Ultraluminous X-ray sources and star formation

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ABSTRACT

Chandra observations of the Cartwheel galaxy reveal a population of ultraluminous X-ray sources (ULXs) with lifetimes ≲ 10^7 yr associated with a spreading wave of star formation which began some 3 × 10^8 yr ago. A population of high-mass X-ray binaries provides a simple model: donor stars of initial masses M_2 ≳ 15 M_⊙ transfer mass on their thermal time-scales to black holes of masses M_1 ≳ 10 M_⊙.

For alternative explanations of the Cartwheel ULX population in terms of intermediate-mass black holes (IMBHs) accreting from massive stars, the inferred production rate ≳ 10^{-6} yr^{-1} implies at least 300 IMBHs, and more probably 3 × 10^4, within the star-forming ring. These estimates are increased by factors of η^{-1} if the efficiency η with which IMBHs find companions of ≳ 15 M_⊙ within 10^7 yr is < 1. Current models of IMBH production would require a very large mass (≳ 10^{10} M_⊙) of stars to have formed new clusters. Further, the accretion efficiency must be low (≲ 6 × 10^{-3}) for IMBH binaries, suggesting super-Eddington accretion, even though intermediate black hole masses are invoked with the purpose of avoiding it.

These arguments suggest either that, to make a ULX, an IMBH must accrete from some as yet unknown non-stellar mass reservoir with very specific properties, or that most if not all ULXs in star-forming galaxies are high-mass X-ray binaries.

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

1 INTRODUCTION

Recent observations of external galaxies have uncovered a population of ultraluminous X-ray sources (ULXs: see Makishima et al. 2000, and references therein) with apparent luminosities well above the Eddington limit L_{Edd} for a stellar-mass black hole (or neutron star). Several authors have suggested that ULXs reveal accretion on to intermediate-mass black holes (IMBHs), with masses between stellar values and the > 10^6 M_⊙ inferred for active galactic nuclei (e.g. Colbert & Mushotzky 1999; Ebisuzaki et al. 2001).

An alternative view (King et al. 2001) holds that ULXs are a bright, short-lived, but common phase of stellar-mass X-ray binary evolution. There is observational support for this, as Grimm, Gilfanov & Sunyaev (2002, see table 1) show that apparently super-Eddington episodes are not uncommon in stellar-mass binaries. For example, the high-mass system V4641 Sgr had a luminosity in the Chandra X-ray band of 3.3 × 10^{39} erg s^{-1}, despite a measured black hole mass of 9.6 M_⊙. The high apparent luminosities of the ULXs may either result from viewing a significantly anisotropic radiation pattern at a favourable angle, or be genuinely super-Eddington (cf. Shaviv 1998, 2000; Begelman 2002), or both. This form of ‘beam- ing’ need not involve relativistic effects, although Markoff, Falcke & Fender (2001) and Koerding, Falcke & Markoff (2002) have suggested that Doppler boosting in a relativistic jet could explain the high luminosities of ULXs.

A major clue to the nature of ULXs comes from the discovery of seven ULXs in Chandra observations of the Antennae (Fabbiano, Zezas & Murray 2001). These strongly indicate a connection with recent massive star formation. IMBH models for ULXs (Miller & Hamilton 2002; Gurkan, Fretag & Rasio 2003) incorporate this by considering dense star clusters. These provide promising sites both for IMBH formation and for capturing stellar companions to provide the accretion source. The X-ray binary picture (King et al. 2001) has a natural connection with massive star formation since it invokes a phase of high-mass X-ray binary (HMXB) evolution. This is the thermal-time-scale mass transfer that must follow the familiar wind-fed HMXB phase, as is probably seen in SS433 (King, Tamm & Begelman 2000). [Note that ULXs are also seen in elliptical galaxies; in the X-ray binary picture these are bright, long-lasting outbursts of soft X-ray transients such as GRS 1915 + 105 (cf. King 2002).]

The spectacular recent Chandra observation of the Cartwheel galaxy (Gao et al. 2003) gives the most graphic illustration so far of the connection between ULXs and star formation. The Cartwheel is well known as a site of recent massive star formation. Most of this
is in a crisp ring expanding about the point where an intruder galaxy plunged through the gas-rich disc of the galaxy about $3 \times 10^4$ yr ago. The Chandra image reveals more than 20 ULXs (defined as $L_{0.5-10\text{keV}} \gtrsim 3 \times 10^{39}$ erg s$^{-1}$). Most of these (about 80 per cent of the entire X-ray emission from the galaxy) are in the dominant star-forming sites located precisely in the southern quadrant of the ring. Each source is brighter ($L_{0.5-10\text{keV}} \gtrsim 6 \times 10^{39}$ erg s$^{-1}$) than the most luminous ULXs seen in the Antennae. The lack of radial spread in these source positions, together with the known expansion velocity of the ring, shows that these ULXs must have ages $\lesssim 10^7$ yr (Gao et al. 2003).

