Compact radio emission in Ultraluminous X-ray sources

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The dates of receipt and acceptance should be inserted later

Key words Galaxies: general – X-rays: general – ISM: HII regions

We present results from our studies of radio emission from selected Ultraluminous X-ray (ULX) sources, using archival Giant Metrewave Radio Telescope (GMRT) data and new European VLBI Network (EVN) observations. The GMRT data are used to find possible faint radio emission from ULX sources located in late-type galaxies in the Chandra Deep Fields. No detections are found at 235, 325 and 610 MHz, and upper limits on the radio flux densities at these frequencies are given. The EVN observations target milliarcsecond-scale structures in three ULXs with known radio counterparts (N4449-X1, N4088-X1, and N4861-X2). We confirm an earlier identification of the ULX N4449-X1 with a supernova remnant and obtain the most accurate estimates of its size and age. We detect compact radio emission for the ULX N4088-X1, which could harbour an intermediate mass black hole (IMBH) of $10^5 M_\odot$ accreting at a sub-Eddington rate. We detect a compact radio component in the ULX N4861-X2, with a brightness temperature $>10^6$ K and an indication for possible extended emission. If the extended structure is confirmed, this ULX could be an HII region with a diameter of 8.6 pc and surface brightness temperature $\geq 10^5$ K. The compact radio emission may be coming from a $\sim 10^5 M_\odot$ black hole accreting at $0.1 \dot{M}_{Edd}$.

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1 Introduction

Several scenarios have been proposed to explain the high luminosities ($L_X > 10^{39}$ erg/s) of Ultraluminous X-ray sources (ULXs), but none of them is able to reveal the physical nature of all ULXs. If ULXs are powered by accretion at the Eddington rate, this would imply accreting compact objects of masses $10^2-10^5 M_\odot$. Such intermediate compact objects can only be black holes (Colbert & Mushotzky 1999) and they would be the missing link between stellar mass black holes and supermassive black holes in the nuclei of galaxies. These Intermediate Mass Black Holes (IMBHs) could form from the death of very massive and hot stars or from multiple stellar interactions in dense stellar clusters (Portegies Zwart 2003). It has also been suggested that ULX objects may harbour secondary nuclear black holes in post-merger galaxies (Lobanov 2008), with masses in excess of $10^5 M_\odot$ and accreting at sub-Eddington rates. Alternatively, ULXs could be neutron stars or stellar mass BHs apparently radiating at super-Eddington luminosities (Begelman 2002).

Radio observations of ULXs bear an excellent potential for uncovering the nature of these objects, by detecting and possibly resolving their compact radio emission, measuring its brightness temperature and spectral properties, and assessing the physical mechanism for its production. Few ULXs have been studied in the radio domain (Kaaret et al. 2003; Körding et al. 2005) and a small sample of ULXs has been cross-identified in the existing radio catalogs (Sánchez-Sutil et al. 2006).

An increase of the number of radio detections and subsequent Very Long Baseline Interferometry (VLBI) studies of detected radio counterparts could potentially help to clarify the nature of ULX sources. With this aim, we 1) analyze archive images of the Chandra Deep Fields taken with the Giant Meterwave Radio Telescope (GMRT) looking for faint radio counterparts of the ULX sources located in this fields; and 2) initiate an European VLBI Network (EVN) program to detect and study milliarcsecond-scale emission in ULX objects with known radio counterparts. In Section 2, we present the two samples of ULX objects studied. The observations and data reduction are explained in Section 3. The results obtained are shown in Section 4, leading to a discussion and final summary presented in Section 5.

Throughout this paper we assume a $\Lambda$ cold dark matter (CDM) cosmology with parameters $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$.

