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A catalogue of ultraluminous X-ray sources in external galaxies⋆

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Abstract. We present a catalogue of ultraluminous X-ray sources (ULXs) in external galaxies. The aim of this catalogue is to provide easy access to the properties of ULXs, their possible counterparts at other wavelengths (optical, IR, and radio), and their host galaxies. The catalogue contains 229 ULXs reported in the literature until April 2004. Most ULXs are stellar-mass-black hole X-ray binaries, but it is not excluded that some ULXs could be intermediate-mass black holes. A small fraction of the candidate ULXs may be background Active Galactic Nuclei (AGN) and Supernova Remnants (SNRs). ULXs with luminosity above 10^{40} ergs s^{-1} are found in both starburst galaxies and in the halos of early-type galaxies.

Key words. X-rays: galaxies – X-rays: binaries – galaxies: general – catalogs

1. Introduction

Compact, off-nuclear galactic X-ray sources with luminosities of 10^{39}–10^{41} ergs s^{-1} are observed in some external galaxies. Because their luminosity is between those of "normal" X-ray binaries and AGNs they are referred to as ultraluminous X-ray sources (ULXs), and sometimes as intermediate-luminosity X-ray objects (IXOs) (see Miller & Colbert 2004; Fabbiano & White 2004, for recent reviews). ULXs were first discovered in the Einstein era (Fabbiano 1989), and studied further with ROSAT and ASCA (Roberts & Warwick 2000, hereafter RW00; Colbert & Ptak 2002, hereafter CP02; Makishima et al. 2000), and recently with the XMM and the Chandra X-ray observatories with higher sensitivity and spatial resolution (Foschini et al. 2002a; Humphrey et al. 2003). Although Irwin et al. (2004) proposed that a ULX should be defined as having a 0.3–10 keV luminosity that exceeds 2×10^{39} ergs s^{-1}, here we use the conventional definition of ULXs. However, young, compact supernova remnants, which can reach luminosities of up to a few 10^{40} ergs s^{-1}, should not be regarded as ULXs.

Because the X-ray flux of ULXs often varies significantly over timescales of months and years, ULXs are thought to be accreting compact objects. The spectra of ULXs in nearby galaxies studied with ASCA by Makishima et al. (2000) are quite soft and well fitted by a multicolour disc blackbody model, suggesting that the compact objects in ULXs are black holes. No optical counterpart of a ULX has yet been confirmed, which implies extreme X-ray to optical flux ratios. So far, there is no unique universally accepted model to account for the huge energy output of ULXs. One suggestion is that some ULXs are binary systems with 10^2–10^4 $M_\odot$ black holes as primaries, i.e. more massive than stellar mass black hole binaries, and substantially less massive than active galactic nuclei (Colbert & Mushotzky 1999). Such black holes, if they exist, would be the missing links between stellar-mass black holes and supermassive black holes in the nuclei of galaxies. However, there is no general consensus on how such objects may form and what could be the source of the accreted matter. Alternatively, the majority of ULXs may be interpreted as stellar-mass black holes (or even neutron stars) with anisotropic X-ray emission (King et al. 2001). In this context, a small fraction of them could be microblazars (Mirabel & Rodriguez 1999), namely, microquasars with relativistically beamed emission close to the line of sight (Köerding et al. 2002). On the other hand, it is possible that the luminosities are truly super-Eddington, if produced in accretion disks with radiation-driven inhomogeneities (Begelman 2002).

Starburst galaxies contain a comparatively larger number of ULXs than spiral galaxies with low rates of massive star formation (e.g. M 31), which is consistent with an association of ULXs with high-mass X-ray binaries (HMXBs). ULXs with luminosities above 10^{40} ergs s^{-1}are associated with regions of intense star formation and so far have not been detected in the old stellar populations of elliptical and S0 galaxies (see

⋆ Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/429/1125

Gilfanov 2003). It has been proposed that the collective X-ray luminosity of high-mass X-ray binaries can be used as an indicator of star formation rate for the host galaxy (Grimm et al. 2002, 2003; Gilfanov et al. 2004a,b; Gilfanov 2004).

