The Metallicity Dependence of the High-mass X-Ray Binary Luminosity Function

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Abstract

In this work, we present detailed constraints on the metallicity dependence of the high-mass X-ray binary (HMXB) X-ray luminosity function (XLF). We analyze ≈5 Ms of Chandra data for 55 actively star-forming galaxies at D ≲ 30 Mpc, with gas-phase metallicities spanning 12 + log(O/H) ≈ 7–9.2. Within the galactic footprints, our sample contains a total of 1311 X-ray point sources, of which ≈49% are expected to be HMXBs, with the remaining sources likely to be low-mass X-ray binaries (LMXBs; ≈22%) and unrelated background sources (≈29%). We construct a model that successfully characterizes the average HMXB XLF over the full metallicity range. We demonstrate that the SFR-normalized HMXB XLF shows clear trends with metallicity, showing steadily increasing numbers of luminous and ultraluminous X-ray sources (log L(erg s−1) ≈ 38–40.5) with declining metallicity. However, we find that the low-luminosity (log L(erg s−1) = 36–38) HMXB XLF appears to show a nearly constant SFR scaling and slope with metallicity. Our model provides a revised scaling relation of integrated LX/SFR versus 12 + log(O/H), and a new characterization of its SFR-dependent stochastic scatter. The general trend of this relation is broadly consistent with past studies based on integrated galaxy emission; however, our model suggests that this relation is driven primarily by the high-luminosity end of the HMXB XLF. Our results have implications for binary population synthesis models, the nature of super-Eddington accreting objects (e.g., ultraluminous X-ray sources), recent efforts to identify active galactic nucleus candidates in dwarf galaxies, and the X-ray radiation fields in the early universe during the epoch of cosmic heating at z ≳ 10.

Unified Astronomy Thesaurus concepts: High-mass x-ray binary stars (733); Metallicity (1031); Star formation (1569); Spiral galaxies (1560); X-ray binary stars (1811); X-ray astronomy (1810); Compact objects (288)

Supporting material: machine-readable tables

1. Introduction

Over the last ≈20 yr, the Chandra X-ray Observatory (Chandra) has accumulated an extensive archive of X-ray imaging data, capable of resolving populations of X-ray binaries (XRBs) within relatively nearby galaxies (≤100 Mpc). Thanks to these Chandra data, along with complementary multwavelength data (e.g., from GALEX, Spitzer, WISE, and SDSS), it is now possible to conduct detailed statistically meaningful studies to characterize how XRB X-ray luminosity functions (XLFs) vary with local physical properties (e.g., star formation rate (SFR), and stellar mass (M*)). Such XRB XLF scaling relations provide important benchmarks for understanding X-ray emission from a variety of galaxy populations, compact object formation and evolution, the binary phase of stellar evolution, and several close-binary subclasses (e.g., gravitational-wave sources, short gamma-ray bursts, and millisecond pulsars).

On the observational side, XRB scaling relations are routinely used to assess whether X-ray detected sources are consistent with stellar-mass XRBs or accreting supermassive black holes (SMBHs; see Mezcua et al. 2018; Latimer et al. 2019; Birchall et al. 2020; Hodges-Kluck et al. 2020; Koudmani et al. 2020, and Scerri et al. 2020 for recent examples). These assessments are often based on XLF-integrated scaling relations and their galaxy population statistical scatter (e.g., the Lx–SFR relation; Ranalli et al. 2003; Colbert et al. 2004; Persic & Rephaeli 2007; Lehmer et al. 2008, 2010, 2016, 2019, 2020; Mineo et al. 2012a, 2012b; Basu-Zych et al. 2013a; Aird et al. 2017). However, due to the often poor sampling of the bright-source ends of XLFs, these relations are likely to become nonlinear, with highly skewed scatter distributions in the low-SFR and low-M* regimes where they are often applied (e.g., Gilfanov et al. 2004; Justham & Schawinski 2012; Lehmer et al. 2019). A detailed characterization of how the XRB XLF varies with galaxy physical properties would provide an appropriate statistical quantification as to how X-ray scaling relations and their scatter vary across these properties.

Thus far, most XRB XLF scaling relation studies have focused on constraining the high-mass XRB (HMXB) and low-mass XRB (LMXB) XLF scalings with SFR and M*, respectively (e.g., Grimm et al. 2002; Gilfanov 2004; Mineo et al. 2012a; Zhang et al. 2012; Lehmer et al. 2019, 2020). However, it has recently become clear, from both theoretical and observational studies of integrated scaling relations, that additional physical parameters, including star formation history...
(SFH) and metallicity, have an important impact on these scaling relations (e.g., Dray 2006; Mapelli et al. 2010; Kaaret et al. 2011; Basu-Zych et al. 2013b, 2016; Fragos et al. 2013a, 2013b; Brorby et al. 2014, 2016; Douna et al. 2015; Lehmer et al. 2017; Antoniou et al. 2019; Fornasini et al. 2019, 2020; Kouroumpatzakis et al. 2020; Kovlakas et al. 2020).

Particular attention has been directed to the metallicity dependence of the HMXB XLF. HMXBs are the most luminous XRB population per stellar mass, and are expected to provide important ionizing radiation from stellar populations, lasting longer than the far-UVM emission from young massive stars, and traversing longer path lengths before being absorbed. Given these properties, HMXBs have been proposed to play roles in (1) interstellar medium feedback (e.g., Pakull et al. 2010; Soria et al. 2010, 2014; Justham & Schawinski 2012; López et al. 2019); (2) the production of Lyman continuum radiation, as well as He II and Lyα emission lines from starbursts (e.g., Kaaret et al. 2017a; Bluem et al. 2019; Schaerer et al. 2019; Svboda et al. 2019; Dittenber et al. 2020; Saxena et al. 2020; Sanchyana et al. 2020); and (3) the heating of the early intergalactic medium at $z \gtrsim 10$ (e.g., Mirabel et al. 2011; Mésinger et al. 2013; Pacucci et al. 2014; Das et al. 2017; Madau & Flogos 2017; Greig & Mésinger 2018; Park et al. 2019; Heneka & Mésinger 2020).

While some basic models have been proposed for the HMXB XLF dependence on metallicity (e.g., Brorby et al. 2014; Basu-Zych et al. 2016; Ponnada et al. 2020), these models are primarily based on interpreting the $L_X$/SFR versus metallicity relation (hereafter, the $L_X$–SFR–Z relation) in terms of a varying HMXB XLF normalization and power-law slope. Furthermore, studies placing direct constraints on the metallicity dependence of point source populations within galaxies have focused primarily on the ultraluminous X-ray source (ULX; $L > 10^{39}$ erg s$^{-1}$) formation rate per unit SFR (e.g., Zampieri & Roberts 2009; Mapelli et al. 2010; Prestwich et al. 2013; Douna et al. 2015; Kovlakas et al. 2020). These studies find a clear decline in the ULX rate with increasing metallicity; however, they do not characterize the luminosity dependence of this trend, and nor do they make a direct connection with more typical lower-luminosity XRB populations.

In a recent study of the XLFs of 38 nearby ($D < 30$ Mpc) galaxies (primarily late-type galaxies), Lehmer et al. (2019; hereafter, L19) showed that the five lowest metallicity galaxies in the sample hosted a factor of $\approx 2$–10 times excess of HMXBs with $L \gtrsim 5 \times 10^{38}$ erg s$^{-1}$ compared to the average galaxy population, while the number of $L \approx (0.1$–$5) \times 10^{38}$ erg s$^{-1}$ sources in these relatively low-metallicity galaxies appeared to be consistent with the full galaxy sample. This suggests that metallicity-dependent XLF evolution is more complex than a simple scaling in the overall normalization and power-law slope of the XLF.

In this paper, we expand on the early results from L19, and characterize more fully how SFR-scaled HMXB XLF normalization and detailed shape vary with metallicity. In Section 2, we discuss our galaxy sample selection and present the galaxy properties. In Section 3, we briefly summarize our Chandra data analysis procedure, which closely follows the approach outlined in L19. In Section 4, we present our global metallicity-dependent HMXB XLF model and fitting results. In Section 5, we discuss our results in the context of past studies, and highlight problems to address in future studies. Finally, Section 6 provides a summary of the key results from this work.

