11

Compact Stellar X-ray Sources in Normal Galaxies

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11.1 Introduction

In the 1995 *X-ray Binaries* book edited by Lewin, van Paradijs and van den Heuvel, the chapter on *Normal galaxies and their X-ray binary populations* (Fabbiano 1995) began with the claim that "X-ray binaries are an important component of the X-ray emission of galaxies. Therefore the knowledge gathered from the study of Galactic X-ray sources can be used to interpret X-ray observations of external galaxies. Conversely, observations of external galaxies can provide us with uniform samples of X-ray binaries, in a variety of different environments. " This statement was based mostly on the *Einstein Observatory* survey of normal galaxies (e.g., Fabbiano 1989; Fabbiano, Kim & Trinchieri 1992). Those results have been borne out by later work, yet at the time the claim took a certain leap of faith. Now, nearly a decade later, the sensitive sub-arcsecond spectrally-resolved images of galaxies from *Chandra* (Weisskopf *et al.* 2000), complemented by the *XMM-Newton* (Jansen *et al.* 2001) data for the nearest galaxies (angular resolution of *XMM-Newton* is ~ 15"), have made strikingly true what was then largely just wishful anticipation.

While a substantial body of *ROSAT* and *ASCA* observations exists, which was not included in the 1995 Chapter, the revolutionary quality of the *Chandra* (and to a more limited degree of *XMM-Newton*) data is such that the present review will be based on these most recent results.

In this Chapter we first discuss the emerging awareness of X-ray ($0.1-10$ keV band, approximately) stellar populations in spiral galaxies: we focus on four well studied galaxies (M31, M81, M83 and M101), and we then discuss the effect of recent widespread star formation on the luminosity functions of the X-ray emitting populations (Section 11.2). We then review the body of observational evidence on the ultraluminous X-ray sources ($L_X > 10^{39}$ ergs s^{-1}), that are associated with active/recent star formation (Section 11.3; see the Chapter by King, in this book, for a review of theoretical work on this subject; see also the chapter by McClintock & Remillard on black hole binaries). We follow with a review of the X-ray population properties of old stellar systems (E and S0 galaxies; Section 11.4). We then discuss the results of correlation analyses of the integrated galaxy emission (Section 11.5), and we conclude with a look at the X-ray evolution of galaxies going back into the deep universe (Section 11.6).

11.2 X-ray binary (XRB) Populations in Spiral Galaxies

Because of their proximity, nearby spiral galaxies is where the early work on extra-galactic XRB populations begun (see Fabbiano 1995). For the same reason, these are the galaxies where the deepest samples of sources have been acquired with *Chandra* and *XMM-Newton*. Here we will discuss first the recent work done on M31, which, not surprisingly, is the galaxy that has been studied in most detail. We will then review the results on M81, M83, and M101, to provide examples of the XRB populations in a wider variety of spirals. We conclude this section with a summary of the work on actively star-forming galaxies. We note that this field is evolving rapidly, with an increasing number of galaxies being surveyed and with the sensitivity limit being pushed to fainter fluxes, with ever deeper *Chandra* observations.

11.2.1 M31

Being at a distance of only $\sim$ 700 kpc, M31 (NGC 224, the Andromeda nebula) is the spiral (Sb) galaxy closest to us. M31 has been observed by virtually all the X-ray observatories since *Uhuru*, the first X-ray satellite (for a history of the X-ray observations of galaxies, see Fabbiano & Kessler 2001). Starting with the *Einstein Observatory* and following on with *ROSAT*, M31 has been the prime target for systematic studies of a population of extragalactic XRBs, and for comparisons with our own Galactic XRBs (e.g., Long & Van Speybroeck 1983; Trinchieri & Fabbiano 1991; Primini, Forman & Jones 1993; Supper *et al.* 1997, 2001). *Chandra* and *XMM-Newton* observations, both by themselves and in combination, are providing new insight on the characteristics of the XRB population of M31. With its subarcsecond resolution, *Chandra* is unique in resolving dense source regions, such as the circum-nuclear region of M31, and detecting faint sources (Garcia *et al.* 2000). Given the proximity of M31 and the relatively low density of luminous XRBs, *XMM-Newton* provides valuable data on the XRB population of this galaxy, if one excludes the centermost crowded core (Shirey *et al.* 2001).

Source variability and counterparts - Multiple observations of the same fields with these two observatories (and comparison with previous observations) have confirmed the general source variability characteristic of XRBs. *XMM-Newton* work, following the first statement of source variability (Osborne *et al.* 2001), includes detailed studies of interesting luminous sources. Trudolyubov, Borozdin & Priedhorsky (2001) report the discovery of three transient sources, with maximum X-ray emission in the 10^{37} ergs s^{-1} range: a candidate low-mass black-hole binary, a source with a long (>1 year) outburst, and a supersoft transient. Trudolyubov *et al.* (2002b) report an 83% modulation with a 2.78 hr period in the X-ray source associated with the globular cluster (GC) Bo 158. Comparison with earlier *XMM-Newton* observations and with the *ROSAT* PSPC data, allows these authors to conclude that the modulation is anticorrelated with the source flux, suggesting perhaps a larger less obscured emission region in high state. This source resembles Galactic 'dip' XRBs, and could be an accreting neutron star. Its period suggest a highly compact system (separation $\sim 10^{11}$cm).

Widespread source variability is evident from *Chandra* observations, both from a 47 ks HRC study of the bulge (Kaaret 2002), from a set of eight *Chandra* ACIS observations of the central 17'×17' taken between 1999 and 2001 (Kong *et al.* 2002), and from a 2.5 years 17 epochs survey with the *Chandra* HRC (Williams *et al.* 2003), which also includes the data from Kaaret (2002).

