Populations of X-Ray Sources in Galaxies

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Abstract

Today's sensitive X-ray observations allow the study of populations of X-ray binaries in galaxies as distant as 20–30 Mpc. Photometric diagrams and luminosity functions applied to these populations provide a direct probe of the evolved binary component of different stellar populations. The study of the X-ray populations of E and S0 galaxies has revamped the debate on the formation and evolution of low-mass X-ray binaries (LMXBs) and on the role of globular clusters in these processes. Though overall stellar mass drives the amount of X-ray binaries in old stellar populations, the amount of sources in star-forming galaxies is related to the star-formation rate. Short-lived, luminous, high-mass X-ray binaries (HMXBs) dominate these young X-ray populations. The most luminous sources in these systems are the debated ultraluminous X-ray sources (ULXs). Observations of the deep X-ray sky, and comparison with deep optical surveys, are providing the first evidence of the X-ray evolution of galaxies.

1. *CHANDRA*: A NEW PARADIGM

This review comes almost two decades after the 1989 *Annual Review* article on the X-ray emission from galaxies (Fabbiano 1989), and a few words on the evolution of this field are in order. In 1989, the *Einstein Observatory* (Giacconi et al. 1979), the first imaging X-ray telescope, opened up the systematic study of the X-ray emission of normal galaxies. The *Einstein* images, in the ∼0.3–4 keV range, with resolutions of ∼5″ and ∼45″ (see the *Einstein Catalog and Atlas of Galaxies*, Fabbiano, Kim & Trinchieri 1992) showed extended and complex X-ray emission, and gave the first clear detection of individual luminous X-ray sources in nearby spiral galaxies, other than the Milky Way. The first ultraluminous (nonnuclear) X-ray sources (ULXs) were discovered with *Einstein*, and the suggestion was advanced that these sources may host $>100\ M_\odot$ black holes, a topic still intensely debated. Hot diffuse halos were discovered in elliptical galaxies and used as a means of estimating the mass of the dark matter associated with these galaxies, but their ubiquity and properties were hotly debated. Super-winds from active star-forming galaxies (e.g., M82), an important component of the ecology of the universe, were first discovered with *Einstein*. All these topics are discussed in the 1989 review.

The subsequent X-ray observatories *ROSAT* (Truemper 1983) and *ASCA* (Tanaka, Inoue, Holt 1994) expanded our knowledge of the X-ray properties of galaxies (see, e.g., a review summary in Fabbiano & Kessler 2001), but did not produce the revolutionary leap originated by the first *Einstein* observations. The angular resolution of these missions was comparable (*ROSAT*) or inferior (*ASCA*, with 2 arcmin resolution) to that of *Einstein*, but the *ROSAT* spectral band (extending down to ∼0.1 keV) and lower background provided a better view in some cases of the cooler X-ray components (halos and hot outflows), while the wide spectral band (∼0.5–10 keV) and better spectral resolution of the *ASCA* CCD detectors allowed both the detection of emission lines in these hot plasmas and the spectral decomposition of integrated emission components (e.g., Matsushita et al. 1994). Overall, however, many of the questions raised by the *Einstein* discoveries remained (see Fabbiano & Kessler 2001).

It is only with *Chandra*'s subarcsecond angular resolution (Weisskopf et al. 2000), combined with photometric capabilities commensurable with those of *ASCA*, that the study of normal galaxies in X rays has taken a second revolutionary leap. With *Chandra*, populations of individual X-ray sources, with luminosities comparable to those of Galactic X-ray binaries, can be detected at the distance of the Virgo Cluster and beyond; the emission of these sources can be separated from the diffuse emission of hot interstellar gases, both spatially and spectrally; detailed measures of the metal abundance of these gaseous components can be attempted (e.g., Martin, Kobulnicky & Heckman 2002; Soria & Wu 2002; Fabbiano et al. 2004a; Baldi et al. 2006a,b); and quiescent supermassive nuclear black holes can be studied (e.g., Fabbiano et al. 2004b, Pellegrini 2005, Soria et al. 2006).

Here, I will concentrate only on one aspect of the emission of normal galaxies, the study of their populations of discrete X-ray sources, with emphasis on compact accreting binary systems (**Table 1**). I avoid detailed discussions of the properties of

Table 1 **Accretion-powered XRBs in galaxies (L_X more than a few 10^{36} erg s^{-1})**

LMXB	Low Mass X-ray Binaries
	Neutron Star (NS) or Black Hole (BH) + later than type A star Time-variable: orbital periods, flares, bursts Spectral/luminosity states in BH XRBs On average soft spectra with kT ∼ 5–10 keV Associated with old stellar populations Found in the stellar field (bulges) and in Globular Clusters Generally believed to be long-lived: lifetimes $\sim 10^{8-9\,\mathrm{years}}$ Exception is model of Bildsten & Deloye (2004), Section 3.6 Discussed in Section 3
HMXB	High Mass X-ray Binaries
	NS or BH + OB star Time-variable luminosities and spectra Orbital periods, outburst, rapid flaring, pulsations On average harder spectra than LMXBs, but BH binaries may have similarly soft spectra Associated with young stellar populations (e.g., spiral arms) Short-lived: lifetimes $\sim 10^{6-7\,\mathrm{years}}$ Discussed in Section 4
ULX	Ultraluminous X-ray sources of debated nature
	$L_X > 10^{39}$ ergs s^{-1} (> Eddington luminosity of NS or ∼5 $M_\odot$ BH) Proposed as intermediate mass BH candidates (>100 $M_\odot$) Tend to be found in active star-forming environments Discussed in Section 6
SSS	Super-Soft Sources (black body kT ∼ 15–80 eV)
	Nuclear burning White Dwarf binaries Discussed in Section 5
QSS	Quasi-Soft Sources discovered with *Chandra*
	kT ∼ 100–300 eV Some exhibit a hard spectral tail Nature is still debated Discussed in Section 5, Section 6

individual nearby galaxies, which are covered in the earlier review by Fabbiano & White (2006, based on publications up to 2003). Also, I do not discuss the properties of the hot interstellar medium (ISM) and of low-level nuclear emission, which were all included in the 1989 review. The field has expanded enough since then that these topics deserve separate reviews. Most of the work discussed in this review is the result of the study of high-resolution *Chandra* images. Whenever relevant (for the most nearby galaxies, and the spectral and time-variability study of ULXs), I will also discuss observations with *XMM-Newton* (the European Space Agency X-ray telescope, which has an effective area ∼3 times larger than *Chandra*, but significantly coarser angular resolution, ∼15″).

This review proceeds as follows: Section 2 is a short discussion of the observational and analysis approaches opened by the availability of high resolution, sensitive X-ray data; Section 3 reviews the results on the old X-ray binary population found in early-type galaxies and spiral bulges; Section 4 addresses the work on the younger X-ray source population of spiral and irregular galaxies; Section 5 and Section 6 discuss two classes of rare X-ray sources, to the understanding of which recent observations of many galaxies have contributed significantly: supersoft sources (SSSs) and ULXs; Section 7 concludes this review with a short discussion of the properties of the galaxies observed in deep X-ray surveys. Section 3, Section 4, and Section 6 are the most substantial. They all start with brief historical introductions, summarize the observational evidence that identifies the X-ray sources with X-ray binaries (XRBs), discuss the X-ray luminosity functions as a means to compare and characterize the XRB populations, address the constraints deriving from the association of the X-ray sources with stellar or other features, and conclude with reviews of the theoretical work and interpretations. Throughout this review, I try to give the reader a feeling for the evolving state of the field by highlighting the different points of view and unresolved questions.

2. POPULATION STUDIES IN X-RAYS

It is well known that the Milky Way hosts both old and young luminous X-ray source populations, reflecting its general stellar makeup. In the luminosity range detectable in most external galaxies with typical *Chandra* observations ($>10^{37}$ erg s^{-1}), these Galactic populations are dominated by XRBs, and include both low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs) (**Table 1**). A few young supernova remnants (SNRs) may also be expected. At lower luminosities, reachable with *Chandra* in Local Group galaxies, Galactic sources include accreting white dwarfs and more evolved SNRs (see, e.g., the review by Watson 1990 for a census of Galactic X-ray sources; Grimm, Gilfanov & Sunyaev 2002 for a study of the X-ray luminosity functions of the Galactic X-ray source populations; White, Nagase & Parmar 1995 for a review of the properties of Galactic X-ray binaries; Verbunt & van den Heuvel 1995 for a review on the formation and evolution of XRBs; Fender & Belloni 2004 on the spectral states of black-hole binaries). **Figure 1** shows the cumulative X-ray luminosity functions (XLFs) of LMXBs and HMXBs in the Galaxy (Grimm, Gilfanov & Sunyaev 2002). Note the high luminosity cut off of the LMXB XLF and the power-law distribution of the HMXB XLF; these basic characteristics are echoed in the XRB populations of external galaxies (Section 3.3 and Section 4.2).

Figure 2 shows two typical observations of galaxies with *Chandra*: the spiral M83 (Soria & Wu 2003) and the elliptical NGC4697 (Sarazin, Irwin & Bregman 2000), both observed with the ACIS CCD detector. The images are color coded to indicate the energy of the detected photons (*red*, 0.3–1 keV; *green*, 1–2 keV; and *blue*, 2–8 keV). Populations of point-like sources are easily detected above a generally cooler diffuse emission from the hot ISM. Note that luminous X-ray sources are relatively sparse by comparison with the underlying stellar population, and can be detected individually

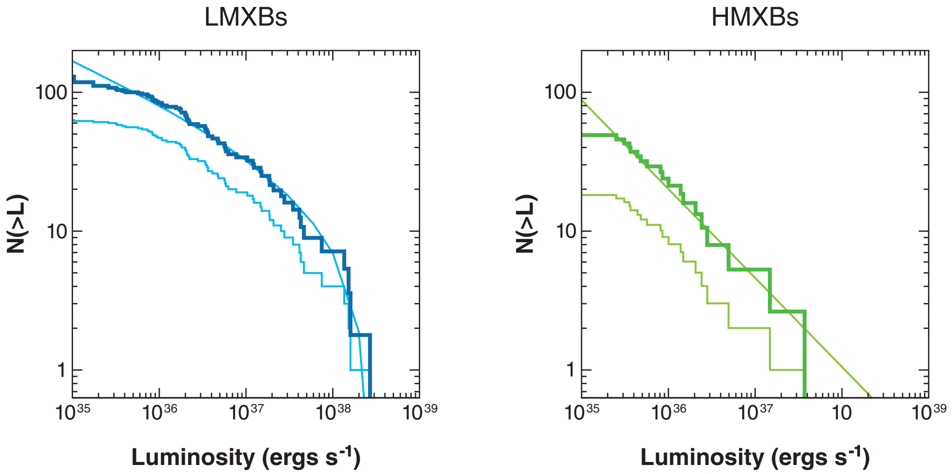

Figure 1

Cumulative X-ray luminosity functions (XLFs) of Galactic low-mass X-ray binaries (LMXBs, *left*) and high-mass X-ray binaries (HMXBs, *right*), from figure 12 of Grimm, Gilfanov & Sunyaev (2002). A mass of $2.5M_\odot$ for the companion star was used as a boundary between LMXBs and HMXBs. The thin and thick histograms are the apparent and volume-corrected distributions, respectively. The lines are the best fits to the volume-corrected distributions: a power law with cumulative slope -0.64 ± 0.15 for the HMXBs and a power law (slope, -0.26 ± 0.08) truncated at $\sim 2.7 \times 10^{38}$ erg s^{-1} for the LMXBs. Note that a similar HMXB power law is also found in the X-ray binaries populations of star-forming galaxies (Section 4.2); the LMXB power law is flatter than those found in the populations of E and S0 galaxies (≤ -1, for $L_X > 2 \times 10^{37}$ erg s^{-1}, Section 3.3), and it may reflect the wider luminosity range covered by the Milky Way observations and a complex XLF shape.

with the *Chandra* subarcsecond resolution (excluding the crowded circumnuclear regions).

The X-ray CCD detectors (present both in *Chandra* and *XMM-Newton*) provide us with a data-hypercube of the observed area of the sky, where each individually detected photon is tagged with a two-dimensional position, energy, and time of arrival. Therefore, for each detected source, we can measure flux (and luminosity), spectral (or photometric) parameters, and time variability. For the most intense sources, it is also possible to study the time variability of spectra if the galaxy has been observed at different epochs (which is still rare in the available data set; see, e.g., Fabbiano et al. 2003a,b). To analyze this wealth of data two approaches have been taken: (*a*) a photometric approach, consisting of X-ray color-color diagrams and color-luminosity diagrams, and (*b*) X-ray luminosity functions.

2.1. X-Ray Photometry

The use of X-ray colors to classify X-ray sources is not new. For example, White & Marshall (1984) used this approach to classify Galactic XRBs, and Kim, Fabbiano & Trinchieri (1992) used *Einstein* X-ray colors to study the integrated X-ray emission of galaxies. Given the lack of standard X-ray photometry to date, different definitions

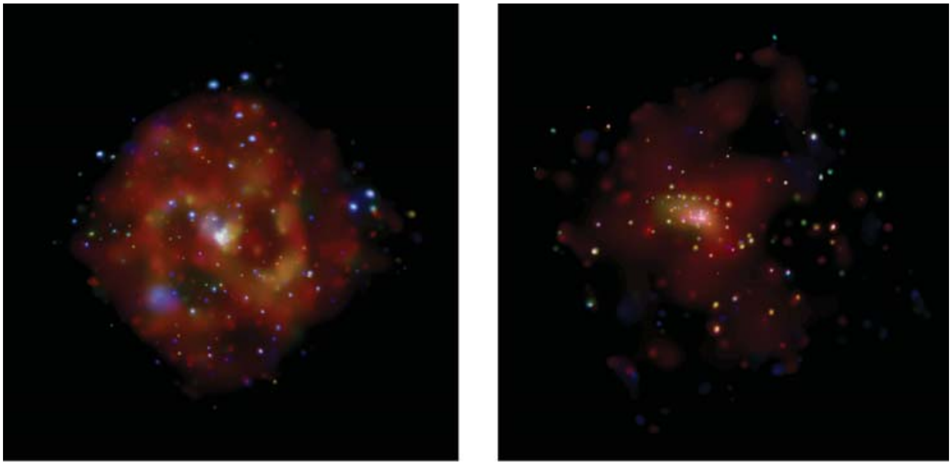

Figure 2

Chandra ACIS images of M83 (*left*, box is 8.57 × 8.86 arcmin) and NGC4697 (*right*, box is 8.64 × 8.88 arcmin). See text for details. Both images are from the Web page **http://chandra.harvard.edu/photo/category/galaxies.html;** credit NASA/CXC).

of X-ray colors have been used in different works; in the absence of instrument corrections, these colors can only be used for comparing data obtained in the same observational set up. Colors, however, have the advantage of providing a spectral classification tool when only a limited number of photons are detected from a given source, which is certainly the case for most X-ray population studies in galaxies.

