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Classifying the Zoo of Ultraluminous X-ray Sources

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Abstract Ultraluminous X-ray sources (ULXs) are likely to include different physical types of objects. We discuss some possible subclasses, reviewing the properties of a sample of ULXs recently observed by *Chandra* and *XMM-Newton*. Sources with an isotropic X-ray luminosity up to a few times $10^{39}\,\mathrm{erg\,s^{-1}}$ are consistent with "normal" stellar-mass X-ray binaries (mostly high-mass X-ray binaries in star-forming regions). Higher black hole (BH) masses ($\approx$ 50–100 $M_\odot$) may be the end product of massive stellar evolution in peculiar environments: they may explain ULXs with luminosities $\approx 1\text{–}2 \times 10^{40}\,\mathrm{erg\,s^{-1}}$. Only a handful of ULXs require a true intermediate-mass BH ($M \gtrsim 500 M_\odot$). Finally, a small subclass of ULXs shows flaring or rapid variability in its power-law spectral component.

Key words: accretion, accretion disks — black hole physics — galaxies: individual: NGC 4559 — X-ray: galaxies — X-ray: stars

1 INTRODUCTION

ULXs are defined as point-like, accreting sources with apparent isotropic luminosities $L_\mathrm{x} > 10^{39}\,\mathrm{erg\,s^{-1}}$, not including supermassive BHs in AGN and quasars. Masses, ages and mechanisms of formation of the accreting objects are still unclear, as is the geometry of emission. In fact, ULXs are likely to include different physical classes of sources. At least four scenarios have been suggested: *a)* intermediate-mass BHs (Colbert & Mushotzky 1999), with masses $\sim 10^2\text{–}10^3 M_\odot$; *b)* normal BH X-ray binaries ($M \lesssim 20 M_\odot$) with mild geometrical beaming, during phases of super-Eddington mass accretion (King et al. 2001); *c)* microquasars with a relativistic jet pointing towards us (Fabrika & Mescheryakov 2001; Körding et al. 2002); *d)* BH X-ray binaries with super-Eddington emission from inhomogeneous disks (Begelman 2002). These different scenarios also predict different duty cycles for the X-ray-bright phases, thus leading to different predictions for the location and total number of such systems (active or quiescent) in a galaxy.

ULXs have been detected in many nearby spiral, irregular and elliptical galaxies; however, most sources brighter than $\approx 2 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ are located in star-forming galaxies, associated with young populations (Irwin et al. 2004). In the few cases when stellar counterparts have been identified (Soria et al. 2004a and references therein), they have masses $\approx$ 15–30 $M_\odot$. X-ray ionized emission nebulae have been found around many ULXs (Pakull & Mirioni 2002; Kaaret et al. 2004): in some cases, they provide evidence against beaming (Holmberg II X-1:

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Pakull & Mirioni 2002); in other cases, they suggest anisotropic emission (IC 342 X-1: Roberts et al. 2003). The presence of a young, massive star cluster near a ULX (as suggested for the ULXs in the Antennae: Zezas et al. 2002) is consistent with the formation of an intermediate-mass BH from merger processes in a cluster core. However, for most of the sources, multi-band observations so far have not been able to rule out any of the alternative scenarios.

2 A CASE STUDY: DIFFERENT TYPES OF ULXS IN NGC 4559

Located at a distance of ≈ 10 Mpc, the late-type spiral NGC 4559 (Type SAB(rs)cd) has been observed by *XMM-Newton* and *Chandra* on various occasions between 2001 and 2003 (Cropper et al. 2004; Soria et al. 2004a; Roberts et al. 2004). It hosts four sources detected at $L_{\rm x} \gtrsim 10^{39}\,{\rm erg\,s^{-1}}$ on at least one occasion. Here we briefly summarize the properties of these four sources: we argue that they may represent four different classes of ULXs.