Unless noted otherwise, we make use of multiband X-ray fluxes and luminosities that have been corrected for Galactic absorption, but not intrinsic absorption. Throughout, we quote X-ray luminosities in the 0.5–8 keV bandpass, using $L$ to denote individual point source luminosities, and $L_X$ to represent population-integrated luminosities. For clearer comparisons with past studies, we often quote SFR and $M_*$ values based on a Kroupa (2001) initial mass function (IMF) at solar abundances, with a SFH which is constant over 13.6 Gyr. As we discuss in Section 2, the assumption of a constant abundance for these calculations has only a minor impact on our results.

2. Sample Selection and Properties

Given our goal to study the effects of metallicity on HMXB formation, we constructed relatively nearby ($D < 30$ Mpc) samples of star-forming galaxies with high specific SFRs (sSFR $= \text{SFR} / M_*$, $\gtrsim 10^{-10}$ yr$^{-1}$), spanning a broad range of metallicity ($12 + \log(O/H) \approx 7$–9.2; $Z \approx 0.02$–3 $Z_\odot$). The adopted sSFR boundary limits contributions from LMXBs which dominate in lower sSFR galaxies (e.g., Lehmer et al. 2010; Kouroumpatzakis et al. 2020). We first assembled a main sample of 33 such objects, comprising both Chandra archival data from the literature, and a suite of multiband X-ray observations spanning the UV to mid-IR. Our main sample contains (1) 23 galaxies from the spectroscopic study by Moustakas et al. (2010) of galaxies in the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003); (2) six objects from Engelbracht et al. (2008) and (3) four additional nearby galaxies (NGC 5253, M83, M101, and DDO68) with deep Chandra exposures (>100 ks). We chose not to include well-studied disk-dominated galaxies with high inclination angles to our line of sight ($\gtrsim 70$ deg; e.g., M82 and NGC 253), due to the highly varied (and occasionally very large) absorption of X-ray point sources through the galactic disks.

In addition to our main sample, we assembled a supplemental sample of 22 extremely metal-poor objects with $12 + \log(O/H) < 8$ and $D < 30$ Mpc, drawn from Prestwich et al. (2013). We note that these galaxies have been utilized in the Brorby et al. (2014) and Douna et al. (2015) studies of X-ray properties of extremely metal-poor galaxies, and include many of the lowest metallicity galaxies known in the local universe. Galaxies in the supplementary sample are compact ($\approx 0.4$–1.4 semimajor axes) dwarf galaxies, and have relatively shallow Chandra and multiband X-ray data compared to our main sample. Therefore, physical parameters are more uncertain for this population, and X-ray constraints are limited only to bright point sources in the galaxies, with some uncertainty as to whether they are XRB or SMBH-dominated.

All galaxies in our samples have oxygen abundance measurements, available either from strong-line calibrations, or a “direct” electron–temperature-based theoretical calibration. The strong-line estimates were originally based on either the theoretical Kobulnicky & Kewley (2004; hereafter, KK04) or 12 Throughout this paper, we quote metallicities in terms of gas-phase oxygen abundances, $12 + \log(O/H)$, and take the solar value to be 8.69 (Allende Prieto et al. 2001). When comparing with theoretical models that explicitly specify metallicities, we assume the conversion $\log(Z/Z_\odot) = \log(O/H) - \log(O/H)_\odot = \log(O/H) + 3.31$. 

the empirical Pettini & Pagel (2004; PP04) calibrations. KK04 estimates were available for the 23 SINGS galaxies in our main sample via Moustakas et al. (2010), who utilized the $R_{23}$ emission-line ratio, $R_{23} = ([O II]\lambda 3727 + [O III] \lambda \lambda 4959, 5007) / H\beta$, and $[O III]\lambda 5007 / [O II] \lambda 3727$. PP04 estimates were available for M83 and M101 (Bresolin et al. 2009 and Hu et al. 2018), and are based on the ratio $([O III]\lambda 5007 / H\beta) / ([N II] \lambda 6584 / H\alpha)$. All other galaxies, including eight main-sample galaxies ($12 + \log(O/H) \lesssim 8.4$), as well as the 22 extremely metal-poor supplemental-sample galaxies, had estimates based on the direct method (see Table 1 for references), which uses the $[O III]\lambda 4959, 5003 / [O III] \lambda 4363$ ratio.

The PP04 strong-line calibrations were empirically calibrated using direct method measurements, and the two methods are consistent for $12 + \log(O/H) \approx 8.09$–8.5. The direct method is generally considered to be robust for relatively low metallicities ($12 + \log(O/H) \lesssim 8.5$; e.g., Stasińska 2005). To bring the metallicities for our full galaxy sample into calibration alignment, we converted all 23 galaxies with KK04 estimates to the PP04 calibration, using the methods described in Kewley & Ellison (2008). In Col.(10) of Table 1, we provide the adopted metallicity values for our sample galaxies.

Following the procedures in L19, we generated SFR and $M_\ast$ maps for main-sample galaxies, using the scaling relations from Hao et al. (2011) and Zibetti et al. (2009), respectively. Values of the SFR and $M_\ast$ quoted for each galaxy were extracted from the maps using the regions defined in Table 1, with NGC 0628, NGC 5194, and NGC 7552, with central regions removed due to potential AGN or confusion. The removal regions were located at the central positions of the galaxies, and were circular in shape, with radii of $r_{\rm remove} = 3$ arcsec for NGC 0628 and NGC 5194, and $r_{\rm remove} = 15$ arcsec for NGC 7552.

For the supplemental sample galaxies, we utilized the extinction-corrected values of $L^{\rm corr}_{\rm X} / M^{\rm corr}_{\rm UV}$ from Prestwich et al. (2013), combined with the relation of Hao et al. (2011), to estimate SFR values. As per previous investigations of this sample (Prestwich et al. 2013; Brorby et al. 2014, 2016; Douna et al. 2015), we do not provide stellar mass estimates for these galaxies. These galaxies were originally selected as blue and actively star-forming, and are expected to have high sSFRs and to contain negligible contributions from LMXBs.

As discussed in Section 1, for the purpose of consistency with other work, the values of SFR and $M_\ast$ above assume conversion factors using solar abundances, and do not incorporate variations due to metallicity. Applying such a variation would have its largest impact on the young massive star population, in which low-metallicity stars are expected to be hotter and to produce more UV emission per unit SFR , as compared to the solar abundance case (e.g., Bicker & Fritze-v. Alvensleben 2005). We have calculated, using PEGASE models (Fioc & Rocca-Volmerange 1997) for constant SFHs over 100 Myr, that the SFR/$L_{\rm FUV}$ conversion factors would be $\approx0.8$ and $\approx1.2$ times the solar value factor at $12 + \log(O/H) = 7$ and 9.2, respectively. Given that past results, as well as the results presented below, show a decline in $L_X / \text{SFR}$ with increasing metallicity, including metallicity dependence in the SFR calculations would act to further promote such a trend at a maximum level of $\approx0.18$ dex across the full metallicity range.

In Table 1, we list the physical properties of galaxies in our main and supplemental samples. Our main sample contains galaxies where $\text{SFR} = 0.02$–9.0 $M_\odot$ yr$^{-1}$ (SFR) = 1.4 $M_\odot$ yr$^{-1}$ and $\log M_\ast / M_\odot = 7.3$–10.4 ($\log (M_\ast / M_\odot) = 9.7$). Our supplemental sample has a range of SFR = 0.0007–0.045 $M_\odot$ yr$^{-1}$ ($\langle \text{SFR} \rangle = 0.012 M_\odot$ yr$^{-1}$). Figure 1 shows binned distributions of oxygen abundances for our main and supplemental samples in terms of numbers of galaxies and cumulative SFR in each bin. Given the HMXB XLF scaling with SFR, the SFR of a given bin can be considered as a proxy for the total number of HMXBs present in the samples. It is clear that the extremely metal-poor galaxy subsample is expected to harbor fewer HMXBs than the main sample, given its low cumulative SFR.

In addition to the relatively low SFRs compared to the main sample, the supplemental sample has available only relatively shallow Chandra exposures (see Section 3 for a detailed discussion of the Chandra data). The supplemental sample mean Chandra exposure is $\approx10$ ks, compared with $\approx150$ ks for the main sample. The combination of these two factors (relatively low-SFR and shallow Chandra data) lead to the supplemental sample containing $\approx200$ times fewer X-ray detected point sources within the galaxy footprints, as compared to the main sample. In fact, the majority of the supplemental sample galaxies (17 out of 22) contain no detected point sources coincident with the galaxies, while all main sample galaxies have at least one detected source.

