X-ray Binary Luminosity Function Scaling Relations for Local Galaxies Based on Subgalactic Modeling

XRB Population Constraints from Local Galaxy Samples

Active

- NGC 4697
- Arp 299 HMXBs
- Zezas +2004

HMXB XLF
Shallow sloped, single power-law with normalization that scales with SFR.

Passive

- NGC 4697 LMXBs
- Sivakoff +2005

LMXB XLF
Steep-sloped, broken power-law with normalization that scales with $M_\star$. 

Mineo et al. (2012)
Zhang et al. (2012)
X-ray Evolution of XRBs From the Chandra Deep Fields

**LMXBs**
- Younger stellar populations
- More massive donor stars and higher accretion rates
- More luminous LMXBs

**HMXBs**
- Lower metallicity populations
- Weaker radiative mass losses lead to less binary widening, more massive compact objects, and longer timescales for luminous accretion.
- More luminous HMXBs

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**Population Synthesis** (Fragos et al. 2013) // [see also Aird et al. 2017; Fornasini et al. 2018]
Metallicity-Dependence from Local Galaxy Studies

- Correlation studies of local galaxy samples show that $L_X$/SFR declines with gas-phase metallicity, similar to population synthesis predictions (e.g., Brorby et al. 2016).

- Low metallicity galaxies appear to have an excess of very luminous ($>10^{40}$ erg/s) ULXs in $\sim$0.3 $Z_\odot$ galaxies, but results suffer from confusion and lack of constraints for typical XRBs.

Goal: Extract empirical constraints on how XRB X-ray luminosity functions vary with population age, metallicity, and dynamical environment?
Local Galaxy Sample (Lehmer et al. 2019)

- Select sample of 38 galaxies, mainly from *Spitzer* Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003):
  - $D < 30$ Mpc (resolve X-ray sources)
  - $M_B < -19$ mag (bright with lots of XRBs)
  - *Chandra* ACIS imaging data (identify XRBs)
  - UV–to–Far-IR data available (local stellar mass, SFR, and sSFR)

- Span broad range of morphology (E to SAc).

- At the subgalactic level ($500 \times 500$ pc$^2$ regions), we have a diversity of environments, at $\log \frac{\text{SFR}}{M_\star}$ (sSFR) = $-12.2$ to $-8.7$ [yr$^{-1}$].

- Have estimates of gas-phase metallicity, mainly from spectroscopy (Moustakas et al. 2010) with $Z = 0.5-1.5$ Z$_\odot$.

- Within the galaxy footprints, we have 2478 X-ray sources, and estimate $\sim 540$ unrelated cosmic X-ray background objects (Kim et al. 2007).
Extracting Subgalactic X-ray Luminosity Functions

High-sSFR (HMXBs)
Intermed-sSFR (HMXBs + LMXBs)
Low-sSFR (LMXBs)

SFR
Stellar Mass ($M_*$)
SFR ($SFR/M_*$)
Specific-SFR Dependent X-ray Luminosity Function

$\log sSFR = -11.8$

$N_{XRB} = 584$

- All seven parameters are well constrained with:

Increasing SF Intensity (higher $sSFR$; HMXB dominated)

$$\frac{dN}{dL_X} = \xi(L_X) \left[ \frac{dN(\text{LMXB})}{dL_X} + \frac{dN(\text{HMXB})}{dL_X} + \text{CXB} \right]$$

$$\frac{dN(\text{HMXB})}{dL_X} = \text{SFR} \cdot K_{\text{HMXB}} \begin{cases} \frac{L_X^{-\gamma}}{0}, & (L_X < L_c) \\ 0, & (L_X \geq L_c) \end{cases}$$

$$\frac{dN(\text{LMXB})}{dL_X} = M_\star \cdot K_{\text{LMXB}} \begin{cases} L_X^{\alpha_1} L_{\alpha_2-\alpha_1} L_X^{-\alpha_2}, & (L_b \leq L_X < L_c) \\ 0, & (L_X \geq L_c) \end{cases}$$