Kong *et al.* find 204 sources, including nine supersoft sources, with a detection limit of $\sim 2 \times 10^{35}$ ergs s^{-1}. This detection limit is 5 times fainter than that of the *ROSAT* HRI catalog (Primini, Forman & Jones 1993), which lists only 77 sources in the surveyed area. They report 22 globular cluster (GC) identifications, 2 supernova remnants, and 9 planetary nebulae associations. By comparing the different individual data sets, they establish that 50% of the sources vary on timescales of months, and 13 are transients. The spectra of the most luminous sources can be fitted with power-laws with $\Gamma \sim 1.8$, and, of these, 12 show coordinated flux and spectral variability. Two sources exhibit harder spectra with increasing count rate, reminiscent of Galactic Z sources (e.g. Hasinger & van der Klis 1989). All these characteristics point to an XRB population similar to that of the Milky Way. The HRC survey (Williams *et al.* 2003) reports fluxes and light curves for 173 sources, and finds variability in 25% of the sources; 17 of these sources are transients, and two of these are identified with variable *HST WFPC2* U band counterparts. One of these two sources is also a transient in the optical and has global properties suggesting a $\sim 10\ M_\odot$ black hole X-ray nova with a period ≥ 9 days. Williams *et al.* (2003) determine that at any given time there are 1.9 ± 1.3 active X-ray transients in M31, and from here they infer that the ratio of neutron star to black hole LMXBs in M31 is ~ 1, comparable to that in the Galaxy.

Globular Cluster (GC) sources - The recent X-ray populations studies of M31 with *Chandra* and *XMM-Newton* demonstrate the importance of large area surveys of the entire galaxian system. A targeted study of GCs with three *Chandra* fields at large galactocentric radii (Di Stefano *et al.* 2002) revives the old suggestion (Long & Van Speybroeck 1983) that the M31 GC sources are more X-ray luminous than Galactic GC sources. This hypothesis had been dismissed with the *ROSAT* M31 survey (Supper *et al.* 1997), which however covered only the central 34' of M31. Di Stefano *et al.* (2002) find that in their fields the most luminous sources are associated with GCs. They detect 28 GCs sources, 15 of which are new detections: 1/3 of these sources have $L_X(0.5-7\ \mathrm{keV}) > 10^{37}$ ergs s^{-1}; 1/10 of the sources have $L_X(0.5-7\ \mathrm{keV}) > 10^{38}$ ergs s^{-1} . The X-ray luminosity function (XLF) of the M31 GC sources differs from the Galactic GC XLF, by both having a larger number of sources, and by extending a decade higher in X-ray luminosity (the most luminous M31 GC is Bo 375 with $L_X > 2 \times 10^{38}$ ergs s^{-1}; compare with Milky Way GCs, that emit less than 10^{37} ergs s^{-1}).

Supersoft sources (SSS) - SSS are very soft X-ray sources, with most of the emission below 1 keV, and spectra that can be fitted with black body temperatures of ≤ 100 eV (see Chapter by Kahabka in this volume). SSS were first discovered in M31 with *ROSAT* (Supper *et al.* 1997). As noted above, Kong *et al.* (2002) reported nine SSS in their *Chandra* observations of M31. Recent work by Di Stefano *et al.* (2003) reports 33 SSSs in the same fields surveyed for GCs by Di Stefano *et al.* (2002), of which only two were known since the *ROSAT* times. Two SSSs are identified with symbiotic stars and two with supernova remnants, but the bulk are likely to be supersoft XRBs. These sources are highly variable, and may be classified in two spectral groups: sources with kT$\leq$ 100 eV, and other sources with harder emission, up to kT$\sim$ 300 eV. Sixteen of them (on average the most luminous) cluster in the bulge, others are found in both the disk and the halo of M31. Di Stefano *et al.* (2003) point out that some of these sources are detected with luminosities well below 10^{37}ergs s^{-1}, the luminosity of a 0.6 $M_\odot$ white dwarf steadily burning hydrogen, and are therefore likely to be lower mass white dwarfs or luminous cataclysmic variables.

The bulge - The XLFs of the global core population [Kaaret 2002 (*Chandra* HRC); Kong *et al.* 2002 (*Chandra* ACIS); Trudolyubov *et al.* 2002a (*XMM-Newton*)] all are in general agreement with each other and with the *Einstein* (Trinchieri & Fabbiano 1991) and *ROSAT* studies (Primini, Forman & Jones 1993). However, because of the resolution and sensitivity of *Chandra*, both Kong *et al.* (2002) and Kaaret (2002) can can look at the bulge source population in greater detail than ever before.

Kong *et al.* divide the detected sources in three groups, based on their galactocentric position: inner bulge (2'×2'), outer bulge (8'×8', excluding the inner bulge sources), and disk (17'×17', excluding the two bulge regions). When considering the entire bulge population, these authors find a general low luminosity break of the XLF at $\sim 2\times10^{37}$ ergs s^{-1}, in agreement with Trudolyubov *et al.* (2002a). However, they also find that the break appears to shift to lower luminosities with decreasing galactocentric radius, going from $0.18 \pm 0.08 \times 10^{37}$ ergs s^{-1} in the inner bulge to $2.10 \pm 0.39 \times 10^{37}$ ergs s^{-1} in the outermost 'disk' region. They note that if the breaks mark episodes of star formation, the more recent of these events must have occurred at larger radii. The slopes of the XLFs also vary (0.67 ± 0.08 in the center, 1.86 ± 0.40 in the outermost region), but this trend is the opposite of that expected from progressively young populations, where more luminous, short lived sources, may be found (see e.g. Kilgard *et al.* 2002; Zezas & Fabbiano 2002; Section 11.2.4). Kong *et al.* suggest that the XRB populations of the central regions of M31 may instead all be old (see Trudolyubov *et al.* 2002a), with the shifts of the break resulting from the inclusion of new classes of fainter sources in the inner regions, rather than from a disappearance of the most luminous sources.

Kaaret (2002) contributes to the debate on the nature of the inner bulge sources by investigating their spatial distribution. He shows that the the number of X-ray sources detected in the centermost regions of the bulge ($< 100''$) is in excess of what would be expected on the basis of the radial distribution of the optical surface brightness, and suggests that this result may be consistent with a GC origin for the LMXBs.

