-ray objects (IXOs) (Roberts & Warwick 2000; Colbert & Mushotzky 1999). In some cases, ULXs have been found to emit in the $\sim 10^{40}$ ergs s^{-1} range (e.g., in M82, Matsumoto et al 2001; Kaaret et al 2001). ULXs were discovered with *Einstein* and studied with *ROSAT* and *ASCA*. With *Chandra* we can now study and locate accurately a number of these sources in distant galaxies, and we can also see how their occurrence is related to the general properties of the XRB and stellar populations of the parent galaxy (see reviews, Fabbiano & White 2003, Miller & Colbert 2004). *XMM* is providing high quality spectra and variability information of nearby luminous ULXs (e.g., Miller et al 2003; Strohmayer & Mushotzky 2003), which can help uncovering their hidden engine.

ULXs are inherently exciting sources, whose nature has been the subject of controversy since their discovery. The possibility of them being SNRs rather than accreting binaries was suggested, based on the discovery of similarly luminous young SNRs (Fabbiano 1989). If these sources are accreting binaries, emitting isotropically at the Eddington limit, masses in excess of those expected from stellar black holes are implied, up to in some cases, $\geq 100 M_\odot$ (see Fabbiano 1989, 1995; Makishima et al. 2000). Colbert & Mushotzky (1999) dubbed this type of black holes 'intermediate mass black holes' (IMBHs). IMBHs would represent the 'missing' component of the BH mass spectrum, with masses in the gap between those of the BHs found in Galactic XRBs, and the supermassive $10^7 - 10^9 M_\odot$ found at the nuclei of galaxies (e.g., Richstone et al 1998).

[1]Harvard-Smithsonian Center for Astrophysics

More recently, a different suggestion has been advanced, that ULXs may represent a normal stage of XRB evolution, being either due to beamed emission from highly accreting high mass XRBs or low-mass XRB transients (King et al 2001; King 2002), or to relativistic jets in XRBs (Körding et al 2001). In the King et al. (2001) model, the apparent (spherical) accretion luminosity is boosted because of geometrical collimation of the emitting area in thick accretion disks, resulting from the large thermal-timescale mass transfer characterizing the later stages of a massive XRB. Exploiting the similarity with Galactic microquasars, the jet emission model of Körding et al. (2002) produces enhanced luminosity via relativistic beaming.

Where do I stand? I am data-driven. While IMBHs are an exciting possibility, *extraordinary claims require extraordinary evidence* (Carl Sagan 1979; Broca's brain, page 73). As I will summarize below, there is a body of evidence suggesting that ULXs may be a heterogeneous family: a large fractions may well be XRBs, possibly beamed, with stellar mass BHs; but there is also increasing circumstantial evidence pointing to IMBHs in some cases.

2. THE FACTS

We now have a large amounts of observational results that we can use to constrain the nature of ULXs. This evidence includes: variability; spectral shapes and variability; counterparts at other wavelengths; ULX environment, both local and as regards their relation to the X-ray luminosity function (XLF) of their host galaxy XRB population.

2.1. *Variability*

Although young SNRs may be responsible for ULX emission in some cases (e.g., Fabbiano 1989, Fabian & Terlevich 1996), there is now sufficient evidence from variability data, to establish that the majority of ULXs are indeed compact systems, most likely accreting binaries. Variability has been observed in times scales from years down to hours or less. Examples include: M81 X-9 (La Parola et al. 2001), varying over several years; variability in a few months time scales in ULX populations observed with *Chandra* in both M82 (Matsumoto et al. 2001; Kaaret et al. 2001) and the Antennae Galaxies (Fabbiano et al 2003a, 2003b); a 2.1 hr variation found in M51 X-7 by Liu et al. (2002); and a 54 mHz QPO reported by Strohmayer & Mushotzky (2003) in the most luminous M82 ULX. This QPO, in particular, may suggest emission from an accretion disk and is incompatible with the radiation being beamed (as in King et al. 2001). Comparing this frequency with the typical frequencies of strong QPOs from Galactic BH's with known masses, these authors suggest a mass in the 100-10,000 $M_\odot$ range.

Transient behavior could be a discriminant between beamed models and IMBH accretion for the origin of ULXs in young, star-forming regions (Henninger et al. 2003). Accretion onto IMBHs can lead to unstable disks and hence transient behavior whereas beamed XRBs have transfer rates that are high enough for the disks to be stable and X-ray emission to be persistent. Therefore long-term monitoring may prove a valuable and possibly unique tool in unraveling the nature of ULXs.