3. Data Analysis

We chose to incorporate all ACIS-S or ACIS-I Chandra imaging observations with aim-points less than 5 arcmin from the galactic centers (see Col.(3) and (4) in Table 1). This led to the selection of 137 and 22 ObsIDs for the 33 and 22 galaxies in our main and supplementary samples, respectively. The cumulative Chandra exposures spanned a range of 5–853 ks (see Col.(12) of Table 1).

Our Chandra data analysis procedure follows that presented in Section 3.2 of L19; we briefly describe our procedure here. For a given galaxy, we reprocessed all ObsIDs to the most recent calibrations, removed bad events from bad columns and pixels, and generated exposure maps. When more than one ObsID was available, we aligned all observations to the longest exposure, and co-added all observations for the purpose of identifying X-ray point sources. X-ray point sources were identified by running wavdetect on ObsID-merged images in the 0.5–2 keV, 2–7 keV, and 0.5–7 keV bands, and resulting point source properties were analyzed using ACIS Extract (AE; Broos et al. 2010, 2012). For each galaxy, AE first analyzes all ObsIDs separately, and subsequently combines them to provide appropriate source photometry and spectra. AE then performs spectral fitting and provides flux measurements for all point sources, which are used for our X-ray point source catalogs.13

For each galaxy, we assessed point source completeness (i.e., fraction of sources recovered by our procedure as a function of luminosity $L$) by running simulations where mock sources were added to images (using MARX point-spread functions generated by AE and custom software) and tested for recovery by re-running our procedure. These completeness curves are critical for correctly modeling the XLFs. The resulting 50% completeness limits span $\log L_{50}(\text{erg s}^{-1}) = 35.9–38.5$, and are listed in Col.(13) of Table 1. Given the variations in Chandra exposure, distance, and galaxy type, the number of X-ray point sources

13 Point source catalogs are summarized in the Appendix, and provided in the electronic version of the paper.
### Table 1

HMXB-Dominant Galaxy Sample and Properties

| GALAXY          | CENTRAL POSITION | SIZE PARAMETERS |
|-----------------|------------------|-----------------|
| NAME            | \( \alpha_{2000} \) | \( \delta_{2000} \) | \( D \) | \( a \) | \( b \) | PA | \( \log M_* \) | SFR | \( 12 + \log(O/H) \) | \( t_{sp} \) | \( \log L_{50} \) | \( N_X \) |
| NGC0024...      | 00 09 56.5       | −24 57 47.3     | 7.30 ± 2.30 | 1.38 | 0.39 | 43.5 | 8.64 | 0.04 | 8.59 ± 0.18 | 43 | 36.8 | 8 |
| NGC0337...      | 00 59 50.1       | −07 34 40.7     | 22.40 ± 2.30 | 0.87 | 0.49 | 157.5 | 9.32 | 1.09 | 8.44 ± 0.07 | 9 | 38.5 | 6 |
| NGC0628 (M74)...| 01 36 41.8       | +15 47 00.5     | 7.30 ± 1.40 | 2.10 | 1.80 | 87.5 | 9.48 | 0.33 | 8.54 ± 0.15 | 268 | 36.4 | 43 |
| NGC0925...      | 02 27 16.9       | +33 34 44.0     | 9.12 ± 0.17 | 1.87 | 0.82 | 105.0 | 9.03 | 0.18 | 8.38 ± 0.15 | 12 | 37.5 | 7 |
| NGC1482...      | 03 54 38.9       | −20 30 08.8     | 23.20 ± 2.30 | 1.42 | 0.82 | 105.5 | 10.43 | 4.80 | 8.52 ± 0.16 | 28 | 38.3 | 7 |

**Main Sample**

| GALAXY          | CENTRAL POSITION | SIZE PARAMETERS |
|-----------------|------------------|-----------------|
| NGC0628 (M74)...| 01 36 41.8       | +15 47 00.5     | 7.30 ± 1.40 | 2.10 | 1.80 | 87.5 | 9.48 | 0.33 | 8.54 ± 0.15 | 268 | 36.4 | 43 |
| NGC0925...      | 02 27 16.9       | +33 34 44.0     | 9.12 ± 0.17 | 1.87 | 0.82 | 105.0 | 9.03 | 0.18 | 8.38 ± 0.15 | 12 | 37.5 | 7 |
| NGC1482...      | 03 54 38.9       | −20 30 08.8     | 23.20 ± 2.30 | 1.42 | 0.82 | 105.5 | 10.43 | 4.80 | 8.52 ± 0.16 | 28 | 38.3 | 7 |

**Supplemental Sample**

| GALAXY          | CENTRAL POSITION | SIZE PARAMETERS |
|-----------------|------------------|-----------------|
| 6dFJ045204-364859... | 04 05 20.3       | −36 49 01.0     | 11.00 | 0.23 | 0.19 | 16.5 | ... | 0.006 | 7.34 ± 0.09 | 5 | 38.0 | 0 |
| HS0822+3542...   | 08 25 55.5       | +35 32 32.0     | 12.70 | 0.10 | 0.05 | 141.4 | ... | 0.003 | 7.44 ± 0.06 | 5 | 38.2 | 0 |
| HS1442+4250...   | 14 44 12.8       | +42 37 44.0     | 10.50 | 0.44 | 0.10 | 63.2 | ... | 0.011 | 7.64 ± 0.02 | 5 | 37.8 | 0 |
| Iz6189...        | 09 34 02.0       | +55 14 28.0     | 17.10 | 0.13 | 0.09 | 145.0 | ... | 0.045 | 7.18 ± 0.03 | 40 | 37.6 | 1 |
| J081239.52+483645.3... | 08 12 39.5 | +48 36 45.0     | 9.04 | 0.21 | 0.11 | 73.7 | ... | 0.001 | 7.28 ± 0.06 | 4 | 37.9 | 0 |

**Note.** The full version of this table contains 15 columns of information for all 33 and 22 galaxies from our main and supplemental samples, respectively (see Section 2). An abbreviated version of the table is displayed here to illustrate its form and content. Col.(1): Adopted galaxy designation with Messier designation, if applicable. Col.(2) and (3): Right ascension and decl. of the galactic center. Col.(4): Adopted distance and 1σ uncertainties in units of Mpc. Col.(5)–(7): Isophotal ellipse parameters, including, respectively, semimajor axis, \( a \), semiminor axis, \( b \), and position angle east from north, PA. The majority of the main-sample galaxies have size parameters based on 2MASS \( K_s \)-band data from Jarrett et al. (2003). In these cases, the \( K_s \)-band 20 mag arcsec\(^{-2} \) ellipses were used to avoid large contamination from background sources; however, for galaxies with \( K_s \)-band 20 mag arcsec\(^{-2} \) semimajor axes \( a \) < 1 arcmin, we chose to adopt the “total” \( K_s \)-band ellipses. For the main-sample galaxies, DDO68, NGC 4861, and IC2574, and all galaxies in the supplemental sample, we adopted the positions and \( D_2s \) sizes using the HyperLeda database (http://leda.univ-lyon1.fr/). Col.(8): Logarithm of the galactic stellar mass, \( M_* \), within the defined regions. Col.(9): Star formation rate within the defined regions. Col.(10): Adopted estimate of the average oxygen abundances, \( 12 + \log(O/H) \); see Col.(15) for references. For consistency with other studies of XRB scaling relations that include metallicity, we have converted all abundances to the Pettini & Pagel (2004) PPD4 calibration, following the prescriptions in Kewley & Ellison (2008). Col.(11): Cumulative Chandra exposure time in ks. Col.(12): Logarithm of the 0.5–8 keV luminosity, corresponding to 50% completeness across the galaxy. Col.(13): Number of X-ray detected sources within the galactic footprints defined by Col.(2)–(3) and (5)–(7). Col.(14) and (15): References to the adopted distances and \( 12 + \log(O/H) \), respectively.

**References.** - 1 = Mousekas et al. (2010) 2 = Engelbracht et al. (2008) 3 = Sacchi et al. (2016) 4 = McQuinn et al. (2016) 5 = Tully et al. (2013) 6 = Freedman et al. (2001) 7 = Nataf (2015) 8 = Skillman et al. (2013) 9 = Bresolin et al. (2009) 10 = Montreal-Ibero et al. (2012) 11 = Hu et al. (2018) 12 = Prestwich et al. (2013) 13 = Guseva et al. (2007) 14 = Izotov et al. (2006) 15 = Izotov & Thuan (2007) 16 = Izotov et al. (2007) 17 = Izotov et al. (2012) 18 = Papaderos et al. (2008) 19 = Pustilnik et al. (2003) 20 = van Zee (2000).

