Hierarchical Merging, Ultraluminous and Hyperluminous X-ray Sources

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ABSTRACT
Various arguments strongly suggest that the population of ultraluminous X-ray sources (ULXs: apparent X-ray luminosity $> Eddington$ limit for $10M_\odot \simeq 10^{39}$ erg s$^{-1}$) in nearby galaxies are mostly stellar–mass X-ray binaries in unusual evolutionary stages. However there are indications that the very brightest systems may be difficult to explain this way. Accordingly we consider the class of hyperluminous X-ray sources (HLXs) (i.e. those with apparent bolometric luminosities $\gtrsim 10^{41}$ erg s$^{-1}$). Because this class is small (currently only the M82 object is a secure member) we do not need to invoke a new formation mechanism for its black holes. We explore instead the idea that HLXs may be the nuclei of satellite galaxies captured during hierarchical merging. The observed correlation between AGN and tidal interactions implies that HLX activity would switch on during passage through the host galaxy, close to pericentre. This suggests that HLXs should appear near the host galaxy, be associated with star formation, and thus possibly with ULXs.

Key words: accretion, accretion discs – black hole physics, stars: formation – galaxies, starburst – galaxies: formation – X-rays: binaries

1 INTRODUCTION
In recent years observations of external galaxies have revealed a significant population of non–nuclear X–ray sources whose apparent X–ray luminosities exceed the Eddington limit for a $10M_\odot$ black hole, i.e. apparent $L_X > 10^{39}$ erg s$^{-1}$. Many of these ultraluminous X-ray sources (ULXs) are seen to vary significantly, ruling out the possibility of superpositions of fainter sources. Several authors (see Colbert & Miller 2005, for a recent review) have suggested that ULXs might contain intermediate–mass black holes (IMBHs), with masses higher than those resulting from current stellar evolution (so that the apparent luminosity becomes sub–Eddington) but still below the supermassive values found in active galactic nuclei.

Such a large population of IMBHs clearly requires a new formation mechanism distinct from the familiar ones of normal stellar evolution and supermassive black hole growth in galactic centres, and there have been several suggestions for such mechanisms. For example primordial (Population III) stars devoid of metals may have formed such objects in the early history of the Galaxy (Madau & Rees 2001). Alternatively, IMBHs might be born in dense star clusters, either as the result of mergers of stellar–mass black holes (Miller & Hamilton 2002), or of stellar mergers on a timescale too short for nuclear evolution (Gürkan, Freitag, Rasio 2004; Portegies Zwart et al. 2004; Hopman, Portegies Zwart & Alexander 2004). However there are objections to all of these suggestions. Primordial IMBHs need to find themselves non–primordial reservoirs (probably stars) to accrete from. Black–hole mergers are subject to gravitational radiation recoil which probably ejects them from the cluster (Merritt et al. 2004; Madau & Quataert 2004) before the mass can grow significantly, and stellar mergers may provoke significant mass loss which limits mass growth.

Here we take a different view. In the next Section we summarize the observational arguments why the majority of ULXs are probably stellar–mass X–ray binaries rather than accreting IMBHs. However there remain a few very bright sources where there may be significantly higher masses. Since this group is small, there is no compelling reason to invoke a new formation mechanism for its members. Accordingly we consider the possibility that these black holes are formed in the second way already familiar to us, i.e. in the centres of galaxies.

2 STELLAR–MASS OR INTERMEDIATE–MASS BLACK HOLES?
Here we summarize the evidence that ULXs are in the main stellar–mass X–ray binaries rather than IMBH. The X–ray luminosity function of nearby galaxies, normalized by star–formation rate, shows no break at $L_X \sim 10^{39}$ erg s$^{-1}$ (Grimm et al. 2003). This strongly suggests that most ULXs are simply X–ray binaries in some unusual shortlived phase. Some stellar–mass X–ray binaries, e.g. GRS 1915+105 (see Done et al. 2004; Belloni et al. 1977a, b) are indeed observed to radiate at apparent luminosities above their Eddington limits. The X–ray spectral temperatures $\sim 1 \sim 2$ keV...
are more easily compatible with stellar–mass than intermediate–mass black holes. The very strong association between ULXs and induced star formation epitomised by the antennae (Fabbiano et al. 2003, 2004) and Cartwheel galaxies (Gao et al. 2003) is not easy to explain in IMBH models. In particular (King 2004), the spreading ring of star formation seen in the Cartwheel requires at least 300 ‘dead’ IMBHs to have formed inside it, demanding \( \geq 10^4 M_\odot / \eta \) in clusters if IMBHs formed in them, where \( \eta \) is the efficiency for an IMBH to find a companion. These number increase considerably if either the distribution of IMBH or companion stars grows exponentially within the ring, and are in any case underestimates unless we are observing at a special epoch where the ring has passed the last few IMBH and there are no more at larger radii. (The argument in King (2001) that ULXs containing IMBH must be largely transient, thus raising the numbers by a further factor (duty cycle)\(^{-1} \geq 10\), does not hold if the companions are sufficiently massive.) Finally, many ULXs are observed just outside star clusters (Kaaret et al. 2004) compatible with supernova kicks for stellar–mass black holes, but not with IMBH formation in the cluster.