2.1 Intermediate-mass BHs in nuclear star clusters?

A variable ($L_{\rm x} \approx 1.5 \times 10^{39}\,{\rm erg\,s^{-1}}$ in 2002 March; $L_{\rm x} < 10^{38}\,{\rm erg\,s^{-1}}$ in 2001 June), point-like X-ray source coincides with the nucleus of NGC 4559. Bulgeless Scd galaxies do not contain a supermassive BH in their nucleus; this is in agreement with the observed relations between the nuclear BH mass and the luminosity and velocity dispersion of the bulge (Magorrian 1998; Ferrarese & Merritt 2000). Instead, many of them contain a bright, massive nuclear star cluster ($M \sim 10^6\,M_\odot$, $L \sim 10^6$–$10^7 L_\odot$; Böker et al. 2004), with a complex history of intermittent star formation. The nuclear star cluster in NGC 4559 has $M_B \approx -12$, $M_I \approx -13$. It is marginally resolved in the *HST*/PC image, with a full-width half maximum of ≈ 5 pc. The Local-Group galaxy M 33 provides another example of a ULX ($L_{\rm x} \approx 1.5 \times 10^{39}$ in the 0.5–10 keV band: Dubus & Rutledge 2002) in the nuclear star cluster ($M_B = -10.2$: Kormendy & McClure 1993) of a bulgeless late-type spiral, without a supermassive BH ($M_{\rm BH} < 1500\,M_\odot$: Gebhardt et al. 2001).

Theoretical and observational studies have investigated the possible formation of intermediate-mass BHs in the core of old globular clusters (Miller & Hamilton 2002) or of young super star clusters (Portegies Zwart et al. 2004; Gürkan et al. 2004). We suggest that nuclear star clusters in late-type spirals may offer another natural environment for these objects, and can be used as a test for BH formation and galaxy merger models.

2.2 Bright high-mass X-ray binaries?

A ULX with $L_{\rm x} \approx 2$–$3 \times 10^{39}\,{\rm erg\,s^{-1}}$ is located in the inner disk of NGC 4559, along a spiral arm, in a region of young star formation. Its spectrum is well fitted by a disk-blackbody model with color temperature $kT_{\rm in} \approx 0.88$–1.07 keV (in 2003 and 2001 respectively), and inner disk radius $\approx 110/(\cos\theta)^{1/2}$ km (in 2003) or $\approx 85/(\cos\theta)^{1/2}$ km (in 2001), where θ is the viewing angle of the disk. Assuming an efficiency ~ 0.1, the mass accretion rate is $\sim$ a few $\times 10^{19}\,{\rm g\,s^{-1}}$, i.e., $\sim$ a few $\times 10^{-7}\,M_\odot\,{\rm yr^{-1}}$. Color temperature and luminosity are consistent with the emission from a standard disk around a ≈ 15–$25\,M_\odot$ BH, accreting close to its Eddington limit, in a high/soft state. Hence, this source can be considered a normal stellar-mass BH X-ray binary, probably with an OB donor star filling its Roche lobe. The BH mass is similar to what is inferred for the most massive BH candidates in the Milky Way: for example, $M = (14.0 \pm 4.4)\,M_\odot$ for the BH in GRS 1915+105 (Harlaftis & Greiner 2004), and $M \approx 16$–$32 M_\odot$ for the BH in Cyg X-1 (Ziolkowski 2004; Gies & Bolton 1986). It is likely that the majority of ULXs with $10^{39} \lesssim L_{\rm x} \lesssim 10^{40}\,{\rm erg\,s^{-1}}$ fall in this category.

