Ultraluminous X-ray sources with the SKA

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Abstract

The discovery almost three decades ago of non-nuclear, point-like X-ray sources with X-ray luminosities $L_X \geq 3 \times 10^{39}$ erg s^{-1} revolutionized the physics of black hole accretion. If of stellar origin, such Ultraluminous X-ray sources (ULXs) would have to accrete at super-Eddington rates in order to reach the observed high X-ray luminosities. Alternatively, ULXs could host sub-Eddington accreting intermediate-mass black holes, which are the long-time sought missing link between stellar and supermassive black holes and the possible seeds of the supermassive black holes that formed in the early Universe. The nature of ULXs can be better investigated in those cases for which a radio counterpart is detected. Radio observations of ULXs have revealed a wide variety of morphologies and source types, from compact and extended jets to radio nebulae and transient behaviours, providing the best observational evidence for the presence of an intermediate-mass black hole in some of them. The high sensitivity of the SKA will allow us to study the faintest ULX radio counterparts in the Local Universe as well as to detect new sources at much larger distances. It will thus perform a leap step in understanding ULXs, their accretion physics, and their possible role as seed black holes in supermassive black hole and galaxy growth.

1 Introduction

Ultraluminous X-ray sources (ULXs) are identified as extragalactic, non-nuclear X-ray objects with X-ray luminosities exceeding the Eddington limit of a $\leq$20 $M_\odot$ stellar-mass black hole (BH). Several types of objects are able to produce these high luminosities (e.g. BHs of different masses and accretion rates, highly accreting neutron stars, ...), hence the debate about the nature of ULXs is still open.

Stellar-mass BHs of up to 100 $M_\odot$ can produce X-ray luminosities up to 5×10^{40} erg s^{-1} if they accrete at rates around or above the Eddington limit. This can cause the launch of radiatively-driven outflows from the inner part of the disk, producing a mild collimation or beaming (e.g., [32]; [2]; [33]; [22]). This, together with the finding of good correlations between the number of ULXs in spiral galaxies and the star-formation rate ([64];[65]) plus studies of the X-ray luminosity function of nearby galaxies (e.g., [66]; [50]; [46]), suggests that the majority of ULXs with X-ray luminosities $\leq 2 \times 10^{40}$ erg s^{-1} are high-mass X-ray binaries with near to or super-Eddington accreting stellar-mass BHs. This is supported by X-ray timing analysis of some ULXs, which show that they have properties similar to those observed in BH binaries, such as variations in timescales of $\sim$100 s, spectral breaks and quasi periodic oscillations (QPOs; e.g. [29]; [3]), and that their timing and spectral characteristics are consistent with super-Eddington emission models ([63]). This is the case of the ULX M82 X-2, for which X-ray timing analysis revealed the presence of a 1.37 s pulse and a 2.5 d sinusoidal modulation in its emission caused by, respectively, the pulsation and orbital period of a ($\leq$1.4 $M_\odot$) neutron star in orbit around a stellar companion ([1]).

In the optical, some ULXs are found surrounded by bubbles of ionised gas that emit nebular lines ([52]; [31]). When detected, these emission lines allow us to determine the redshift and thereby to confirm if a ULX candidate is associated to the galaxy. Some of the donor stars in ULXs are expected to be blue supergiants on the basis of their location in or near young star clusters (e.g. [23]) and on the blue colours of the optical counterparts. However, a blue colour is also consistent with optical emission from an irradiated accretion disc. While a recent work advocates for the dominance of an irradiated accretion disc in the UV/optical ([67]), the detection of bright near infrared counterparts of 11 ULXs in a sample of 67 sources within 10 Mpc suggests that these may contain red supergiant donor stars ([28]). This implies that it may be possible to measure dynamical masses in some ULXs using infrared photospheric lines. Measuring dynamical masses of ULXs in the optical has proved extremely difficult given the need of high-resolution images to resolve the optical counterpart from unrelated objects in the host galaxy, the usual faintness of the optical counterparts ($V > 23$), the weakness of the absorption features from the donor star and the strong contamination from superimposed nebular lines. The most reliable mass determination has been obtained for the ULX P13 in NGC 7793, a binary system with a B9Ia donor star and an orbital period of $\sim$64 days, for which the BH mass was constrained to less than 15 $M_\odot$ ([51]). P13, together with M82 X-2, constitute the most compelling evidence of a high-mass X-ray binary in a ULX, indicating that some ULXs are powered by supercritical accretion on to stellar-mass BHs and even neutron stars.