In light of some of this evidence King et al. (2001) suggested instead that most ULXs are high–mass X–ray binaries in which the donor star is initially more massive than the black hole and fills its Roche lobe. As a result mass transfer is on a short (thermal) timescale, and thus super–Eddington. Population synthesis fills its Roche lobe. As a result mass transfer on the star’s nuclear time is also high enough to cause disc warping (Pringle 1996) or other forms of scattering of matter, which spreads (Begelman 2002) or because it becomes super–Eddington at large disc radii (Shakura & Sunyaev 1973). In all three cases, the mechanism by which accretion switches on in AGN

\[ L_E = 4.4 \times 10^{39} M_{20} \text{ erg s}^{-1} \]  

(1)

where \( M_{20} \) is the black hole mass in units of \( 20 M_\odot \). Hence stellar–mass models can explain ULX bolometric luminosities up to a value

\[ \sim 4 \times 10^{40} \text{ erg s}^{-1} \]  

(2)

without real difficulty.

3 ULXS AND HLXS

The observational considerations summarized above strongly suggest that most ULXs are probably stellar–mass X–ray binaries in unusual phases. However King et al. (2001) emphasize that these kinds of population argument cannot rule out the possibility that a few systems might contain IMBHs. In particular, the ULX in M82 (Matsumoto et al. 2001; Kaaret et al. 2001) is very bright (\( L_X \sim 10^{41} \text{ erg s}^{-1} \)) for stellar–mass models. There are also a number of interesting, although not clinching, arguments that suggest a more exotic origin for the very brightest ULXs (for a review see Colbert & Miller 2005). To avoid confusion we therefore follow Gao et al. (2003) and consider *hyperluminous X–ray sources* (HLXs) as those with apparent \( L_X \geq 10^{41} \text{ erg s}^{-1} \). To date, the only secure member of the HLX class is the M82 object. Although the brightest of the Cartwheel sources formally exceeds the defining limit, there is as yet no demonstration (e.g. of variability) which would firmly rule out a superposition of fainter sources. We retain the designation ULX for systems with lower apparent \( L_X \). We note that the luminosity of the HLX class is comparable with that of the intrinsically faintest active galactic nuclei (AGN).

Accepting that most if not all ULXs are stellar–mass binaries leaves us to explain the HLXs. The incidence of this class is at most one per several galaxies. Accordingly, finding a model for it is a much more tractable task than inventing a new model for the entire ULX class. Indeed Occam’s razor suggests that we should not look for new ways of making and feeding black holes, but instead consider ways of using the black holes we already know of.

4 HLXS AND HIERARCHICAL MERGING

Black hole formation and feeding is well established in two contexts:

(i) stellar–mass binaries, and

(ii) the centres of galaxies.

By hypothesis we are abandoning attempts to explain HLXs (as opposed to ULXs) in terms of stellar–mass black holes, so we can only use (ii). The obvious possibility to consider is that the hierarchical merger picture of structure formation (White & Rees 1978) predicts that in the present Universe, large galaxies have captured between 10 – 100 dwarf satellite galaxies. If a sufficient fraction of these satellites have retained their central black holes, and the attendant structure such as the dense star clusters probably implicated in X–ray activity, we may expect some of them to become active and appear as HLXs from time to time. In the simplest picture of sub–Edington accretion and isotropic X–ray emission, any black hole of mass \( M_{BH} \gtrsim 170 M_\odot \) (for accretion of hydrogen–rich matter) is a candidate for explaining HLXs, provided it can be fed at a rate \( \sim 10^{-5} M_\odot \text{ yr}^{-1} \).

This picture offers a straightforward explanation for the required black hole mass. The observed \( M_{BH} - \sigma \) relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Merritt & Ferrarese 2001) suggests that even a dwarf spheroidal with velocity dispersion \( \sim 20 \text{ km s}^{-1} \) would have \( M_{BH} \sim 10^4 M_\odot \). We note that explanations of the \( M_{BH} - \sigma \) relation in terms of self–limited black hole growth during galaxy formation (Silk & Rees 1998; King 2003) work independently of the value of \( \sigma \).

