High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Ultraluminous X-ray source populations in the Chandra Source Catalog 2.0

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Abstract. The nature and evolution of ultraluminous X-ray sources (ULXs) is an open problem in astrophysics. They challenge our current understanding of stellar compact objects and accretion physics. The recent discovery of pulsar ULXs further demonstrates the importance of this intriguing and rare class of objects.

In order to overcome the difficulties of directly studying the optical associations of ULXs, we generally resort in statistical studies of the stellar properties of their host galaxies. We present the largest such study based on the combination of Chandra archival data with the most complete galaxy catalog of the Local Universe. Incorporating robust distances and stellar population parameters based on associated multi-wavelength information, and we explore the association of ULXs with galaxies in the (star formation rate, stellar mass, metallicity) space.

We confirm the known correlation with morphology, star formation rate and stellar mass, while we find an excess of ULXs in dwarf galaxies, indicating dependence on age and metallicity.

Keywords. X-rays: binaries, X-rays: galaxies, catalogs

1. Introduction

Ultraluminous X-ray sources are X-ray binaries exceeding the Eddington limit for a stellar black hole ($L_X \gtrsim 10^{39}\,\mathrm{erg\,s^{-1}}$), challenging our understanding of accretion physics and binary evolution (for a review, see Kaaret *et al.* 2017). Links with cosmological (IGM heating during the reionization era; e.g. Madau & Fragos 2017) and gravitational wave research (ULXs as progenitors of binary mergers; e.g. Marchant *et al.* 2017) further demonstrate their importance. While studies of individual objects provide significant input for understanding accretion physics in ULXs, statistical studies probe their formation and evolution via the connection with their environment, e.g. the star formation rate (SFR), stellar mass ($M_\star$) and metallicity (Z) of the host galaxy (Swartz *et al.* 2011; Wang *et al.* 2016). Such studies provide input for population synthesis models (e.g. Fragos *et al.* 2015), addressing key questions, such as the nature of the compact objects in ULXs and their evolutionary paths.

Using the new *Chandra Source Catalog 2.0* (*CSC 2.0*; Evans *et al.* 2010) we revisit the correlation of the ULX populations with global parameters of their host galaxies by creating the most up-to-date census of ULXs in the Local Universe. By associating the *CSC 2.0* with a complete catalog of galaxies, we will

(*a*) provide the most up-to-date census of ULXs and host galaxy properties
(*b*) study the correlation of the number of ULXs with stellar population parameters
(*c*) constrain the rate of Hyperluminous X-ray sources
(*d*) study the high-end of the luminosity function of High Mass X-ray Binaries

2. The Sample

The first step is to create a sample of galaxies in the Local Universe for which we have reliable information on their SFRs, $M_\star$ and Z. We select all *HyperLEDA* (Paturel *et al.* 2003; Makarov *et al.* 2014) galaxies with recession velocity less than 14000 km s^{-1} ($\lesssim$ 200 Mpc.) We collect all redshift-independent distances from *NED-D* (Steer *et al.* 2017) and derive the distance and its uncertainty for the galaxies with distance measurements. Via a Kernel Regression technique, the redshifts and distances of these galaxies are used to derive redshift-dependent distances for the the rest of the sample.

We incorporate stellar population parameters (SFR, $M_\star$, Z) or compute them using multi-wavelength information, by associating our sample with the:

- Revised Bright Galaxy Sample (Sanders *et al.* 2003)
- Revised IRAS-FSC Redshift Catalogue (Wang *et al.* 2014)
- 2MASS Extended Source Catalogue (Jarrett *et al.* 2000)
- 2MASS Large Galaxy Atlas (Jarrett *et al.* 2003)
- GALEX-SDSS-WISE Legacy Catalog (Salim *et al.* 2016)
- WISE forced photometry for SDSS galaxies (Lang *et al.* 2016)
- Firefly Stellar Population parameters (Comparat *et al.* 2017)
- MPA-JHU (Kauffmann *et al.* 2003; Brinchmann *et al.* 2004; Tremonti *et al.* 2004)

The result is the Heraklion Extragalactic CATaloguE (*HECATE*), a compilation of $\sim$163000 galaxies in the Local Universe, providing photometric/spectral data, star formation rates, stellar masses, metallicities, AGN content, etc.

