Abstract. A significant fraction of ultraluminous X-ray sources appear to be embedded in observable ionized nebulae that take the form of large, several 100 pc diameter interstellar bubbles. Here we review optical observations of these bubbles, their importance for our understanding of the nature of ULXs, the energetics involved and their formation and evolution. Among the results obtained are new arguments against conventional superbubble scenarios and hypernova remnants, and we present the case in favour of ULX-wind/jet driven bubbles. We report the discovery of new ULXs in very large SNR candidates in nearby galaxies, and finally present an image of a triple X-ray source coincident with the radio-bright bubble S26 in the galaxy NGC 7793 which appears to be a clone of the microquasar SS433/W50 system.

1. Introduction

In recent years it has become obvious that the nature of UltraLuminous X-ray sources (ULXs) in nearby galaxies cannot be elucidated from X-ray observations alone. In particular, the question whether or not ULXs harbour specimen of the well-advertised intermediate mass black holes (IMBH) lying in between the stellar and the AGN variety has stimulated numerous investigations. Other ideas put forward to overcome the classical Eddington luminosity limit \(10^{39}\) \(L_\odot/(10 M_\odot)\) erg/s include beamed emission into our line of sight - either geometrically or relativistically - and highly Super-Eddington accretion rates, presumably coupled with the occurrence of massive outflows from the systems.

Optical follow-up observations of nearby ULXs have in many cases revealed the presence of extended ionized nebulae \(\text{(Pakull \\& Mirioni 2002, 2003)}\) and of stellar associations \(\text{(Grisé \textit{et al.} 2006, 2008)}\) that both can be used to derive important constraints on possible formation scenarios, ages and on the photon- and mechanical luminosities involved. X-ray photoionisation arguments have previously been used to exclude strongly-beamed X-ray emission from the very luminous ULX in Holmberg II. In this contribution we will mainly focus on the effects of mechanical power that is released by ULXs and is injected into the ISM.

2. Photoionisation versus Shock Excitation

Galactic massive X-ray binaries are generally not located in regions of high interstellar density. That is why observable X-ray photoionized nebulae \(\text{(XIN)}\), as, e.g. N 159F around the black hole candidate LMC X-1 \(\text{(Pakull \\& Angebault 1986)}\) are rare. The key observation which indicated that X-ray emission is largely responsible for the high ionization structure of N 159F came from the detection of extended nebular He II \(\lambda 4686\) recombination radiation.
This line is not present in normal H II regions because even the hottest O stars do not emit significant amounts of $\text{He}^+$ Lyman continuum photons that could ionize observable He III regions (exception: hot Wolf-Rayet stars with unusually weak winds). An even more powerful XIN is embedded in the star forming region HSK 70 located in the M81 group dwarf galaxy Holmberg II. This He III region is excited by the bright ULX in that galaxy (Pakull & Mirioni 2002) and allows, through Zanstra-type $\lambda$4686 photon counting arguments, to establish the flux of the ionizing $\text{He}^+$ Lyman continuum to be compatible with the $10^{40}$ erg/s isotropic luminosity measured with X-ray telescopes. In other words, optical observations have been employed to exclude the possibility that the source is beamed towards us. Possibly, a further XIN example is provided by the $\lambda$4686 emitting 30 pc diameter supernova remnant candidate MF16 around the ULX NGC 6946 X-1 (Abolmasov et al. 2007). However, in this case, the observed expansion velocity is quite high, $\sim$ 230 km/s (Dunne, Gruendl & Chu 2000), which implies that shock-ionization must play a key role here.

We have previously commented on the similarity of optical spectra displayed by XIN on the one hand and by shock excited gas on the other hand. The situation is analogous to the ambiguity in the interpretation of spectra of the LINER subgroup of AGN and of extended emission line regions (EELR), where both shocks and ionisation by hard non-stellar continua have been put forward to explain their characteristics.

3. Structure and Energetics of Large ULX Bubbles

It came as quite a surprise when it was realized that a significant fraction of ULXs are surrounded by large bubble-like nebulæ (hereafter ULXB) of some 200-500 pc diameter. Their optical spectra are reminiscent of the generally more than 10 times smaller supernova remnants, i.e. shock-ionized gas combining strong emission from low-ionisation species like [OII]λ6300 and [SII]λ6716, 31 with emission from more highly ionized gas, as e.g. [OIII]λ5007. The latter forbidden transition is excited only at sufficiently high shock speeds, $v_s$, and the diagnostic $\lambda$5007/$\lambda$H$\alpha$ ratio varies by a factor $\geq 10$ in the very narrow critical range of 80-100 km/s (somewhat dependent on the pre-shock conditions) before leveling off at about unity at higher velocities (Dopita et al. 1984).