- HMXBs
  - $K_{\text{HMXB}} = 1.96 \pm 0.14 \ (M_\odot \ yr^{-1})^{-1}$
  - $\gamma = 1.65^{+0.03}_{-0.02}$
  - $\log L_c = 40.7^{+0.4}_{-0.2}$

- LMXBs
  - $K_{\text{LMXB}} = 33.8^{+7.3}_{-3.6} \ (10^{11} \ M_\odot)^{-1}$
  - $\alpha_1 = 1.28^{+0.06}_{-0.09}$
  - $L_b = 1.48^{+0.70}_{-0.66} \ (10^{38} \ erg \ s^{-1})$
  - $\alpha_2 = 2.33^{+0.27}_{-0.21}$
• The LMXB XLF in late-types is somewhat below that derived from Zhang et al. (2012) for elliptical galaxies, potentially due to differences in GC LMXB populations and star-formation histories.

• The HMXB XLF is similar to the Mineo et al. (2012) XLF; however, we identify a more complex shape that should have implications for population synthesis models.
Galaxy-by-Galaxy X-ray Luminosity Functions
Evidence for a Metallicity Dependence

The average galaxy gas-phase metallicity is $\sim Z_\odot$. We identified a subset of four $\sim 0.5Z_\odot$ galaxies in the sample and inspected their XLFs.

Low-metallicity XLF has a factor of $\sim 3$ to $10$ times excess of $L > 10^{39}$ ergs s$^{-1}$ sources and potential deficit of lower-luminosity objects. This is overall consistent with $L_X$/SFR varying with metallicity. Future work is planned to explore the detailed variations in the XLF with metallicity.
Summary and Future Work

1. Self-consistently modeled the HMXB and LMXB populations in subgalactic regions from a sample of 38 galaxies (mainly late-types) and decomposed the HMXB and LMXB XLFs and parameterized their shapes.

2. The LMXB XLF in our sample has a relatively shallow high-$L$ ($>10^{38}$ ergs/s) slope and fewer $L < 10^{38}$ ergs/s sources compared to large ellipticals. This is likely due to differences in GC LMXB populations and younger star-formation histories.

3. The HMXB XLF is basically consistent with previous studies; however, we identify a more complex shape that should have implications for population synthesis models.

4. We find low-metallicity galaxies are outliers to our global parameterization, and contain an excess of ULXs ($L > 10^{39}$ ergs/s) and potentially a deficit of $L \approx 10^{37} - 10^{38}$ ergs/s sources.

5. Our results have implications for quantifying the scatter in integrated emission scaling relations (e.g., $L_X$ vs. SFR relation), constraining detailed population synthesis models, quantifying XRB populations when studying AGN, and predicting future mission (e.g., eROSITA and Athena) X-ray detections of normal galaxies (see Lehmer et al. 2019).

Future Direction

- Long-term goal would be to carefully quantify empirically how the generalized XRB XLFs vary with star-formation history and metallicity using as many relevant data sets as possible.

- Data from such efforts could then be used as a critical set of constraints on stellar population evolution models that include the effects of mass-transfer on binaries (e.g., BPASS; Eldridge et al. 2017) and help put into context interacting binary phenomena like gravitational wave sources.
Best-Fit XLF Parameter Constraints

\[
\frac{dN(\text{HMXB})}{dL_X} = SFR \times K_{\text{HMXB}} \begin{cases} 
L_X^{-\gamma} & (L_X < L_c) \\
0 & (L_X \geq L_c)
\end{cases}
\]

\[
\frac{dN(\text{LMXB})}{dL_X} = M_\star \times K_{\text{LMXB}} \begin{cases} 
L_X^{-\alpha_1} & (L_X < L_b) \\
L_b^{\alpha_2-\alpha_1} L_X^{-\alpha_2} & (L_b \leq L_X < L_c) \\
0 & (L_X \geq L_c)
\end{cases}
\]