By cross-matching *HECATE* with the current state of *CSC 2.0* and correcting for background contamination, we obtain the largest census of ULXs in the widest up-to-date range of environments (four orders of magnitude in SFR and $M_\star$). Out of the 13286 X-ray sources in 1678 galaxies with *Chandra* data, we find 2352 ULX candidates ($L_X > 10^{39}\,\mathrm{erg\,s^{-1}}$) in 1435 galaxies.

3. First Results

For the following analysis, we select 280 galaxies with distance less than 40 Mpc (to avoid source confusion effects) for which we have reliable estimates on the star formation rate and stellar mass. After accounting for AGN contamination, in these galaxies we estimate to have about 300 ULXs.

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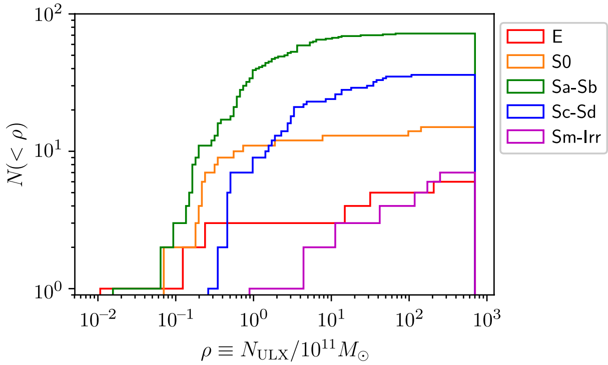

Figure 1. Cumulative number of galaxies in our sample of various morphological types (see legend), as a function of number of ULXs per $10^{11}\mathrm{M}_\odot$ stellar mass.

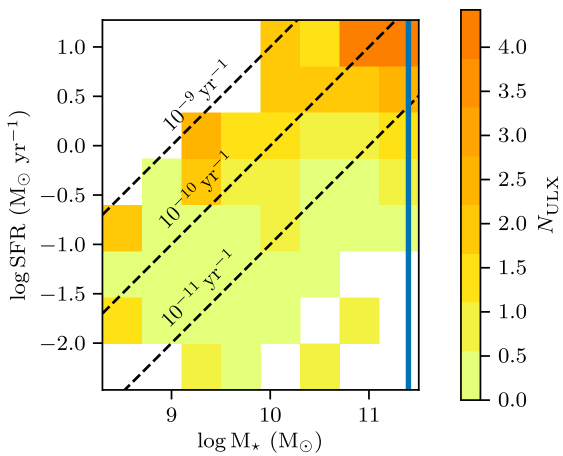

Figure 2. Average number of ULXs per galaxy as a function of SFR and stellar mass of their host galaxies. Diagonal lines correspond to equal specific SFRs. The blue vertical shows the stellar mass for which the contamination by low mass X-ray binaries (LMXB) is expected to be significant (one source above $10^{39}\,\mathrm{erg\,s^{-1}}$ assuming the LXMB luminosity function from Zhang *et al.* 2012). The average number of ULXs per galaxy increases with SFR and stellar mass.

Using the stellar mass as a proxy for the galaxy size, we compute the number of ULXs per stellar mass. In Figure 1 we present the cumulative distribution of this quantity for various morphological types. We find that early-type galaxies are characterized by small number of ULXs, while late-type galaxies typically host one ULX per $10^{11}M_\odot$. Additionally, irregulars host about 10 times more ULXs than spirals of the same mass.

In Figure 2, we show the average number of ULXs per galaxy as a function of SFR and stellar mass of the host galaxy. To quantify the correlation, we employ a Maximum Likelihood Estimator where we model the observed number of ULXs ($n_{\rm obs}$) as a Poisson variate with rate depending linearly on its SFR and $M_\star$, while accounting for the contamination by background AGN, $n_{\rm bkg}$, from Kim *et al.* (2007):

$$n_{\rm obs} \sim \mathrm{Pois}\left(a \times \mathrm{SFR} + b \times \mathrm{M}_\star + n_{\rm bkg}\right) \tag{3.1}$$