(This table is available in its entirety in machine-readable form.)
detected in the galaxy footprints ranges from 0–363 (see Col. (14) in Table 1).

To build our metallicity-dependent HMXB XLF model, we first divided our combined main and supplemental galaxy samples into five bins of $12 + \log(O/H)$ that were chosen to have similar cumulative SFRs (except for the lowest metallicity bin). For each bin, we constructed an observed distribution of luminosities using all point sources (including HMXBs, LMXBs, and background sources) collected for all galaxies in the bin. These distributions are presented as histograms for the five metallicity bins in Figure 2 (black histograms). Using our derived completeness functions, along with galactic sky area and $M_*$ measurements, we estimated for each galaxy the expected contribution to the point source luminosity distribution for unrelated background sources from the cosmic X-ray background (hereafter, CXB) and LMXBs, respectively. We utilized extragalactic number counts from Kim et al. (2007) to estimate the CXB component, and the $M_*$-normalized LMXB relation from L19 to estimate LMXB contributions. For all cases, the CXB and LMXB model components (shown as green-dotted and red long-dashed curves in Figure 2) were comfortably below the observed X-ray point source distributions, and indicate that our selection criteria result in a dominance of HMXB populations.

In Figure 3, we show the CXB-and-LMXB subtracted and completeness-corrected cumulative XLF for each of the metallicities ranges, normalized by the cumulative SFR in each bin. For comparison, the average HMXB XLF model fit from L19, which consists of a single-slope power-law with a cut-off luminosity, is displayed in each panel (thin blue curves). We stress that this representation of the data was not used when fitting for the metallicity-dependent HMXB XLF (see below), due to its cumulative form, subtraction of model components (i.e., CXB and LMXBs), and large corrections for completeness at the low-$L$ ends of the distributions. However, this representation provides guidance on the overall form of the metallicity dependence to the shape and normalization of the HMXB XLF.

The data in Figure 3 show clear trends with metallicity, which can be gleaned from comparisons with the L19 HMXB XLF curve (blue solid curve). HXMB XLFs at all metallicities

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**Figure 1.** Sample distributions of metallicities ($12 + \log(O/H)$), plotted in terms of total numbers of galaxies (top panel) and cumulative SFRs (bottom panel) per metallicity bin. Our main sample is shown as solid black histograms, and our supplemental sample of 22 $12 + \log(O/H) < 8$ objects from Prestwich et al. (2013) is shown as dashed gray histograms. The cumulative SFR is a proxy for the number of HMXBs expected to be present within the galaxy sample. The supplemental sample has a low collective SFR, and generally shallow Chandra observations. Although it helps to extend the metallicity range into the $12 + \log(O/H) < 8$ regime, the supplemental sample provides only weak constraints on the HMXB XLF.

**Figure 2.** Observed distributions of X-ray point source luminosities for galaxy subsamples binned by $12 + \log(O/H)$ (black histograms). The metallicity range and number of galaxies within the bin, $N_{gal}$, are annotated in each panel. The detailed shapes and X-ray luminosity ranges of the distributions are dependent on both the intrinsic distributions of the point source populations and the completeness characteristics of the observations, which can vary substantially between galaxies. Our best-fit metallicity-dependent HMXB XLF model predictions are shown as short-dashed blue curves, with the model contributions from CXB sources and LMXBs shown as dotted green and long-dashed red curves, respectively. The CXB and LMXB model contributions for each galaxy vary with X-ray completeness and scale only with the galaxy sky coverage and stellar mass, respectively, and do not vary with metallicity (see Section 3 for details). The summed contributions of these model components constitute our total point source models, which are shown in each panel as solid curves of varying color.
show similar steep power law like slopes and SFR normalizations at $L \lesssim (3-10) \times 10^{37}$ erg s$^{-1}$. However, at $L \gtrsim 10^{38}$ erg s$^{-1}$ the distribution flattens and extends to increasingly higher luminosities with declining metallicity. For example, we find that the number of ULXs (i.e., $L > 10^{39}$ erg s$^{-1}$) per SFR increases from $\approx 0.5 (M_\odot \text{yr}^{-1})^{-1}$ to $\approx 2 (M_\odot \text{yr}^{-1})^{-1}$ from $12 + \log(O/H) \approx 9$ to 8 (see Section 5.1 for further discussion on ULXs).

The trends observed in Figure 3 indicate that the $L_X$–SFR–Z relations examined in the literature (see Section 1 and references therein) result from a complex variation in the bright-end of the HMXB XLF with metallicity, instead of a simple change in normalization, as has been proposed in previous investigations (e.g., Brorby et al. 2014; Basu-Zych et al. 2016; Ponnada et al. 2020). Motivated by the observed metallicity-dependent HMXB XLF behavior in Figure 3, we chose to model the data using the following functional form:

$$\frac{dN_{\text{HMXB}}}{dL} = \text{SFR} A_{\text{HMXB}} \exp[-L/L_c(Z)] \times \begin{cases} L^{-\gamma_1} & (L < L_b) \\ L_b^{\gamma_2(Z)} - L^{-\gamma_2(Z)} & (L > L_b) \end{cases}$$  \hspace{1cm} (1)

where

$$\gamma_2(Z) = \gamma_{2,\odot} + \frac{d\gamma_2}{d \log Z}[12 + \log(O/H) - 8.69],$$  \hspace{1cm} (2)

and

$$\log L_c(Z) = \log L_{c,\odot} + \frac{d \log L_c}{d \log Z}[12 + \log(O/H) - 8.69].$$  \hspace{1cm} (3)

The above model contains seven free parameters, including both metallicity-invariant parameters such as the overall normalization per SFR, $A_{\text{HMXB}}$, the broken power law component faint-end slope, $\gamma_1$, and break luminosity, $L_b$, as well as the metallicity-dependent bright-end power-law slope, $\gamma_2(Z)$, and exponential cut-off luminosity, $L_c(Z)$. The latter, metallicity-dependent quantities each include solar metallicity reference values ($\gamma_{2,\odot}$ and $\log L_{c,\odot}$) and their first derivative with respect to the logarithm of the metallicity $(d\gamma_2/d \log Z)$ and $(d \log L_c/d \log Z)$.

To fit the parameterization specified by Equations (1)–(3) we made use of the MCMC approach described in Sections 4.1 and 4.3 of L19. For a given galaxy, the X-ray point source luminosity distribution (equivalent to Figure 2 but for each galaxy individually) was modeled as:

$$M(L) = \xi(L) \Delta \log L \left[ \frac{dN_{\text{HMXB}}}{d \log L} + \frac{dN_{\text{LMXB}}}{d \log L} + \text{CXB}(L) \right].$$  \hspace{1cm} (4)

where $\xi(L)$ is the luminosity-dependent completeness function for the galaxy, and $dN_{\text{LMXB}}/d \log L$ and $\text{CXB}(L)$ are the LMXB XLF and differential number counts, respectively. The $dN_{\text{LMXB}}/d \log L$ and CXB model components are uniquely specified for a galaxy, given its stellar mass and sky area, respectively. Although we expect the LMXB component to have some metallicity dependence, we note that (1) the metallicity range associated with the old stellar populations harboring the LMXBs is likely to be smaller than the gas-phase metallicity values used here, since the LMXBs would have formed at earlier epochs of cosmic history; (2) the metallicity dependence of LMXB formation is predicted to be weaker than that of the HMXB population (see, e.g., Figure 2 of Fragos et al. 2013a); and (3) the LMXB component is expected to be negligible for the majority of our galaxies with $12 + \log(O/H) \lesssim 8.5$, even if some plausible metallicity dependence is applied.

In our fitting procedure, an MCMC model was quantitatively compared with the observed distributions of X-ray point source...
luminosities, \( N(L) \), and evaluated on a global basis using the C-statistic (Cash 1979):

\[
C = 2 \sum_{i=1}^{n_y} \left( \sum_{j=1}^{n_x} M_{ij} - N_{ij} \ln(N_{ij}/M_{ij}) \right),
\]

where \( n_{gal} = 55 \) galaxies in our sample (\( i \)th index), and \( n_X = 100 \) X-ray luminosity bins (\( j \)th index) spanning \( \log L \) (erg s\(^{-1}\)) = 35–41.7. We note that the majority of our galaxies do not have non-zero completeness across all 100 X-ray luminosity bins, and bins with zero completeness do not contribute to \( C \).

