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# Ultraluminous X-ray Sources: Bubbles and Optical Counterparts

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**Abstract.** Optical studies of ultraluminous X-ray sources (ULX) in nearby galaxies have turned out to be instrumental in discriminating between various models including the much advertised intermediate mass black hole hypothesis and various beaming scenarios. Here we report on ESO VLT and SUBARU observations of ULX that have revealed the parent stellar clusters with ages of some 60 million years in two cases. Thus we are able to derive upper limits of about 8 $M_\odot$ for the mass donors in these systems. The optical counterparts are dominated by X-ray heated accretion disks, and the discovery of the He II $\lambda$4686 emission line now allows to derive dynamical masses in these systems. Apparent radial velocity variations of 300 km/s have been detected in NGC 1313 X-2 which, if confirmed by further observations, would exclude the presence of IMBH in these systems.

**Keywords.** galaxies: individual (NGC 1313, Holmberg IX), ISM: bubbles, X-rays: galaxies, X-rays: binaries.

## 1. The enigma of ultraluminous X-ray sources

One of the most significant results from recent X-ray studies of nearby galaxies is the discovery of a number of non-nuclear point sources (Ultraluminous X-ray sources – ULX) with apparent (isotropic) X-ray luminosities of $10^{39}$–$10^{41}$ erg/s, a factor of 10–1000 times brighter than typical luminous X-ray binaries in our Galaxy.

From X-ray timing and spectral studies it is clear that ULXs are accreting compact objects. Therefore, their luminosity should not exceed the Eddington limit $L_{\rm E} = 1.3 \times 10^{38}$ M/$M_\odot$ erg/s. One possible explanation is that the accreting object powering an ULX is an intermediate-mass black hole (IMBH), with M $\sim 10^2$–$10^4$ $M_\odot$ (Colbert & Mushotzky 1999, Makishima *et al.* 2000, Miller, Fabian & Miller 2004). An alternative explanation is that the emission is beamed along the observer's line of sight, either by geometrical effects (King *et al.* 2001), or due to relativistic jets like in microquasars (Fabrika & Mesheryakov 2001), so that the true total luminosity does not exceed the Eddington limit of a stellar-mass black hole. Yet another possibility is that the accretor is a stellar BH genuinely emitting above the classical Eddington limit (Begelman 2002).

At the same time, one has to explain the high accretion rate (up to $\sim 10^{-6}$ $M_\odot$/yr) required by the inferred luminosities. Wind accretion (typical for high-mass X-ray binaries) or Bondi-type accretion from the interstellar medium are clearly too inefficient. It is more likely that the mass transfer occurs via Roche-lobe overflow from a donor star to the black hole. Stable, high mass transfer can proceed on a nuclear time scale ($\leqslant$ several $10^7$ yr), if the mass donor is massive – but not much more massive than the black hole (cf. Rappaport, Podsiadlowski & Pfahl 2005).

## 2. Bubble Nebulæ

An important piece of information for our understanding of ULX comes from the discovery of huge ionised bubble nebulæ around a significant fraction of unobscured ULX in nearby galaxies (Pakull & Mirioni 2002, 2003). It is even likely that all ULX sources are surrounded by such structures. Close to the X-ray source, we sometimes observe X-ray ionisation effects which in the case of Holmberg II X-1 has allowed to independently measure the (ionising) X-ray luminosity (Pakull & Mirioni 2002). The presence in the outer regions of strong [S II] and [O I] emission lines and of supersonic expansion speeds of 80-250 km/s derived from the width of H$\alpha$ emission show that (at least the outer parts of) the bubbles are shock-excited rather then photoionised.

Among the best-studied large ULX bubbles are MH 9-11 around Holmberg IX X-1 (cf. Grisé *et al.*, this symposium) and NGC 1313 X-2 which both have diameters of about 500 pc, i.e. they are much larger than supernova remnants.