2 Observing targets

We use archival GMRT data to search for radio counterparts of 24 ULX objects identified in the Chandra Deep Field North (CDFN), Chandra Deep Field South (CDFS), and Extended CDFS (Lehmer et al. 2006). All these ULXs have luminosities $L_X \geq 10^{39}$ erg/s in the 0.5-2.0 keV band, and are located in optically bright irregular and late-spiral galaxies. Ten of the 24 X-ray sources appear to be coincident with optical knots of emission, with optical properties that are consistent with those of giant HII regions in the...
local universe, suggesting that these ULX sources trace distant star formation (Lehmer et al. 2006).

The objects targeted in our EVN observations are selected from a sample of 11 ULX objects with radio counterparts (Sánchez-Sutil et al. 2009) in the VLA FIRST catalog (Becker et al. 1995). We select three ULX which are brighter than 1 mJy and clearly away from the nuclear region in their respective host galaxies. The first target, N4449-X4, is identified as the most luminous and distant member of the class of oxygen-rich Supernova Remnants (SNRs) (Blair et al. 1983) and classified as an ULX source by Liu & Bregman 2005. A detailed study of this source is described in Mezcua & Lobanov (in prep.). The second target, N4088-X1, is an ULX located at a distance of 13.0 Mpc in the asymmetric spiral galaxy NGC 4088. This ULX is located within the extended emission of a spiral arm and is coincident with a conspicuous maximum of radio emission of 1.87 mJy (at 1.4 GHz) with an offset of 3.62” to the X-ray peak (Sánchez-Sutil et al. 2006). The ULX has a X-ray luminosity in the 0.3-8.0 keV band of 5.86 x 10^39 erg/s (Liu & Bregman 2005) who don’t rule out the possibility of it being an HII region). The third target, N4861-X2, is located in the spiral galaxy NGC 4861 and has an X-ray luminosity of 8.4 x 10^39 erg/s (Liu & Bregman 2005). Its radio counterpart is offset from the X-ray position by 1.97”. This ULX has been suggested to coincide with an HII region powered by massive early OB type stars (Pakull & Mirioni 2002).

3 Observations and data reduction

We use archival GMRT data of the Hubble Deep Field North (overlapping with our CDFN region of interest) at 235 MHz (experiments 01NIK04 & 11TMA01) observed on 2001 December 17, 2002 January 4 and 2002 January 26, and of the CDFS at 325 & 610 MHz (experiments 03IAA01 & 11RNA01), observed on 2003 February 13-17 and 2007 February 11-12, respectively. The observations were carried out using the standard GMRT phase calibration mode and spectral line mode. The data were analyzed with the NRAO Astronomical Image Processing System (AIPS). In order to detect very faint sources, we first image the entire primary beam area and extract all strong point-like objects. Then the cleaned field of strong sources is subtracted from the visibility data, and deeper imaging is performed. Finally self-calibration is applied to increase the dynamic range of the resulting image. At 610 MHz, 3 pointings of the same field (CDFS) are observed.

The EVN observations (project codes EM072A & EM072B) have been made on June 1st & 2nd 2009, in two separate blocks of 12 hours in duration, using 9 antennas (Ef, Jb−1, Cm, Wb, On, Mc, Nt, Tr, Sh) at the wavelength of 18 cm. In order to detect weak emission from the ULX objects, we use the phase-referringencing technique, calibrating the phases of the target objects with nearby strong and point-like calibrators. The data reduction was performed in the standard way using AIPS. Uniform weighting was used in the imaging, and tapering of the longest baselines was applied for N4088-X1 and N4861-X2 to improve the detection of extended emission.

4 Results

4.1 ULX sources in the Chandra Deep Fields

We show the final GMRT images obtained at 235 MHz and 325 MHz in Fig. 1. The primary beam sizes are 114 arcmin at 235 MHz, 81 arcmin at 325 MHz, and 43 arcmin at 610 MHz. The respective rms noise in the maps at each frequency are 1.4, 0.6, and 0.8 mJy/beam. No radio counterparts of the ULX sources located in the CDFs are detected in a circle radius for each ULX position of 28 arcsec, which is more than 10 times the Chandra positional error circle. Upper limits on their flux densities at each frequency are given in Table 1 (for ULX located in the CDFN) and Table 2 (ULXs in the CDFS), obtained by estimating the local rms at the ULX locations. These upper limits range between 2-4.6 mJy at 235MHz, 1-2.5 mJy at 325 MHz, and 0.5-2 mJy at 610MHz. The position of only three ULX sources fall in the images at 610MHz, thus only 3 upper limits are given at this frequency.