Observations of bright spiral galaxies with Einstein revealed substantial numbers of very bright X-ray sources external to the nuclear regions, 16 of which were ULXs (Fabbiano 1989). In a survey of nearby galaxies with ROSAT, Roberts & Warwick (2000) found 28 ULXs outside the nuclei. Similarly, Colbert & Ptak (2002) investigated extranuclear X-ray sources in 54 galaxies finding 87 ULXs. Chandra observations of galaxies have revealed a large number of previously unknown ULXs (Humphrey et al. 2003; Colbert et al. 2004), suggesting that they may be quite common. The amount of new literature and the number of ULXs have grown so much that it is now useful to concentrate the information in a catalogue of ULXs. Here we present the catalogue of 229 ULXs reported in the literature up to 2004 April.

2. Description of the table

Table 1 lists the 229 ULXs we have extracted from the literature. The catalogue is the extragalactic extension of the galactic X-ray binary catalogues (Liu et al. 2000, 2001). The format of the table is similar to that of the catalogues of galactic X-ray binaries. In Table 1 the galaxies are ordered according to right ascension. Part of the (mainly numerical) information on ULXs and their host galaxies is arranged in nine columns, below which for each galaxy additional information is provided in the form of key words with references. The information on the host galaxies is given in the first line, and the X-ray information on the ULXs is given in the following lines, one line for each ULX. The columns have been arranged as follows.

In Line 1 the first column contains the galaxy name. Alternative galaxy names are given in the second column. The third column in Line 1 lists the morphological type of the galaxy, taken from *the Third Reference Catalogue of Bright Galaxies* (*RC*3, de Vaucouleurs et al. 1991). The fourth column is the mean numerical index of stage along the Hubble sequence (T) of the galaxy, which is also taken from *RC*3, where –5 is Elliptical, 0 is S0a and 10 is Irregular. The fifth column is the distance of the galaxy in Mpc. The distance is extracted from the *Nearby Galaxies Catalog* by Tully (1988) if the recessional velocity (cz) listed in *RC*3 is smaller than 1000 km s^{-1}, otherwise it was computed from the recessional velocity using $H_0 = 75$ km s^{-1} Mpc^{-1}. The sixth column is the Galactic hydrogen column $N_{\rm H}$ in 10^{20} cm^{-2} units taken from Dickey & Lockman (1990). In the last three columns of the first line, the B-band photographic magnitude (M_B), the near infrared magnitude (M_{K_s}), and the far infrared magnitude ($M_{\rm FIR}$) are listed. The B-band photographic magnitude is taken from *RC*3; the near-infrared K_s-band magnitude is calculated from the 20 mag arcsec^{-2} isophotal magnitude listed in the 2*MASS Large Galaxy Atlas* (Jarrett et al. 2003); the far-infrared magnitude is calculated from $M_{\rm FIR} = -20.0 - 2.5 \log FIR$, where FIR is the far infrared continuum flux measured at 60 and 100 microns as listed in the *IRAS Point Source Catalog* (1987).

In the following lines the first column contains the ULX names we have designated, ULX1, ULX2, and so on. Alternative ULX names that had been used previously are given in the second column. The third and fourth columns in the lines contain the right ascension (RA) and declination (Dec) of the ULXs for the epoch 2000. In Cols. 5 and 6, the peak X-ray luminosities, in units of 10^{39} ergs s^{-1}, and the energy range in keV are given. Column 7 is the nuclear offset, i.e. radius from nucleus in arcseconds, assuming that the galaxy center is at the *RC*3 optical position.