One of the many interesting aspects of ULX bubbles is that we might estimate the kinetic energy involved in the ULX phenomenon. Two possibilities for bubble formation have been discussed: either they were formed in an explosive event with kinetic energy $E_0$ (possibly the SN explosion that created the compact component in the ULX), or they are being inflated by ULX stellar wind/jet activity with mechanical energy $L_w$. Assuming for simplicity that energy is largely conserved (Sedov-Taylor solution), we have for the SNR case

$$E_0 \approx 1.9\ 10^{52}\ erg\ R_2^3\ v_2^2\ n \qquad t_6 \approx 0.4\ R_2\ v_2^{-1} \tag{2.1}$$

and for the wind/jet case

$$L_w \approx 3.8\ 10^{39}\ erg\, s^{-1}\ R_2^2\ v_2^3\ n \qquad t_6 \approx 0.6\ R_2\ v_2^{-1} \tag{2.2}$$

Here $R_2$ is the radius in units of 100 pc, and $v_2$ is the expansion velocity in units of 100 km/s of a bubble having an age of $10^6$ $t_6$ yrs. The interstellar particle density, n, into which the bubble expands can be estimated from comparing the observed H$\alpha$ emission with the intensity $I_\alpha = 10^{-6}$ $I_{\alpha,-6}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ of a fully radiative shock (Dopita & Sutherland 1996):

$$n \approx 0.6\ cm^{-3}\ I_{\alpha,-6}\ v_2^{-2.4} \tag{2.3}$$

Straightforward application of these equations to ULX bubbles yields typical ages of $10^6$ yrs and densities in the range of 0.1–1.0 cm$^{-3}$. This results in very large energy/power requirements of $\sim 10^{52-53}$ erg for the SNR case, and $\sim 10^{39-40}$ erg s$^{-1}$ for continuous inflation. However, a SNR is likely to expand into a region of very low density that has previously been excavated by the stellar winds from an evolving cluster (see below) before hitting the walls of that 'superbubble'. In this way, energy requirements could well be ten times lower, and more akin to typical SN energies of $10^{51}$ erg. Another complication arises from the clumpiness of the interstellar medium which results in smaller shock velocities in the dense optically emitting clouds as compared to a higher velocity of the main shock in the intercloud medium. Taking into account this effect, Blair *et al.* (1981) estimated the kinetic of SNR to be:

$$E_0 \approx 4\ 10^{50}\ erg\ R_2^3\ n(SII) \tag{2.4}$$

where n(SII) is the density in the recombination zone behind the shock, as measured by the well-known forbidden [SII] line ratio. However, this method is not without severe problems either, as the energy calculated in this way appears to be positively correlated with the remnant diameter, an effect that may be related to the magnetic pressure in the dense clouds.

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As outlined below, we favour the possibility of ongoing inflation by stellar winds/jets which would require for reasonable mass loss rates $\leqslant 10^{-6}$ $M_{\odot}$/yr mildly relativistic ejection velocities akin to the famous v=0.26 c jets in SS 433. However, inflation into a cloudy medium would also lower the power requirements somewhat.

## 3. Clusters

Most massive stars are born in clusters or associations. Searching for such birthplaces of ULX thus opens the possibility to learn more about their ages and possible formation scenarios. For the relatively isolated ULX in Holmberg IX and in NGC 1313 X-2 we have been able to identify small faint clusters of stars that in each case are clearly associated with the ULX (cf. Grisé *et al.*, this symposium). Multicolour photometry and isochrone fitting yield ages of some 40–70 Myrs and total cluster masses of some $10^3$ $M_{\odot}$. Thus, all ionising O stars have already exploded a long time ago, implying again that the nebulæ cannot possibly be photoionized by stellar EUV continua. This has an important consequence for the mass donor component in the ULX: it cannot be more massive then about 8 $M_{\odot}$. Furthermore, if the bubble nebulæ indeed represent the remnants of the formation process of the ULX black holes, then these explosions (which took place about 1 Myr ago) have taken place in an advanced stage of cluster evolution, i.e. the progenitor stars of the ULX accretors would not have been much more massive then the current donors (i.e. $\leqslant$ 10 $M_{\odot}$). Such stars are of course not likely to become massive black holes.