2.3 Young, massive BHs from stellar evolution?

The brightest ULX in NGC 4559, X7, has a 0.3–10 keV luminosity $\approx 2\text{–}3 \times 10^{40}\,\mathrm{erg\,s^{-1}}$, and an extrapolated bolometric luminosity $> 5 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ (Cropper et al. 2004). Hence, it is too bright to be a "normal" stellar-mass remnant, if we assume strictly Eddington-limited isotropic emission. We have discussed the case for three possible mass ranges (Soria et al. 2004a). A stellar-mass BH ($M \lesssim 20\,M_\odot$) would require either strong, collimated beaming (it would effectively be a microblazar) or strongly super-Eddington emission. A $\sim 50\text{–}100\,M_\odot$ BH accreting from a 15–25 $M_\odot$ supergiant companion would require mildly anisotropic emission (geometrical beaming of a factor $\sim$ 5–10; King 2004) or mildly super-Eddington luminosity. An intermediate-mass BH ($M \gtrsim 500\,M_\odot$) would be consistent with isotropic, sub-Eddington emission.

Our X-ray spectral and timing study (Cropper et al. 2004) has shown the presence of a very soft thermal component ($kT_{\mathrm{in}} \approx 0.12\text{–}0.15$ keV), and a break in the power-density-spectrum at 0.03 Hz. These findings are not consistent with a microblazar scenario, and suggest a BH mass $\gtrsim 50\,M_\odot$. The optical data indicate an association with a young region of massive star formation at the edge of the galactic disk (age < 30 Myr). They also rule out an association between the ULX and any star clusters; hence, they rule out at least one mechanism of formation for an intermediate-mass BH. Other formation processes have been proposed (e.g., from Pop-III stars), but they are more difficult to reconcile with a young age and disk location. Therefore, the X-ray and optical data together are more consistent with a young 50–100 $M_\odot$ BH originating from massive stellar evolution and accreting from an OB supergiant companion (Soria et al. 2004a).

Such a massive remnant would require a progenitor star at least twice as massive. One can only speculate that such massive stars, not observed in the Milky Way, may exist, and evolve into massive remnants, in other galactic environments. NGC 4559 X7 is located in a region of active star formation triggered by a satellite galaxy collision (Soria et al. 2004a), and in a metal-poor environment. These two conditions are also a characteristic of many other bright ULXs. We speculate that such environments can affect the equation of state of the gas, and the balance of heating and cooling, reducing the fragmentation process in the collapse of a molecular cloud core, and leading to the formation of more massive stars (Spaans & Silk 2000). Low metal abundance has an effect at later stages of the stellar evolution, by reducing the mass-loss rate in the radiatively-driven wind (Pakull & Mirioni 2002). This leads to a more massive stellar core, which may then collapse into a more massive BH.

2.4 NGC 4559 X10: still a mystery

Another source with isotropic luminosity $L_{\mathrm{x}} \gtrsim 10^{40}\,\mathrm{erg\,s^{-1}}$ (NGC 4559 X10) is located in the inner galactic disk, in an inter-arm region, away from young OB associations or HII regions. Its X-ray spectrum is consistent with a simple power-law (photon index $\Gamma \approx 2$), without a significant disk component. Its nature is still a mystery, and may well be different from the three classes of ULXs described above. Possible speculations include an isolated intermediate-mass BH accreting from a molecular cloud (R. Mushotzky, priv. comm.; see also Krolik 2004), or a stellar-mass microblazar. Further *HST* observations of this source are scheduled for 2005 March; we are also planning to carry out radio observations.

3 TRUE INTERMEDIATE-MASS BHS IN COLLIDING SYSTEMS?

Colliding and tidally-interacting systems seem to offer the most favorable environment for ULXs. For example, ULXs have been found in the Antennae (Zezas et al. 2002), the Cartwheel ring (Gao et al. 2003), M 82 (Griffiths et al. 2000), the Mice (Read 2003), the M 81 group dwarfs (Wang 2002). NGC 4559 X7 is also associated with a minor collisional event: we have suggested (Soria et al. 2004) that the initial perturbation responsible for the expanding wave of star formation was caused by a satellite dwarf galaxy crossing the gas-rich outer disk of NGC 4559.