Although the ULX counterparts often appear to be part of moderately rich stellar associations (Grise et al. 2006, 2008), the clusters are mostly too old ($\geq$20-40 Myrs) to photoionize observable H II regions. Naturally, even $v_s \sim$ 100 km/s shocks become unobservable once the IS density drops below, say, $\sim$ 0.3 cm$^{-3}$, when the $\lambda$H$\alpha$ recombination line intensity behind the shock – which is proportional to the preshock density $n$ (not $\sim n^2$!) – drops below a threshold where fluctuations of the diffuse galactic background emission become important.

Optical observations of ULX bubbles show an amazing variety of filamentary and shell morphologies, as well as varying nebular excitation displayed by diagnostic emission line ratios. This is well illustrated by the huge, 500 pc diameter shell-like ULXB MH 9-11 around Holmberg IX X-1 (Fig. 1) first described by Miller (1995), and which also displays expansion velocities in the critical range. The image underlines the markedly different OIII vs $\lambda$H$\alpha$ morphology in the bubble and shows a green-coded $\lambda$5007 dominated extension towards the South-East (MH 11). A possible explanation is in terms of shocks that propagate into a pre-ionized medium and which at the same time are back-illuminated by the ionizing radiation of the ULX; see, e.g. Dufour (1989). This prevents the formation of a full recombination region, and the emission is characteristic of an uncomplete shock (Raymond et al. 1988).

Age and energetics of ULXB can readily be estimated from the diameters and expansion velocities of these structures, depending on whether we assume a SNR like nature or a continuously inflated wind/jet-driven bubble, see, e.g. Pakull, Grise & Motch (2006). It turns
out that the 400 pc diameter, $v_s \sim 100$ km/s, prototype ULXs around Holmberg IX X-1 and NGC 1313 X-2 are typically $\sim 1$ million years old, have an energy content of $\sim 10^{53}$ erg, or equivalently, have experienced an average inflating wind/jet power of $\sim 10^{40}$ erg/s over the age of the ULXB.

4. What ULX Bubbles can tell us about the Central Sources and their Jets

An obvious question to ask is how ULX bubbles are being formed. In principle they could be superbubbles (SBs) blown by the combined action of many O stars and supernova remnants. However, two considerations argue against this interpretation: known SBs don’t expand fast enough to create the fast shocks that are seen in the SNR-like spectra of ULXs. And perhaps more convincingly, we point out that a mechanical energy input of $10^{40}$ erg/s, equivalent to 10-50 SN explosions within $10^6$ years, requires a massive cluster of at least $\sim 10^6 M_\odot$. However, what we see in the case of NGC1313 X-2 and Holmberg IX X-1 are stellar associations with masses below $10^4 M_\odot$ (Grisé et al. 2008); in other words, the expected mechanical power of the observed population falls short by two orders of magnitude, or more.

Alternatively, there is the possibility of a rare energetic hypernova injecting $> 10^{52}$ erg into the ISM (Nomoto et al. 2003; Roberts et al. 2003); i.e., most probably the event that created the BH in the ULX system. Although such a scenario has again recently been proposed by Lozinskaya & Moiseev (2007) to account for a large non-thermal radio bubble in the Local Group galaxy IC 10, we think that the alternative scenario of a ULX wind/jet blown bubble is more likely, not least for the following reason:

After the SN explosion and the formation of a BH in the binary system, mass transfer from the companion commences only after a certain time span in which the new elliptical orbit circularizes by tidal forces, and during which the star evolves and expands on a nuclear
time scale (few $10^6$ yrs) until it fills its Roche lobe. The aforementioned ULXB MF16 in NGC 6946 is the smallest, most rapidly expanding, and therefore youngest object in this group with a (Sedov) age of $2.5 \times 10^4$ yrs (Dunne, Gruendl & Chu 2000). Indeed, this period would by far be too short for the onset of mass transfer in this system. We therefore believe that MF 16 provides ample evidence that hypernovae are not the events that create ULX bubbles. Instead, the view that ULXBs are being inflated by quasi-relativistic winds or jets with mechanical power of some $10^{39-40}$ erg/s (i.e. not unlike the famous SS433/W50 "beambag" system (Begelman et al. 1980)) begins to materialize. Support for this idea also comes from the discovery of a small (by ULXB standards) $\sim 5$ pc diameter radio and optical bubble around the famous black hole X-ray binary Cyg X-1 (Gallo et al. 2005) which we now interpret as a downscaled version (in jet power) of the bubbles described here, i.e. as a $\mu$ULXB.