The mechanism by which accretion switches on in AGN is not yet well understood, and the same must hold for
the satellite nuclei we consider (for discussions see e.g. Taniguchi 1999; Cavaliere & Vittorini 2000; Kewley & Dopita 2003; Corbin 2000; Virani, De Robertis & VanDalfsen 2000; De Robertis, Yee & Hayhoe 1998; and references therein). There has been considerable discussion of the idea that the activity results from the capture and disruption of a small satellite galaxy. In this paper we investigate what consequences this idea might have for HLXs.

The satellite galaxies must have very eccentric orbits about the host galaxy. Only those approaching close to the centre of the host will feel strong tides. Deduced HLX accretion rates consume a star in only $10^6 - 10^7$ yr, short compared with the orbital timescale near pericentre. So any activity must necessarily occur only when the satellite is very close to the centre of the host galaxy. Moreover, the passage of the satellite through the host must trigger star formation (Mihos & Hernquist 1994), as spectacularly observed in the Cartwheel (Gao et al. 2003). This kind of activity leads in turn to ULX formation on a timescale $\sim 10^7$ yr (cf. King 2004). Thus our picture naturally predicts that HLXs occur near their host galaxy, and may be accompanied by starburst phenomena such as ULXs.

### 4.1 How close to the host do we expect HLXs?

In order to answer this question, we need to know how the satellite nucleus is activated. Since the mechanisms responsible for feeding AGN are not well understood, we cannot make any precise statements. However, since large impact distances are much more likely, it is clear that a mechanism which works with smaller tides is preferred.

If the satellite has any remaining gas, it may be channeled to the nuclear region either directly by the tides due to the host galaxy or by a stellar bar in the satellite the formation of which was triggered by the flyby. However, dwarf galaxies generally host little gas. Alternatively, the tidal forces may push several satellite stars onto radial orbits, so that they will either feed the BH directly or stir the nucleus sufficiently to activate a dormant accretion disk. Finally, the BH may feed directly on the gas or stars of the host galaxy.

We now estimate the impact distance $R$ required for the tidal forces to generate significant perturbation to the central region of the satellite. The tidal force generated at projected distance $x$ from the centre of the satellite which is at impact distance $R$ from the centre of the host is

$$F_t \approx \frac{x \sigma_s^2}{R^2},$$

where $v_h$ is the circular speed of the host. For an encounter with velocity $V$, this force acts during a time $\Delta t \sim 2R/V$ and, according to the impulse approximation, generates a velocity change $\Delta v \sim F_t \Delta t = 2x \sigma_s^2 / RV$. This velocity change affects only stars for which $\Delta t > t_{\text{dyn}}$; otherwise the tidal force changes are adiabatic. If the satellite dwarf galaxy has a central (1D) velocity dispersion $\sigma_s$ and core radius $r_s$, then the dynamical time in its centre is $t_{\text{dyn}} \sim 2r_s / \sigma_s$ and the tidal shock is impulsive for all stars if

$$R < \frac{r_s V}{\sigma_s}. \tag{3}$$

We may now estimate the relative change of the kinetic energy of the satellite core (assuming impulsive shock for all stars)

$$\frac{\langle \Delta E \rangle}{E} = \frac{\langle (\Delta v)^2 \rangle}{2M \sigma_s^2} \leq \frac{4}{15} \left( \frac{r_s v_h}{R} \right)^2 \tag{4}$$

where we have used $\langle x^2 \rangle = r_s^2 / 3$ for a near homogeneous density core. The relative change $\langle (\Delta E)^2 \rangle / E^2$ is even a factor 2 larger. If we now assume that the encounter occurs at a distance as given by equation (3), we find

$$\frac{\langle (\Delta E)^2 \rangle}{E^2} \sim \frac{8}{15} \left( \frac{v_h}{V} \right)^4. \tag{5}$$

For typical values of $v_h \sim 200 \text{ km s}^{-1}$ and $V \sim 500 \text{ km s}^{-1}$, the right-hand side of equation (5) amounts to only 1.4%. Thus, the condition that the shock is impulsive for all stars does not necessarily mean that it is strong. For the shock to be strong ($\langle (\Delta E)^2 \rangle / E^2 \gtrsim 10\%$), we require

$$R \lesssim 2 \frac{r_s v_h^2}{V \sigma_s}. \tag{6}$$

If we assume $r_s \sim 100 \text{ pc}$, $\sigma_s \sim 20 \text{ km s}^{-1}$ and values for $v_h$ and $V$ as used above, we find $R \lesssim 1 \text{ kpc}$ for the tidal forces to significantly perturb the inner regions of the satellite galaxy.