X-ray source populations in different galaxian fields - With the increased rate of papers on M31, resulting from the *XMM-Newton* and *Chandra* surveys of this galaxy, we are now realizing that the X-ray source population of M31 is more varied than previously thought, and that there are correlations between the properties of the X-ray sources and those of the stellar field to which they belong.

In contrast with previous reports (e.g. Trinchieri & Fabbiano 1991; Kong *et al.* 2002), Trudolyubov *et al.* (2002a), by using a larger definition for the radius of the bulge (15'), with *XMM-Newton* observations conclude that, although the XLFs of bulge and disk sources have a similar cumulative slope (-1.3), disk sources are all fainter than $L_X < 2 \times 10^{37}$ ergs s^{-1}, while bulge sources can have luminosities

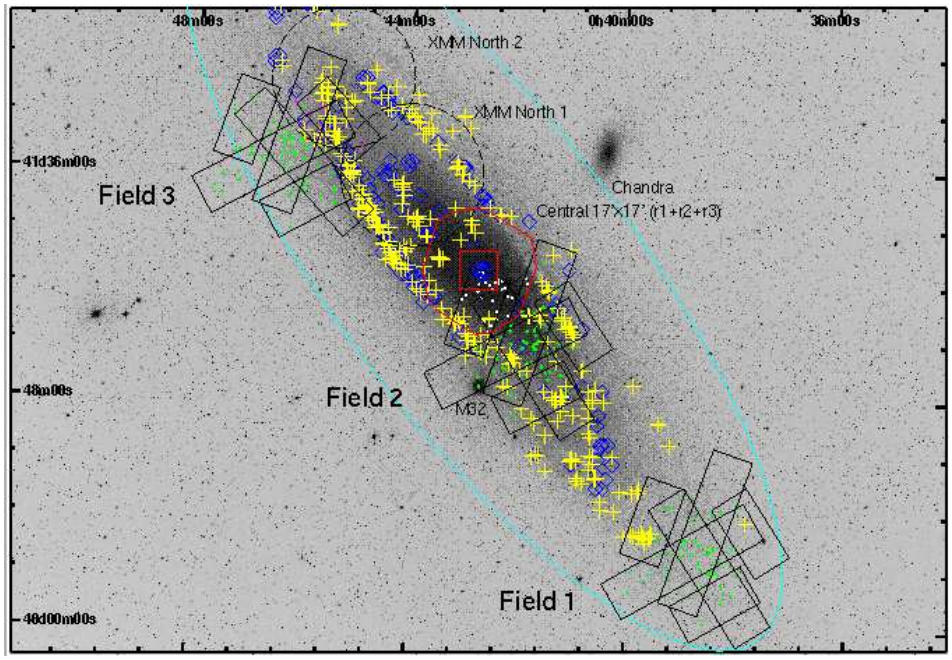

Fig. 11.1. Regions of M31 observed with *Chandra* and *XMM-Newton*. Dots are detected *Chandra* sources; yellow crosses and blue diamonds identify supernova remnants and OB associations in the field (not X-ray sources), respectively (from Kong *et al.* 2003).

as high as $L_X \sim 10^{38}$ ergs s^{-1}. They suggest that the most luminous sources are associated with the older stellar population, as in the Milky Way (Grimm, Gilfanov & Sunyaev 2002). However, the fields studied by Trudolyubov *et al.* (2002a) do not include the areas surveyed by Di Stefano *et al.* (2002), where the most luminous GC sources are found (see Fig. 11.1).

A *Chandra ACIS* study of XLFs from different regions of M31 (Fig. 11.1; Kong *et al.* 2003), uses a follow-up of the Di Stefano *et al.* (2002) survey. The results (Fig. 11.2) show that the sources in the central 17'×17' region are overall more luminous than those from the outer fields (as noticed by Trudolyubov *et al.* 2002a), but only if one removes the GC population, which appears to have a relatively more numerous high luminosity component than the central sources. The slopes of the XLFs of the external fields also vary, and there is an indication that these differences are related to variations in the stellar populations of the different fields: Field 1, which has the steepest slope (cumulative $-1.7^{+0.34}_{-0.15}$) and also the lowest density of X-ray sources, does not appear to have a large young population of stars; Field 2, with the largest X-ray source population and the flattest XLF slope (cumulative -0.9) is in the region with the youngest stellar population. This slope is the closest to that (0.63 ± 0.13) derived by Grimm, Gilfanov & Sunyaev (2002) for the high mass X-ray binaries (HMXBs) in the Galaxy; Field 3, with an intermediate XLF slope instead does not appear to cover a large stellar population. The overall integrated slope is instead similar to that found by Grimm *et al.* for the Galactic low-mass X-ray binary