5. More Tests with ULXBs

Considering that extragalactic ultraluminous X-ray sources are often (we estimate in $\geq 30\%$ of the cases) surrounded by large ULXB we might test the hypothesis of beamed emission by searching for (isotropically emitting) ULXB-like nebulae without associated ULX. To be more specific: assuming a mild beaming factor of 10 as often proposed (King et al. 2005) we would expect, for each visible ULX, to see about ten such systems that are pointed away from us. To that end, we have looked for large shocked ionized nebulae in our VLT images of the galaxy NGC 1313 which harbours two ultraluminous sources, X-1 and X-2, both of which are embedded in ULXBs (Pakull & Mirioni 2002). Although we find one possible such case, we certainly don’t see 20 such nebulae without associated compact X-ray sources in that galaxy. Therefore, we conclude that ULXs emit largely isotropically, as previously shown for Holmberg II X-1 on the basis of optical Zanstra-method arguments.

Large shock-ionized bubbles without detectable X-ray point source content may well represent systems that once contained ULX, but which are no longer active; consider a typical 1 million years old standard ULXB "beambag" of 400 pc diameter and 100 km/s expansion velocity which is suddenly being deprived of wind/jet mechanical power input. What would happen? The answer is that it would still be visible for another $3 \times 10^6$ years. Here we have assumed that the decreasing expansion velocity must still be significantly supersonic (i.e. $\geq 40$ km/s) in order to form an observable radiative shock. In view of some ULXBs that had previously been listed in SNR catalogues of nearby galaxies – sometimes as overlapping remnants that turned out to be part of one bigger structure (Pakull & Mirioni 2003) – we have extended our search by looking for point-like X-ray sources at the position of unusually large ($\geq 100$ pc) SNRs. This exercise has already revealed some interesting results:

- The well-known variable ULX NGC 2403 X-1 which is located near the galactic nucleus lies in between the SNR candidates MFBL 14 and 15 listed by Matonick et al. (1997). This has lead Schlegel & Pannuti (2003) to effectively discard a likely association. However, archival HST Hα images show that the individual SNRs are part of a larger structure of some 300 pc diameter, i.e., here is a new textbook ULXB.

- In their survey for SNR in the 7.0 Mpc distant spiral NGC 5885, Matonick & Fesen (1997) pointed out the enormous dimension of their candidate #1 (we measured $200 \times 300$ pc). It has the form of a regular elongated bubble, not unlike the ULXB around NGC 1313 X-2 (Pakull, Grisé & Motch 2006). Unfortunately, an earlier proposal for XMM/Newton observations of this galaxy was turned down, but a recent
public Chandra ACIS image now reveals a bright point source with a luminosity of about $10^{39}$ erg/s right in the middle of the 'remnant': another beautiful example of a ULXB.

- Finally, we mention the Chandra X-ray counterpart of the well-known huge SNR candidate S26 in the Sculptor group galaxy NGC 7793 (Blair & Long 1997), which is bright at both radio and optical wavelengths (Pannuti et al. 2002). Deep Hα images show an elongated bubble with some filamentary structure and large extent of 300 pc. Overlaying the outer Hα contour on a deep archival Chandra image reveals a very interesting configuration shown in Fig. 2: Here the X-ray source is resolved into a linear triplet, with the outer very soft sources being coincident with the endpoints of the large axis of the optical bubble. Similarities with X-ray images of SS433 and its X-ray lobes (Watson et al. 1983) are striking, and we believe that this system is indeed the long-searched (for nearly 30 years) extragalactic analogue of this famous microquasar. We finally mention that the observed X-ray output ($L_x \sim 10^{37}$ erg/s) of the central source is far from ‘ultraluminous’, a property it shares with the X-ray weak SS433. Future work on S26 will certainly shed more light on the controversial relations between SS433 and ULXs on the one hand, and between W50 and ULXB beambags on the other hand.

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