Compared with the traditional X-ray data analysis approach of deriving spectral parameters via model fitting, color-color diagrams provide a relatively assumption-free comparison tool. Early *Chandra*-based examples of this approach can be found in Zezas et al. (2002a,b) and Prestwich et al. (2003). Color diagrams are used frequently to classify the discrete source populations of galaxies (see Sections 3 and 4); although useful, it is important to remember that some ambiguity in the outcome is unavoidable. Both the choice of spectral boundaries and the sensitivity of a given telescope-detector combination are important (see, for example, the identification of supersoft and quasi-soft sources, Pietsch et al. 2005, Di Stefano et al. 2004; Section 5). Moreover, both spectrum and flux of XRBs may vary in time, so that the classification of a given source may change when repeated observations become available.

2.2. X-Ray Luminosity Functions

Luminosity functions are a well-known tool of observational astrophysics. XLFs have been used to characterize different XRB populations in the Milky Way (e.g., Grimm, Gilfanov & Sunyaev 2002; see **Figure 1**), but these studies have always required a model of the spatial distribution of the sources, and of the intervening absorption, in order to estimate their luminosities; these corrections are inherently sources of uncertainty. External low-inclination galaxies, instead, provide clean source samples all at the same distance. Moreover, the detection of X-ray source populations in a wide range of different galaxies allows us to explore global population differences that may be connected with the age and or metallicity of the parent stellar populations. XLFs establish the observational basis of X-ray population synthesis (Belczynski et al. 2004). The first early attempts to construct and compare XLFs of X-ray source populations in external galaxies include the comparisons of the XLFs of M31 and of the disk of M81 with *Einstein* data (Fabbiano 1988; see also Fabbiano 1995), concluding that in M81 there is a relative surplus of very luminous sources, and the conclusion of a flat XLF in M101, connected with massive accreting young binaries (Trinchieri, Fabbiano & Romaine 1990). These early results are in general agreement with the trends suggested by the XLFs of LMXB and HMXB in the Milky Way (**Figure 1**) and with the results discussed in this review.

In principle XLFs are simple to construct, but care must be taken to apply corrections for observational biases and statistical effects. These include the incomplete detection of low-luminosity sources that may cause flattening of the XLF at the low-luminosity end; the artificial "brightening" of threshold sources because of statistical fluctuations (Eddington bias; Eddington 1913); the varying amount of diffuse emission around the source from a hot ISM (e.g., Zezas & Fabbiano 2002), which affects the detection threshold; and source confusion in crowded regions especially near the galaxy centers. In the case of *Chandra* the detection efficiency is also affected by the radial dependence of the degradation of the mirror resolution off-axis (see Kim & Fabbiano 2003, 2004; Gilfanov 2004). These low-luminosity biases have not been treated consistently in the literature, giving rise in some cases to potentially spurious results (Section 3.3). For galaxies extending over large angular sizes, the effect of background active galactic nuclei (AGNs) and stellar interlopers in the XLF must also be considered (e.g., Finoguenov & Jones 2002, Gilfanov 2004, Grimm et al. 2005).

At the high luminosity end, the paucity of very luminous X-ray sources in galaxies makes uncertain the parameterization of the XLF of individual populations; this problem has been approached by coadding "consistent" samples of X-ray sources (Kim & Fabbiano 2004). This same effect is responsible for uncertainties in the measurement of the total X-ray luminosity of a galaxy from the relatively small number of X-ray sources detected in short or insensitive observations (Gilfanov, Grimm & Sunyaev 2004b).

Compact X-ray sources are notorious for their variability and this variability could in principle also affect the XLF, which is typically derived from a snapshot of a given galaxy. However, repeated *Chandra* observations in the cases of NGC5128 (Kraft et al. 2001), M33 (Grimm et al. 2005) and the Antennae galaxies (Zezas et al. 2004) empirically demonstrate that the XLF is remarkably steady against individual source variability.

3. OLD X-RAY BINARY POPULATIONS

At variance with most previous reviews of X-ray observations of galaxies, which tend to concentrate first on nearby well-studied spiral and irregular galaxies, I will begin by discussing the X-ray populations of old stellar systems: E and S0 galaxies. By comparison with spirals, these galaxies present fairly homogeneous stellar populations, and therefore one can assume that their XRB populations are also more uniform, providing a "cleaner" baseline for population studies.

I begin this Section with a historical note (Section 3.1), followed by a summary of the detection of ubiquitous discrete X-ray source populations in spheroids and their spectral and variability properties (Section 3.2), which point to LMXB populations. I then address the characterization of these populations by means of XLFs (Section 3.3), and give an overview of the association of these sources with globular clusters (GCs) and of the properties of GC sources in comparison with field sources (Section 3.4). Finally, I summarize the discussion generated by these results for the dependence of LMXB formation in GCs on the metallicity and dynamical properties of the cluster (Section 3.5), and address the current debate on the formation and evolution of the entire LMXB populations, including both formation in GCs and evolution of field native binary systems (Section 3.6). I conclude this Section with a short discussion of results that may suggest evolution of the X-ray populations of some E and S0 galaxies (Section 3.7).

3.1. Low-Mass X-Ray Binaries in Early-Type Galaxies: There They Are—Past and Present

In the 1989 review (Fabbiano 1989) I argued that LMXBs should be present in E and S0s and might even dominate the X-ray emission of some of these galaxies. This was a controversial issue at the time, because LMXBs could not be detected individually, and their presence was supported only by statistical considerations (e.g., Trinchieri & Fabbiano 1985). Although the spectral signature of LMXBs was eventually detected (Kim, Fabbiano & Trinchieri 1992; Fabbiano, Kim & Trinchieri 1994; Matsushita et al. 1994), uncontroversial detection of samples of these sources in all early-type galaxies has become possible only with the subarcsecond resolution of *Chandra* (such a population was first reported in NGC4697, where 80 sources were detected by Sarazin, Irwin & Bregman 2000; see **Figure 2**).

A statistical analysis of a large sample of early-type galaxies observed with *Chandra* is still to come, but the results so far confirm the early conclusion (see Fabbiano 1989; Kim, Fabbiano & Trinchieri 1992; Eskridge, Fabbiano & Kim 1995a,b) that LMXBs account for a very large fraction of the X-ray emission of some early-type galaxies (those formerly known as "X-ray faint," i.e., devoid of large hot gaseous halos): for example, in NGC4697 (Sarazin, Irwin & Bregman 2000) and NGC1316 (Kim & Fabbiano 2003) the fraction of detected counts attributable to the hot ISM is ~23% and ~50%, respectively. In both cases, given the harder spectrum of LMXBs, these sources dominate the integrated luminosity in the 0.3–8 keV range. In NGC1316 the integrated LMXB emission, including nondetected LMXBs with luminosities below threshold, could be as high as 4×10^{40} erg s^{-1}. Sivakoff, Sarazin & Irwin (2003) reach similar conclusions for NGC4365 and NGC4382.

Although this review focuses on the X-ray binary populations, I cannot help remarking that the *Chandra* results demonstrate unequivocally that ignoring the contribution of the hidden emission of LMXBs was a source of error in past analyses. In

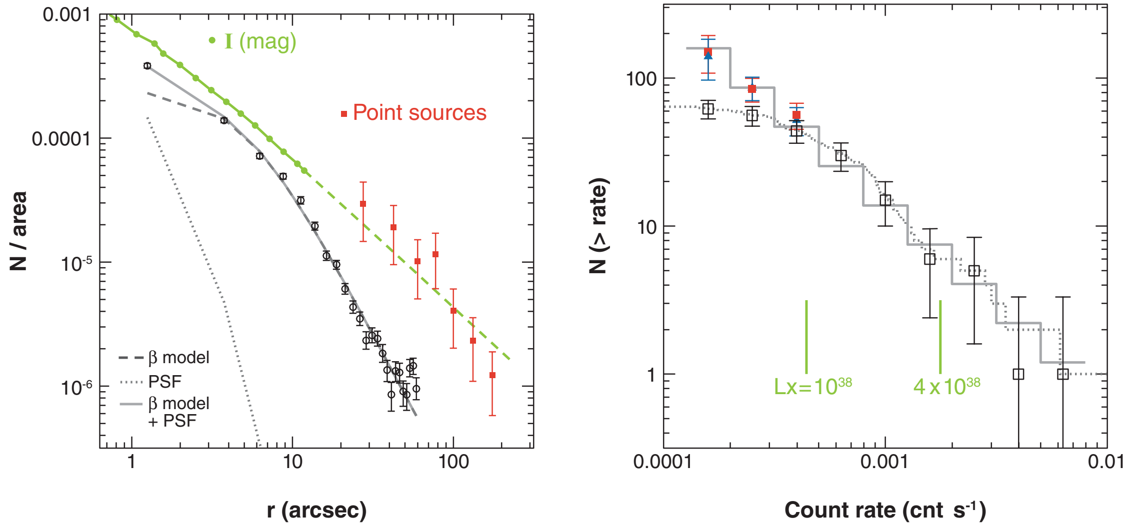

Figure 3

Left: Radial profile of the low-mass X-ray binary distribution (*red dots*) in NGC1316 compared with the profiles of the optical light (*green*) and diffuse hot interstellar medium emission (*black data points* and best-fit model); Right: X-ray luminosity function (XLF) before (*squares* are the binned data and the *dotted line* gives the unbinned XLF) and after completeness correction (*filled dots*; the *solid line* gives the best-fit power-law model, binned to resemble the data). These figures are figures 6 and 10 of Kim & Fabbiano (2003).

particular, estimates of galaxy dynamical mass were affected, as discussed in the 1989 review (see also Trinchieri, Fabbiano & Canizares 1986). NGC1316 (Kim & Fabbiano 2003) provides a very clear illustration of this point. In this galaxy the LMXBs are distributed like the optical light and dominate the emission at large radii. Instead, the hot ISM follows a steeper profile (see **Figure 3**, *left*), with temperature possibly decreasing at larger radii, suggestive of galactic winds. Use of lower-resolution *Einstein* data, with the assumption that the entire detected emission originated from a hot ISM in hydrostatic equilibrium, resulted in a large mass estimate for this galaxy (2.0×10^{12} $M_\odot$; Forman, Jones & Tucker 1985). This result is not sustained by the present data; because the gaseous halo is less extended than assumed in the *Einstein* paper, its temperature is lower (because the *Einstein* spectrum was clearly contaminated by the harder LMXB emission), and the halo may not be in hydrostatic equilibrium.

Estimates of the metal abundance of the hot ISM also must be reconsidered. In NGC1316, spectral analysis of the integrated X-ray emission obtained with *ASCA* suggested extremely subsolar values (0.1 solar, Iyomoto et al. 1998). This extremely low metallicity is typical of *ASCA* results for E and S0 galaxies, and cannot be reconciled with the predictions of stellar evolution (e.g., Arimoto et al. 1997). Spectral analysis of the NGC1316 *Chandra* data (Kim & Fabbiano 2003), after subtraction of the detected LMXBs, and taking into account the unresolved LMXB component, allows larger metallicities of the hot ISM (up to 1.3 $Z_\odot$), more in keeping with the expected values.

3.2. Source Spectra and Variability

Populations of several tens to hundreds of sources have been detected in E and S0 galaxies with *Chandra* (see review by Fabbiano & White 2006), and their number is growing as more galaxies are observed and the depth of the observations increase. With the exception of a few SSSs reported in some galaxies (see Irwin, Athey & Bregman 2003; Humphrey & Buote 2004), the X-ray colors and spectra of these sources are consistent with those expected of LMXBs, and consistent with those of the LMXBs of M31 (Blanton, Sarazin & Irwin 2001; Sarazin, Irwin & Bregman 2001; Finoguenov & Jones 2002; Irwin, Athey & Bregman 2003; Kim & Fabbiano 2003; Sivakoff, Sarazin & Irwin 2003; Humphrey & Buote 2004; Jordan et al. 2004; Kim & Fabbiano 2004; Randall, Sarazin & Irwin 2004; Trudolyubov & Priedhorsky 2004; David et al. 2005).

The most extensive spectral study to date is that of Irwin, Athey & Bregman (2003), who studied 15 nearby early-type galaxies observed with *Chandra*.They found that the average spectrum of sources fainter than 10^{39} erg s^{-1} is remarkably consistent from galaxy to galaxy, irrespective of the distance of the sources from the center of the galaxy. These spectra can be fitted with either power laws with photon index $\Gamma = 1.56 \pm 0.02$ (90%) or with bremsstrahlung emission with $kT = 7.3 \pm 0.3$ keV. Sources with luminosities in the $(1\text{–}2) \times 10^{39}$ erg s^{-1} range instead have softer spectra, with power law $\Gamma \sim 2$, consistent with the high-soft emission of black-hole binaries (with masses of up to $15M_\odot$ expected for these luminosities, based on the Eddington limit). Within the errors, these results are consistent with those reported in other studies, although sources in different luminosity ranges are usually not studied separately in these works. Jordan et al. (2004) confirm the luminosity dependence of the average source spectrum in M87; their color-color diagram suggests a spectral softening for sources more luminous than 5×10^{38} erg s^{-1}.

Relatively little is known about the time variability of these sources, because repeated monitoring of the same galaxy is not generally available. Type I X-ray bursts have been detected in some GC sources in M31, identifying these sources as neutron star LMXBs (Pietsch & Haberl 2005). Time variable sources and at least five transients (dimming by a factor of at least 10) have been detected in NGC5128, with two *Chandra* observations (Kraft et al. 2001). Variable sources are also detected with two observations of NGC1399, taken two years apart (Loewenstein, Angelini & Mushotzky 2005). Sivakoff, Sarazin & Irwin (2003) report time variability in a few sources in NGC4365 and NGC4382 within 40ks *Chandra* observations; Humphrey & Buote (2004) report two variable sources in NGC1332. Sivakoff, Sarazin & Jordan (2005) report short-timescale X-ray flares from 3 out of 157 sources detected in NGC4697; two of these flares occur in GC sources and are reminiscent of the superbursts found in Galactic neutron star binaries, while the third could originate from a black-hole binary. Maccarone (2005) suggests that these flares may be periodic events resulting from periastron accretion of eccentric binaries in dense globular clusters. The spectral characteristics of the point sources detected in E and S0 galaxies, their luminosities, and their variability, show that these sources are compact accreting X-ray binaries.