We find $a = 0.408^{+0.040}_{-0.037}\ \mathrm{M}_\odot^{-1}$ yr, in agreement with with previous results (e.g. Swartz *et al.* 2011). For the stellar mass scaling factor we find $b = \left(3.98^{+1.35}_{-1.27}\right) \times 10^{-12}\ \mathrm{M}_\odot^{-1}$ which is consistent with the LMXB contribution that we calculate from Zhang *et al.* (2012) (one luminous LMXB per $2.5 \times 10^{11}\ \mathrm{M}_\odot$ stellar mass; see blue line in Figures 2 and 4.) In

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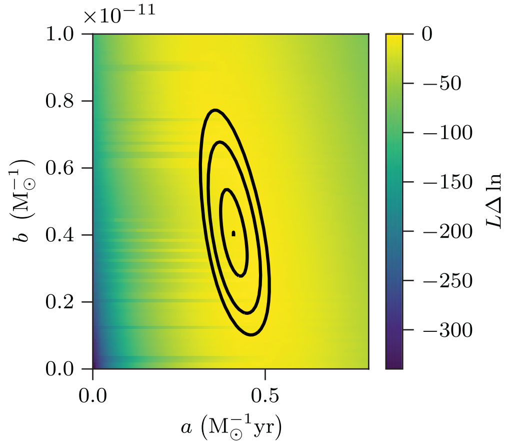

Figure 3. Relative likelihood, $\Delta \ln L = \ln(L/L_{\max})$ as a function of the scaling factors a and b (for SFR and stellar mass contribution, respectively.) The black point corresponds to the maximum likelihood, while the black contours represent the regions with confidence levels 68%, 95% and 99%. We find $a = 0.408^{+0.040}_{-0.037}$ $\mathrm{M}_\odot^{-1}$ yr and $b = \left(3.98^{+1.35}_{-1.27}\right) \times 10^{-12}$ $\mathrm{M}_\odot^{-1}$, consistent with previous results (see text for more details.)

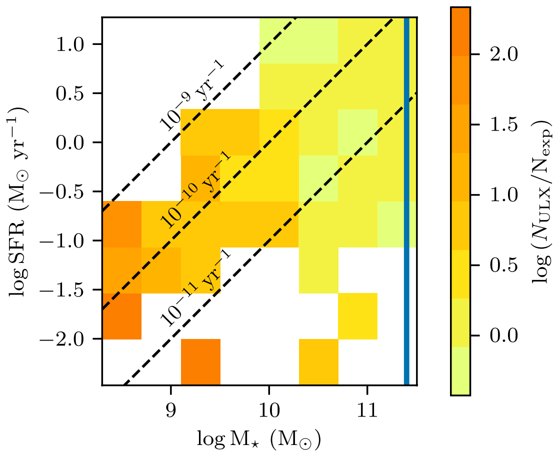

Figure 4. Same as Figure 2 but now the number of ULXs is divided by the expected number of ULXs based on the fitted model of Equation 3.1. An excess is found for galaxies with low $M_\star$, indicating higher formation efficiency of ULXs in the low-Z environment of dwarf galaxies.

Figure 3 we plot the likelihood relative to the maximum likelihood, and confidence regions on the parameter space of the fit. The SFR scaling factor is better constrained than the $M_\star$ factor, indicating that the observed ULX populations are primarily correlated with the SFR of the host galaxy. We attibute the covariance between a and b to the correlation of SFR and $M_\star$ in star forming galaxies (e.g. Maragkoudakis *et al.* 2017; Rodighiero *et al.* 2011).

Dividing the number of ULXs in different bins of the SFR-$M_\star$ plane by their expected number according to the fitted model (see Equation 3.1), we can probe the region of the parameter space that can form ULXs more efficiently. As we see in Figure 4, galaxies with low $M_\star$ or SFR are more efficient in forming ULXs, in agreement with previous results (Lehmer *et al.* 2016; Basu-Zych *et al.* 2016). As galaxies with low $M_\star$ are generally metal-poor (e.g. Sánchez *et al.* 2017), we interpret this excess of ULXs as the metallicity

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effect suggested by theoretical studies (e.g. Linden *et al.* 2011; Fragos *et al.* 2013) and observations (e.g. Prestwich *et al.* 2013).

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