### 4. Results

In Table 2, we provide the resulting MCMC median and 16\%–84\% confidence range for each parameter in our model, as specified in Equations (1)–(3). We adopt the “best model” as the model in our MCMC run which produced the minimum value of \( C \) in Equation (5). Our best model XRB source count distributions, together with SFR-normalized cumulative HMXB XLFs are shown for the five \( 12 + \log(O/H) \) bins in Figures 2 and 3, respectively.

Our best-fit model recovers the main observed features of the metallicity-dependent HMXB XLF discussed in Section 3, including the transition from a nearly single power-law slope at high metallicity to a broken power law with a relatively flat extension at \( L \approx (1-50) \times 10^{38} \) erg s\(^{-1}\) at low metallicity. At solar metallicity, our HMXB XLF slopes straddle the best-fit single power-law values presented by Mineo et al. (2012a) and L19, and are consistent with values presented in studies of HMXB XLFs that are based on direct-counterpart classifications of X-ray sources (e.g., Tüllmann et al. 2011 and Williams et al. 2015 for M33, and Chandar et al. 2020 for M101).

We evaluated the goodness of fit of our model in both a “metallicity-averaged” and more stringent “universal” regime. In the metallicity-averaged regime, we assessed whether our model provided a good characterization of the average metallicity-dependent HMXB XLF, using the data and model as represented by the five metallicity bins presented in Figure 2. We computed the C-statistic following Equation (5), replacing \( n_{gal} \) with \( n_{metal} = 5 \) metallicity bins. We then used the methods of Kastra (2017) to calculate the expected C-statistic, \( C_{exp} \) and its variance, \( C_{var} \) based on Poisson statistics, and evaluated the null-hypothesis probability, \( P_{null} \), following:

\[
P_{null} = 1 - \text{erf} \left( \frac{(C - C_{exp})^2}{2 C_{var}} \right).
\]

We found that in the metallicity-averaged sense, the data are statistically consistent with being drawn from our model, with \( P_{null} = 0.108 \) overall, and \( P_{null} = 0.060–0.574 \) for the five bins (see Table 2). For comparison, the L19 HMXB XLF model (with no metallicity dependence) is ruled out, with \( P_{null} < 0.0001 \) overall for the same data. However, the L19 model is acceptable only for the \( 12 + \log(O/H) = 8.6–8.8 \) and \( 8.4–8.6 \) bins (\( P_{null} = 0.857 \) and 0.703, respectively), which is to a degree expected, given that the majority of the L19 galaxies have metallicities in these ranges. The failure of the L19 model for the highest metallicity and two lowest metallicity bins further illustrates how our model represents an improvement in the HMXB XLF characterization.

For the universal regime, we evaluated the null-hypothesis probability, using the C-statistic generated by Equation (5), for all 55 galaxies from the combined main and supplemental samples. This approach was used to determine our best-fit parameters in Section 3, and requires that all galaxies are reasonably well characterized by our model, since a small number of strong outliers can have a non-negligible influence on the total value of \( P_{null} \). Under this more strict evaluation, we found that our model was ruled out with \( P_{null} < 0.001 \) overall. Thus, while our model provides a good characterization of how the “average” HMXB XLF varies with metallicity, it fails to provide a “universal” model of the HMXB XLF for all galaxies in our sample.

The failure of our model in the universal regime can be tied primarily to three of the 55 galaxies, NGC 925, NGC 5408, and NGC 5474, all of which are main-sample sources with \( P_{null} < 0.001 \), and are deemed to be significant outliers. All four galaxies are observed to have excesses of \( \approx 2–5 \) times the numbers of X-ray point sources compared to those predicted by our model without any clear trends with point source luminosity (across \( \log L \) (erg s\(^{-1}\)) = 37–39). In addition to these significant outliers, there are an additional four galaxies displaying some tension with our model at the \( P_{null} < 0.05 \) level; we list these galaxies in Table 2. With the exception of NGC 1569, these galaxies also appear to have excesses of X-ray point sources compared to the model. We expect that unmodeled physical variations in SFH, as well as gradients in the metallicities within the galaxies themselves, are plausible causes for the deviations from the model in the outlier population; we discuss these possibilities in more detail in
Uncertainty related to stochasticity is not included in this uncertainty range; however, its impact is discussed and quantified in Section 5.1. \( L_X \) values for main-sample galaxies represent the estimated HMXB X-ray luminosities after correcting for model contributions from LMXB and CXB sources. For the supplemental galaxies, open circles and 84% range implied by our model and its parameter uncertainties, which we show in Figure 4 (black curve and gray shaded region). In Col.(5) of Table 3, we tabulate the median values and 16%–84% ranges of \( L_X / \text{SFR} \) from our model.

For comparison with past studies, in Figure 4 we overlay the best-fit power-law models of \( L_X / \text{SFR} \) versus 12 + log(O/H) from Brorby et al. (2016; blue-dashed line) and Fornasini et al. (2020; green-dotted line).14 We further overlay the XRB population synthesis theoretical best model median curve from Fragos et al. (2013b; magenta long-dashed curve). In the 12 + log(O/H) > 8 regime, our metallicity-dependent HMXB XLF model exhibits a trend in excellent agreement to the data and relation reported by Fornasini et al. (2020), albeit with a somewhat divergent trend appearing below 12 + log(O/H) ≈ 8.2, where no data was reported by Fornasini et al. The Brorby et al. (2016) relation is notably shallower, and predicts relatively higher values of \( L_X / \text{SFR} \) in this regime, compared to those found in this study and the Fornasini et al. (2020) relation. It is possible that contributions from LMXBs or AGN, which were not explicitly considered, could explain the relative elevation of the Brorby et al. relation. For example, the significant outlier at 12 + log(O/H) ≈ 8.8, KUG 0842+527, has been reported to be a radio galaxy and have a large stellar mass (see Svoboda et al. 2019). Moreover, in this regime we find that the Fragos et al. (2013b) best model...
appears consistent with our model from 12 + log(O/H) = 8–8.5, but quickly diverges to much lower predictions of \( L_X / \text{SFR} \) at higher metallicities. The divergence at metallicities above solar is likely to be due to the stellar wind prescription becoming more aggressive in terms of removing mass from binary systems, resulting in a larger fraction of binaries avoiding mass transfer (and X-ray luminous) phases. Stellar wind prescriptions in this regime are highly uncertain, due to a lack of observationally constrained mass-loss rates.

In the extreme metal-poor regime, the uncertainties in our model increase substantially due to weak constraints. However, the trajectory of \( L_X / \text{SFR} \) with metallicity for our model appears to flatten, diverging from a simple power-law extrapolation from Brorby et al., and Fornasini et al. It is certainly the case that a power-law form will become unphysical at some low value of metallicity, since the predicted \( L_X \) diverges for the metal-free case. In fact, the Fragos et al. (2013b) model predicts that a turnover will occur in this regime, consistent with our best-fit model. Improved constraints on the XLF in this regime, involving deeper observations and observations of additional galaxies, are required to definitively characterize this effect.

5. Discussion

5.1. The \( L_X \)-SFR–Z Relation and its Scatter

As discussed in Section 1, the \( L_X \)-SFR–Z relation is of particular importance in a variety of astrophysical investigations. Such investigations may require, e.g., assessments of the likelihoods that specific X-ray detected objects are XRBs versus AGN, or estimates of the X-ray radiation field during the epoch of heating at \( z \gtrsim 10 \), where HMXBs are thought to dominate. For such studies, clear predictions for the \( L_X \)-SFR–Z relation and its statistical scatter are of great use. In the following discussion, we assume that the statistical scatter is dominated by sampling stochasticity. Additional scatter related to luminous transient and variable source populations (e.g., BeXRBs and supergiant fast X-ray transients; see, e.g., Reig 2011 and Martínez-Núñez et al. 2017) is also expected to be present. Thus far, such forms of scatter have not been extensively investigated; however, a study of variable source populations in NGC 500 finds that variability does not have a detectable impact on the derived XLF for the galaxy (see, e.g., Binder et al. 2017). Nonetheless, future studies to assess how variable and transient source populations affect XLF scatter in a variety of environments would help clarify this picture.