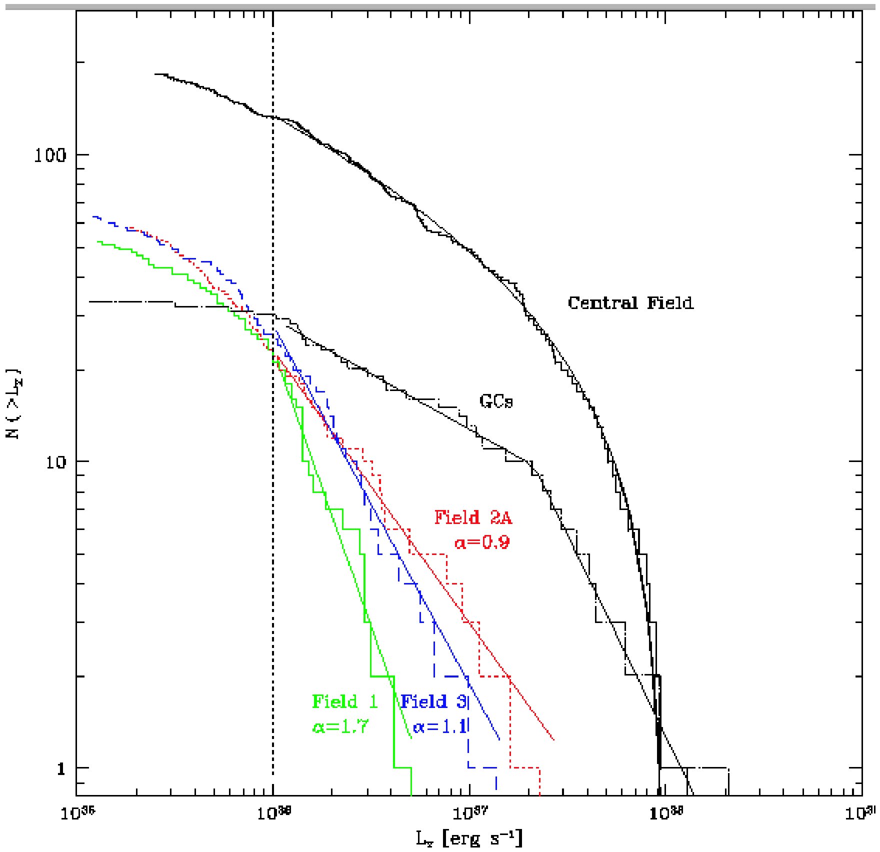

Fig. 11.2. Cumulative XLFs and best-fit power-laws from different fields of M31 (Kong *et al.* 2003).

(LMXB) population, suggesting that these sources dominate the X-ray emission of M31.

Williams *et al.* (2003), using the *Chandra HRC* survey of M31, distinguish between a roughly radially symmetric bulge population (within a 7' radius) and a field population, outside this inner region. They report different XLFs for bulge and disk sources, with a flatter broken power-law representing well the disk distribution. Their survey has a wider (although shallower) coverage of the entire M31 galaxy, than the Trudolyubov *et al.* (2202a) work, and covers also the southern half of the disk, where the X-ray sources are significantly more luminous than in the northern disk, surveyed with *XMM-Newton* by Trudolyubov *et al.*.

The Trudolyubov *et al.* (2202a), Kong *et al.* (2003), and Williams *et al*. (2003) papers are illuminating in demonstrating the variability of the XLF in different regions, and in pointing out how a good spatial sampling and supporting multi-wavelength information, are needed to get a complete picture of the XRB population of M31.

11.2.2 M81

As discussed in Fabbiano (1995), M81 (NGC 3031) is a nearby (3.6 Mpc, Freedman *et al.* 1994) Sb galaxy optically similar to M31; however, in X-rays it displays a significantly more luminous population of individual sources (even discounting the nuclear AGN). To get a feel of the progress in sensitivity of X-ray telescopes in the last ∼ 20 years, it is interesting to compare the *Einstein* observations of M81, where 9 extra-nuclear sources with $L_X \geq 2 \times 10^{38}$ ergs s^{-1} were detected (Fabbiano 1988; total ∼ 35 ks exposure time), with the *ROSAT* results that led to detection of 26 extra-nuclear sources with $L_X > 10^{37}$ ergs s^{-1} (Immler & Wang 2001; 177 ks - HRI, 101 ks - PSPC), and finally with the *Chandra* results: 124 sources detected within the optical D_{25} isophote to a limiting luminosity of $\sim 3 \times 10^{36}$ ergs s^{-1} in ∼50 ks (Swartz *et al.* 2003).

The *Chandra* results show that 88% of the non-nuclear emission is resolved into individual sources. The brightest of these sources have luminosities exceeding the Eddington luminosity for a spherically accreting neutron star (see Fabbiano 1995), i.e. they are among the sources dubbed 'Ultraluminous X-ray Sources' (ULX; see Section 11.3). Of the 66 sources that lie within *Hubble Space Telescope (HST)* fields, 34 have potential counterparts (but 20±4 chance coincidences are expected). Five sources are coincident with supernova remnants in the spiral arms (including the well studied SN 1993J), but one of them (the ULX X-6) is identified with a XRB, based on it X-ray spectrum. Only four potential GC identifications are found. For one of the M81 sources, Ghosh *et al.* (2001) report a 10-year *ROSAT*-*Chandra* X-ray transient light curve.

Nine of the sources found in the *Chandra* observation of M81 are supersoft (SSS; Swartz *et al.* 2002), with $L_X(0.2 - 2.0$ keV) in the range of $> 2 \times 10^{36} - 3 \times 10^{38}$ ergs s^{-1}, and a blackbody emission temperature of 40-80 eV. The fraction of SSS is consistent with the expected values, based on the Galaxy and M31. Four sources are in the bulge and five in the disk; of the latter, four are on the spiral arms. With the exception of the most luminous of these systems, which has a bolometric luminosity $L_{bol} \sim 1.5 \times 10^{39}$ ergs s^{-1}, and will be discussed in Section 11.3, all these sources are consistent with the nuclear-burning accreting white dwarf picture of SSS (van den Heuvel *et al.* 1992; see the Chapter by Kahabka in this book). The SSS associated with the spiral arms tend to have higher emission temperatures, suggesting more massive white dwarf counterparts, which would result from relatively massive stars in a relatively younger stellar population.

The first report of XLF studies in M81 (Tennant *et al.* 2001; Fig.11.3) showed dramatic differences in the XLFs of bulge and disk sources. While the XLF of the bulge is reminiscent of the bulge of M31, with a relatively steep power-law flattening at $L_X(0.2-8.0\ \mathrm{keV}) < 4 \times 10^{37}$ ergs s^{-1}, the XLF of the disk follows a uninterrupted shallow power law (cumulative slope -0.50).