2.2. *Spectral Variability*

Variability has been observed also in the spectral properties of ULXs, correlated with the overall source luminosity. Both high/soft-low/hard states, akin to those of some Galactic BH binaries, and the reverse variability pattern, reminiscent of microquasars, have been reported (e.g., Kubota et al 2001; Liu et al 2002; Fabbiano et al 2003a). *Chandra* observations of the ULX at the nucleus of M33 have revealed a two-component (power-law and disk) spectrum and have established luminosity-spectral variability patterns, reminiscent of the BH binary LMC X-3 (La Parola et al. 2003). This spectral variability may be indicative of the competition between the relative dominance of the accretion disk versus the innermost hot accretion flow; several scenarios for spectral variability are discussed in Fabbiano et al. 2003a and references therein.

2.3. *Spectra: Do we See IMBH Accretion Disks?*

In the assumption that ULXs are accreting systems, the spectra should reflect the presence of an accretion disk. In particular (see e.g., Makishima et al 2000), one would expect to see a soft spectral component with $kT_{in} \sim 1.2\ keV\ (M/10M_\odot)^{-1/4}$.

For an IMBH this component should have a temperature in the range of a few tens to $\sim$ 100 eV. However, ASCA spectra of ULXs were typically too 'hot', leading to the suggestion of Kerr BHs, if the IMBH hypothesis were to be retained (Makishima et al 2000). Softer components are now being reported with *XMM* and *Chandra* (e.g., Miller et al 2003; Kaaret et al 2003). In particular, a low-temperature component was discovered in the *XMM* spectrum of a 'normal' ULX in NGC 1313, which does not require a Kerr BH, and is entirely consistent with emission from an IMBH accretion disk (Miller et al. 2003). A much higher kT was derived from the ASCA observations of the same ULX in the Makishima paper

https://doi.org/10.1017/S0252921100151863 Published online by Cambridge University Press

This was shown by Miller et al. to be the likely result of the poorer statistics of the *ASCA* data, which did not reveal the two-component spectrum evident in the *XMM* data.

The *Chandra* detections of super-soft ULXs (e.g., Swartz et al. 2002, in M81) could be interpreted as evidence for IMBHs. However, in some cases, variability of these sources suggest that the emitting region may not be associated with the inner regions of IMBH accretion disks, but may be due to Eddington-driven outflows from a stellar mass black hole (Mukai et al. 2003; Fabbiano et al. 2003b).

2.4. *ULX Counterparts: Ambiguous Evidence*

In some cases, the IMBH hypothesis is supported by the association of the ULX with diffuse Hα nebulae, suggesting isotropic illumination of the interstellar medium by the ULX, and therefore absence of beaming (e.g. Pakull & Mirioni 2002 in the case of the NGC 1313 sources, see Miller *et al.* 2003). M81 X-9 is also associated with an optical nebula, which also contains hot gas (La Parola *et al.* 2001; Wang 2002). Wang (2002) considers the possibility that this nebula may be powered by the ULX and also speculates that it may be the remnant of the formation of the ULX. Weaver *et al.* (2002) discuss a heavily absorbed ULX in the nuclear starburst of NGC 253; this source appears to photoionize the surrounding gas. Weaver *et al.* speculate that it may be an IMBH, perhaps connected with either the beginning or the end of AGN activity. The luminous M82 ULX appears to be at the center of an expanding molecular superbubble with 200 pc diameter (Matsushita *et al.* 2000). However, in at least one case (IC 342 X-1, Roberts *et al.* 2003), there is a suggestion of anisotropic photoionization, that may indicate beamed emission from the ULX.

In the Antennae galaxies (NGC 4038/9), comparison with *HST* data shows that the ULXs are offset from starforming stellar clusters. While coincidence with a stellar cluster may be due to happenstance because of the crowded fields, the absence of an optical counterpart is a solid result and suggests that the ULXs may have received kicks at their formation (Zezas & Fabbiano 2002), which may be unlikely in the case of a massive IMBH forming in a dense stellar cluster (e.g. Miller & Hamilton 2002). An alternate IMBH scenario, discussed by Zezas & Fabbiano, is that of primordial IMBHs drifting through stellar clusters after capturing a companion (Madau & Rees 2001). Displacements from star forming clusters are not unusual; they were also found in M82 and NGC5253 for less luminous X-ray sources (Kaaret et al 2004). By analogy, this may suggest that the Antennae ULXs are also normal XRBs.