Our metallicity-dependent HMXB XLF framework can be used to quantify statistical properties of the \( L_X \)-SFR–Z relation beyond the model uncertainties discussed in Section 4. As shown by Gilfanov et al. (2004), XLFs with relatively shallow power-law slopes (\( \gamma < 2 \)), such as those representative of the HMXB population, result in integrated \( L_X / \text{SFR} \) values that are subject to non-negligible stochastic scatter, due to partial sampling of the full-\( L \) range of the XLF. For instance, the SFR-normalized cumulative XLF shown in the first panel of Figure 3 (i.e., for 12 + log(O/H) = 8.8–9.2), suggests that a typical galaxy with \( SFR = 1 M_{\odot} \text{ yr}^{-1} \) would host its brightest source at around \( L_{\text{max}} \approx 3 \times 10^{38} \text{ erg s}^{-1} \), while a galaxy with \( SFR = 10 M_{\odot} \text{ yr}^{-1} \) would be expected to have \( L_{\text{max}} \approx 10^{40} \text{ erg s}^{-1} \). For these cases, the typical (i.e., median) values of the \( L_X / \text{SFR} \) would be dominated by the brightest sources,

\[
L_X / \text{SFR} \approx \frac{1}{\text{SFR}} \int_0^{L_{\text{max}}} dN / dL L \, dL \propto L_{\text{max}}^{2-\gamma} / \text{SFR},
\]  

and would take on different values for the 1 \( M_{\odot} \text{ yr}^{-1} \) and 10 \( M_{\odot} \text{ yr}^{-1} \) galaxy populations. As a corollary, populations of galaxies at a fixed metallicity would be expected to have SFR-dependent statistical distributions and scatter of \( L_X / \text{SFR} \), but with a SFR-independent mean value that follows the black curve in Figure 4. We note that the stochastic variations of \( L_X / \text{SFR} \) are not expected to influence our HMXB XLFs themselves, since we use Poisson modeling of the differential
XLF in narrow bins of \( L \), including bins that extend well beyond the most luminous detected sources.

In addition to the SFR-dependent scatter, our HMXB XLF model shape is also metallicity-dependent, implying that the statistical distributions of \( L_X / \text{SFR} \) are also metallicity-dependent. To quantify the scatter-related SFR and metallicity-dependent probability distribution functions of \( L_X / \text{SFR} \), we employed Monte Carlo simulations, following the procedures outlined in Section 5.3 of L19. Briefly, a given Monte Carlo trial uses a chosen pair of SFR and \( 12 + \log (O/H) \) values to uniquely specify our model’s HMXB XLF (Equations (1)–(3)), which provides a prediction for the total number of HMXBs, \( N_{\text{MC}}^{\text{HMXB}} \), in the population, together with their \( L \)-dependent distribution. We then probabilistically sample from this distribution to assign luminosity values to the \( N_{\text{MC}}^{\text{HMXB}} \) simulated HMXBs, and sum the luminosities to generate \( L_{\text{MC}}^{\text{HMXB}} \). This procedure is repeated 1000 times to build up the distribution of \( L_{\text{MC}}^{\text{HMXB}} \) for a given SFR and \( 12 + \log (O/H) \) pair. We note that this procedure provides stochastic distributions of \( L_{\text{MC}}^{\text{HMXB}} \) for the best-fit model solution, and does not include parameter uncertainties. In Table 3 (Col.6–10), we list the statistical properties inferred from our simulations, including the median and 16%–84% limits on \( \log L_{\text{HMXB}} / \text{SFR} \) for various SFR and \( 12 + \log (O/H) \) pairs.

In the left panel of Figure 5, we show the median \( L_{\text{MC}}^{\text{HMXB}} / \text{SFR} \) versus SFR at five metallicity values (corresponding to values close to those used in Figures 2 and 3). At high-SFR, all curves asymptote to the metallicity-dependent mean \( L_{\text{MC}} / \text{SFR} \) values (i.e., Col.(5) in Table 3). However, at SFR \( \lesssim 0.1 \), the curves for all metallicities converge to similar values. This occurs when the expected brightest source in the distribution is below the break luminosity \( (L_{\text{max}} \ll L_b) \), where our XLF model is metallicity-independent (see the \( L \leq L_b \) branch in Equation (1)). For reference, we also display the 1\( \sigma \) and 2\( \sigma \) scatter regimes for the \( 12 + \log (O/H) = 8.4 \) curve. Unsurprisingly, the scatter decreases in size with increasing SFR, varying from \( \approx 0.05 \) dex at SFR \( = 0.01 M_{\odot} \) yr\(^{-1} \) to \( \approx 0.01 \) dex at SFR \( = 100 M_{\odot} \) yr\(^{-1} \); at the high-SFR end, the scatter is expected to be smaller than the current model uncertainty on \( (L_X / \text{SFR}) \) itself (see Col.5 of Table 3).

In the right panel of Figure 5, we display the probability distributions of \( L_{\text{MC}}^{\text{HMXB}} / \text{SFR} \) at four SFR values for \( 12 + \log (O/H) = 7.6 \) (bottom) and 8.6 (top). These distributions vary, with high levels of skewness at low-SFR (e.g., SFR \( = 0.1 \) and \( 1 M_{\odot} \) yr\(^{-1} \)), and approaching Gaussian-like distributions, centered around the mean, at SFR \( \gtrsim 2–5 M_{\odot} \) yr\(^{-1} \). It is also apparent from the right-hand panels of Figure 5 that metallicity has a significant impact on the shapes of the distributions. For example, for SFR \( = 0.1 M_{\odot} \) yr\(^{-1} \), the median values of \( L_{\text{MC}}^{\text{HMXB}} / \text{SFR} \) are similar for both \( 12 + \log (O/H) = 7.6 \) and 8.6, but their distributions are notably different at high \( L_{\text{MC}}^{\text{HMXB}} / \text{SFR} \).

5.2. Ultraluminous X-Ray Source Populations

As discussed above, our metallicity-dependent HMXB XLF analysis indicates that the \( L_X - \text{SFR} - Z \) relation is driven primarily by a metallicity dependence in the \( L > 10^{38} \text{ erg s}^{-1} \) HMXB population. Of particular interest are ULXs (see, e.g., Kaaret et al. 2017b for a review), which are typically defined as off-nuclear X-ray sources with \( L \gtrsim 10^{39} \text{ erg s}^{-1} \). Under isotropic emission assumptions (as used here), ULX luminosities can exceed the Eddington rates of \( 10–100 M_{\odot} \) black holes. This fact has led to an assumption that ULXs primarily host black holes, with some potentially having “intermediate masses” of \( 10^2–10^4 M_{\odot} \), well above the black hole masses predicted by stellar evolution (e.g., Colbert & Mushotzky 1999).

Over the last decade, XMM-Newton and NuSTAR observations have revealed nearly ubiquitous high-energy turnovers.
at $E \gtrsim 3$ keV in ULX spectra, suggesting relatively cool Comptonization components and/or advection-dominated accretion disks, which are expected for stellar-mass accretors with super-Eddington mass-transfer rates and beamed emission (e.g., Gladstone et al. 2009; Sutton et al. 2013; Middleton & King 2016; Walon et al. 2018), however, some intermediate mass black hole candidates remain (e.g., HLX-1; Farrell et al. 2009). Although attempts to measure directly ULX compact object masses reveal relatively weak constraints (e.g., Liu et al. 2012; Cseh et al. 2013), recent discoveries of pulsations in several ULXs betray the neutron star nature of their accretors (Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2017; Brightman et al. 2018; Carpano et al. 2018; Earnshaw et al. 2018; Chandra et al. 2020), sometimes revealing enormous beaming factors (e.g., M82 X-2 and NGC 5907 ULX1 have observed $L/L_{\text{Edd}} \approx 100–500$, assuming a $2 M_\odot$ neutron star; Bachetti et al. 2014; Israel et al. 2017). Detailed binary evolution models suggest that such NS ULX binaries originate from intermediate X-ray binaries (e.g., Misra et al. 2020), which is in tension with parametric population synthesis models that predict $\approx M_\odot$ giant donor stars (e.g., Wicktorowicz et al. 2017).