The subsequent more complete study of Swartz *et al.* (2003) confirms the break in the bulge XLF and suggests that it may be due to an aging ∼ 400 Myr old population of LMXBs. The extrapolation of this XLF to lower luminosities can only explain 10% of the unresolved bulge emission, which, however, has the same spatial distribution as the detected bulge sources: besides some gaseous emission, this may suggest an undetected steepening of the XLF due to a yet fainter older population of sources

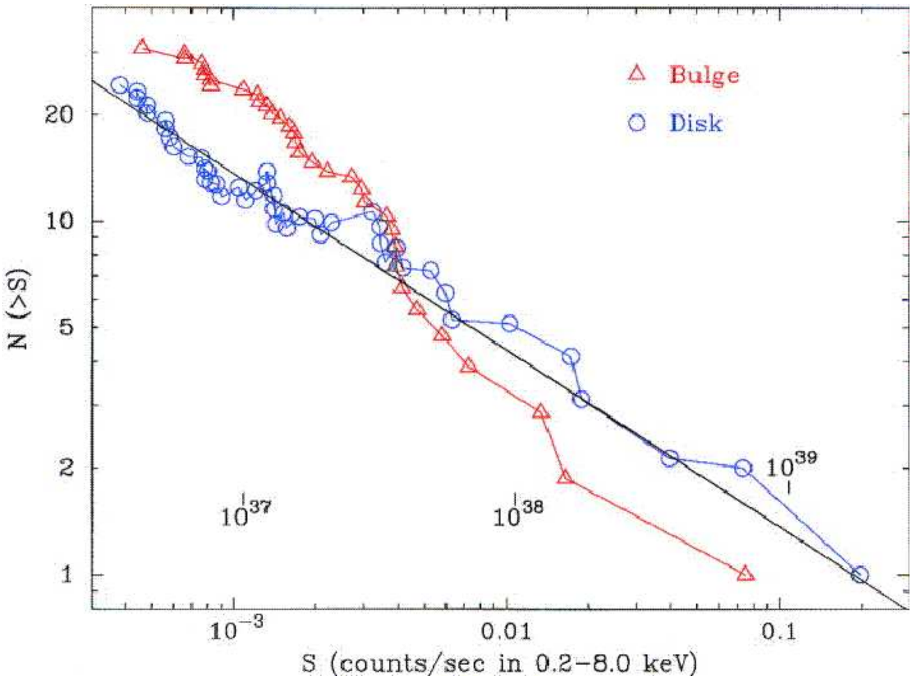

Fig. 11.3. Bulge and Disk XLFs for M81. The straight line is the best-fit power-law to the disk XLF (Tennant *et al.* 2001).

in the central regions. The disk population has different XLFs, depending on the source distance from the spiral arms (Fig. 11.4): in particular, the very luminous ($> 10^{38}$ ergs s^{-1}) sources responsible for the flat power law are all concentrated on the arms; a break at high luminosities appears when spiral arm sources are excluded. Swartz *et al.* (2003) suggest that these most luminous sources are likely to be very young XRBs resulting from the star formation stimulated by the spiral density waves.

11.2.3 M83 and M101

M83 (NGC 5236) and M101 (NGC 5457) are both face-on Sc galaxies. M83 is likely to be a member of the Centaurus group, with a distance of ∼ 4 Mpc (de Vaucouleurs *et al.* 1991); M101 is more distant (∼ 7 Mpc; Stetson *et al.* 1998), but still in the nearby universe.

M83 is a grand design, barred spiral, with a starburst nucleus. Is has been observed extensively in the pre-*Chandra* era, but here we discuss only the *Chandra* observations, that are the most relevant for the study of the X-ray source population. M83 was observed with *Chandra* ACIS-S3 for ∼ 50 ks (Fig. 11.5). Soria & Wu (2002) detect 81 sources in these data, of which 18 had been detected previously with *ROSAT*; 15 sources are resolved in the previously confused nuclear region, which has the highest source density. The XLF of the sources in the nuclear-bar region, where a young stellar population is likely to prevale, follows a fairly flat unbroken power-law (cumulative slope -0.8). The XLF of the disk sources is instead steeper (slope -1.3),