Another example of a ULX in a colliding system was found at the intersection of the collisional ring of NGC 7714 (mostly old stars, with negligible gas or star formation) with the gas-rich bridge between NGC 7715 and NGC 7714 (Soria & Motch 2004). The bridge contains a string of young super star clusters, though none is found near the ULX position. Hydrodynamical simulations of the interaction between the two galaxies (Struck & Smith 2003) suggest that the connecting bridge consists of multiple components, and that the most recent star-formation episode (responsible for the string of young clusters) was triggered by their interaction, which shocked or compressed the gas. It was also suggested that part of the gas in the bridge is currently infalling onto NGC 7714, impacting the outer disk at approximately the ULX location. The ULX luminosity reached $\approx 6 \times 10^{40}$ erg s^{-1} in 2002 December (0.3–12 keV band), implying an estimated bolometric luminosity $\gtrsim 1.5 \times 10^{41}$ erg s^{-1}. If isotropic, it requires an accreting BH with a mass $\gtrsim 500\,M_{\odot}$, ruling out its origin from single stellar evolution processes. The X-ray spectrum is featureless, and in the absence of an accurate *Chandra* position and of an identified optical counterpart, none of the proposed scenarios can be ruled out at present.

At least three other bright ULXs fall in this category: a source in NGC 2276 (tidally interacting with NGC 2300), with a luminosity $\approx 1.1 \times 10^{41}$ erg s^{-1} in the 0.5–10 keV band (Davis & Mushotzky 2004); a ULX in the colliding Cartwheel galaxy, with $L_{\rm x} \approx 1 \times 10^{41}$ erg s^{-1} (Gao et al. 2003); and a variable source in M 82 with a $L_{\rm x} \approx 1$–9×10^{40} erg s^{-1} (Matsumoto et al. 2001). The last source has been interpreted as an intermediate-mass BH ($M \sim 800$–$3000\,M_{\odot}$), from numerical simulations of runaway collisions in cluster cores (Portegies Zwart et al. 2004). This explanation seems more difficult to reconcile with the ULXs in NGC 2276 and NGC 7714.

4 ULXS WITH SHORT-TERM VARIABILITY

X-ray observations may provide two methods to constrain the mass of the accreting BH. When a soft thermal component is present in the spectrum, fitting a disk model provides the color temperature at the inner disk boundary; hence, one can infer the radius of the last stable orbit and the BH mass. For example, thermal components at $kT \approx 0.15$ keV have been found in many ULXs, and were initially used as evidence for an intermediate-mass BH (Miller et al. 2003). However, this method is based on highly questionable assumptions on the accretion flow structure, and the mass estimates thus derived are probably unreliable.

Alternatively, X-ray timing observations can provide the characteristic variability time-scale in the X-ray emitting region; this is also assumed to be related to the inner-disk size and hence to the BH mass. A linear correlation appears to exist between the mass of an accreting BH and a characteristic break frequency in its power-density-spectrum (e.g., McHardy et al. 2004; Markowitz et al. 2003). Evidence for characteristic breaks has been found in a few sources, most notably for the ULX in the metal-poor starburst dwarf galaxy NGC 5408 ($L_{\rm x} \approx 10^{40}$ erg s^{-1}: Soria et al. 2004b; Kaaret et al. 2003). The position of the break, at ≈ 2.5 mHz, suggests a mass at least one order of magnitude larger than Cyg X-1. Moreover, the flux variability is associated with a spectral change. The X-ray spectrum can be interpreted as the sum of a constant or slowly-variable soft thermal component ($kT_{\rm bb} \approx 0.12$ keV) and a rapidly variable power-law component (photon index $\Gamma \approx 2.7$), responsible for the flaring behaviour (Soria et al. 2004b). The source gets harder at higher fluxes, at the flare peaks.