These observations clearly place very tight constraints on models for ULXs. I examine these below.

2 ULXS AND STAR FORMATION

King et al. (2001) examined the statistics of ULX formation, independently of the adopted model. If $n$ is the number of currently observed ULXs in some region of a galaxy, they showed that the total number of potentially active ULXs in this region is actually

$$N = \frac{n}{bd},$$

(1)

where $b \lesssim 1$ is the beaming (radiation anisotropy) factor, and $d \lesssim 1$ is the duty cycle. If for example $bd \ll 1$, most ULXs would either be radiating in directions away from our line of sight, or currently in low states. In the Cartwheel we can say more: the dearth of observed ULXs inside the expanding star-forming ring means that most have now ‘died’, i.e. ceased accreting. The total number of dead ULXs inside the ring is thus

$$N_{\text{tot}} = N \frac{t_{\text{life}}}{t_{\text{life}}} = \frac{n}{bd} \frac{t_{\text{life}}}{bd} \geq \frac{300}{bd},$$

(2)

where $t_{\text{life}} \sim 3 \times 10^4$ yr is the time since the wave of star formation began to propagate outwards, $t_{\text{life}} \lesssim 10^7$ yr is the ULX lifetime in the ring, and I have used equation (1) with $n \sim 10$. This estimate could be still larger if, as usual, the gas surface density in the pre-intrusion galaxy increased exponentially towards the dynamical centre.

Secondly, King et al. (2001) showed that the mass-transfer lifetime of a ULX is

$$\tau = 10^6 \frac{m_2 a}{bd L_{40}} \text{yr},$$

(3)

Here $m_2$ is the initial mass (in $\odot$) of the reservoir from which the compact object accretes, $a \leq 1$ is the acceptance rate, i.e. the fraction of transferred reservoir mass actually gained by the accretor, and $L_{40}$ is the apparent (isotropic) bolometric luminosity of the ULX in units of $10^{40}$ erg s$^{-1}$. Dividing (3) into (1) gives the important result that the required birthrate of ULXs is independent of both anisotropy $b$ and duty cycle $d$ (King et al. 2001). The Cartwheel observations now imply a further pair of constraints. Clearly, one of these is that the mass-transfer lifetime must be smaller than the inferred ULX lifetime, i.e. $\tau < t_{\text{life}}$. Using (3) this gives

$$m_2 < 10 \frac{bd}{a} L_{40}.$$  

(4)

If the mass reservoir for the ULX is a binary companion star, we must also require that its main-sequence lifetime is less than $t_{\text{life}}$. Otherwise ULXs with initially wide separations would start mass transfer only long after the wave of star formation had passed. This would lead to a roughly uniform distribution of ULXs inside the ring, quite unlike the sharp concentration at the ring edge actually observed. This constraint translates directly into a limit on the initial companion mass

$$m_2 \gtrsim 15$$

(e.g. Iben 1967). With (4) this gives

$$a < 0.6 bd L_{40}.$$  

(6)

This inequality must be satisfied by a comfortable margin to avoid the requirement that all ULXs should form with a narrow range of companion masses near 15 $\odot$. We can now apply the constraints (2), (5) and (6) to the two types of models for ULXs.

2.1 Stellar-mass ULXs

If the ULXs in the Cartwheel are stellar-mass binaries obeying the Eddington limit, we must have $b \lesssim 0.1$. Constraint (5) tells us that these systems must be HMXBs, as expected. This probably means that $d \sim 1$, so that (2) implies $N_{\text{tot}} \gtrsim 3000$.

This is quite reasonable for a population of HMXBs. Finally (6) gives

$$a \lesssim 0.06,$$

i.e. the accretion process must be very inefficient, with most of the mass lost by the companion failing to accrete on to the compact object. This requirement is easily satisfied for thermal-time-scale mass transfer: the mass-loss rate from the companion is $M_{\text{L}}/k_{\text{th}} \lesssim 10^{-3} M_\odot$ yr$^{-1}$, where $k_{\text{th}}$ is the Kelvin–Helmholtz time-scale, giving $a \lesssim 0.01$ for a 10-$\odot$ black hole accretor if the Eddington limit applies.