Given their high luminosities and associations with star-forming galaxies (e.g., Swartz et al. 2011; Walton et al. 2011; Wang et al. 2016; Earnshaw et al. 2019; Kovlakas et al. 2020), ULXs are often assumed to be a subset of the HMXB population, with young massive donor stars readily capable of driving large mass transfer rates via Roche lobe overflow (e.g., King et al. 2001). Studies aimed at isolating ULX counterparts have revealed direct associations with massive stars (see, e.g., Liu et al. 2012; Motch et al. 2014; Heida et al. 2019), or close spatial proximity to young luminous star clusters (e.g., Swartz et al. 2009; Poutanen et al. 2013; Egorov et al. 2017; Oskinova et al. 2019), providing direct evidence that many ULXs are indeed HMXBs. However, given the complexity of ULX accretion mechanisms, along with uncertainties in the distributions of accretor types and beaming factors in the observed population, theoretical models predict a large range of formation frequencies of ULXs within galaxies (i.e., number of ULXs per SFR or $M_*$) which would be visible as ULXs from Earth (e.g., Belczynski et al. 2004; Linden et al. 2010; King & Lasota 2016; Wicktorowicz et al. 2017, 2019; Kuranov et al. 2020). Going forward, these models would benefit from observational benchmarks, such as those provided by our study.

In Figure 6, we show our constraints on the metallicity-dependent observed number of ULXs per SFR that have apparent luminosities (i.e., under the isotropic emission assumption) greater than 1, 3, and $10 \times 10^{39}$ erg s$^{-1}$. Our XLF model constraints are overlaid as continuous curves, with the model uncertainty indicated as a shaded region for the $10^{39}$ erg s$^{-1}$ case. These values are tabulated in Col. (2)-(4) in Table 3. For comparison, we show recent constraints from Kovlakas et al. (2020) on the ULX frequency as a function of $12 + \log(O/H)$, for 40 late-type galaxies with $D < 40$ Mpc (lavender filled squares). These estimates are based on a galaxy subsample excluding elliptical/lenticular galaxies, galaxies with uncertain morphological classification in HyperLEDA ($e_i > 1.0$), objects without complete sky coverage, and sources where SFR and $M_*$ were calculated in their HECATE catalog (see Kovlakas et al. 2020 for details). These estimates are in good agreement with our estimates, except at $12 + \log(O/H) \approx 8.8$, where the Kovlakas et al. (2020) ULX frequency is lower than our estimate by a factor of 2–5. Further investigations, beyond the scope of this paper, will be required to clarify the source of this discrepancy.

We further display, in Figure 6, the Wicktorowicz et al. (2019) population synthesis predictions of the ULX frequency for the case of a continuous SFH of 6 $M_\odot$ yr$^{-1}$ over a period of 100 Myr (thus tracing HMXB ULXs) at 0.1 $Z_\odot$ and $Z_\odot$, which correspond to $12 + \log(O/H) = 7.69$ and 8.69, respectively. These predictions are based on their Startrack XRB population synthesis models (Belczynski et al. 2002, 2008) and the mass-transfer-rate-dependent beaming prescriptions outlined in King et al. (2001), and King (2009). As such, the models account for those XRB populations that would appear as ULXs along a given line of sight, while tracking the intrinsic ULX population properties, including the accretor type. The predictions shown in Figure 6 correspond to the expected number of observed ULXs per SFR, after including the effects of beaming (i.e., as they would be observed externally). We show both the neutron star accretor and total (neutron star plus black hole) ULX predictions.

We find that the Wicktorowicz et al. (2019) predictions for neutron stars are somewhat lower than the total rates observed for all ULXs in this study. When including black holes, the theoretical ULX frequencies exceed the observations presented here. In the case of the 0.1 $Z_\odot$ population, the theoretical models are a factor of 5–10 times higher than those observed, suggesting that the black hole prescription itself overestimates the prevalence of these sources.

Since XRB population synthesis model predictions are highly variable, depending on their assumptions (see, e.g., the case study by Tzanavaris et al. 2013), we are unable to make additional detailed physical conclusions regarding the nature of ULX accretors based on these results. For example, the population synthesis work by Kuranov et al. (2020) shows that highly magnetized neutron star accretors can produce ULX populations comparable to, or larger than, those predicted by Wicktorowicz et al. (2019), depending on the populations’
averaged magnetic moment and accretion disk structure. These models produce ULX luminosities through the accretion columns themselves, and do not require strong beaming. These variations in predictions highlight the need for future population synthesis studies, using these empirical results as direct constraints on models.

5.3. Toward a Universal Model for XRB XLFs

In Section 4, we showed that our metallicity-dependent HMXB XLF model provides a statistically acceptable prescription for average metallicity trends. Constraints on these trends can be improved with the combination of deeper and more numerous observations of those galaxies in the extreme metal-poor regime \((12 + \log(O/H) < 8)\) that make up our supplemental sample (see, e.g., the constraints in this regime from Figures 2, 3, and 4). Building on the constraints in this regime will also be critical for clarifying the potential impact of HMXB radiation during the epoch of heating at \(z \gtrsim 10\), when the majority of galaxies are expected to have abundances in this regime (see, e.g., Torrey et al. 2019).

Although our model is acceptable in a metallicity-averaged sense, it has been ruled out as universal (see Section 4). Given our large sample of 55 galaxies, we expect \(\approx3\) galaxies to have \(P_{\text{null}} \lesssim 0.05\); however, none of the three galaxies listed in Table 2 with \(P_{\text{null}} \lesssim 0.001\) would be expected in terms of statistical scatter alone.

Some observational factors not inherent to the HMXB populations themselves, such as enhanced absorption due to high disk inclinations or morphologically disturbed systems, could distort the observed XLFs, causing our model framework to be non-universal. However, we have eliminated the influence of such factors in our galaxies by means of our selection criteria, and the most egregious outliers in our sample (NGC 925, NGC 5408, and NGC 5474) are all found to have an excess of observed HMXBs over the model predictions, suggesting some other factors intrinsic to the HMXB populations are at work.

As discussed in Section 1, in addition to metallicity, SFH variations in the \(<100\) Myr population can impact on HMXB populations, as well as estimates of SFRs. Explicit theoretical predictions from Linden et al. (2010) and Wiktorowicz et al. (2017, 2019) suggest that the formation efficiencies of ULXs (e.g., number per unit stellar mass) can vary by more than an order of magnitude within \(10–100\) Myr following a burst of star formation. Furthermore, less luminous HMXBs in the nearby Small Magellanic Clouds, and in M33, have also been shown to exhibit notable formation efficiency variations on the same timescales as those where predominant XRB donor stars transition to lower masses with increasing age (e.g., Lehmer et al. 2017; Garofali et al. 2018; Antoniou et al. 2019).

Given the above, bursty SFHs, such as those found in low-mass, low-metallicity galaxies, could easily result in variations in the HMXB XLF, and the presence of a number of outlier galaxies in our sample. In future work, we plan to characterize the SFHs of a large number of local galaxies, including those in this work, and reassess the combined influence of metallicity and SFH on the XLF. These steps will be crucial for the ultimate development of a universal model for XRB XLFs in galaxies.

6. Summary

We have demonstrated that the SFR-normalized HMXB XLF depends on gas-phase metallicity, and have provided a model detailing this dependence. Some of the key results of this study are included below.

1. We quantify and model the HMXB XLF across the luminosity range \(\log L(\text{erg s}^{-1}) \approx 36–41\) for 33 galaxies in the metallicity range of \(12 + \log(O/H) = 7–9.2\). However, archival data for extremely metal-poor objects with \(12 + \log(O/H) \lesssim 8\) contain only dwarf galaxies with relatively shallow data, limiting our HMXB XLF inferences in this metallicity range.

2. The impact of metallicity on the SFR-normalized HMXB XLF is most significant for HMXBs with \(L \gtrsim 10^{38} \text{ erg s}^{-1}\). Below this limit, the XLF shape appears to follow a nearly universal power-law distribution, with slope \(\gamma \approx 1.7\). Above this limit, the HMXB XLF goes from being power-law-like at nearly solar metallicities, to developing an increasingly flattened distribution with high-\(L\) cut-off as metallicity declines (see Figure 3).

3. We provide a new parameterization of the SFR-and-metallicity dependence of the HMXB XLF, which provides a significant statistical improvement over the widely-used constant SFR-dependent HMXB XLF models (see Sections 3 and 4 and comparison in Figure 3).