However, some ULXs, in particular those whose X-ray luminosities of $\sim 5 \times 10^{41}$ erg s^{-1}

cannot easily be explained by the stellar-mass scenario (see e.g., [19]), could be intermediate-mass BHs (IMBHs) of $10^2 - 10^5$ $M_\odot$ accreting at sub-Eddington rates ([6]) or, in a reduced number, recoiling supermassive BHs (see e.g. [30]). IMBHs may play a key role in the formation of supermassive BHs ([18]) and in the formation and evolution of galaxies. They could come from very young and massive stars ([39]), from stellar mergers in dense stellar clusters ([57]), from the direct collapse of pre-galactic gas disc ([37]), or from the merging of compact objects in the discs of active galactic nuclei (AGN; [40]). Despite their importance, observational evidence of IMBHs is scarce.

Some IMBH candidates were suggested in globular clusters (e.g. [21]; [69]; [38]), for which the non-detection of a radio counterpart, in some cases down to 1.5 μJy beam^{-1}, yielded stringent BH mass upper limits (down to 360 $M_\odot$, e.g., [7]; [71]; [62]). The most compelling evidence for IMBHs has been found in the nucleus of low-mass and dwarf galaxies (e.g. [56]; [25, 26]; [68]; [16, 17]; [58]) and in ULXs showing X-ray variability and/or radio emission ([19]; [12]; [42]; [43, 45, 47]; [54]). [24] showed that the amplitude of the X-ray variations in some ULXs was fully consistent with them being accretion-dominated objects with IMBHs of 10^4 $M_\odot$. Based on a mass-scaling relation between the soft X-ray time lag (estimated from variability studies) and the BH mass obtained for AGN ([13]), a BH mass of $\sim 10^4$ $M_\odot$ was suggested for the ULX NGC 5408 X-1 ([14]), in favour of the IMBH scenario ([15]; [4], although see [48] supporting the stellar super-Eddington accretion scenario, instead). This is also the case for the ULX M 82 X-1, in which the presence of an IMBH was also argued by identifying the QPO frequency and applying mass-frequency scaling relationships ([20]; [5]; [54]).

ULXs offer thus a unique testbed for studies of high accretion rate physics (i.e. super-Eddington accretion on to stellar-mass BHs or neutron stars) as well as open a new window in where to look for the elusive IMBHs. However, despite the breadth of studies carried out in the optical, near-infrared, and X-ray regimes, even for the most studied ULXs a consensus on the mechanism producing the high X-ray luminosities has not yet been reached [e.g. the spectral and timing properties of NGC 5408-X-1 suggest either a stellar mass BH ([48]) or an IMBH ([15]; [4]; [14])].

Determining the ULX BH masses in the optical and X-rays has been proven to be very difficult and time-consuming. An alternative method to estimate the BH mass has however been provided by radio observations, which have in the past few years shed light on understanding the nature of ULXs.

2 Radio investigation of ULXs

The detection of radio emission allows us to measure the brightness temperature, spectral index (from which the physical mechanism responsible for the radio emission can be assessed, e.g., synchrotron radiation or brehmstrahlung emission), and study possible flux variability. Furthermore, very long baseline interferometry (VLBI) radio observations can possibly resolve the radio emission and indicate the presence of a relativistic jet. Combined with *Chandra* X-ray observations, radio observations can be also used to derive accurate positions to search for optical and infrared counterparts.

Studies of ULX radio counterparts have allowed us to reveal the nature of some ULXs as powerful nebulae, which discards relativistic beaming as the origin of the high X-ray luminosities (e.g., [49]; [35]; [8]; [9]; [61]), while interferometric and VLBI radio observations of ULXs have yielded the resolved structure of one of the youngest known supernova remnants (SNR 4449-1; [44]) and the detection of jet radio emission (compact and extended) in a few ULXs (N4088-X1, N4861-X2, [42], [46]; N5457-X9, [43]; Holmberg II X-1; [10]; HLX-1, [70], [11]; NGC2276-3c, [45]; [47]). In the case of compact radio emission, the location of a ULX in the fundamental plane of accreting BHs (e.g. [41]; [34]) can be used to estimate its BH mass. The fundamental plane is a correlation between radio core luminosity, X-ray luminosity, and BH mass, valid from stellar to supermassive BHs ([27]) accreting at sub-Eddington rates. The combination of radio observations with the use of the fundamental plane revealed the existence a non-nuclear IMBH of 0.3–30 $\times$ 10^4 $M_\odot$ in the galaxy ESO 243-49 (HLX-1, e.g., [19]; [12]; [70]; [11]), the discovery of a parsec-scale radio jet from an off-nuclear IMBH of 5 $\times$ 10^4 $M_\odot$ in the spiral arm of NGC 2276 (NGC2276-3c; [47]), and the possible presence of an IMBH in an HII region in the spiral arm of NGC 5457 (ULX N5457-X9; [43]). In all these three cases, the IMBH is thought to be the nucleus of a stripped satellite galaxy. The study of ULX radio counterparts is thus crucial not only for clarifying the ULX nature and their environment but also for revealing their possible role in galaxy evolution in the case of hosting IMBHs.