3.3. X-Ray Luminosity Functions of Low-Mass X-Ray Binary Populations

The luminosities of individual sources range from the detection threshold (typically a few 10^{37} erg s^{-1}, depending on the distance of the galaxy and the observing time) up to $\sim 2 \times 10^{39}$ erg s^{-1}. XLFs have been derived in most *Chandra* studies of early-type galaxies, and modeled to characterize their functional shape (power-law slopes, eventual breaks) and normalization. In the following I first review the work on the shape of the XLF and then discuss the drivers of the normalization (i.e., the total LMXB content of a galaxy).

The high luminosity ($L_X >$ a few 10^{37} erg s^{-1}) shape of the XLF has been parameterized with models consisting of power laws or broken power laws. The overall shape (in a single power-law approximation in the range of $\sim 7 \times 10^{37}$ to a few 10^{39} erg s^{-1}) is fairly steep, i.e., with a relative dearth of high luminosity sources, when compared with the XLFs of star-forming galaxies (Section 4.2; see also Kilgard et al. 2002, Colbert et al. 2004, Fabbiano & White 2006), but the details of these shapes and the related presence of breaks have been a matter of some controversy.

Two breaks have been reported in the XLFs of E and S0 galaxies: the first is a break at $\sim 2\text{–}5 \times 10^{38}$ erg s^{-1}, near the Eddington limit of an accreting neutron star, first reported by Sarazin, Irwin & Bregman (2000) in NGC4697, which may be related to the transition in the XLF between neutron stars and black-hole binaries (Blanton, Sarazin & Irwin 2001 in NGC1553; Finoguenov & Jones 2002 in M84; Kundu, Maccarone & Zepf 2002 in NGC4472; Jordan et al. 2004 in M87; Gilfanov 2004, Kim & Fabbiano 2004, and also Di Stefano et al. 2003 for the XLF of the Sa Sombrero galaxy, NGC4594); the second is a high luminosity break at $\sim 10^{39}$ erg s^{-1}, first reported by in NGC720 by Jeltema et al. (2003; see also Sivakoff et al. 2003, Jordan et al. 2004). Both breaks are somewhat controversial, because the interpretation of the observed XLFs is crucially dependent on a proper completeness correction (see Section 2.2).

Kim & Fabbiano (2003, 2004) show that incompleteness effects are particularly relevant for the detection of the Eddington break, because the typical exposure times of the data and the distances of the target galaxies in most cases conspire to produce a spurious break at just this value (see **Figure 3**, *right*, for an example). Interestingly, no break was required in the case of NGC5128 (Kraft et al. 2001), where the proximity of this galaxy rules out incompleteness near the neutron star Eddington luminosity. An apparent Eddington break that disappears after correction for completeness is also found by Humphrey & Buote (2004) for the XLF of NGC1332. Similarly, Eddington breaks are absent in NGC4365 and NGC4382 (Sivakoff, Sarazin & Irwin 2003), whereas a high luminosity cut-off at $0.9\text{–}3.1 \times 10^{39}$ erg s^{-1} could be allowed; these researchers also consider the effect of incompleteness in their results.

Other recent papers, however, do not discuss, or do not apply, completeness corrections to the XLFs, so their conclusions on the presence of Eddington breaks need to be confirmed. Randall, Sarazin & Irwin (2004) report a break at $\sim 5 \times 10^{38}$ erg s^{-1} in NGC4649, with large uncertainties, but do not discuss the derivation of the XLF. Jordan et al. (2004) derive and fit the XLF of M87, and compare it with their own fit of those of NGC4697 and M49 (NGC4472), using the data from Sarazin, Irwin & Bregman (2001) and Kundu, Maccarone & Zepf (2002) respectively. However, completeness corrections are not applied, although the low-luminosity data are not fitted. Jordan et al. (2004) report breaks at 2–3 × 10^{38} erg s^{-1} in all cases, or a good fit with a single power law truncated at 10^{39} erg s^{-1}. Note that these results are not consistent with those of Kim & Fabbiano (2004) where the corrected XLFs of NGC4647 and NGC4472 are well fitted with single unbroken power laws.

Kim & Fabbiano (2004) derive corrected luminosity functions for a sample of 14 E and S0 galaxies, including some with previously reported breaks, and find that all the individual corrected XLFs are well fitted with single power laws with similar differential slopes (−1.8 to −2.2; cumulative slopes are −0.8 to −1.2) in the observed luminosity range. None of these fits require an Eddington break. However, a break may be hidden by the poor statistics in each case. The statistical consistency of the individual power laws justifies coadding the data to obtain a high significance composite XLF of early-type galaxies (**Figure 4** *left*). This composite XLF is not consistent with a single power law, suggesting a break at (5 ± 1.6) × 10^{38} erg s^{-1}. The best-fit differential slope is −1.8 ± 0.2 in the few 10^{37} to 5 × 10^{38} erg s^{-1} luminosity range for the coadded XLF; at higher luminosity, above the break, the differential slope is steeper (−2.8 ± 0.6). These results are confirmed by the independent work of Gilfanov (2004), who analyzes four early-type galaxies, included in the Kim & Fabbiano (2004) sample (**Figure 4** *right*); however, Gilfanov's differential slope for the high luminosity portion of the XLF is somewhat steeper (−3.9 to −7.3). Both the

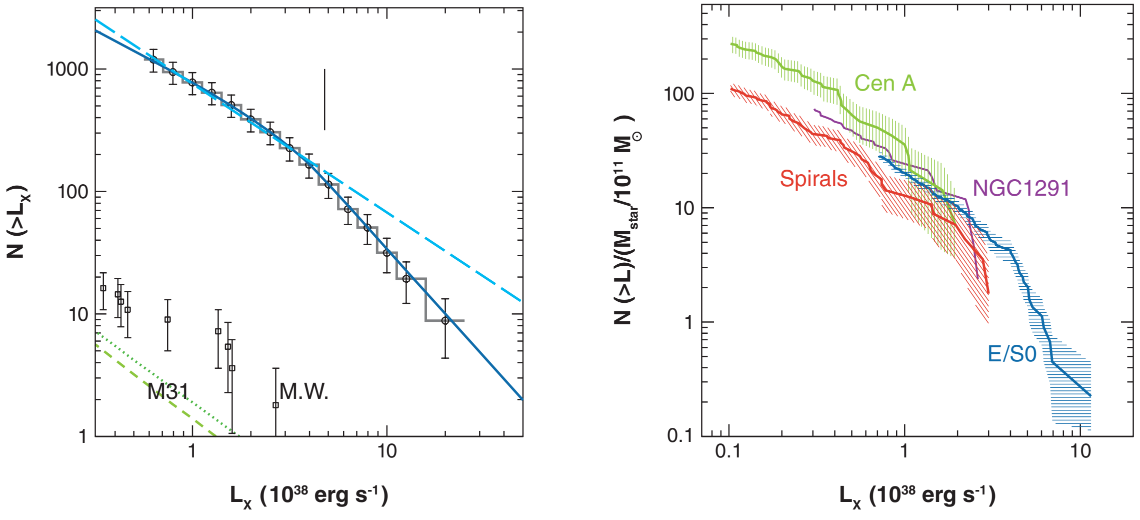

Figure 4

Left: Cumulative X-ray luminosity function (XLF) of 14 E and S0 galaxies (figure 7 of Kim & Fabbiano 2004), with the single power-law best fit (*dashed line*), and the broken power-law model (*solid line*); the M31 and Milky Way low-mass X-ray binary (LMXB) XLFs are sketched in the left lower corner. Right: Cumulative LMXB XLFs from figure 5 of Gilfanov (2004). Note the similarity of the XLFs and the break at ~5 × 10^{38} erg s^{-1} in the E/SO XLF.

Kim & Fabbiano and Gilfanov analyses are consistent with a cut-off of the XLF of LMXBs at a few 10^{39} erg s^{-1}. A more recent paper (Xu et al. 2005) is in agreement with the above conclusions, reporting a consistent Eddington break in the corrected XLF of NGC4552; on the basis of a simulation, this paper concludes that the break may or may not be detected in any individual galaxy XLF, given the relatively small number of sources present in each case.

The $(5 \pm 1.6) \times 10^{38}$ erg s^{-1} break is at somewhat higher luminosity than would be expected from the Eddington luminosity of normal neutron star binaries. It may be consistent with the luminosity of the most massive neutron stars ($3.2 \pm 1\ M_{\odot}$; see Ivanova & Kalogera 2006), He-enriched neutron star binaries ($1.9 \pm 0.6\ M_{\odot}$; see Ivanova & Kalogera 2006), or low-mass black-hole binaries. This break may be caused by the presence of both neutron star and black-hole binary populations in early-type galaxies; it may also be the consequence of a true high luminosity break in the XLF (e.g., Sivakoff, Sarazin & Irwin 2003). Whatever the cause, the shape of the XLF points to a dearth of very luminous sources in E and S0 galaxies. Note that a high luminosity cut-off is also present in the XLF of Galactic LMXBs (**Figure 1**).

With the exception of NGC5128 (Cen A), for which the XLF has been measured down to $\sim 2 \times 10^{36}$ erg s^{-1} (Kraft et al. 2001, Voss & Gilfanov 2006), the available *Chandra* data does not allow the detection of LMXBs in E and S0 galaxies with luminosities below the mid or high 10^{37} erg s^{-1} range. By including Cen A and the LMXB (bulge) population of nearby spirals (Milky Way; see **Figure 1**, *M*31, *M*81) in his study, Gilfanov (2004) suggests that the XLF flattens below 10^{37} erg s^{-1}. A recent reanalysis of the Cen A data confirms this result (Voss & Gilfanov 2006). Direct deep observations of "normal" early-type galaxies are needed to see if this suggestion is generally valid; a legacy *Chandra* program will provide the necessary data for NGC3379 and NGC4278 by the end of 2007. These future studies may show complex behavior in the low-luminosity XLFs. For example, in *M*31 a radially dependent XLF break has been reported in the bulge, which could be related to an increasingly older population at the inner radii (Kong et al. 2002). Also, the GC XLF of *M*31 has a distinctive break at $2\text{–}5 \times 10^{37}$ erg s^{-1} (Kong et al. 2003, Trudolyubov & Priedhorsky 2004). The discovery of a similar break in the E and S0 XLFs may argue for a GC-LMXB connection in these galaxies. The "outburst peak luminosity—orbital period" correlation (King & Ritter 1998) predicts a break at this luminosity if a large fraction of the sources are short-period neutron star systems. This is intriguing, because the formation of ultracompact LMXBs is favored in Milky Way GCs (Bildsten & Deloye 2004; see also Section 3.6).

The normalization of the XLF is related to the number of LMXBs in a given galaxy. X-ray-optical/near-IR correlations in bulge-dominated spirals observed with *Einstein* (Fabbiano, Gioia & Trinchieri 1988; Fabbiano & Shapley 2002) had suggested a connection between the number of LMXBs and the overall stellar content of a galaxy. This connection has now been demonstrated to hold for the LMXB populations of E and S0 galaxies (Gilfanov 2004; Kim & Fabbiano 2004). That stellar mass is the main regulator of the number of LMXBs in a galaxy is not surprising, considering that LMXBs are long-lived systems, but there may be other effects. White, Sarazin & Kulkarni (2002) suggested a link with GC specific frequency (the number of GC per unit light in a galaxy) using low-resolution *ASCA* data. Kim & Fabbiano (2004; see also Humphrey & Buote 2004 for general agreement with this correlation in the case of NGC1332) find a correlation between K-band luminosity (which is proportional to stellar mass) and integrated LMXB luminosity, but also note that this correlation has more scatter than would be expected in terms of measurement errors. This scatter appears correlated with the GC-specific frequency, confirming a role of GCs in LMXB evolution.

3.4. Association of Low-Mass X-Ray Binaries with Globular Clusters: The Facts

In virtually all E and S0 galaxies with good coverage of GCs, both from the ground and better from *Hubble*, a fraction of the LMXBs is found in GCs (see earlier reviews by Verbunt & Lewin 2006, Fabbiano & White 2006). Sarazin, Irwin & Bregman (2000) first reported this association in NGC4697 and speculated on a leading role of GCs in LMXB formation, revisiting the original suggestion of Grindlay (1984) for the evolution of bulge sources in the Milky Way. Below, I summarize the observational results on the association of LMXBs with GCs from the large body of papers available in the literature. In Sections 3.5 and 3.6, I will discuss the implications of these results.

3.4.1. Statistics. It appears that in general ∼4–5% of the GCs in a given galaxy are likely to be associated with a LMXB (e.g., NGC1399—Angelini, Loewenstein & Mushotzky 2001; NGC4472—Kundu, Maccarone & Zepf 2002; NGC1553, NGC4365, NGC4649, NGC4697—Sarazin et al. 2003; NGC1339—Humphrey & Buote 2004; M87—Jordan et al. 2004, Kim et al. 2006). Not surprisingly, as first noticed by Maccarone, Kundu & Zepf (2003), the number of LMXBs associated with GCs varies, depending on the GC-specific frequency of the galaxy, which is also a function of the morphological type. Sarazin et al. (2003) point to this dependence on the galaxy Hubble type, with the fraction of LMXBs associated with GCs increasing from spiral bulges (MW, M31) ∼10–20%, to S0s ∼20% (NGC1553, Blanton, Sarazin & Irwin 2001; see also NGC5128, where 30% of the LMXBs are associated with GCs, Minniti et al. 2004), E ∼50% (NGC4697—Sarazin, Irwin & Bregman 2000; NGC4365—Sivakoff, Sarazin & Irwin 2003; NGC4649—Randall, Sarazin & Irwin 2004; see also NGC4552, with 40% of sources in GCs—Xu et al. 2005), cD ∼ 70% (in NGC1399—Angelini, Loewenstein & Mushotzky 2001; see also M87, where 62% of the sources are associated with GCs—Jordan et al. 2004).

3.4.2. Dependence on low-mass X-ray binary and globular cluster luminosity. In NGC1399 (Angelini, Loewenstein & Mushotzky 2001) the most luminous LMXBs are associated with GCs. No significant LMXB luminosity dependence of the LMXB-GC association is instead seen in NGC4472 (Kundu, Maccarone & Zepf 2002) or in the four galaxies studied by Sarazin et al. (2003); if anything, a weak trend is present in the opposite sense. The reverse is, however, consistently observed: more luminous GCs are more likely to host a LMXB (Angelini, Loewenstein & Mushotzky 2001;

Kundu, Maccarone & Zepf 2002; Sarazin et al. 2003; Minniti et al. 2004; Xu et al. 2005; Kim et al. 2006); this trend is also observed in M31 (Trudolyubov & Priedhorsky 2004). Kundu, Maccarone & Zepf (2002) suggest that this effect is just a consequence of the larger number of stars in optically luminous GCs. Sarazin et al. (2003) estimate that the probability per optical luminosity of LMXBs to be found in a GC is $\sim 2.0 \times 10^{-7}$ LMXBs per $L_{\odot,I}$ for $L_X \geq 3 \times 10^{37}$ erg s^{-1}.