4. As a consequence of our results, we establish that the population-integrated \(L_X – \text{SFR} – Z\) relations reported in the literature are driven by the metallicity dependence of the \(L \gtrsim 10^{38} \text{ erg s}^{-1}\) population. For \(12 + \log(O/H) \gtrsim 8.2\), our model predicts a similar \(L_X – \text{SFR} – Z\) relation to that of Fornasini et al. (2020), but differs somewhat from that of Brorby et al. (2016) and the theoretical relations of Fragos et al. (2013a) (see Figures 4 and 5, and Section 5.1). At \(12 + \log(O/H) \lesssim 8\), our best-fit relation appears to flatten in relation to lower metallicity; however, our results are highly uncertain in this regime. Nonetheless, this behavior is similar to the theoretical predictions of Fragos et al. (2013a), but is different from the empirical extrapolations of power-law parameterizations presented in past studies (e.g., Brorby et al. 2016; Fornasini et al. 2020). Our model predictions for the \(L_X – \text{SFR} – Z\) relation and its statistical properties are provided in Table 3.

5. Our HMXB XLF framework also allows for observational insight into the metallicity dependence of the ULX population. We quantify the metallicity and \(L\) dependence of the ULX population, and compare our results with the previous population synthesis models of Wiktorowicz et al. (2019). Our ULX constraints are similar to the population synthesis predictions near solar metallicity; however, the observed ULX population is 5–10 times lower than predictions at \(\approx0.1\) Z$_\odot$. Our constraints provide new benchmarks for future population synthesis studies, and may aid our understanding of the nature of these complex sources (see Section 5.2).

6. Finally, we show that a number of galaxies in our sample host HMXB populations are significantly elevated, as compared to our model’s predictions. These galaxies are good candidates for harboring recent SFHs that deviate from the average young population within galaxies. Future studies taking account of SFH will help to
quantify the effect of SFH on the HXMB population (see Section 5.3).

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Facilities: Chandra, Herschel, GALEX, Sloan, Spitzer, Swift, 2MASS, DES, Pan-STARRS.

Software: ACIS Extract (v2016sep22; Broos et al. 2010, 2012), MARX (v5.3.2; Davis et al. 2012), CIAO (v4.8; Fruscione et al. 2006), xspec (v12.9.1; Arnaud 1996), Lightning (Frasio et al. 2017), PÉGASE (Fioc & Rocca-Volmerange 1997)

Appendix

In Table A1, we provide the X-ray point source catalogs, based on the analyses presented in Section 3. The columns include the following: Col.(1): Name of the host galaxy. Col.(2): point source identification number within the galaxy. Col.(3) and (4): Right ascension and decl. of the point source. Col.(5): Offset of the point source with respect to the average aim point of the Chandra observations. Col.(6) and (7): 0.5–7 keV net counts (i.e., background subtracted) and 1σ errors. Col.(8)–(9) and (10)–(11): Best-fit column density $N_H$, and photon index $\Gamma$, respectively, along with their respective 1σ errors, based on spectral fits to an absorbed power-law model ($TBABS\times TBABS\times POW$ in xspec). For sources with small numbers of counts (<20 net counts), we adopted only Galactic absorption appropriate for each galaxy, and a photon index of $\Gamma = 1.7$. Col.(12) and (13): the respective 0.5–8 keV flux and luminosity of the source. Col.(14): Flag indicating the location of the source within the galaxy. Flag = 1 indicates that the source has $L > 10^{35}$ erg s$^{-1}$, is within the galactic footprint adopted in Table 1, and is outside a central region of avoidance, if applicable. All XLF calculations are based on Flag = 1 sources. Flag = 2 indicates that the source is within the adopted galactic footprint, but has a luminosity of $L < 10^{35}$ erg s$^{-1}$, and was thus excluded from our XLF analysis. Flag = 3 indicates that the source is outside the adopted galactic footprint.

| GALAXY ID | $\alpha_{2000}$ (deg) | $\delta_{2000}$ (deg) | $\theta$ (arcmin) | $N_{PB}$ (counts) | $N_{HI}$ (10$^{17}$ cm$^{-2}$) | $\Gamma$ | log $F_{PB}$ (erg cm$^{-2}$ s$^{-1}$) | log $L_{PB}$ (erg s$^{-1}$) | Location Flag |
|-----------|----------------------|----------------------|-------------------|-------------------|--------------------------|-------|------------------|-----------------|----------------|
| NGC0024   | 00 09 44.06          | −24 58 16.38         | 2.9               | 27.1 ± 5.4        | 0.021                    | 1.7   | −14.2            | 37.6            | 3              |
| 2          | 00 09 44.73          | −24 59 03.40         | 3.0               | 15.8 ± 4.3        | 0.021                    | 1.7   | −14.5            | 37.3            | 3              |
| 3          | 00 09 45.89          | −24 56 00.46         | 3.0               | 66.0 ± 9.9        | 0.194 ± 0.326            | 1.85 ± 0.77 | −13.9           | 37.9            | 3              |
| 4          | 00 09 48.20          | −24 58 58.92         | 2.2               | 33.0 ± 7.3        | 0.100 ± 0.322            | 1.88 ± 0.94 | −14.0           | 37.8            | 3              |
| 5          | 00 09 49.87          | −24 57 42.08         | 1.5               | 7.7 ± 4.3         | 0.021                    | 1.7   | −14.8            | 37.0            | 3              |
| 6          | 00 09 50.25          | −25 00 02.24         | 2.7               | 5.3 ± 2.4         | 0.021                    | 1.7   | −14.9            | 36.3            | 3              |
| 7          | 00 09 51.27          | −24 59 28.45         | 2.1               | 9.8 ± 4.6         | 0.021                    | 1.7   | −14.6            | 37.2            | 3              |
| 8          | 00 09 53.62          | −24 58 32.01         | 1.0               | 36.0 ± 7.5        | 0.226 ± 0.484            | 1.68 ± 0.97 | −14.1           | 37.7            | 1              |
| 9          | 00 09 54.63          | −24 56 57.60         | 0.9               | 23.0 ± 6.3        | 1.657 ± 0.077            | 0.98 ± 1.76 | −14.0           | 37.8            | 3              |
| 10         | 00 09 54.85          | −24 57 58.96         | 0.4               | 6.6 ± 2.6         | 0.021                    | 1.7   | −14.9            | 36.9            | 1              |
| 11         | 00 09 55.22          | −24 57 49.50         | 0.3               | 4.6 ± 2.2         | 0.021                    | 1.7   | −15.0            | 36.8            | 1              |
| 12         | 00 09 55.82          | −24 59 29.46         | 1.7               | 31.9 ± 7.2        | 0.230 ± 0.413            | <2.41 | −14.3           | 37.5            | 3              |
| 13         | 00 09 56.19          | −24 58 02.13         | 0.3               | 13.4 ± 3.7        | 0.021                    | 1.7   | −14.6            | 37.2            | 1              |
| 14         | 00 09 56.27          | −24 57 33.72         | 0.2               | 24.0 ± 6.4        | 1.396 ± 0.887            | <2.75 | −14.3           | 37.5            | 1              |
| 15         | 00 09 56.27          | −24 57 57.28         | 0.2               | 9.6 ± 3.2         | 0.021                    | 1.7   | −14.7            | 37.1            | 1              |
| 16         | 00 09 57.31          | −24 57 42.01         | 0.2               | 25.4 ± 5.1        | 0.021                    | 1.7   | −14.3            | 37.5            | 1              |
| 17         | 00 09 58.90          | −24 56 57.15         | 1.0               | 8.5 ± 3.0         | 0.021                    | 1.7   | −14.8            | 37.0            | 1              |
| 18         | 00 10 00.94          | −24 57 27.96         | 1.0               | 19.1 ± 5.9        | 0.021                    | 1.7   | −14.5            | 37.4            | 3              |
| 19         | 00 10 03.29          | −24 57 30.24         | 1.6               | 19.5 ± 5.9        | 0.021                    | 1.7   | −14.4            | 37.4            | 3              |
| 20         | 00 10 03.50          | −24 55 28.14         | 2.8               | 17.0 ± 5.7        | 0.021                    | 1.7   | −14.5            | 37.3            | 3              |

Note. The full version of this table contains 2915 sources, including all 1311 sources used in our XLF analyses (i.e., Flag = 1). An abbreviated version of the table is displayed here to illustrate its form and content. A description of the columns is provided in the Appendix. (This table is available in its entirety in machine-readable form.)

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