Only strong X-ray sources with enough counts have X-ray spectral fits. In Col. 8 we give the best fit model of recent X-ray observation of ULXs, and the fit results are given in Col. 9, with the spectral index listed for a power-law fit and the inner temperature in keV for a thermal model fit. If a two-component fit is needed, we use the symbol "+" between the two fit models and fit results for the two-component best fit. The following abbreviations have been used for the fit model:

- PL: power-law model;
- BB: blackbody;
- MCD: multicolor disk (Mitsuda et al. 1984);
- MKL: MEKAL;
- BR: bremsstrahlung;
- RS: Raymond-Smith thermal model (Raymond & Smith 1977).

3. Some remarks

229 ULXs have been found in 85 galaxies. Another 31 ULX candidates were found in the Cartwheel galaxy (Gao et al. 2003), but the galaxy is too far away, and the resolution is not high enough to tell whether they are point sources or diffuse sources. Also Colbert et al. (2004) mentioned that there are 3 ULXs in NGC 1395, 2 ULXs in NGC 4579, 2 ULXs in NGC 4736, and 1 ULX in NGC 4945, but only the total numbers and total X-ray luminosities of ULXs in each galaxy are given, with no detailed position and X-ray luminosities for individual sources.

We emphasize here that the properties of some ULXs listed in this catalogue are still uncertain. They should be considered with caution. For instance, Chandra images showed that the ULX (IXO 52) in NGC 4373 (CP02) is a clump of hot gas rather than a point source. Some of the ULX candidates might be very young supernova remnants, while at least a small part of the ULXs might be unrelated, background/foreground objects, especially those objects positioned at large projected radii from the galaxy nucleus (e.g., NGC 4150 X-1 in LLJ00; the ULX in NGC 4698 in Foschini et al. 2002b; and NGC 4168 ULX1 in Masetti et al. 2003). Moreover, some ULXs have X-ray luminosities slightly above the 10^{39} ergs s^{-1} threshold, and would fall below this threshold if their host galaxies are slightly closer than assumed. Finally, for some of the ULXs, fitting their spectra, rather than assuming a certain spectral model, may yield luminosities less than 10^{39} ergs s^{-1}.

In general ULXs are quite variable (e.g., M 74 X-1; M 82 ULX5; NGC 4136 X-1), and some are transients (e.g.,

NGC 3628 X-1; M 74 ULX2; NGC 4559 ULX3; NGC 5128 IXO 76; M 101 ULX2). Some ULXs are positioned near faint optical sources in the DSS images, and many more are located in the disks of spiral galaxies or are known from more recent optical observations to have possible optical counterparts (e.g., NGC 5204 X-1, Roberts et al. 2001; Liu et al. 2004; see also Pakull & Mirioni 2003). Follow-up studies of these potential optical counterparts using Chandra X-ray positions would be very useful.

Although ULXs are often overabundant in starburst galaxies (e.g., Roberts et al. 2002), ULXs are found both in spiral and elliptical galaxies, and with larger numbers in elliptical galaxies than in spirals. In fact, there is a significant population of ULXs in the halos of some elliptical galaxies, where there is no apparent recent star formation. Moreover, ULXs with luminosity above 10^{40} ergs s^{-1} are detected in both, starburst galaxies as well as in elliptical and S0 galaxies. For example, in the haloes of the early type galaxies NGC 1399 and Fornax A (NGC 1316) have been found 11 and 6 ULXs, respectively. However, NGC 1399 is at the center of a difuse cluster of dwarf galaxies (some of them irregulars), and Fornax A may be a merger between an early type galaxy and a gas-rich galaxy. The nature of ULXs in early type galaxies and their relation to the properties of the host galaxies remains an open question that deserves further study.

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Note added in proof: While the paper was under referee, Nolan, L. A. et al. (2004, MNRAS, 353, 221) reported on 3 ULX candidates in NGC 3921 and at least 6 ULXs (probably 13 ULXs) in NGC 7252, and Guainazzi, M. et al. (2004, MNRAS, 355, 297) reported on 1 ULX with X-ray luminosity of $L_X \sim 4 \times 10^{40}$ erg/s in NGC 5643, which are not included in the catalogue.

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