This probability is consistent with past estimates based on the Milky Way and is a few hundred times larger than the probability of LMXBs occurring in the field per unit integrated stellar light in a galaxy, in agreement with the conclusion that dynamical interactions in GCs favor LMXB formation (Clark 1975).

3.4.3. Dependence on globular cluster color.

The probability that a GC hosts a LMXB is not a function of the GC luminosity alone. GC color is also an important variable, as first reported by Angelini, Loewenstein & Mushotzky (2001) in NGC1399 and Kundu, Maccarone & Zepf (2002, see also Maccarone, Kundu & Zepf 2003) in NGC4472, and confirmed by subsequent studies (e.g., Sarazin et al. 2003, Jordan et al. 2004, Minniti et al. 2004, Xu et al. 2005, Kim et al. 2006). In particular, the GC populations in these galaxies tend to be bi-modal in color (e.g., Zepf & Ashman 1993), and LMXBs preferentially are found in red, younger and/or metal-rich clusters (V-I >1.1), rather than in blue, older and/or metal-poor ones. The association of LMXBs with high metallicity GCs was observed in the Galaxy and M31 (Bellazzini et al. 1995, Trudolyubov & Priedhorsky 2004). In NGC4472, red GCs are three times more likely to host a LMXB than blue ones (Kundu, Maccarone & Zepf 2002). Similarly, in M87, which has a very rich LMXB population, the fraction of red GCs hosting a LMXB is 5.1% ± 0.7% versus 1.7% ± 0.5% for blue GCs (Jordan et al. 2004), also a factor of three discrepancy. In a sample of six ellipticals yielding 285 LMXB-GC associations (Kim et al. 2006), the mean probability for a LMXB-GC association is 5.2%, the probability of a blue GC to host a LMXB is ~2% for all galaxies except NGC1399 (where it is 5.8%), while that of LMXB-red GC association is generally larger, but varies from one galaxy to another (2.7% to 13%).

3.4.4. X-ray colors.

Maccarone, Kundu & Zepf (2003) reported that in NGC4472 LMXBs associated with blue GCs have harder "stacked" X-ray spectra than those in red GCs. However, this result is not confirmed by the analysis of the much larger sample of sources assembled by Kim et al. (2006), where no significant differences are found in the X-ray colors of LMXBs associated with either red or blue GCs. Also, no significant differences are found in the X-ray colors of LMXBs in the field or in GCs (Sarazin et al. 2003; Kim et al. 2006).

3.4.5. Spatial distributions of field and globular cluster low-mass X-ray binaries.

To obtain additional constraints on LMXB formation and evolution, the radial distributions of the LMXBs have been compared with those of the GCs and of the field stellar light. Some of these comparisons have used the entire sample of detected LMXBs, irrespective of GC counterpart; others have also investigated differences between the LMXBs associated with GCs and those in the field.

Investigating the overall LMXB distribution in NGC4472, Kundu, Maccarone & Zepf (2002) suggest that it follows more closely the distribution of the GCs than the stellar light (which differ, with the GC one being more extended) and infer an evolutionary connection of all LMXBs with GCs (see Section 3.6). Other authors instead conclude that overall the LMXB distribution and the stellar light trace each other in E and S0 galaxies (NGC1316, Kim & Fabbiano 2003, shown in **Figure 3** *left*; NGC1332, Humphrey & Buote 2004). As for the XLFs, incompleteness may affect these comparisons and account for some of the discrepant reports: sources may be missed in the crowded inner parts of a galaxy, resulting in an apparently more extended distribution than the real one (see Kim & Fabbiano 2003, Gilfanov 2004).

Comparisons of the radial distributions of field and GC X-ray sources do not reveal any measurable differences (Sarazin et al. 2003; Jordan et al. 2004; Kim et al. 2006). A first comparison of these LMXB distributions with those of the stellar light and GCs was attempted in M87, but was inconclusive, given the statistical uncertainties (Jordan et al. 2004). With their significantly larger LMXB and GC samples, Kim et al. (2006) instead find that the LMXB radial profiles, regardless of association with either red or blue GCs, are closer to the more centrally peaked field stellar surface brightness distribution, than to the overall flatter GC distributions (**Figure 5**). The implication of this result for the GC sources is that the probability of a GC being associated with a LMXB increases at smaller galactocentric radii.

3.4.6. X-ray luminosity functions of field and globular cluster low-mass X-ray binaries.

No significant differences have been found in the XLFs of LMXBs in the field and in GCs (Kundu, Maccarone & Zepf 2002; Jordan et al. 2004). The coadded XLFs of field and GC LMXBs in six ellipticals (Kim et al. 2006) are also consistent within the errors, with a similar percentage of high luminosity sources with $L_X > 10^{39}$ erg s^{-1}.

This similarity of field and GC XLFs does not extend, however, to the X-ray populations of the Sombrero galaxy (Di Stefano et al. 2003) and M31 (from a comparison of the XLFs of bulge and GC sources; Trudoyubov & Priedhorsky 2004). In both cases, the GC XLFs show a more pronounced high luminosity break than the field (bulge) XLFs. In M31 the XLF of GC sources is relatively more prominent at the higher luminosities than that of field LMXBs; in the Sombrero galaxy, GC sources dominate the emission in the 1–4 × 10^{38} erg s^{-1} range, but there is a high luminosity tail in the field XLF, which, however, could be due to contamination from a younger binary system belonging to the disk of this galaxy (see Di Stefano et al. 2003).

3.5. Metallicity and Dynamical Effects in Globular Cluster Low-Mass X-Ray Binary Formation

The preferential association of LMXBs with red clusters could be either an age or a metallicity effect. A correlation between the number density of binaries and the metallicity of GCs was first suggested by Grindlay (1987), who ascribed this effect to a flatter IMF in higher metallicity GCs, resulting in a larger number of neutron stars and thus LMXBs. Kundu et al. (2003) argue that metallicity is the main driver, based on the

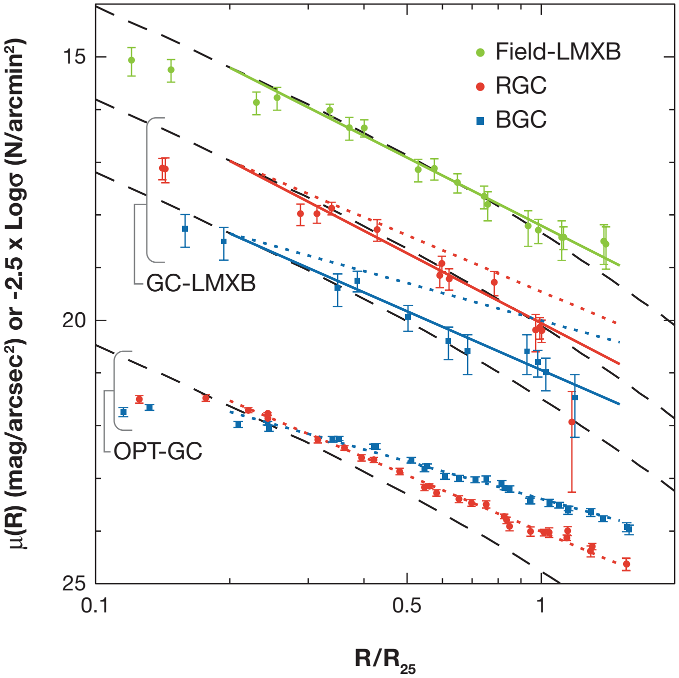

Figure 5

Radial distributions of low-mass X-ray binaries (LMXBs) in the field (*green*), in red GCs (*red*) and in blue GCs (*blue*), compared with the best-fit GC distributions (*red* and *blue* at the bottom of the figure), plotted versus the radius normalized to R_{25} for a sample of six galaxies. The flattening of the distributions at small radii is likely to be an incompleteness effect. The dotted blue and red lines are the best-fit models of the red and blue GC distributions. The solid lines show the best fits of the LMXB distributions. The black dashed lines represent the stellar light distribution (Kim et al. 2006).

absence of any correlations of LMXB association with different age GC populations in NGC4365. Maccarone, Kundu & Zepf (2004) propose irradiation-induced winds in metal-poor stars to speed up evolution and account for the observed smaller numbers of LMXBs in blue GCs. These winds, however, would cause absorption and thus harder X-ray spectra. Although these authors tentatively reported this spectral effect in NGC4472, studies of a larger sample of sources do not confirm this conclusion (see Section 3.4.4).

Jordan et al. (2004) revisit the IMF-metallicity effect, because the resulting increase in the number of neutron stars agrees with their conclusion that the probability that a GC contains a LMXB is driven by the dynamical properties of the cluster. Based on their study of M87, these researchers propose that the probability p_X for a given GC to generate a LMXB has the form $p_X \sim \Gamma \rho_0{}^{-0.42 \pm 0.11} \, (Z/Z_\odot)^{0.33 \pm 0.1}$, where Γ is a parameter related to the tidal capture and binary-neutron star exchange rate and ρ_0 is the central density of the cluster. This conclusion agrees with three-dimensional hydrodynamical calculations of the dynamical formation of ultracompact binaries in

GCs, from red giant and neutron star progenitors (Ivanova et al. 2005). Kim et al. (2006) also invoke dynamical effects to explain the increasing probability of LMXB-GC association at smaller galactocentric radii. They suggest that the GCs nearer to the galaxy centers are likely to have more compact cores and higher central densities to survive tidal disruption, compared with the GCs at the outskirts, characteristics that would also increase the chance of dynamical LMXB formation.

3.6. Constraints on the Formation and Evolution of Low-Mass X-Ray Binaries: Field Binaries or Globular Cluster Sources?

The formation processes of LMXBs have been debated since these sources were discovered in the Milky Way (see Giacconi 1974). LMXBs may result from the evolution of a primordial binary system, if the binary is not disrupted when the more massive star undergoes collapse and a supernova event, or may be formed by capture of a companion by a compact remnant in GCs (see Grindlay 1984, reviews by Verbunt 1993, Verbunt & van den Heuvel 1995). The same scenarios are now being debated for the LMXB populations of E and S0 galaxies. If GCs are the principal (or sole) birthplaces, formation kicks or evaporation of the parent cluster have been suggested as an explanation for the existence of field LMXBs in these galaxies (see e.g., Kundu, Maccarone & Zepf 2002).

The correlation of the total LMXB luminosity in a galaxy with the GC specific frequency (White, Sarazin & Kulkarni 2002; Kim & Fabbiano 2004; see Section 3.3) suggests that GCs are important in the formation of LMXBs. White, Sarazin & Kulkarni (2002) proposed formation in GCs as the universal LMXB formation mechanism in early-type galaxies. Other authors have supported this hypothesis, because of the similarity of field and GC LMXB properties (see Section 3.4; e.g., Maccarone, Kundu & Zepf 2003). However, this conclusion is by no means certain or shared by all. Beside uncertainties in the correlations (Kim & Fabbiano 2004), the relationship between the fraction of LMXBs found in GCs and the GC specific frequency (see Section 3.4.1) is consistent with the simple relationship expected if field LMXBs originate in the field while GC LMXBs originate in GCs (Juett 2005; Irwin 2005). This picture would predict different spatial distributions of field and GC LMXBs, an effect not seen so far, although, as Juett (2005) notes, the prevalence of LMXBs in red (more centrally concentrated) GCs and the effect of supernova kicks in the distribution of binaries may make the two distributions less distinguishable.

Piro & Bildsten (2002) and Bildsten & Deloye (2004) compare the observational results with theoretical predictions for the evolution of field and GC binaries. Piro & Bildsten remark that the large X-ray luminosities of the LMXBs detected in early-type galaxies ($>10^{37}$ and up to 10^{39} erg s^{-1}) imply large accretion rates ($>10^{-9}$ M$_\odot$ yr^{-1}). In an old stellar population these sources are likely to be fairly detached binaries that accumulate large accretion disks over time, and undergo transient X-ray events when accretion is triggered by disk instabilities. These transients would have recurrence times greater than 100 years and outbursts of 1–100 years duration. In this picture field binaries should be transient, a prediction that is supported by the detection of transients in the NGC5128 LMXB population (Kraft et al. 2001) and by the discovery of a population of quiescent X-ray binaries in the Sculptor dwarf spheroidal galaxy (Maccarone et al. 2005). Piro & Bildsten also point out that GC sources tend to have shorter orbital periods and would be persistent sources, reducing the fraction of transients in the LMXB population. Interestingly, Trudolyubov & Priedhosky (2004) report only one recurrent transient in their study of GC sources in M31, although 80% of these sources show some variability; however, they also find six persistent sources in the 10^{38} erg s^{-1} luminosity range.

Bildsten & Deloye (2004) instead look at ultracompact binaries formed in GCs to explain the bulk of the LMXBs detected in E and S0 galaxies. A motivation for this work is the large probability of finding LMXBs in GCs (per unit optical light, see Section 3.4.2), which makes formation in GCs more efficient than in the field. Ultracompact binaries would be composed of an evolved low-mass donor star (a white dwarf), filling its Roche lobe, in a 5–10 minute orbit around a neutron star or a black hole. The entire observable life of such a system is $\sim 10^7$ years, much shorter than the age of the galaxies and the GCs, therefore their total number would be indicative of their birth rate. From this consideration Bildsten & Deloye derive a XLF with a functional slope in excellent agreement with the measurements of Kim & Fabbiano (2004) and Gilfanov (2004). Bildsten & Deloye also predict a break at $L_X \sim 10^{37}$ erg s^{-1} in the XLF, which would correspond to the luminosity below which such a system would be a transient. As discussed in Section 3.3, there is some evidence of a low-luminosity break in the composite XLF of Gilfanov (2004), which, however, includes data from spiral bulges as well.

Confirmation of this break in a number of E and S0 populations by itself would not be proof of the Bildsten & Deloye scenario, because the break may occur from the evolution of field binaries. For example, a flattening of the XLF at the lower luminosities is found in the population synthesis of Pfahl, Rappaport & Podsiadlowski (2003, their figure 3), if irradiation of the donor star from the X-ray emission of the compact companion is considered in the model. More recently, Postnov & Kuranov (2005) have proposed that the mean shape of the XLF of Gilfanov (2004) can be explained by accretion on neutron star from Roche lobe overflow driven by gravitational wave emission, below $\sim 2 \times 10^{37}$ erg s^{-1}, and by magnetic stellar winds at higher luminosities. Optical identification of X-ray sources with GCs and an estimate of the transient fraction at different luminosities would help to discriminate among possible scenarios; planned deep time-monitoring *Chandra* observations may provide the observational constraints.