Unfortunately, no radio emission is detected from most ULXs due to the sensitivity limits of the current radio observing facilities. The cross-match of the VLA FIRST survey with the ULX catalogs of [64] and [36] yielded the detection of only 11 and 7 ULX radio counterparts, respectively ([59]; [55]; which corresponds to 27% and 19%, respectively, of the total number of ULXs in the survey area covered by FIRST), while only 1 out of 7 extreme ULXs was detected with the VLA at 5 GHz down to an rms of 0.01 mJy/beam ([45]). The faintest radio detections of ULXs correspond to radio luminosities of 10^{34} erg s^{-1} and distances up to 15 Mpc (with the exception of HLX-1 and NGC2276-3c, which are located at 95 Mpc and 33.3 Mpc respectively). An effort to increase the number of ULX radio counterparts is thus required and will be possible thanks to the advent of the SKA.

3 A new era: studying ULXs with the SKA

The sensitivity and large-scale area of the SKA will allow us to monitor known ULX radio counterparts, determine their spectral and timing properties, detect new radio counterparts beyond distances $>$ 100 Mpc, investigate the properties of jets in ULXs and their feedback on the environment, and study ULX powered radio nebulae.

3.1 The ULX environment

Some of the ULXs at distances $<$ 5 Mpc are observed to power radio nebulae of a few tens of pc across and radio luminosities $L_{5\mathrm{GHz}} \sim 10^{34}$–$10^{35}$ erg s^{-1} (e.g. [9]; [10]; [43]; [60]; [61]).

ULXs radio bubbles of 10^{33} erg s^{-1} could be detected up to distances of 10 Mpc with only one hour of integration time per field with the SKA1-MID (rms $\sim$0.6 μJy beam^{-1}), to up to 30 Mpc with one hour of integration time per field with the SKA-MID, and to up to 40 Mpc when considering the 1.4 GHz all-sky SKA Ultra Deep survey of 1 deg^2 and rms 0.05 μJy beam^{-1} (see [72], fig. 1). Phase 1 of the SKA will thus already allow us to extend the study of radio nebulae to distances two times larger than the ones permitted by the current facilities, reaching distances far beyond the Local Universe for SKA Phase 2.

3.2 Core radio emission

The compact object powering a ULX can present either steady extended jet emission or radio outbursts denoting possible state transitions as that observed in XRBs. Examples of these have been observed with the currently available facilities up to distances of $\sim$100 Mpc and radio luminosities of $\sim 10^{37}$ erg s^{-1} (NGC2276-3c, [45]; [47]; HLX-1, [70], [11]), corresponding to the brightest ULX radio counterparts detected so far. Identifying more of these bright ULX radio counterparts will be possible with the wide-field SKA surveys, though a combination of SKA and VLBI observations (SKA-VLBI; [53]) will be required to resolve the ULX radio emission from the host galaxy nuclear emission for distances >100 Mpc. The accurate positions, on milliarcsec scales, provided by the SKA-VLBI observations will in addition allow us to properly search for the optical and infrared ULX counterparts in crowded environments.

Moreover, the high sensitivity of the SKA and its rapid survey speed will permit detecting new flaring events and monitoring transient emission from ULXs with much shorter integration times than current facilities. For example, bright transients with peak radio luminosities like the microquasars MQ1 ([61]) or S26 ([60]) will be detected up to distances of 40 Mpc with only 1 hour on-source integration time with the SKA1-SUR and at distances of $\sim$100 Mpc with the same integration time with the SKA1-MID, while transients with peak luminosities like the Galactic GRS1915+105 ($\sim 10^{32}$ erg s^{-1}) will be detected up to distances of $\sim$10 Mpc with 1-hour on-source integration time with the SKA-MID (see [72], fig. 2).

The all-sky surveys at 1.4 GHz that will be performed with the SKA already in its phase 1 will reach resolutions of 0.5 arcsec and sensitivities of 2 μJy beam^{-1}. This will permit detecting and distinguishing from galactic nuclear emission faint ULXs (down to 10^{33} erg s^{-1}) up to distances of 5 Mpc and bright ULXs ($> 10^{35}$ erg s^{-1}) up to 150 Mpc. The SKA, with a sensitivity for the SKA-MID already 10 times better than the current most sensitive array, will thus not only increase the number of ULX radio counterparts and allow us to distinguish between nebular, steady or transient radio emission, but also to detect new radio sources beyond the Local Universe. For those ULXs where timing/X-ray spectroscopy or dynamical mass measurements are not possible, the detection of a radio counterpart with the SKA will permit estimating the BH mass using the fundamental plane of accreting BHs, a correlation that will be further tested and understood with SKA observations of BH XRBs and AGN (see Chapters by J.M. Paredes & J. Martí and I. Agudo et al., this book).

The SKA will be thus a key tool for revealing the nature of ULXs either as IMBHs or stellar-mass sources that, combined with observations from state-of-the-art instruments in the optical/infrared and X-ray regimes, will provide a breadth understanding of the accretion mechanism governing ULXs.

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