Other optical studies find counterparts to ULXs, and set indirect constraints on the nature of the accretor. A blue optical continuum counterpart to the variable ULX NGC 5204 X-1 was found by Roberts et al. (2001), and subsequently resolved by Goad et al. (2002) with *HST*. These authors conclude that the stellar counterpart points to an early-type binary. Similarly, Liu, Bregman & Seizer (2002) find an 08V star conterpart for M81 X-1, a ULX with average $L_X \sim 2 \times 10^{39}$ ergs s^{-1}. These counterparts may be consistent with the picture of King et al. (2001), of ULXs as XRBs experiencing thermal timescale mass transfer.

In at least one case, the variable luminous ULX 2E1400.2-4108 in NGC 5408, there is observational evidence that may point to the relativistic jet model: Kaaret et al. (2003) find weak radio emission associated with the X-ray source, and argue that the both the multi-wavelength spectral energy distribution, and the X-ray spectrum are consistent with the Körding et al. (2002) scenario, although the IMBH is not dismissed.

2.5. *Where Do We Find ULXs?*

With *Chandra*'s ability to resolve the emission on physical sizes of tens of parsecs in nearby galaxies, and the related sensitivity, studies of XRB populations in different galaxies are now possible (see e.g. review by Fabbiano & White 2003). A result is a clear correlation between the appearance of ULXs in a galaxy and the presence of a young stellar population. ULXs are more numerous in actively star forming galaxies or galaxian components (e.g., Tennant et al 2001, Swartz et al 2003, the disk of M81; the Antennae galaxies, Fabbiano et al 2001, Zezas & Fabbiano 2002; see also Kilgard et al. 2002; Grimm et al 2003). This association, and the apparent universal shape of the XLF of starforming galaxies (Grimm et al 2003), may suggest that ULXs are not exceptional objects (IMBHs), but just a stage of young XRB evolution, consistent with the King et al (2001) scenario.

ULXs have been reported in Elliptical galaxies, possibly associated with Globular Clusters, where IMBHs could form (Angelini et al 2001), but their numbers are small, and it has also been suggested that we may just be detecting background AGNs (Irwin et al 2003). However, the sample of galaxies analyzed by Irwin et al is not large. We will need to wait until more data are analyzed before we can reach a conclusive assessment on this issue.

https://doi.org/10.1017/S0252921100151863 Published online by Cambridge University Press

3. SUMMARY

What do the facts tell us on the nature of ULXs? Possibly that there is not a simple explaination. Although a few ULXs may be young SNRs, variability points towards compact accretors in most cases. While spectral variability is overall consistent with the patterns of Galactic XRBs, suggesting a possibly beamed stellar BH emission (e.g. King et al 2001, Körding et al 2002), the QPO detected in the M82 ULX (Strohmayer & Mushotzky 2003) and soft (100 eV) spectral components detected in some cases (e.g., Miller et al 2003) suggest an IMBH. The soft component, however, may also be reconciled with a Eddington-driven BH photosphere (Mukai et al 2003). Early-type star optical counterparts of some ULXs suggest high mass XRBs, and therefore beamed emission, but the presence of spherically symmetric ionized nebulae is instead consistent with IMBHs. The association with the young stellar population and the displacement observed in the Antennae galaxies between ULXs and star-forming clusters, are consistent with the normal (beamed) XRB hypothesis, but it does not exclude IMBHs, if these can be connected in some ways with star formation.

In conclusion, there is no simple answer on the nature of ULXs. It is possible that ULXs are a heterogeneous family, including both XRBs, possibly beamed, with stellar mass BHs, and some IMBH in the most luminous extreme cases, such as in the M82 source.

This work was supported by NASA contract NAS 8-39073 (CXC) and NASA Grant G02-3135X. I thank Phil Kaaret for comments.