2.2 Intermediate-mass black hole ULXs

If the Cartwheel ULXs contain IMBHs accreting from massive stars we get a different set of constraints. Even without any assumptions about radiation anisotropy or duty cycle, (2) requires at least $N_{\text{tot}}$ = 300 inactive IMBHs within the star-forming ring. However Kalogera et al. (2003, see also King et al. 2001) show that all such IMBH binaries are likely to be transient, with accretion discs subject to the standard thermal–viscous instability. This by definition means that the duty cycle $d < 1$. Disc theory does not yet provide quantitative estimates of $d$, however, observed disc-unstable systems have $d \lesssim 10^{-2}$, and there is considerable observational evidence (Ritter & King 2001) to suggest that long-period systems with large discs, as in these ULX binaries, have even smaller duty cycles $d \lesssim 10^{-3}$. We thus get from (2) the constraint

$$N_{\text{tot}} \gtrsim \frac{3 \times 10^4}{bd_{-2}},$$

(9)

where $d_{-2}$ is $d$ in units of $10^{-2}$. From (6) we get

$$a < 6 \times 10^{-3} bd_{-2},$$

(10)

3 DISCUSSION

I have considered the explanations of the ULXs of the Cartwheel galaxy in terms of stellar-mass and IMBH binaries. Section 2.1 suggests that a population of HMXBs offers a reasonable picture. These systems must accrete at super-Eddington rates, as expected in the thermal-time-scale mass-transfer phase. These rates in turn suggest possible lines of explanation for the high apparent luminosities. The accretors in these HMXBs must be black holes with typical masses.
$M_1 \gtrsim 10$ M$_\odot$, as Roche lobe overflow is dynamically rather than thermally unstable for initial mass ratios $M_1/M_2$ below some critical value (Webbink 1977; Hjellming 1989) which is probably of the order of 0.5 for the massive donors ($M_2 \gtrsim 15$ M$_\odot$) in these HMXBs. (Dynamical-time-scale mass transfer is ruled out as it would extinguish the binaries as X-ray sources.) Black hole accretors with $M_1 \gtrsim 10$ M$_\odot$ also satisfy the constraint that their progenitors must have lifetimes $\lesssim 10^7$ yr, whereas this is probably not true of neutron stars, for example.

Explanations of the Cartwheel ULXs invoking IMBHs accreting from massive stars run into problems. The required production rate $\sim 10^{-6}$ yr$^{-1}$ of IMBHs implies a minimum total $N_{\text{tot}}$ of $\gtrsim 300$, or more probably $\gtrsim 3 \times 10^4$, within the star-forming ring. Each of these IMBHs must have found a stellar partner of $\gtrsim 15$ M$_\odot$. If this process has efficiency $\eta < 1$ the above estimates of $N_{\text{tot}}$ increase by factors of $\eta^{-1}$, i.e. to $N_{\text{tot}} \gtrsim 3 \times 10^5$ $\eta^{-1}$. Models of IMBH formation in clusters (Miller & Hamilton 2002; Gürkan et al. 2003) predict that only one IMBH is produced by a typical cluster mass of $3 \times 10^5$ M$_\odot$. Hence if all the ULXs in the Cartwheel are assumed to be IMBHs this requires a mass $\gtrsim 10^{10} \eta^{-1}$ M$_\odot$ to have appeared in star clusters since the intrusion event, which seems unlikely. Finally it appears that the accretion efficiency $\alpha$ must be low ($\lesssim 6 \times 10^{-4}$) for IMBH binaries. Of course this is not implausible for transient outbursts in which the accretion rate is very high; however, it is perhaps disappointing to find super-Eddington accretion rates reappearing in a model specifically designed to exclude them.

Given these results, one should consider ways of rescuing the IMBH idea. There appear to be three main possibilities.

(i) Conditions at the current position of the star-forming ring may be highly unrepresentative of the region within it. This idea lacks plausibility, and would be completely ruled out if similar results were found in other galaxies.

(ii) IMBHs do not accrete from stars to make ULXs in starburst galaxies, but from some other kind of mass reservoir. There is no obvious candidate for this reservoir, and the constraints that accretion must occur at rates $\gtrsim 10^{-6}$ M$_\odot$ yr$^{-1}$ and shut off after $\sim 10^7$ yr are severe.

(iii) Most if not all of the ULXs found in regions of star formation are indeed HMXBs. However, there is currently no clinching argument against a small minority containing IMBHs, as all the arguments presented here refer to population rather than individual source properties.

This last idea appears the most plausible. It is supported by the work of Grimm, Gilfanov & Sunyaev (2003), who show that ULXs fit to the X-ray luminosity functions of nearby star-forming galaxies when these are normalized by the star formation rate.

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