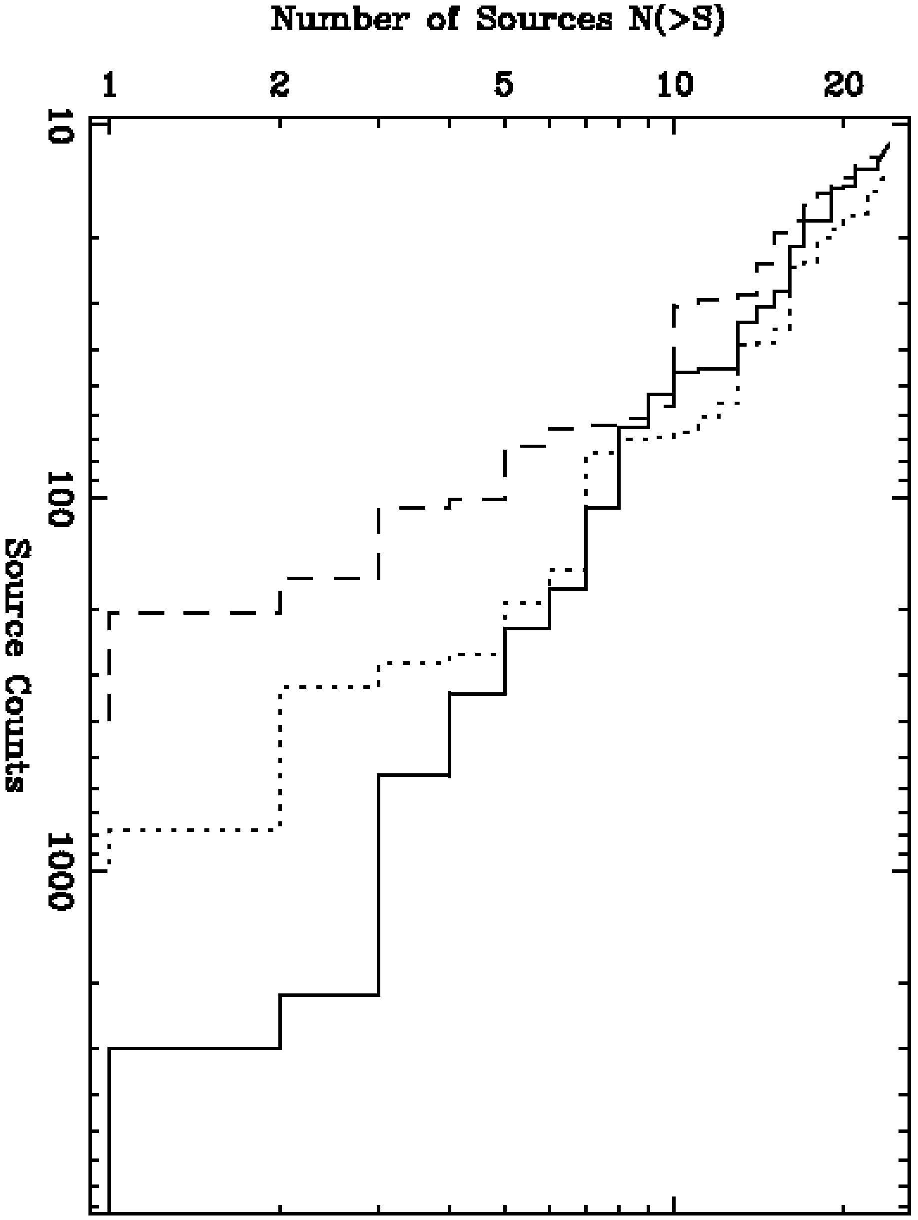

Fig. 11.4. Steepening XLFs of disk sources of M81, at increasing distance from the spiral arms (solid line; Swartz *et al.* 2003).

with a break at ~ 6×10^{37} ergs s^{-1}, becoming flatter at the lower luminosities. This behaviour is reminiscent of the XLFs of the bulges of M31 and M81, and suggests an older XRB population.

In M101, 110 sources (27 of which are expected to be backround AGN) were detected in a 98 ks *Chandra* ACIS-S3 observation, with a limiting luminosity of

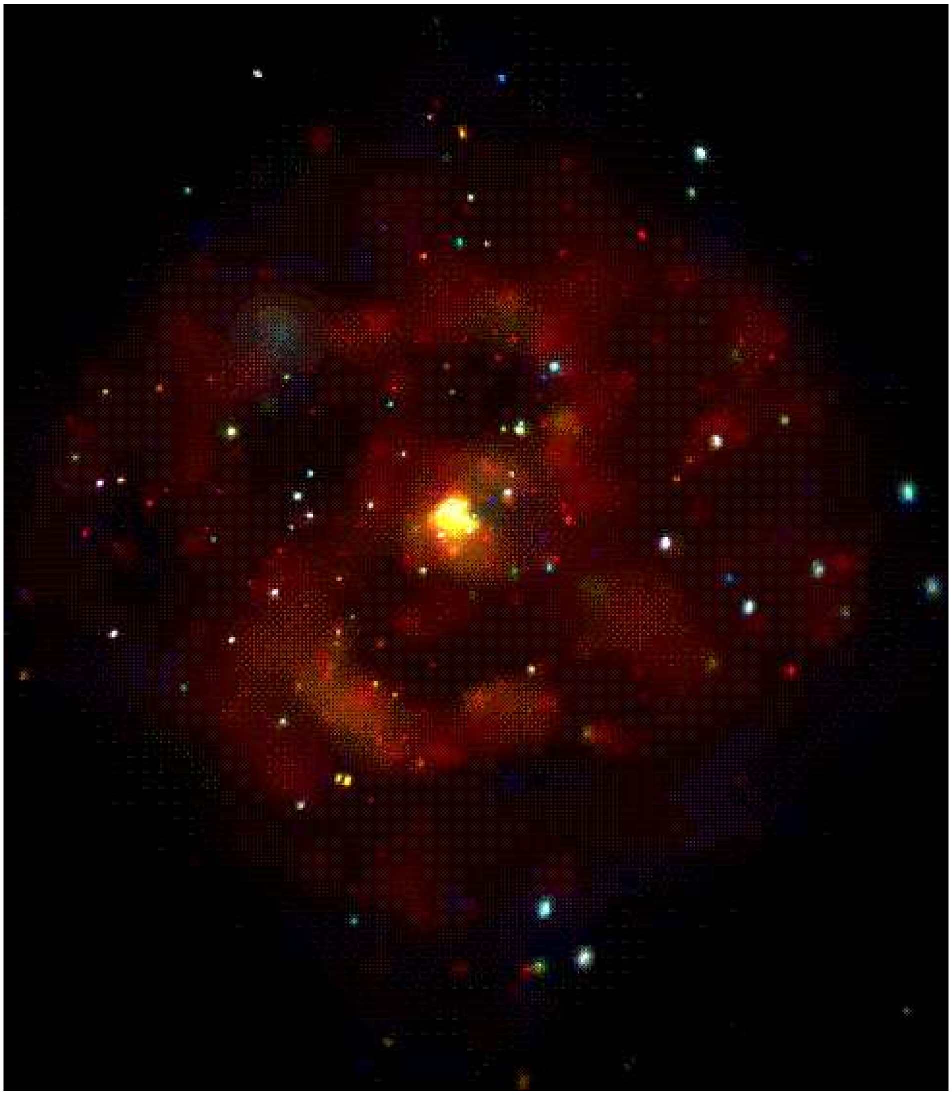

Fig. 11.5. M83 as seen with *Chandra*. Note the population of point-like sources and the softs diffuse emission (possibly from hot ISM), associated with the spiral arms (from http://chandra.cfa.harvard.edu/photo/2003/1154/index.html).

10^{36} ergs s^{-1} (Pence, Snowden & Mukai 2001). The sources cluster along the spiral arms, and, interestingly, sources in the interarm regions tend to have X-ray colors compatible with AGNs. Twelve sources are spatially coincident with supernova remnants, but, based on their variability, two of them are identified with XRBs. Eight other luminous sources exhibit variability in the *Chandra* data, and two more are found variable by comparison with previous *ROSAT* observations. Ten sources are supersoft, and a correlation between black-body temperature and total source luminosity is suggested by the data. The XLF of the M101 sources can be modelled with a power-law (cumulative slope -0.8) in the $10^{36} - 10^{38}$ ergs s^{-1} range.