ULXs with short-term variability are comparatively rare (Roberts et al. 2004). M 74 X-1 has a 0.3–10 keV luminosity varying from $\approx 5 \times 10^{38}$ to 1.2×10^{40} erg s^{-1}, over timescales of a few $\times 10^{3}$ s, and is harder at higher fluxes (Krauss et al. 2004). The flaring behaviour has been attributed to the power-law component, while the thermal component is less variable. Similar behaviour is exhibited by NGC 6946 X-11 ($\approx 2.5 \times 10^{39}$ erg s^{-1}: Roberts & Colbert 2003), with a rapidly-varying power-law component (timescale $\lesssim 350$ s). There are at least three possible interpretations for the spectral variability properties of ULXs such as NGC 5408 X-1, M 74 X-1 and NGC 6946 X-11. The first scenario is that the power-law flaring may be due to intermittent ejections and variable emission at the base of a jet. If so, these ULXs would be microquasars or microblazars; the accreting BH would still have to be rather massive ($M \gtrsim 40\,M_\odot$ for NGC 5408 X-1) to explain the non-beamed thermal disk emission, which provides a lower limit to the mass. Alternatively, the variability could be due to magnetic reconnections in the disk corona (Reeves et al. 2002). Finally, in the framework of the two-component accretion model (Chakrabarti & Titarchuk 1995), the power-law variability can be due to rapid changes in the sub-Keplerian (halo) accretion rate, $\dot{M}_{\rm h} \approx 0.5$–$1\dot{M}_{\rm Edd}$, at a constant disk accretion rate $\dot{M}_{\rm d}$, when $\dot{M}_{\rm d} \approx 0.1$–$0.5\dot{M}_{\rm Edd}$ (corresponding to the transition regime between the "canonical" hard and soft states).

5 CONCLUSIONS

ULXs are likely to contain different physical types of sources, in terms of BH mass, age, mechanism of formation and geometry of emission. We have briefly discussed some possible subclasses, reviewing the properties of a sample of ULXs recently observed by *Chandra* and *XMM-Newton*. Sources with an isotropic X-ray luminosity up to a few times $10^{39}\,{\rm erg\,s^{-1}}$ are consistent with bright X-ray binaries (in particular, young high-mass X-ray binaries in a star-forming region) containing a stellar-mass BH, in the same mass range as those inferred for Milky Way BH candidates. BH masses ≈ 50–$100\,M_\odot$ are required to explain a group of sources with X-ray luminosities ≈ 1–$2 \times 10^{40}\,{\rm erg\,s^{-1}}$. We speculate that they, too, could be the end product of single stellar evolution, in metal-poor environments. Only a handful of sources so far are strong candidates for the intermediate-mass BH class ($M \gtrsim 500 M_\odot$). Coalescence of smaller bodies in the cores of young super star clusters and nuclear star clusters are possible mechanisms of formation for intermediate-mass BHs; this scenario may apply to the brightest ULX in M 82 (Portegies Zwart et al. 2004). However, most of the brightest ULXs do not reside in clusters, and may have been formed via other processes. Finally, we have reviewed a sub-sample of ULXs which exhibit short-term variability and flaring in their Comptonised (power-law) emission component, and we have briefly discussed possible interpretations.

While we expect the number of ULXs in the high-mass X-ray binaries subclass to be proportional to the star-formation rate, there is mounting evidence that the brightest sources are preferentially found in colliding or tidally interacting systems. It is not yet clear whether star formation triggered by molecular cloud collisions can allow the formation of very massive stars, or whether there is another mechanism at play there: for example, the accretion or infall of primordial BHs from the galactic halo towards gas-rich parts of a galaxy, or the accretion and subsequent tidal stripping of satellite dwarfs with a nuclear intermediate-mass BH. Multiwavelength observations will be necessary to disentangle the various subclasses of ULXs: for example, radio detections would identify microquasars and microblazars; infra-red surveys might allow us to find the reprocessed radiation from anisotropic X-ray sources not oriented along our line of sight (i.e., sources that would not be identified as ULXs); optical studies of X-ray ionized nebulae can constrain the total luminosity from the central sources.

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