REFERENCES

Angelini, L., Loewenstein, M. & Mushotzky, R. F. 2001, ApJ, 557, L35
Colbert, E. J. M., Mushotzky, R. F. 1999, ApJ, 519, 89
Fabbiano, G. 1989, ARA&A, 27, 87
Fabbiano, G. 1995, in X-Ray Binaries, W. H. G. Lewin, J. van Paradijs and E. P. J. van den Heuvel, eds. (CUP: Cambridge), 390-416
Fabbiano, G., King, A. R., Zezas, A., 2003b, ApJ, 591, 843
Fabbiano, G., Zezas, A., King, A. R., et al., 2003a, ApJ Letters, 584, 5
Fabbiano, G., Zezas, A. & Murray, S. S. 2001, ApJ, 554, 1035
Fabbiano, G. & White, N. E. 2003, astro-ph/0307077
Fabian, A. C. & Terlevich, R. 1996, MNRAS, 280, L5
Goad, M. R. Roberts, T. P., Knigge, C. & Lira, P. 2002, MNRAS, 335, L67
Grimm, H.-J., Gilfanov, M. & Sunyaev, R. 2003, MNRAS, 339, 793
Henninger, M., et al., 2003, ApJ, in preparation
Irwin, J. A., Athey, A. E., Bregman, J. N. 2003, ApJ, 587, 356
Kaaret, P. *et al.* 2001, MNRAS, 321, L29
Kaaret, P., Corbel, S., Prestwich, A. S. & Zezas, A. 2003, Science, 299, 365
Kaaret, P., Alonso-Herrero, A., Gallagher, J. S., et al., 2004, MNRAS, 348, L28
Kilgard, R. E., Kaaret, P., Krauss, M. I., Prestwich, A. H., Raley, M. T., Zezas, A. 2002 ApJ, 573, 138
King, A. R. 2002, MNRAS, 335, L13
King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G. & Elvis, M. 2001, ApJ, 552, L109
Körding, E., Falcke, H. & Markoff, S. 2002, A&A, 382, L13
Kubota, A., *et al.* 2001, ApJ, 547, L119
La Parola, V., Peres, G., Fabbiano, G., et al., 2001, ApJ, 556, 47
La Parola, V., Damiani, F., Fabbiano, G. & Peres, G. 2003, ApJ, 583, 758
Liu, J.-F., Bregman, J. N., Irwin, J., Seitzer. P. 2002, ApJ, 581, L93
Liu, J.-F., Bregman, J. N. & Seitzer, P. 2002, ApJ, 580, L31
Madau, P. & Rees, M. J. 2001, ApJ, 551, L27
Makishima, K. *et al.* 2000, ApJ, 535, 632
Matsumoto, H., *et al.* 2001, ApJ, 547, L25
Matsushita, S., Kawabe, R., Matsumoto, H., Tsuru, T. G., Kohno, K., & Vila-Vilaro, B. 2001, in ASP Conf. Ser. 249: The Central Kiloparsec of Starburst and AGN: The La Palma Connection, p. 711
Miller, J. M., Fabbiano, G., Miller, M. C. & Fabian, A. C. 2003a, ApJ (letters), 585, 37
Miller, M. C. and Colbert, E. J. M. 2004, Int.J.Mod.Phys. D13, 1-64
Miller, M. C. & Hamilton, D. P. 2002, MNRAS, 330, 232
Mukai, K., Pence, W.D., Snowden, S.L., Kuntz, K.D., 2003, ApJ, 582, 184
Pakull, M. W. & Mirioni, L. 2002, (astro-ph/0202488)
Richstone, D. *et al* 1998, Nature, 395, 14
Roberts, T. P., Goad, M. R., Ward, M. J., Warwick, R. S. 2003, MNRAS, 342, 709
Roberts, T. P., *et al* 2001, MNRAS, 325, L7
Roberts, T. P. & Warwick, R. S. 2000, MNRAS, 315, 98
Strohmayer, T. E. & Mushotzky, R. F. 2003, ApJ, 586, L61
Swartz, D. A., Ghosh, K. K., Sulemainov, V., 2002, ApJ, 574, 382
Swartz, D. A., Ghosh, K. K., McCollough, M. L., 2003, ApJ,Suppl., 144, 213
Tennant, A. F., Wu, K., Ghosh, K. K., et al., 2001, ApJ, 549, L43
Wang, Q. D. 2002, MNRAS, 332, 764
Weaver, K. A., Heckman, T. M., et al., 2002, ApJ, 576, L19
Zezas, A. & Fabbiano, G. 2002, ApJ, 577, 726