In summary, with *Chandra*, X-ray source population studies are finally coming of age. The sub-arcsecond resolution of the *Chandra* mirrors (Van Speybroeck *et al.* 1997) allows both the separation of discrete sources from surrounding diffuse emission and the detection of much fainter sources than previously possible.

The XLFs of sources in a given system reflect the formation, evolution, and physical properties of the X-ray source population. These differences are evident in different regions of M31, M81 and M83. Comparison of the XLFs of nearby galaxies (and components thereof) with the XLFs of more distant systems provides a general coherent picture, pointing to steeper XLFs in older stellar populations (relative lack of very luminous sources). The XLFs of E and S0 galaxies have cumulative slopes in the range -1.0 to -2.0 (see Section 11.4.3), generally consistent with those of the bulges of M31 and M81. These slopes are significantly steeper than those of sources associated with younger stellar fields in M31, M81, and M83. A recent study of 32 nearby galaxies extracted from the *Chandra* archive (Colbert *et al.* 2003) confirms this basic difference between XLFs of old and younger stellar populations, finding cumulative slopes of ~ 1.4 and $\sim 0.6 - 0.8$ for elliptical and spiral galaxies respectively.

11.2.4 XRBs in Actively Starforming Galaxies

Observations show flatter XLF slopes (i.e., an increased presence of very luminous sources) in galaxies with more intense star formation. The best example is given by the merger system NGC 4038/39 (The Antennae), where nine ultraluminous X-ray sources (ULXs; $L_X > 10^{39}$ ergs s^{-1}, for a distance of 19 Mpc) were discovered with *Chandra* (Fabbiano, Zezas & Murray 2001). Other examples of exceptionally luminous sources are found in M82 (Kaaret *et al.* 2001; Matsumoto *et al.* 2001), the Circinus galaxy (Smith & Wilson 2001; Bauer *et al.* 2001) and NGC 1365 X-1 (Komossa & Schultz 1998). Consequently, flatter XLFs occur in galaxies with more intense star formation: the cumulative XLF slope is - 0.45 in The Antennae (Zezas & Fabbiano 2002; Kilgard *et al.* 2002; Fig. 11.6).

Grimm, Gilfanov & Sunyaev (2003) suggest that the XLFs of star forming galaxies scale with the star formation rate (SFR), thus advocating that HMXBs may be used as a star formation indicator in galaxies. They find that at high SFRs the total X-ray luminosity of a galaxy is linearly correlated to the SFR, and suggest a 'universal' XLF of starforming galaxies described by a power law with cumulative slope of ~ -0.6 and a cut-off at $L_X \sim$few$\times 10^{40}$ ergs s^{-1}. This result of course depends on how well is the SFR of a given galaxy known. This is a subject of considerable interest at this point, since various indicators are differently affected by extinction. The conclusion of a universal slope of the XLF of starforming galaxies may be at odd with the reported correlation between the XLF slope and the 60μm luminosity from a minisurvey of spiral and starburst galaxies observed with *Chandra* (Kilgard *et al.* 2002). Also, theoretical models (Kalogera et al. 2003) suggest that XLF slopes depend on the age of the starburst, so it is possible that the 'universal' XLF slope is not truly universal, but reflects a selection bias, in that the sample used by Grimm, Gilfanov & Sunyaev (2003) may be dominated by starburtsts of similar ages.

Comparison of the XLFs for different galaxies, and modeling of the same, provide

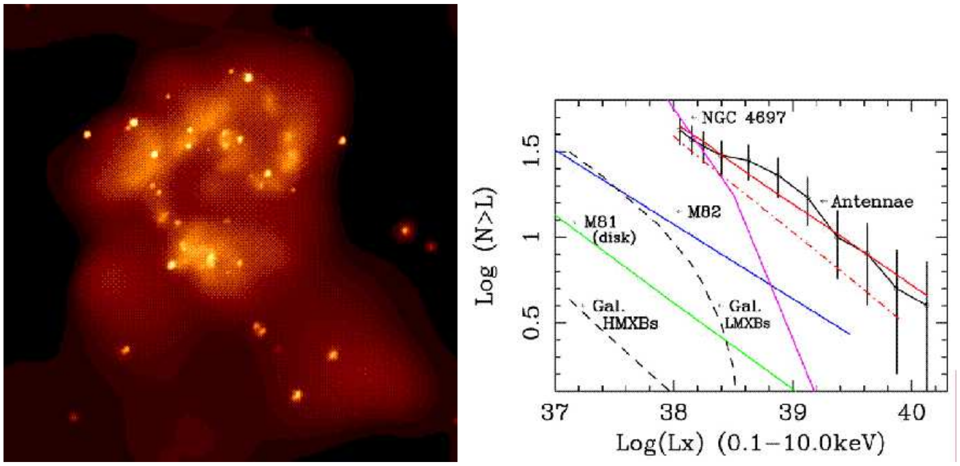

Fig. 11.6. Left: *Chandra* ACIS image of The Antennae (Fabbiano *et al.* 2001); Right: the XLF of The Antennae (points with error bars) compared with other galaxies, as labelled. Note the steep XLFs of the Galactic HMLXBs (bulge) and of the early-type galaxy NGC 4697 (Zezas & Fabbiano 2002).

powerful tools for understanding the nature of the X-ray sources and for relating them to the evolution of the parent galaxy and its stellar population. Early theoretical work has attempted to interpret the XLFs, using *ad hoc* power-law models, and accounting for aging and impulsive birth of XRB populations (Wu 2001, Kaaret 2002, Kilgard *et al.* 2002). Spurred by the recent observational developments, Kalogera and collaborators have developed the first models of synthetic XLFs, based on XRB evolutionary calculations (Belczynski et al. 2003). Such models provide us with a potentially powerful tool for studying the origin and evolution of XRB populations in stellar systems and their connection to galactic environments. A preliminary examination of such models for starburst galaxies (Kalogera et al. 2003; see Fig. 11.7) successfully shows that predictions and consistency checks for the shapes and normalizations of XLFs are possible with theoretical XRB modeling. These new developments demonstrate that the predictions of 1995 are coming true (see Section 11.1).