The nature of the most luminous sources in E and S0 galaxies (those with L_X above the 5×10^{38} erg s^{-1} break, Kim & Fabbiano 2004) is the subject of a recent paper by Ivanova & Kalogera (2006). These researchers point out that only a small fraction of these luminous sources are associated with GCs (at least in M87, see Jordan et al. 2004) and that they are too luminous to be explained easily with accreting neutron star systems that may form in GCs (Kalogera, King & Rasio 2004). With the assumption that these sources are accreting black-hole binaries, these authors explore their nature from the point of view of the evolution of field native binaries. In this picture most donor stars would be of low enough mass (<1–$1.5\ M_\odot$ given the age of the stellar populations in question) that the binary would be a transient (see Piro & Bildsten 2002) and therefore populate the XLF only when in outburst emitting at the Eddington luminosity; this would happen from main-sequence, red-giant, and white-dwarf donors. In this case the XLF is a footprint of the black-hole mass spectrum in these stellar populations, which is an important ingredient for linking the massive star progenitors with the resulting black hole. Ivanova & Kalogera derive a differential slope of ~ -2.5 for the black-hole mass spectrum, and an upper black-hole mass cut-off at $\sim$20 $M_{\odot}$, to be consistent with the observed cumulative XLF of Kim & Fabbiano (2004) and Gilfanov (2004). Depending on the magnetic breaking prescription adopted, either red-giant donors or main-sequence donors would dominate the source population. A word of caution is in order here, because the similar shape of GC and field LMXB XLFs (Kim et al. 2006, see Section 3.4.6) suggests that high-luminosity black-hole sources may also be found in GCs, at odds with theoretical discussions (e.g., Kalogera, King & Rasio 2004).

3.7. Young Early–Type Galaxies and Rejuvenation

There have been some puzzling and somewhat controversial results suggesting that the stellar populations of some early-type galaxies may not be uniformly old, as implied by their optical characteristics, but may hide a small fraction of younger stars, which give rise to luminous and easily detectable X-ray binaries. Rejuvenation (e.g., by a merger event or close encounter with a dwarf galaxy) has been suggested to explain the presence of very luminous and asymmetrically distributed X-ray source populations in some galaxies [NGC720—Jeltema et al. 2003; NGC4261 (shown in **Figure 6**) and NGC4697—Zezas et al. 2003]. Sivakoff, Sarazin & Carlin (2004) report an exceptionally luminous population of 21 sources with $L_X > 2 \times 10^{39}$ erg s^{-1} (in the ULX regime, see Section 6) in the X-ray bright elliptical NGC1600, which is twice the number of sources that would be expected from background AGNs and suggests an XLF slightly flatter than in most ellipticals. In all these cases, however, both cosmic variance affecting the background AGN density and distance uncertainties may play a role. Moreover, Giordano et al. (2005) report the identification of the NGC4261 sources with GCs, undermining the suggestion that they may be linked to a rejuvenation event.

The behavior opposite the one just discussed is reported in an X-ray and optical study of the nearby lenticular galaxy NGC5102 (Kraft et al. 2005). In this galaxy, where the stellar population is young ($<3 \times 10^9$ years old), and where there is evidence of two recent bursts of star formation, a definite lack of X-ray sources is observed. NGC5102 has also a very low specific frequency of GC ($\sim$0.4). Kraft et al. speculate that the lack of LMXBs may be related either to insufficient time for the evolution of a field binary and/or to the lack of GCs.

4. YOUNG XRB POPULATIONS

The association of luminous X-ray sources (HMXBs, and the less luminous SNRs) with the young stellar population has been known since the dawn of X-ray astronomy (see Giacconi 1974). The presence of X-ray source populations in Local Group

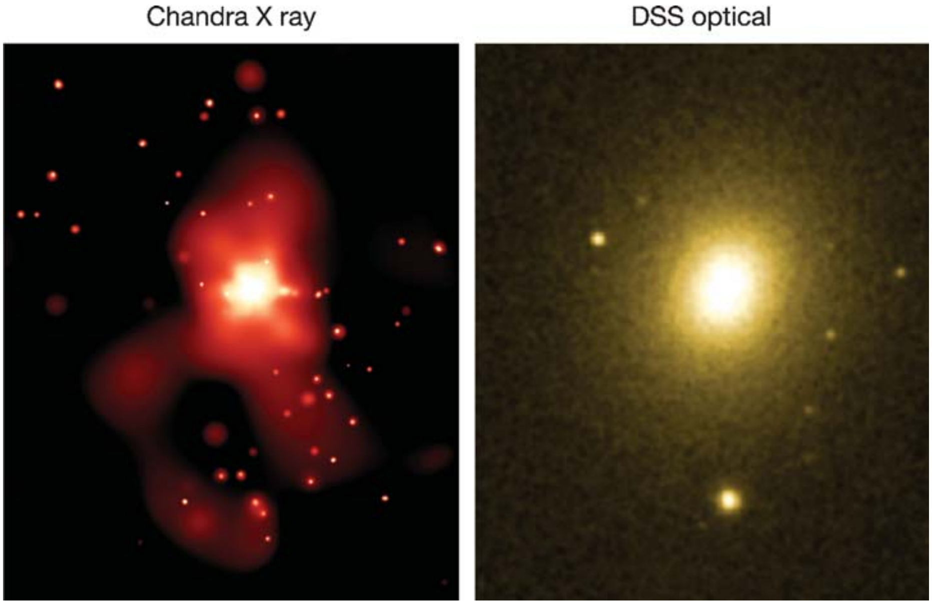

Figure 6

The left panel shows a *Chandra* image of NGC4261; note the distribution of the luminous point sources, which clearly do not follow the optical light shown in the right panel; Both images are from **http://chandra.harvard.edu/photo/category/galaxies.html;** credit NASA/CXC; Zezas et al. (2003).

and nearby spiral and irregular galaxies was clearly demonstrated by the early *Einstein* observations (see the 1989 review, Fabbiano 1989; and the *Einstein Catalog and Atlas of Galaxies*, Fabbiano, Kim & Trinchieri 1992). Luminous HMXBs are expected to dominate the emission of star-forming galaxies (Helfand & Moran 2001). These sources, resulting from the evolution of a massive binary system where the more massive star has undergone a supernova event, are short-lived ($\sim 10^{6-7}$ years) and constitute a marker of recent star formation: their number is likely to be related to the galaxy star-formation rate (SFR). This X-ray population–SFR connection was first suggested as a result of the analysis of the sample of normal galaxies observed with *Einstein*, where a strong correlation was found between global X-ray and FIR emission of late-type star-forming galaxies (Fabbiano & Trinchieri 1985; Fabbiano, Gioia & Trinchieri 1988; David, Forman & Jones 1991; Shapley, Fabbiano & Eskridge 2001; Fabbiano & Shapley 2002), and has been confirmed by analyses of *ROSAT* observations (Read & Ponman 2001; Lou & Bian 2005).

Though HMXBs are likely to dominate the X-ray emission of galaxies where star formation is most violent, they are also expected to be found in more normal spirals (see the Milky Way population; Section 2), albeit in smaller numbers and mixed with more aged X-ray populations. In bulge-dominated spirals, HMXBs may constitute only a small fraction of the X-ray-emitting population; for example, witness the strong correlation between X-ray and H-band luminosity found in these systems

(Shapley, Fabbiano & Eskridge 2001; Fabbiano & Shapley 2002). The study of HMXB populations is then less straightforward than that of LMXBs, because in many cases HMXBs must be culled from the complex X-ray source populations of spiral galaxies.

Below, I first discuss the detection and characterization of populations of X-ray sources in spiral and irregular galaxies with X-ray imaging and photometry (Section 4.1), and then review the work on the XLFs of these star-forming populations (Section 4.2).

4.1. X-Ray Source Populations of Spiral and Irregular Galaxies

Reflecting the complex stellar populations of these galaxies, *Chandra* and *XMM-Newton* observations are discovering complex X-ray source populations. Typically, in each observed galaxy, from a few tens to well over hundreds of sources have been detected. Time variability and spectral analysis have been carried out for the most luminous sources, confirming that these sources are accreting binaries; the results are reminiscent of the spectral and temporal-spectral behavior of Galactic XRBs, including soft and hard spectral states [e.g., M31 (NGC224)—Trudolyubov, Borodzin & Priedhorsky 2001; Trudolyubov et al. 2002a; Kaaret 2002; Kong et al. 2002; Williams et al. 2004; Trudolyubov & Priedhorsky 2004; Pietsch, Freyberg & Haberl 2005; M33 (NGC598)—Grimm et al. 2005; Pietsch et al. 2004; NGC1068—Smith & Wilson 2003; NGC1637—Immler et al. 2003; NGC2403—Schlegel & Pannuti 2003; M81 (NGC3031)—Swartz et al. 2003; M108 (NGC3556)—Wang, Chavez & Irwin 2003; NGC4449—Miyawaki et al. 2004; M104 (NGC4594; Sombrero)—Di Stefano et al. 2003; M51 (NGC5194/95)—Terashima & Wilson 2004; M83 (NGC5236)—Soria & Wu 2002; M101 (NGC5457)—Pence et al. 2001; Jenkins et al. 2004, 2005].

Most detected sources, however, are too faint for detailed analysis; their position relative to the optical image of the galaxy (e.g., bulge, arms, disk, GCs), their X-ray colors, and in some cases optical counterparts have been used to aid in classification. Typically, as demonstrated by Prestwich et al. (2003) who applied this method to five galaxies (**Figure 7**), color-color diagrams can discriminate between harder XRB candidates (with relatively harder neutron star HMXBs and softer LMXBs; rare black-hole HMXBs would also belong to this "softer" locus), softer SNR candidates, and very soft sources (SSSs, with emission below 1 keV).

Similarly, XRBs, SNRs, and SSSs are found with *XMM-Newton* X-ray colors in IC342, where most sources are near or on the spiral arms, associating them with the young stellar population (Kong 2003). In M33, the Local Group Scd galaxy with a predominantly young stellar population, *Chandra* and *XMM-Newton* colors, luminosities, and optical counterparts indicate a prevalence of (more luminous) HMXBs and a population of (fainter) SNRs (Pietsch et al. 2004; Grimm et al. 2005). In M83 (**Figure 2**, *left*), the X-ray source population can be divided into three groups, based on their spatial, color, and luminosity distributions (Soria & Wu 2003): fainter SSSs, soft sources (with no detected emission above 2 keV), and more luminous and harder XRBs. The positions of the soft sources are strongly correlated with current star-formation regions, as indicated by $H\alpha$ emission in the spiral arms and the starburst nucleus, strongly suggesting that they may be SNRs.

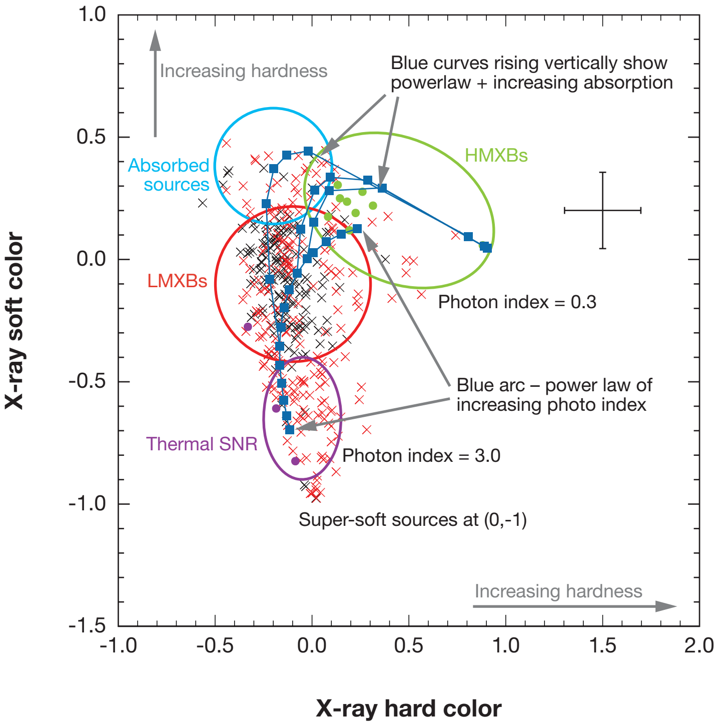

Figure 7

Chandra color-color diagram (figure 4 of Prestwich et al. 2003). Energy bands chosen for this diagram are S = 0.3–1 KeV, M = 1–2 KeV, and H = 2–8 KeV. Soft color = (M–S)/(S + M + H), hard color = (H–M)/(S + M + H).

Chandra X-ray colors (or hardness ratios) were also used to study the X-ray source populations of M100 (NGC4321; Kaaret 2001), M101 (Jenkins et al. 2005), NGC1637 (Immler et al. 2003), NGC4449 (Summers et al. 2004), NGC5494 (the Sombrero galaxy, a Sa, with a predominantly older stellar population; Di Stefano et al. 2003), and the star-forming merging pair NGC4038/9, the Antennae galaxy (Fabbiano, Zezas & Murray 2001; Fabbiano et al. 2004a), where spectral and flux variability is revealed by color-color and color-luminosity diagrams (Fabbiano et al. 2003a,b; Zezas et al. 2002a,b, 2005). Colbert et al. (2004) employ *Chandra* color diagrams to classify the X-ray source populations in their survey of 32 nearby galaxies of all morphological types, suggesting that hard accreting X-ray pulsars do not dominate the X-ray populations and favoring softer black-hole binaries.

These spectral, photometric and time-variability studies all point to the prevalence of XRB emission at the higher luminosities in the source population, in agreement with what is known from the X-ray observations of the Milky Way and Local Group galaxies (e.g., Helfand & Moran 2001). Comparison of accurate *Chandra* source positions with the stellar field in three nearby starburst galaxies shows that some of these sources experience formation kicks, displacing them from their parent star cluster (Kaaret et al. 2004), as observed in the Milky Way. The X-ray luminosity functions, which are discussed below, can then be considered as reflecting the XRB contribution (LMXBs, and HMXBs), with relatively little contribution from the SNRs. This point is confirmed by the direct comparison of HMXB and SNR luminosity functions in M33 (Grimm et al. 2005).