Table 1 ULX in the CDFN at 235.5MHz.

| Name                                  | S [mJy/beam] |
|---------------------------------------|--------------|
| CXO HDFN J123631.66+620907.3          | < 3.63       |
| CXO HDFN J123632.55+621039.5          | < 2.76       |
| CXO HDFN J123637.18+621135.0          | < 2.88       |
| CXO HDFN J123641.81+621132.1          | < 3.20       |
| CXO HDFN J123701.47+621845.9          | < 2.35       |
| CXO HDFN J123701.99+621122.1          | < 3.12       |
| CXO HDFN J123706.12+621711.9          | < 2.06       |
| CXO HDFN J123715.94+621158.3          | < 4.58       |
| CXO HDFN J123721.60+621246.8          | < 4.37       |
| CXO HDFN J123723.45+621047.9          | < 4.58       |
| CXO HDFN J123727.71+621034.3          | < 4.21       |
| CXO HDFN J123730.60+620943.1          | < 2.11       |

4.2 Compact radio emission in ULX sources

In Fig. 2 we show the final images of N4088-X1 (left) and N4861-X2 (right). The noise levels achieved are 26µJy/beam for N4088-X1 and 3µJy/beam for N4861-X2, and the restoring beams are 31 x 29 mas and 11 x 5 mas, respectively.

For N4088-X1, we identify a compact component of flux density 0.1 mJy at a 5σ level. The component is centered at RA(J2000) = 12h05m31.7110s ± 0.0003s, DEC(J2000) = 50°32′46.729" ± 0.002".

For this component, we estimate a brightness temperature of T_B > 7 x 10^4 K and an upper limit of 34 x 26 mas for the size. Adopting a distance of 13.0 Mpc yields, for N4088-X1, an integrated 1.6 GHz radio luminosity of 3.8 x 10^{34} erg/s.
The ULX N4861-X2 (Fig 2 right) has a compact component A centered at RA(J2000) = 12h59m00s.3563037 ± 0.0000008, DEC(J2000) = 34°50′42.87500″ ± 0.00002″. It has a flux density of ≈80 mJy (for which we derive a radio luminosity $L_{1.6\,\text{GHz}} = 3.3 \times 10^{34}$ erg/s assuming a distance to the host galaxy of 14.80 Mpc) and a size upper limit of 9.8 \times 3.8\,\text{mas}, corresponding to a brightness temperature $T_B > 1.1 \times 10^6\,\text{K}$. Two additional components (B and C), with a total flux density of $\sim 70\,\text{mJy}$ are detected, but cannot be firmly localized with the present data. If this extension were confirmed, the whole structure (including component A, B & C) would have a total flux density of 0.18\,mJy, a luminosity of $L_{1.6\,\text{GHz}} = 7.7 \times 10^{34}$ erg/s and diameter $D \sim 120\,\text{mas}$. This diameter corresponds to 8.6 pc at the distance of the host galaxy, and it is in agreement with the typical size of HII regions found in our Galaxy, like G18.2-0.3 (Fürst et al. (1987)), which has a size of 200 mas, a luminosity of $L_{1.4\,\text{GHz}} = 1.1 \times 10^{33}$ erg/s and is formed by several discrete sources.