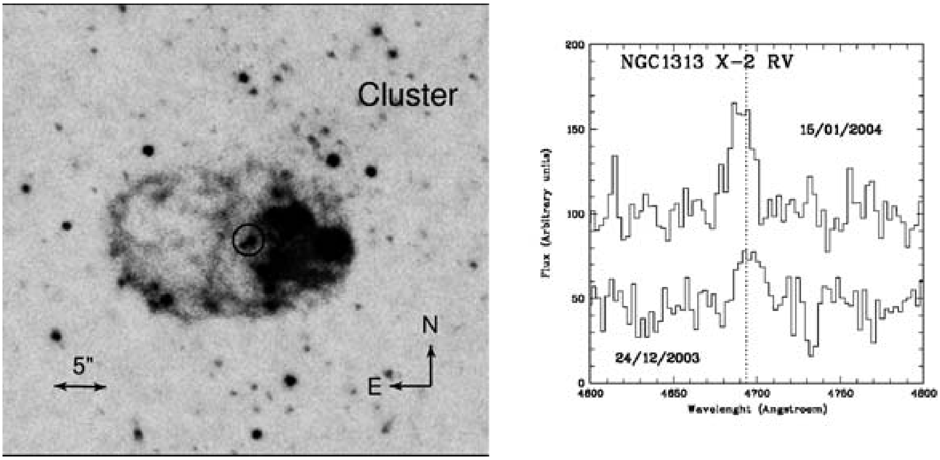


**Figure 1.**
*Left:* Multicolor image (including H$\alpha$) of the 400 pc diameter bubble around the ULX NGC 1313 X-2. The Chandra error circle includes a close pair of stars (star C in Zampieri *et al.* 2004). The N-W component is the optical counterpart.
*Right:* Blue range spectra of the counterpart taken 3 weeks apart. Most prominent is the He II $\lambda$4686 emission line which appears to have moved by 300 km/s.

We are therefore left with the hypothesis that the ULX nebulae represent Begelman *et al.* (1980) 'beambags' of jet inflation like the 'ears' in the (radio) nebula W 50 around SS 433.

## 4. Optical counterparts

The optical counterparts of ULXs Holmberg IX and NGC 1313 X-2 (see Fig. 1) have visual magnitudes of 22.9 and 23.4, respectively, and blue optical colors (B-V$\sim$0.0); at

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a distance of 3–4 Mpc this translates into $M_V \sim -5$. Optical spectra taken with the ESO VLT and with the SUBARU telescope reveal the presence of stellar He II λ4686 emission with equivalent widths of 10 and 18 Å, respectively. This high excitation line can be considered a hallmark of X-ray binaries, being formed in the X-ray heated disk around the compact component. In Galactic high mass X-ray binaries (such as the $L_X = 10^{38}$ erg/s systems Cen X-3, SMC X-1, LMC X-4, etc) the corresponding EWs are more than an order of magnitude smaller, attesting to their much smaller X-ray luminosities. Therefore, the presence of strong He II λ4686 emission in ULX might also be taken as strong evidence against the X-ray beaming scenarios mentioned earlier. We note by the way that a He II λ4686 emitting Wolf-Rayet star interpretation can be ruled out given the advanced age of the cluster.

Strong support for an accretion disk interpretation comes also from its position in the famous van Paradijs & McClintock (1994) $\Sigma - M_v$ diagram of low mass X-ray binaries (i.e. of X-ray ionised disks), at the very high-luminosity end of this relation. Here Σ is proportional to the optical light expected from an accretion disk that is heated by a given X-ray luminosity; we here have assumed a semi-detached binary of some 20 $M_\odot$ total mass.

The Right panel of Fig. 1 illustrates two observations of the NGC 1313 X-2 counterpart separated by about three weeks. Here the He II λ4686 emission appeared to have varied in radial velocity (RV) by about ∼300 km/s around the velocity of the local H I gas in the galaxy (dotted line). *If* this variation reflects real RV changes (as opposed to possible profile changes of the line having intrinsic FWHM ∼600 km/s), then the object in the center of the accretion disk cannot be very massive, i.e. one could rule out the presence of an IMBH.

We finally mention variations by ∼0.2 mag amplitude over 9 nights in our B band photometry of the optical counterpart of NGC 1313 X-2. However, no stricly periodic signal is seen, such as expected from ellipsoidal variations, and we ascribe these changes to variable X-ray heating of the accretion disk.

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**Discussion**

MACCARONE: The detection of moving emission lines is very exciting but I think one should be cautious about interpreting them as disk lines rather than as possible mixtures of disk lines and narrow Bowen fluorescence components from the irradiated surface of the donor star, as used e.g. by Hynes *et al.* to measure the rotation curve of GX 339-4.

PAKULL: Narrow components are fainter than broad components, in most or all cases, and trace the motion of the accretion disk in most or all cases.

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