4.2. X-Ray Luminosity Functions—the X-Ray Luminosity Function of the Star-Forming Population

The XLF of LMXB populations (at high luminosity, at least) is well defined by the study of early-type galaxies, which have fairly uniform old stellar populations, and where little if any contamination from a young X-ray source population is expected (Section 3.3). The XLFs of late-type galaxies (spirals and irregulars) are instead the sum of the contributions of different X-ray populations, of different age and metallicity. This complexity was clearly demonstrated by the first detailed studies of nearby galaxies, including a comparison of different stellar fields of M31, with *XMM-Newton* and *Chandra*, yielding different XLFs (e.g., Trudolyubov et al. 2002b, Williams et al. 2004, Kong et al. 2003), and the *Chandra* observations of M81. In this Sab galaxy, the XLF derived from disk sources is flatter than that of the bulge (Tennant et al. 2001; shown in **Figure 8**, *left*). In the disk itself, the XLF becomes steeper with increasing distance from the spiral arms. In the arms the XLF is a pure power law with cumulative slope −0.48 ± 0.03 (Swartz et al. 2003), pointing to a larger presence of high luminosity sources in the younger stellar population.

To derive the XLF of HMXB populations, to a first approximation, one must either evaluate the different contributions of older and younger source populations to the XLFs of spiral galaxies, as discussed above in the case of M81, or study galaxies where the star-formation activity is so intense as to produce a predominantly young X-ray source population. Both approaches suggest that the HMXB XLF is overall flatter than that of the LMXBs, with a cumulative power-law slope of −0.6 to −0.4 (to be compared with a cumulative slope of $\leq$–1 for LMXBs, e.g., Kim & Fabbiano 2004); in other words, young HMXB populations contain on average a larger fraction of very luminous sources than the old LMXB populations (see the comparisons of Eracleous et al. 2002; Kilgard et al. 2002; Zezas & Fabbiano 2002; Colbert et al. 2004). These comparisons also show that flatter XLF slopes of about −0.4 to −0.5 (cumulative) are found in intensely star-forming galaxies, such as the merging pair NGC4838/9 (the Antennae galaxies) and M82 (Zezas & Fabbiano 2002; Kilgard et al. 2002). In particular, Kilgard et al. (2002) find a correlation of the power-law slope with the 60-μm luminosity of the galaxy (shown in **Figure 8**, *right*), which suggests that such a flat power law may describe the XLF of the very young HMXB population. A comparison of the XLFs of dwarf starburst galaxies with those of spirals (Hartwell et al. 2004) is consistent with the above picture; cumulative XLF slopes for spirals are −1.0 to −1.4, whereas slopes for starbursts are lower, −0.4 to −0.8. The connection of the slope with the SFR is demonstrated by comparisons with the 60/100-μm ratio, 60-μm luminosity, and FIR/B ratio.

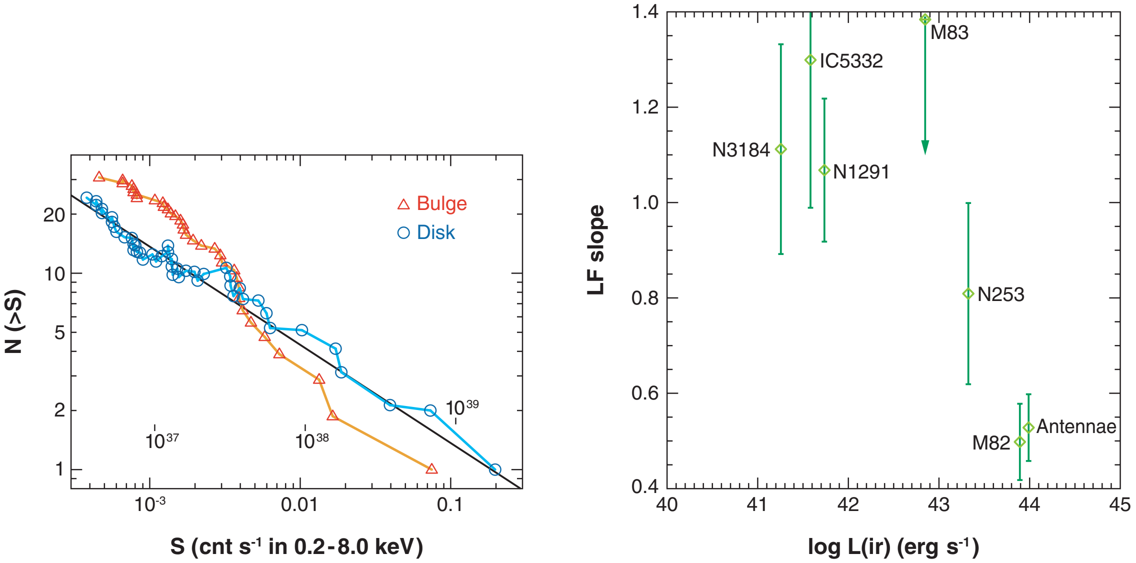

Figure 8

Left: Bulge and disk X-ray luminosity functions (XLFs) of M81 (figure 3 of Tennant et al. 2001). Right: XLF slope versus infrared luminosity for seven galaxies (figure 2 of Kilgard et al. 2002). Younger stellar populations have flatter XLFs.

Grimm, Gilfanov & Sunyaev (2003) took these considerations a significant step further by comparing the XLFs of 10 star-forming galaxies (taken from the literature), observed with *Chandra* and *XMM-Newton*, with the HMXB luminosity functions of the Small Magellanic Cloud and the Milky Way. They suggest that there is a universal XLF of star-forming populations, stretching over four decades in luminosity ($\sim 4 \times 10^{36}$–10^{40} erg s^{-1}), with a simple power law with cumulative slope -0.6. They reach this conclusion by considering that the XLFs of star-forming galaxies are dominated by young and luminous short-lived HMXBs, whose number would be proportional to the SFR per unit stellar mass; when normalized relative to SFR, the XLFs these authors consider in their study collapse into a single -0.6 power law. Postnov (2003) suggests that this empirically observed slope might result from the mass-luminosity and mass-radius relations in wind-accreting high mass binaries. The possibility of a "universal" HMXB XLF is an interesting result, although there are clear variations in the individual luminosity functions used by Grimm, Gilfanov & Sunyaev (2003), with slopes ranging from ~ -0.4 (the Antennae; Zezas & Fabbiano 2002, where the data were corrected for incompleteness at the low luminosities) to -0.8 (M74-NGC628; Soria & Kong 2002).

A number of XLFs of spiral galaxies have cumulative slopes close to the -0.6 slope of Grimm, Gilfanov & Sunyaev (2003) (IC342—Kong 2003; Bauer, Brandt & Lehmer 2003; NGC5253—Summers et al. 2004; NGC4449—Summers et al. 2003; NGC2403—Schlegel & Pannuti 2003; NGC6946—Holt et al. 2003; NGC1068—Smith & Wilson 2003; NGC2146—Inui et al. 2005). However, different and more complex XLFs are also observed, pointing to complexity or evolution of the X-ray source populations. In NGC1637 (Immler et al. 2003), the cumulative XLF is reported to follow a power law of slope −1 for the entire luminosity range covered ($\sim 6 \times 10^{36}$–10^{39} erg s^{-1}); though a possible break of the XLF ($L_X > 1 \times 10^{37}$ erg s^{-1}) is reported, there is no discussion of completeness correction. In NGC2403 (Schlegel & Pannuti 2003), the XLF has cumulative slope −0.6, but this galaxy does not follow the XLF slope; FIR correlation of Kilgard et al. (2002) suggesting it may have stopped forming stars, and we may be observing it after the massive stellar population has evolved, but the HMXBs are still emitting. In NGC6946 (Holt et al. 2003), though the cumulative XLF slope is generally consistent with the Grimm, Gilfanov & Sunyaev (2003) conclusions, differences are seen comparing the XLF of the sources in the spiral arms (slope −0.64) with that of sources within two arcminutes of the starburst central region, which is flatter (−0.5). The XLF of NGC5194 (M51, Terashima & Wilson 2004) follows an unbroken power law with slope −0.9.

In a detailed *Chandra* study of M83, a grand design spiral with a nuclear starburst, Soria & Wu (2003) find that the XLFs of different groups of sources identified by their X-ray colors differ. SSSs (see Section 5), which are found in regions with little or no $H\alpha$ emission, have steep XLFs, typical of old populations; soft SNR candidates, which tend to be associated with the spiral arms, also have fairly steep XLFs, although they extend to luminosities higher than that of the SSSs; the hard XRB candidates dominate the overall X-ray emission, and therefore the overall XLF. For these sources differences in the XLF are also found, which can be related to stellar age. The XLF of the actively star-forming central region is a power law with cumulative slope −0.7; the XLF of the outer disk has a break at $L_X \sim 8 \times 10^{37}$ erg s^{-1}, follows a power law with slope −0.6 below the break, and gets considerably steeper at higher luminosities (−1.6). This type of broken power law has also been found in the disk of M31 (Williams et al. 2004, Shirey et al. 2001). In M83, a dip is seen in the XLF at $\sim 3 \times 10^{37}$ erg s^{-1}, corresponding to 100–300 detected source counts (well above source detection threshold), for sources in the disk and spiral arms where confusion is not a concern. The XLF rises again (toward lower luminosities) after the $\sim 3 \times 10^{37}$ erg s^{-1} dip, so incompleteness effects are not likely here. Soria & Wu (2003) speculate that this complex XLF (shown in **Figure 9**) may result from an older population of disk sources mixing with a younger (but aging) population of spiral arm sources.

The highest reaches of a star-forming XLF are found in the Cartwheel galaxy (Wolter & Trinchieri 2004), whose detected XRB population is dominated entirely by ULXs. This XLF has a slope consistent with that of Grimm, Gilfanov & Sunyaev (2003) and a large normalization, which suggests a SFR of ∼20–25 $M_{\odot}$ yr^{-1}.

Grimm et al. (2005) and Shtykovskiy & Gilfanov (2005) explore the lowest luminosity reaches of the HMXB XLF with the *Chandra* survey of M33 (reaching $\sim 10^{34}$ erg s^{-1}) and with the *XMM-Newton* observations of the Large Magellanic Cloud (reaching $\sim 3 \times 10^{33}$ erg s^{-1}), respectively. In both galaxies, a large number of the detected sources are background AGNs. In M33, the XLF, corrected for interlopers and incompleteness, is consistent with the HMXB XLF of the Milky Way (Grimm,

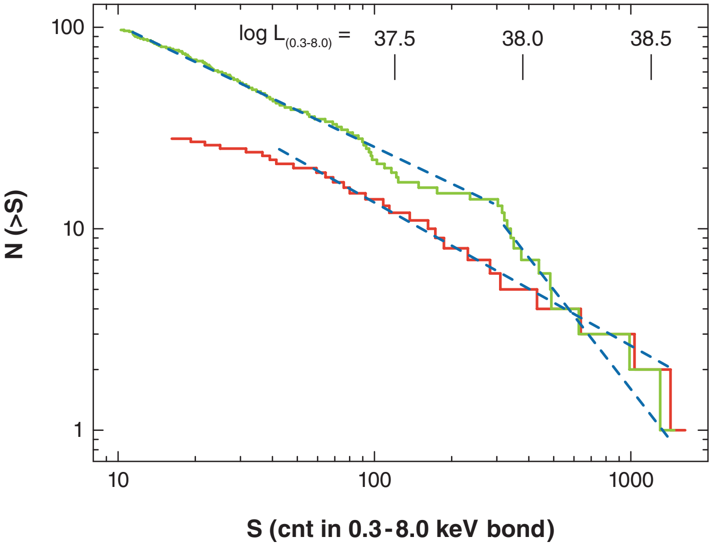

Figure 9

X-ray luminosity functions of inner regions (*red*, d < 60″ from galactic center) and outer disk (*green*) of M83 (figure 11 of Soria & Wu 2003).

Gilfanov & Sunyaev 2002). In the Large Magellanic Cloud, the corrected XLF, with spurious sources removed and rescaled for the SFR, globally fits the HMXB XLF of Grimm, Gilfanov & Sunyaev (2003) at the high luminosities ($\sim 10^{37}$ erg s^{-1}). The dearth of low-luminosity sources in this XLF leads Shtykovskiy & Gilfanov to suggest a propeller effect (i.e., the magnetic field stopping the accretion flow away from the pulsar surface of the pulsar for relatively low accretion rates). Observing regions of intense local star formation (as indicated by $H\alpha$ and FIR maxima), where no HMXBs are found, these researchers also suggest an age effect: these star-forming regions could be too young for HMXBs to have evolved, as HMXBs take on the order of 10 Myr to emerge after the star-formation event. Tyler et al. (2004) advanced a similar suggestion in their comparison of $H\alpha$, mid-IR, and *Chandra* images of 12 nearby spiral galaxies.

In conclusion, the XLFs of sources in a given galaxy reflect the formation, evolution, and physical properties of the X-ray source populations. These differences are evident, for example, in different regions of M81 and M83 (see **Figures 8** and **9**), by comparing elliptical and spiral galaxies and by comparing star-forming galaxies with different SFRs. These differences may be related to the aging of the X-ray source population, which will be gradually depleted of luminous young (and short-lived) sources associated with more massive, faster-evolving donor stars, and also to metallicity effects (Wu 2001; Belczynski et al. 2004). In the future, these X-ray population studies will constitute the baseline against which to compare models of X-ray population synthesis. An early effort toward this end can be found in Belczynski et al. (2004).

5. SUPER-SOFT SOURCES (SSSs) AND QUASI-SOFT SOURCES (QSSs)

SSSs, as a new class of luminous X-ray sources, were discovered with *ROSAT*. These sources— first found in the Miky Way, M31, the Magellanic Clouds and NGC55— are detected only at energies below 1 keV and are characterized by spectra that can be fitted with black-body temperatures ~15–80 eV (see review by Kahabka & van den Heuvel 1997). Their bolometric luminosities are in the 10^{36}–10^{38} erg s^{-1} range, and they are believed to be nuclear-burning white dwarfs (van den Heuvel et al. 1992).

Chandra observations have led to the discovery of populations of very soft sources in several galaxies. These newly discovered populations stretch the spectral definition of SSSs, including both slightly harder sources, typically fitted with black-body temperatures ~100–300 eV and sources with a small extra hard component in addition to a typical SSS spectrum (dubbed QSSs; see Di Stefano & Kong 2003, Di Stefano et al. 2004). A new class of supersoft ULXs has also been found (in M101, Mukai et al. 2003; in the Antennae, Fabbiano et al. 2003b; see Section 6). Time variability has been reported in some cases, supporting the idea that these sources are accretion binaries. In M31, a comparison of *Chandra* and *ROSAT* SSSs establishes a variability timescale of several months (Greiner et al. 2004); in NGC300 a luminous (10^{39} erg s^{-1}) variable SSS is found in *XMM-Newton* data, with a possible 5.4 hr period when in low state (Kong & Di Stefano 2003); the supersoft ULXs in M101 and the Antennae are both highly variable (Mukai et al. 2003, 2005; Kong, Di Stefano & Yuan 2004; Fabbiano et al. 2003b).