Clearly, at larger distances from the satellite centre, the tidal perturbations are stronger and likely to be disruptive. We should note that close to the host any direct observations of the stellar body of the satellite are difficult if not impossible.

The one clear member of the HLX class, namely the M82 source, is about 200 pc from the nucleus, in agreement with our rough estimate above. There are two other objects which come into consideration as HLXs. The ULX in NGC2276 (Davis & Mushotzky 2004) has a 0.5–2.0 keV luminosity of $3.2 \times 10^{40} \text{ erg s}^{-1}$, extrapolated to a 0.5–10 keV luminosity of $1.1 \times 10^{41} \text{ erg s}^{-1}$. The source is seen to vary between $2.2 \times 10^{40} \text{ erg s}^{-1}$ and $4.4 \times 10^{40} \text{ erg s}^{-1}$ in the 0.5–2.0 keV band, suggesting a varying source of at least $5.5 \times 10^{40} \text{ erg s}^{-1}$. This source is in the outer disc of the galaxy. The colliding galaxy NGC7714 has a source with luminosity $7 \times 10^{40} \text{ erg s}^{-1}$ in XMM data (Soria & Motch 2004), extrapolated to a bolometric luminosity of $\sim 1.5 \times 10^{41} \text{ erg s}^{-1}$. The source is observed to vary by a factor 2, suggesting a luminosity of at least $7.5 \times 10^{40} \text{ erg s}^{-1}$. This source is at the junction of the tidal tail from the colliding galaxy NGC7715 with the collisional star formation ring of NGC7714, and is about 4 kpc from the nucleus of the latter. It is not itself in a region of star formation. Both objects are formally below our (slightly arbitrary) luminosity limit for HLXs.

### 4.2 The estimated frequency of HLXs

We may try to estimate the frequency of HLXs per host galaxy from the frequency of satellite galaxies close to the centre of the host. Simulations of hierarchical structure formation consider dark matter only, and usually find the number density of subhaloes to be constant for the inner regions of a host halo (e.g. Diemand, Moore & Stadel 2004). From the high-resolution galaxy halo simulations of these authors, we estimate $\sim 10^{-6}$ kpc$^{-3}$ subhaloes with masses $\sim 10^{-4}$ that of their host. If a distance of $\sim 1$ kpc is necessary to trigger an HLX, we get an HLX frequency of $\sim 10^{-6} - 10^{-5}$ per host. This estimate is rather crude because the simulations do not include the galaxies (stars and gas) and their influence on the dynamics of sub-structure.

One might instead try to use observational constraints on the number of satellite galaxies in the close vicinity of their hosts. However, for distances as close as required here observations are incomplete, and there is very little information in the literature. If we assume that structure is scale–free as in CDM simulations, (e.g., Carlberg, Yee & Ellinson 1997; Łokas & Mamon 2003) extrapolating from the number density of galaxies in clusters suggests a number of satellites per galaxy some 100 to 1000 times larger.
We thus conclude that the frequency of HLX per host galaxy lies somewhere between $\sim 10^{-6}$ and $10^{-2}$. Our limited knowledge of substructuring on kpc scales prevents a more accurate estimate. Observations of HLXs, if indeed caused by IMBHs at the centres of satellite galaxies, may prove useful for understanding both the formation of satellite galaxies and the triggering of AGN.

5 DISCUSSION

Our explanation of the brightest non-nuclear X–ray sources has followed two stages; first, the recognition that the ULX population ($10^{39}$ erg s$^{-1} \lesssim L_X \lesssim 10^{41}$ erg s$^{-1}$) is mainly a collection of stellar–mass binaries in unusual states; and second, the identification of the HLX class ($L_X \gtrsim 10^{41}$ erg s$^{-1}$) as a much smaller group of possible higher–mass systems. The resulting low incidence of HLXs per galaxy led us to explore the idea that they could represent the nuclei of some of the satellite galaxies predicted by hierarchical merging. The observed correlation between AGN and tidal interactions suggests that HLX activity is switched on by passage through the host galaxy, close to pericentre. This suggests that HLXs should be associated with star formation and thus possibly with ULXs. Further tests of our idea exploring the connection with the merger history of galaxies may have to wait for the accumulation of a larger sample of HLXs.

IMBH models of the entire ULX class inevitably have to postulate a new mode of black hole formation and a new method of feeding the hole. By separating the small HLX class from the majority of ULXs we can instead confine ourselves to formation and feeding processes which are well established from observations of X–ray binaries and AGN. In addition, the proposed link to hierarchical merging suggests that HLX may have something to tell us about galaxy formation.

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