5 Discussion

We use the upper limits obtained from the GMRT data on the radio flux densities of the ULX objects to locate them in the fundamental plane of sub-Eddington accreting black holes (cf., Corbel et al. 2003; Gallo et al. 2003; Merloni et al. 2003; Falcke et al. 2004) as defined by a correlation between radio core ($L_R$) and X-ray ($L_X$) luminosity and black hole mass, $M_{\text{BH}}$, $\log L_R = 0.6 \log L_X + 0.78 \log M_{\text{BH}} + 7.33$. For our calculations, we assume a radio spectral index $\alpha_R \simeq 0.15$ and a X-ray spectral index $\alpha_X \simeq -0.6$ adopted previously by Falcke et al. (2004). The resulting radio and X-ray luminosities of the ULX objects in our sample are compared in Fig. 3 to the results of Corbel et al. (2003) and Merloni et al. (2003). The resulting high upper limits on the BH masses do not provide strong constraints on the nature of these ULX objects.

A similar relation is shown in Fig. 4 for the most compact components in the EVN images of N4088-X1 and N4861-X2. Using our radio luminosity at 1.6 GHz appropriately scaled to 5 GHz, the X-ray luminosity scaled to the 2-10
keV band, and assuming a sub-Eddington accretion regime, we derive a black hole mass of \(10^{5.1}\ M_\odot\) and of \(10^{4.9}\ M_\odot\) for N4088-X1 and N4861-X2 (component A), respectively. These masses are in agreement with the IMBH scenario for both objects.

Higher sensitivity observations are needed, and observational time has already been guaranteed, to try to detect and/or confirm possible extended structure for both N4088-X1 and N4861-X2.

### 6 Summary

Radio observations of ULX sources can help to unveil the nature of these objects. Analysis of archival GMRT data of the Chandra Deep Fields at 235, 325 & 610 MHz have not yielded any radio counterparts for these sources but yielded upper limits on their flux densities. These ULXs are too weak for deep field radio observations so higher sensitivity is needed in order to detect any faint radio emission.

New EVN observations of three ULXs with known radio counterparts yielded first milliarcsecond-scale images of all three objects. The EVN observations have confirmed the earlier identification of the ULX N4449-X1 with a SNR and obtained the most accurate estimates of its size and age (Mezcua & Lobanov in prep.). For the two other ULXs studied, N4088-X1 and N4861-X2, the EVN measurements have provided improved estimates of the compact radio flux, yielding better localizations of these objects in the \(L_X - L_{\text{radio}}\) diagram. The suggested nature of these objects can be best verified with more sensitive observations at 5 GHz aimed at both improving the brightness temperature estimates and obtaining spectral index information. The success of the EVN observations also calls for expanding this study to more ULX objects.

**Acknowledgements.** The authors are grateful to M. López-Corredoira and M. W. Pakull for their valuable comments. M. Mezcua was supported for this research through a stipend from the International Max Planck Research School (IMPRS) for Radio and Infrared Astronomy at the Universities of Bonn and Cologne.

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Fig. 3 Location of the 24 ULXs (red arrows) in the fundamental plane of sub-Eddington accreting black holes. The parallel lines correspond to the labeled black hole mass relative to that of the Sun. We show for comparison the Corbel et al. (2003) data for the X-ray binary GX 339-4 (filled circles), and the Merloni et al. (2003) data for the Low Luminosity AGN (LLAGN) NGC 2787, NGC 3147, NGC 3169, NGC 3226, and NGC 4143 (inverted triangles).

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Fig. 4 Old (Sánchez-Sutil et al. 2006, grey squares) and new (this work, red squares) location of the ULX sources N4088-X1 and N4861-X2 in the fundamental plane of sub-Eddington accreting black holes. The parallel lines correspond to the labeled black hole mass relative to that of the Sun. We show for comparison the Corbel et al. (2003) data for the X-ray binary GX 339-4 (filled circles), and the Merloni et al. (2003) data for the Low Luminosity AGN (LLAGN) NGC 2787, NGC 3147, NGC 3169, NGC 3226, and NGC 4143 (inverted triangles).