These very soft sources are associated with both old and young stellar populations. They are found in the elliptical galaxies NGC1332 (Humphrey & Buote 2004) and NGC4967 (Di Stefano & Kong 2003, 2004), in the Sombrero galaxy (an Sa; Di Stefano et al. 2003), and in a number of spirals (M31—Kahabka & van den Heuvel 1997; Kong et al. 2002; Di Stefano et al. 2004; M81—Swartz et al. 2002; M101—Pence et al. 2001; Di Stefano & Kong 2003, 2004; M83—Di Stefano & Kong 2003, 2004; Soria & Wu 2003; M51—Di Stefano & Kong 2003, 2004; Terashima & Wilson 2004; IC342—Kong 2003; NGC300 with *XMM-Newton*—Kong & Di Stefano 2003; NGC4449—Summers et al. 2003). Very soft sources are found both in the arms of spiral galaxies, suggesting systems of 10^8 years of age or younger (see, e.g., Di Stefano & Kong 2004), and in the halo and bulges, suggesting older counterparts; very soft sources in bulges tend to concentrate preferentially nearer the nuclei (Di Stefano et al. 2003, 2004). A QSS is associated with a GC in the Sombrero galaxy (Di Stefano et al. 2003). Pietsch et al. (2005) report a significant association of SSSs with optical novae in both M31 and M33.

As discussed in several of the above-mentioned papers, these results, and the spectral and luminosity regimes discovered with *Chandra* and *XMM-Newton*, strongly suggest that these very soft sources may constitute a heterogeneous population, including both hot white dwarf systems (SSSs), and black-hole (or neutron star) binaries (QSSs, supersoft ULXs). Pietsch et al. (2005) stress that classic SSSs with black-body temperatures below 50 eV can be cleanly identified only using X-ray colors with boundaries below 1 keV. Contamination by supernova remnants has also been pointed out in a recent study of M31, when using the color choice of most *Chandra* papers (Orio 2006).

6. ULTRALUMINOUS X-RAY SOURCES

The most widely used observational definition of ULXs is that of sources detected in the X-ray observing band-pass with luminosities of at least 10^{39} erg s^{-1}, implying bolometric luminosities clearly in excess of this limit. ULXs (also named intermediate luminosity X-ray objects—IXOs; Colbert & Ptak 2002) were first detected with *Einstein* (Long & Van Speybroeck 1983; see the review by Fabbiano 1989). These sources were dubbed super-Eddington sources, because their luminosity was significantly in excess of the Eddington limit of a neutron star ($\sim 2 \times 10^{38}$ erg s^{-1}), suggesting accreting objects with masses of 100 $M_{\odot}$ or larger. Because these masses exceed those of stellar black holes in binaries (which extend up to ~ 30 $M_{\odot}$; Belczynski, Sadowski & Rasio 2003), ULXs could then be a new class of astrophysical objects, possibly unconnected with the evolution of the normal stellar population of a galaxy. They could represent the missing link in the black-hole mass distribution, bridging the gap between stellar black holes and the supermassive black holes found in the nuclei of early-type galaxies. These "missing" black holes have been called intermediate mass black holes (IMBH), and could be the remnants of the collapse of primordial stars in the early universe (Madau & Rees 2001; Volonteri, Haardt & Madan 2003; Volonteri & Perna 2005; see the review by Bromm & Larson 2004), or they could be forming in the core collapse of young dense stellar clusters (e.g., Miller & Hamilton 2002).

Conversely, ULXs could represent a particularly high-accretion stage of X-ray binaries, possibly with a stellar black-hole accretor (King et al. 2001), or even be powered by relativistic jets, as in Doppler-beamed microquasars (Koerding, Falke & Markoff 2002). Other models have also been advanced (very young SNRs, e.g., Fabian & Terlevich 1996; young Crab-like pulsars, Perna & Stella 2004), but cannot explain the bulk of the ULXs, given their spectral and time variability characteristics that point to accretion systems (see below).

Given these exciting and diverse possibilities it is not surprising that ULXs have generated a large amount of both observational and theoretical work. An in-depth discussion of all this work is beyond the scope of the present review. Among the recent reviews on ULXs presenting different points of view are those of Fabbiano (2004), Miller & Colbert (2004), Mushotzky (2004), and Fabbiano & White (2006). Two recent short articles in *Nature* and *Science* (McCrady 2004 and Fabbiano 2005) are also useful examples of different perspectives on this subject: McCrady argues for the IMBH interpretation of ULXs, whereas Fabbiano instead concludes that although a few very luminous ULXs are strong candidates for IMBHs, the majority may be just sources at the upper luminosity end of the normal XRB population.

Here, I will discuss the main points of the current debate on ULXs, as they pertain to the discourse on X-ray populations, quoting only recent and representative work. In Section 6.1 I discuss the association of ULXs with star formation, in Section 6.2 their spectral and time variability, suggesting the presence of accreting binaries, and in Section 6.3 identification with optical and radio objects. In Section 6.4 I give a summary of the current theoretical debate on the nature of ULXs.

6.1. Association of ULXs with Active Star-Forming Stellar Populations

From a population point of view it is useful to see where we find ULXs. The heightened recent interest in ULXs has spurred a number of studies that have sought to take a systematic view of these sources. These include both works using the *Chandra* data archive and those revisiting the *ROSAT* data and the literature. From a mini-survey of 13 galaxies observed with *Chandra*, including both ellipticals and spirals, Humphrey et al. (2003) suggested a star-formation connection on the basis of a strong correlation of the number of ULXs per galaxy with the 60-μm emission and a lack of correlation with galaxy mass. Swartz et al. (2004) published spectra, variability, and positions for 154 ULXs in 82 galaxies from the *Chandra* ACIS archive, confirming their association with young stellar populations, especially those of merging and colliding galaxies. This conclusion is in agreement with that of Grimm, Gilfanov & Sunyaev (2003), based on a comparison of XLFs of star-forming galaxies (see Section 4.2). The strong connection of ULXs with star formation is also demonstrated by the analysis of a catalog of 106 ULXs derived from the *ROSAT* HRI observations of 313 galaxies (Liu & Bregman 2005). Liu & Mirabel (2005) instead compile a catalog of 229 ULXs from the literature, together with optical, IR, and radio counterparts, when available; they observe that the most luminous ULXs (those with $L_X > 10^{40}$ erg s^{-1}), which are the most promising candidates for IMBHs, can be found in either intensely star-forming galaxies or in the halo of ellipticals (the latter, however, are likely to be background QSOs, see below). The association of ULXs with high SFR galaxies is exemplified by the discovery of 14 of these sources in the Antennae galaxies, the prototype galaxy merger (**Figure 10**).

As discussed in Section 3.3, the XLFs of E and S0 galaxies are rather steep, i.e., the number of very luminous sources in these LMXB populations is relatively small, especially in comparison with star-forming galaxies; however, sources with luminosities in excess of 10^{39} erg s^{-1} exist (see an earlier discussion of this topic in Fabbiano & White 2005; see also Section 3.7).

Several authors have considered the statistical association of ULXs with early-type galaxies (E and S0s, old stellar populations). Swartz et al. (2004) find that the number of ULXs in early-type galaxies scales with galaxy mass and can be explained with the high luminosity end of the XLF (see Gilfanov 2004 and discussion in Section 3.3). They also point out that ULX detections in early-type galaxies are significantly contaminated by background AGNs, in agreement with the statistical works of Ptak & Colbert (2004) and Colbert & Ptak (2002), which are based on *ROSAT* HRI (5″ resolution) observations of galaxies. Irwin, Bregman & Athey (2004) find that sources in the 1×10^{39} erg s^{-1} -2×10^{39} erg s^{-1} luminosity range are likely to belong to the associated galaxies and have spectra consistent with those of Galactic black-hole binaries (Irwin, Athey & Bregman 2003). The sample of sources more luminous than 2×10^{39} erg s^{-1} (if placed at the distance of the associated galaxy) is

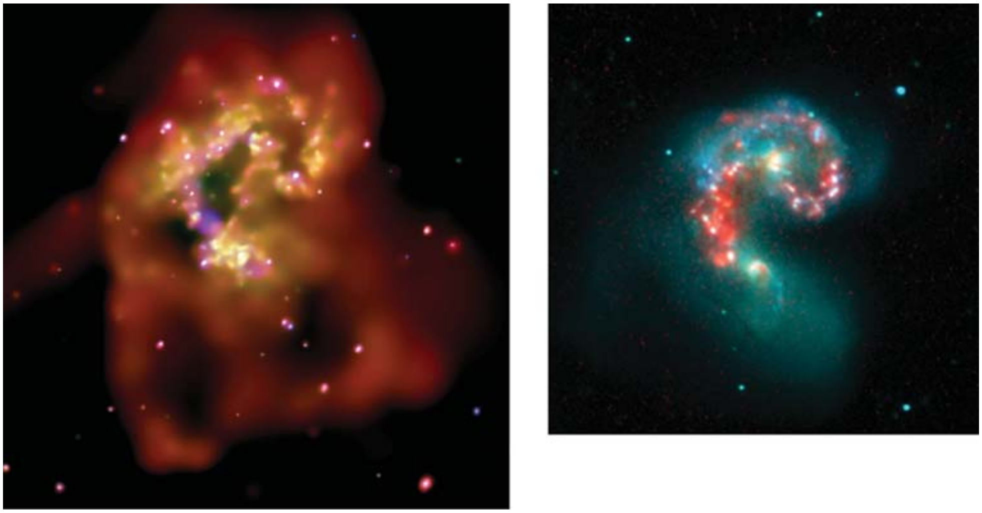

Figure 10

Left: *Chandra* ACIS image of the Antennae from two years of monitoring ($4.8'$ side box; from the web page **http://chandra.harvard.edu/photo/category/galaxies.html;** credit NASA/CXC; Fabbiano et al. 2004a). The regions of most intense emission, where most of the X-ray sources are clustered, correspond to regions of intense star formation. Note that the region of most intense star formation is obscured in X ray (*blue*). Right: *Spitzer* IR (3.6–8-μm in *red*) and optical composite image from the web page **http://www.spitzer.caltech.edu/Media/releases/ssc2004-14/ssc2004-14a.shtml** (Credit: NASA/JPL-Caltech/Z. Wang).

instead consistent with the expected number and spatial distribution of background AGNs.

This growing body of results demonstrates that ULXs are associated with the star-forming population. The presence of ULXs in early-type galaxies has been debated, but there is no strong statistical evidence for the existence of a population of sources with $L_X > 2 \times 10^{39}$ erg s^{-1} in these galaxies. In the following I will only discuss ULXs in star-forming galaxies.

6.2. Spectra and Time Variability from *Chandra* and *XMM-Newton*

Chandra and *XMM-Newton* work has confirmed that ULXs are compact accreting sources, building on the more limited observations of nearby ULXs with *ASCA* (Makishima et al. 2000, Kubota et al. 2001). Flux-color transitions have been observed in a number of ULXs, suggesting the presence of an accretion disk (in the Antennae—Fabbiano, Zezas & Murray 2001; Fabbiano et al. 2003a,b, 2004a; Zezas et al. 2006; M101—Jenkins et al. 2004; NGC7714—Soria & Motch 2004; M33—LaParola et al. 2003; Dubus, Charles & Long 2004; Foschini et al. 2004; Ho II X-1—Dewangan et al. 2004; and a sample of 5 ULXs in different galaxies monitored with *Chandra*—Roberts et al. 2004). Some of these spectra and colors are consistent with or reminiscent of those of black-hole binaries (see above references and Colbert et al. 2004, Liu et al. 2005). A recent spectral survey with *XMM-Newton* finds different spectral types, suggesting either spectral variability or a complex source population (Feng & Kaaret 2005).

Shorter-term time variability is also consistent with the presence of X-ray binaries and accretion disks. In particular a ULX in NGC253 has recently been shown to be a recurrent transient (Bauer & Pietsch 2005). Moreover, features in the power density spectra have been used to constrain the mass of the accreting black hole (Strohmayer & Mushotzky 2003; Soria et al. 2004). In the very luminous M82 ULX ($L_x > 10^{40}$ erg s^{-1}, $L_{bol} \sim 10^{41}$ erg s^{-1}), which is the most compelling IMBH candidate, Strohmayer & Mushotzky (2003) detect a 55mHz QPO, also confirmed by Fiorito & Titarchuck (2004).

The most statistically significant spectra are those obtained with *XMM-Newton* in nearby very bright ULXs where confusion with unresolved emission in the detection area is not severe. In several cases, a composite power-law plus very soft accretion disk is the simplest model that optimizes the fit to the observed spectra (there are exceptions, e.g., for the 10^{41} erg s^{-1} ULX in NGC2276, where a multicolored disk model is preferred, Davis & Mushotzky 2004). A very soft component was first reported by Kaaret et al. (2003) for the ULX NGC5408 X-1, and soon after by Miller et al. (2003) for the ULX NGC1313 X-2, with temperatures of ~110 and 150 eV, respectively. These soft components would be consistent with the emission of an accretion disk surrounding an IMBH of nearly 1000 $M_\odot$ (but see a more recent estimate of 100 $M_\odot$ for NGC1313 X-2, Zampieri et al. 2004). Similar soft components were found in other ULXs (Miller, Fabian & Miller 2004a; Miller et al. 2004; Jenkins et al. 2005; Roberts et al. 2005).

Unfortunately, these results are not the smoking gun that one may have hoped for to conclusively demonstrate the presence of IMBHs in ULXs. Two other models have been proposed that fit the data equally well, but are consistent with normal stellar black-hole masses. One is the slim disk model (e.g., Watarai et al. 2005, Ebisawa et al. 2004, advanced to explain the emission of an accretion disk in a high accretion mode; see Foschini et al. 2005, Roberts et al. 2005). The second model is a physical Comptonized disk model (Kubota, Makishima & Done 2004). Although both models are significantly more complex than the power-law + soft-component model, nature can easily be wicked, and the models are physically motivated. The controversy is raging, given the tantalizing possibility of proving the discovery of IMBHs (see Fabian, Ross & Miller 2004; Miller, Fabian & Miller 2004b; Wang et al. 2004; Goad et al. 2006).

The recurrent variable very soft ULX in M101 provides an excellent case study to illustrate the difficulty of reaching a firm conclusion on the presence of an IMBH. Given their very soft spectra, SSSs and QSSs in the ULX luminosity range are IMBH candidates (in Sombrero—Di Stefano et al. 2003; M101—Mukai et al. 2003, 2005; Kong, Di Stefano & Yuan 2004; the Antennae—Fabbiano et al. 2003b). These sources are too luminous to be explained in terms of hot white dwarfs, unless the emission is beamed, which is unlikely (e.g., Fabbiano et al. 2003b).

The expanding black-hole photosphere of a stellar black hole was first suggested to explain the M101 very soft ULX (Mukai et al. 2003), but the subsequent detection of a hard power-law component and low/hard–high/soft spectral variability pointed to a Comptonized accretion disk in a black-hole binary (Kong, Di Stefano & Yuan 2004; Mukai et al. 2005); but what kind of black hole?

Based on the *XMM-Newton* spectrum, which can be fitted with an absorbed blackbody, and implies outburst luminosities in the 10^{41} erg s^{-1} range, Kong, Di Stefano & Yuan (2004) advanced the IMBH candidacy. Mukai et al. (2005), instead, argue for a 20–40 $M_\odot$ stellar black-hole counterpart. Their main point is that the high L_X derived in the previous study results from the adoption of an emission model with a considerable amount of line-of-sight absorption; the colors of the optical counterpart, instead, are consistent with very little absorption; moreover, if the obscuring material were close to the black hole it would be most likely ionized (warm absorber). Adopting an accretion disk plus emission line model, Mukai et al. (2005) obtain luminosities in the 10^{39} erg s^{-1} range. They also use the variability power density spectrum of the source to constrain the emission state, and with the luminosity, the mass of the black hole. This is another example where a considerable amount of ambiguity exists in the choice of the X-ray spectral model, and X-ray spectra alone may not give the conclusive answer. The luminous optical counterpart makes this source an obvious candidate for future studies aimed at obtaining the mass function of the system.

6.3. Counterparts at Other Wavelengths

As shown by the example at the end of Section 6.2, identification of ULXs may be crucial for understanding their nature. Three main classes of counterparts have been discussed in the literature: stellar counterparts, ionized or molecular nebulae, and radio sources. Stellar counterparts tend to have very blue colors, suggesting early-type stars, although the colors could also arise from the optical emission of the accretion disk (Kaaret, Ward & Zezas 2004; Liu, Bregman & Seitzer 2004; Soria et al. 2005; Zampieri et al. 2004; Rappaport, Podsiadlowski & Pfahl 2005; see also Fabbiano & White 2006 for earlier references). These counterparts would point to the high accretion rate model of ULXs, if they were indeed early-type stars (e.g., King et al. 2001; Rappaport, Podsiadlowski & Pfahl 2005). However, even ignoring the uncertainty on the nature of the optical counterpart, these results cannot firmly constrain the nature of the compact object. A recent paper by Copperwheat et al. (2005) proposes a model, including irradiation by X-rays of both the accretion disk and the companion star, which when supplemented by variability data and IR photometry, could be used to constrain both the nature of the companion star and the mass of the accreting black hole.

Nebular counterparts suggest isotropic emission in some cases, and therefore a truly large L_X, thus arguing against a substantial amount of beaming and pointing to fairly massive black holes (Roberts et al. 2003; Pakull & Mirioni 2003; Kaaret, Ward & Zezas 2004); radio counterparts have alternately been found consistent with either beamed sources or IMBHs (Kaaret et al. 2003; Neff, Ulvestad & Campion 2003; Miller, Mushotzy & Neff 2005; Koerding, Colbert & Falke 2005). Optical variability studies of the stellar counterparts are needed to firmly measure the mass of the system. The new generation of large-area, high-resolution, optical telescopes are likely to solve the nature of these ULXs.

In more distant systems, like the Antennae (D ∼ 19 Mpc—Zezas et al. 2002a,b, 2005) or the Cartwheel galaxies (D ∼ 122 Mpc—Gao et al. 2003, King 2004, Wolter & Trinchieri 2004), where spectacular populations of ULXs are detected, individual stellar counterparts cannot be detected. However, comparison with the optical emission field also provides very interesting results. In the Antennae, ULXs tend not to coincide with young star clusters, suggesting that either the system has been subject to a supernova formation kick to eject it from its birthplace (thus implying a normal HMXB with a stellar mass black hole; Zezas et al. 2002b; Sepinsky, Kalogera & Belczynski 2005), or that the parent cluster has evaporated, in the core collapse model of IMBH formation (e.g., Zwart et al. 2004). However, a recent paper suggests that some of these displacements may be reduced with better astrometric corrections (Clark et al. 2005). In the Cartwheel, the ULXs are associated with the most recent expanding star-formation ring, setting strong constraints to the IMBH hypothesis and favoring the high accretion HMXB scenario (King 2004). It must be said, however, that given the distance of this galaxy, and the lack of time monitoring, it cannot be excluded that the ULXs may represent clumps of unresolved sources.

Higher red-shift galaxy and QSO counterparts to ULXs have also been found in some cases (Masetti et al. 2003; Arp, Gutierrez & Lopez-Corredoira 2004; Gutierrez & Lopez-Correidora 2005; Burbidge et al. 2004; Galianni et al. 2005; Clark et al. 2005; see also H. Arp & E.M. Burbidge, submitted; Ghosh et al. 2005). Although at this point these identifications are still few and consistent (within small number statistics) with chance coincidences with background AGN, some of the above authors (H. Arp, E.M. Burbidge, G. Burbidge and collaborators) have raised the hypothesis of a physical connection between the QSO and the parent galaxy; clearly this possibility cannot be extended to the entire body of ULXs, given the results of other identification campaigns (see above).

6.4. Models of ULX Formation and Evolution, and Paths for Future Work

I will summarize here some of the more recent theoretical work on ULXs, and refer the reader to the reviews cited earlier for details on earlier work. As I've already noted, the two principal lines of thought are: (*a*) most ULXs are IMBHs; (*b*) most ULXs are luminous X-ray sources of "normal" stellar origin and the IMBH explanation should be sought only for the ULXs with $L_{bol} > 10^{41}$ erg s^{-1} (the M82 ULX—Kaaret et al. 2001, Matsumoto et al. 2001; the NGC2276 ULX—Davis & Mushotzky 2004; the most luminous ULX in the Cartwheel galaxy—Gao et al. 2003, Wolter & Trinchieri 2004; and the variable ULX in NGC7714—Soria & Motch 2004; Smith, Struck & Nowak 2005).

The stellar evolution camp was originally stimulated by the abundance of ULXs in star-forming galaxies (King et al. 2001; King 2004) and by the apparently universal shape of the XLF of the star-forming population (Grimm, Gilfanov & Sunyaev 2003; see Section 4.2). The variability and spectra of these systems (see Section 6.2) point to accretion binaries. In this paradigm, the problem is to explain the observed luminosities. Both relativistic (Koerding, Falke & Markoff 2002) and nonrelativistic beaming (King et al. 2001), and super-Eddington accretion disks (Begelman 2002; both spectra and observed variability patterns can be explained, M. Belgelman, private communication) have been suggested as a way to explain the source luminosities inferred from the observations. With the exception of relativistic beaming, these mechanisms can account for a factor of 10 enhancement of the luminosity above the Eddington value. If black-hole masses of a few tens solar masses exist (Belczynski, Sadowski & Rasio 2004), most or all the ULXs could be explained this way. For example, Rappaport, Podsiadlowski & Pfahl (2005) have combined binary evolution models and binary population synthesis, finding that for donors with $M \geq 10\ M_\odot$, accretion binaries can explain the ULXs, with modest violation of the Eddington limit.

The IMBH camp has generated a larger volume of papers. IMBHs may be remnants of collapse in the early universe (e.g., Heger & Woosley 2002; Islam, Taylor & Silk 2004; Van der Marel 2004), or may result from the collapse of dense stellar clusters (e.g., Gurkan, Freitag & Rasio 2004; Zwart et al. 2004.). In the cosmological remnant options, one would expect IMBHs to be particularly abundant in the more massive elliptical galaxies, contrary to the observed association with star-forming galaxies (Zezas & Fabbiano 2002). However, IMBHs would not be visible unless they are fueled, and fuel is more readily available in star-forming galaxies, in the form of dense molecular clouds (Schneider et al. 2002; Krolik 2004). Accretion from a binary companion is an efficient way of fueling an IMBH, and consequently a number of papers have explored the formation of such binaries via tidal capture in GCs. In this picture, the ULX may not be still associated with the parent cluster because of cluster evaporation (Hopman, Zwart & Alexander 2004; Li 2004; Zwart, Dewi & Maccarone 2004; Zwart et al. 2004). A twist to the cosmological hypothesis is given by the suggestion that the very luminous ULXs, with $L_{bol} > 10^{41}$ erg s^{-1} such as the M82 ULX, may be the nuclei of satellite galaxies, switching on in the presence of abundant fuel (King & Dehnen 2005).

Some of this work has resulted in predictions that can be directly compared with the data, and complement the tests based on the study of the optical and multiwavelength counterparts discussed in Section 6.3. In particular, the slope and normalization of the high-luminosity XLFs of star-forming galaxies have been reproduced in both IMBH (Islam, Taylor & Silk 2004; Krolik 2004) and jet models (Koerding, Colbert & Falke 2004). Zezas & Fabbiano (2002) discuss the effect of either a beamed population of ULXs or a population of IMBHs in the context of the XLF of the Antennae. Gilfanov, Grimm & Sunyaev (2004b) predict a change of slope in the L_X-SFR relation, where L_X is the total X-ray luminosity of a galaxy, if a new population of IMBHs is present at the higher luminosities (see Section 7).

Other properties have also been investigated, including the X-ray spectral distribution (Section 6.2), the presence of radio emission from IMBHs and the comparison of radio and X-ray properties with those of AGN and stellar black-hole Galactic binaries (e.g., Merloni, Heinz & Di Matteo 2003), and time variability-based tests. The latter include studying the QPO frequency (which may be a function of back-hole mass, Abramowicz et al. 2004), the observation of long-term transient behavior (expected from IMBH binaries, whereas thermal-timescale mass transfer onto stellar black holes would produce stable disks; Kalogera et al. 2004) and the detection of eclipses (expected more frequently in stellar black-hole binaries than in IMBHs, Pooley & Rappaport 2005). These time variability tests require long-term monitoring of ULXs and future larger X-ray telescopes.

7. X-RAY EMISSION AND GALAXY EVOLUTION

Chandra observations of galaxies at high redshift ($z > 0.1$), either from identification of deep survey sources or from stacking analysis of distant galaxy fields, have been reviewed recently in the literature (see Fabbiano & White 2006; Brandt & Hasinger 2005) and will not be discussed in detail here. In summary, the emission from normal galaxies becomes an increasingly greater component of the X-ray emission at the deepest X-ray counts (Bauer et al. 2004; Ranalli, Comastri & Setti 2005); moreover, the hard X-ray emission is a direct diagnostic of star formation, as demonstrated by the good FIR-X-ray correlations and by the work on the XLFs of star-forming galactic populations discussed earlier in this review (Fabbiano & Shapley 2002; Grimm, Gilfanov & Sunyaev 2003; Ranalli, Comastri & Setti 2003; Colbert et al. 2004; Gilfanov, Grimm & Sunyaev 2004a; Persic et al. 2004). It is clear that the study of the global properties and luminosity functions of galaxies at different redshifts can give information in this area, and this work is beginning to gather momentum (e.g., Georgakakis et al. 2003; Norman et al. 2004; Hornschemeier et al. 2005; Ranalli, Comastri & Setti 2005), given the availability of *XMM-Newton* surveys of the nearby universe and the increasingly deep *Chandra* surveys.

Enhanced star formation early in the life of a galaxy is expected to produce enhancements in its X-ray emission at different epochs, related to the formation and evolution of HMXB and LMXB populations (Ghosh & White 2001). Lehmer et al. (2005) report such an effect in their stacking analysis of Lyman break galaxies in the *HST GOODS* fields covered by deep (1–2 Ms exposure) *Chandra* fields (**Figure 11**). Conversely, if the SFR is independently known, the relation between the integrated luminosity of galaxies and the SFR can be used to measure the maximum luminosity of a HMXB and the presence of a very high luminosity IMBH population not related to stellar sources (Gilfanov, Grimm & Sunyaev 2004b). These authors, based on the XLF-SFR connection (Grimm, Gilfanov & Sunyaev 2003), explore the statistical properties of a population of discrete sources and demonstrate that a break is expected in the relation between the total X-ray luminosity L_X of the galaxies and the SFR, which depends on the high luminosity cut-off of the XRB population. Comparing the local galaxy sample with the *Hubble* Field North galaxies, they suggest a cut-off luminosity $\sim 5 \times 10^{40}$ erg s^{-1} for HMXBs. They also suggest that a population of very luminous IMBHs ($L_X > 10^{40}$ erg s^{-1}) would reveal itself with a steeper L_X-SFR relation at higher luminosities and star-formation regimes.

The *Chandra* observations of nearby galaxies have significantly increased our understanding of X-ray source populations, and will deepen this understanding in the next several years. These results and the tantalizing possibility of studying the X-ray evolution of galaxies show that future very deep, high-resolution X-ray observations

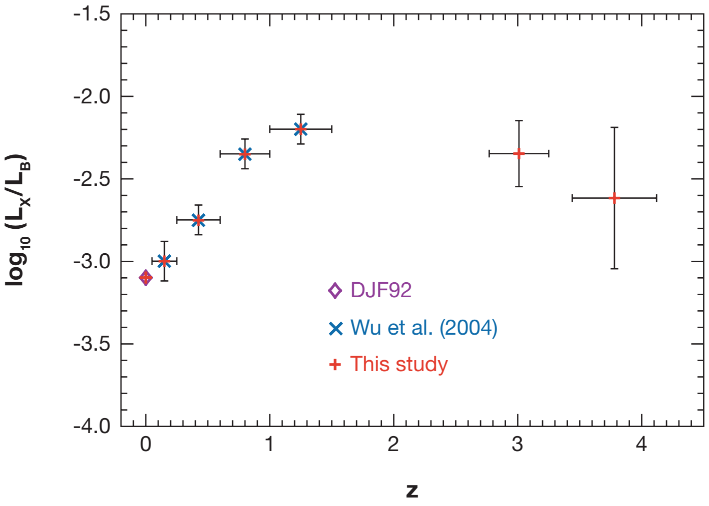

Figure 11

Evolution of the X-ray-to-optical ratio of galaxies with redshift, peaking at z ∼ 1.5–3 (from figure 5 of Lehmer et al. 2005).

are essential. Unfortunately, there are no plans for X-ray missions with comparable angular resolution to follow *Chandra*. These types of studies may have to wait for several decades for a large area, subarcsecond resolution X-ray mission (e.g., the *Generation-X* mission, for which a NASA-funded vision study is in progress).

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