11.3 Ultra Luminous X-ray Sources - ULXs

ULXs are also named super-Eddington sources (see Fabbiano 1989, 1995), super-luminous sources, and intermediate luminosity X-ray objects (IXOs) (Roberts & Warwick 2000; Colbert & Mushotzky 1999; Colbert & Ptak 2003). All these names aim to convey the fact that they are extremely luminous X-ray sources, emitting well in excess of the Eddington luminosity of a spherically accreting and emitting neutron star ($\sim 2 \times 10^{38}$ ergs s^{-1}). Usually, sources emitting at $\sim 10^{39}$ ergs s^{-1} or above are included in this category. If these sources are emitting isotropically at the Eddington limit, masses in excess of those expected from stellar black holes are implied, up to in some cases, $\geq 100 M_\odot$ (e.g. Fabbiano 1989, 1995; Makishima *et al.* 2000). Colbert & Mushotzky (1999) dubbed this type of black holes 'intermediate mass black holes' (IMBH), to distinguish them from the stellar mass black holes found in Galactic

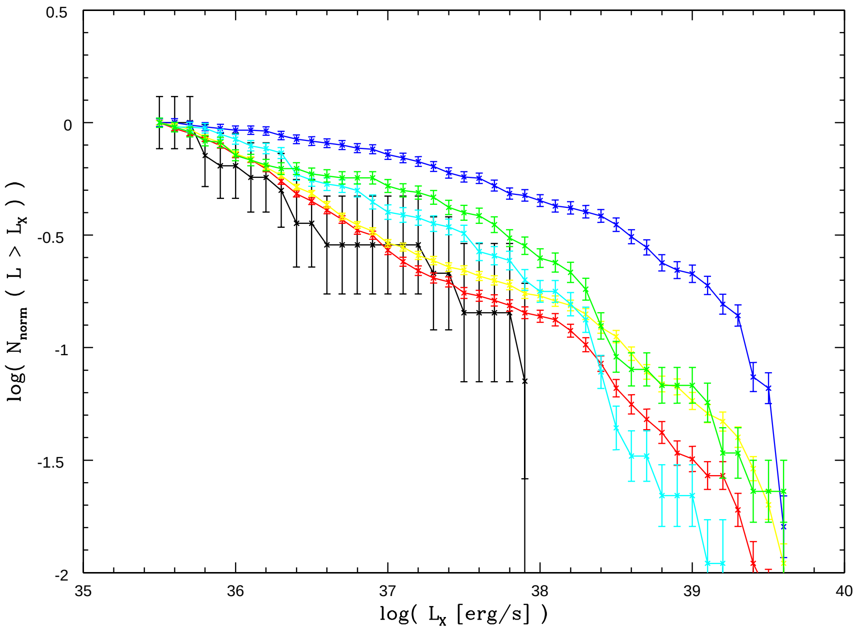

Fig. 11.7. Comparison of XRB population models (from Kalogera et al. 2003) with the observed XLF of NGC 1569 (bottom points, in black; data taken from Martin et al. 2002, ApJ, 574, 663). Models were constructed to match the star-formation history of NGC 1569 (recent star-burst duration and metallicity) and model XLFs are shown at different times since the beginning of the starburst. Top to bottom: 10Myr (blue), 50Myr (yellow), 110Myr (red), 150Myr (cyan), 200Myr (green). Note that based on observations in other wavelengths, the age of the starburst is estimated to be 105-110Myr.

black hole binaries, and also from the supermassive $10^7 - 10^9 M_\odot$ found at the nuclei of galaxies that are responsible for AGNs.

11.3.1 Spectra and spectral variability

Although young supernova remnants may be responsible for ULX emission in some cases (e.g Fabian & Terlevich 1996), there is now sufficient evidence from spectral and variability data, to establish that the majority ULXs are indeed compact systems, most likely accreting binaries. *ASCA* X-ray spectra suggested accretion disk emission. These spectra, however, also require temperatures much larger than those expected from black holes of the mass implied by the luminosities of these sources, leading to the suggestion of rotating Kerr black holes (Makishima *et al.* 2000; Mizuno, Kubota & Makishima 2001). In The Antennae ULXs the *Chandra* spectra (Zezas *et al.* 2002a, b) tend to be hard, and their average co-added spectrum requires both a power law ($\Gamma \sim 1.2$) and a disk-blackbody component consistent with the *ASCA* results, with kT$\sim$ 1.1 keV. A *XMM-Newton* survey of 10 galaxies reports ULX spectra consistent with black hole binaries in either high or low state (Foschini *et al.* 2002), but the data quality is too poor for detailed modelling. Similar general spectral results can be found in a *Chandra* survey of ULXs in different galaxies (Humphrey *et al.* 2003). Instead, *XMM-Newton* high quality spectra of two ULXs in NGC 1313 (X-1 and X-2) led to highly significant detections of soft accretion disk components, with temperatures of kT$\sim$ 150 eV, consistent with accretion disks of IMBHs (Miller *et al.* 2003a; Fig. 11.8).

The XRB hypothesis is reinforced by observations of correlated luminosity-spectral variability similar to the 'high/soft-low/hard' behavior of Cyg X-1 (e.g., in M81 X-9, La Parola *et al.* 2001, with a variety of X-ray telescopes, Fig. 11.9; and in two ULXs in IC 342, Kubota *et al.* 2001 with *ASCA*). However, more recently, Kubota, Done & Makishima (2002) argue that these power-law ULX spectra should not be identified with the low/hard state, but rather may be due to a strongly Comptonized optically thick accretion disk, analogous to the Comptonization-dominated 'very high/anomalous state' in Galactic black-hole binaries. *ASCA* observations of one of the IC 342 sources in high state (disk-dominated) revealed a 'high/hard-low/soft' low-level variability, with a possible 30-40 hr periodicity, as could be produced by a massive main sequence star orbiting a black hole (Sugiho *et al.* 2001).

With *Chandra* and *XMM-Newton* an increasing number of ULXs are being discovered and studied in galaxies. Variability in the *Chandra* observations of M82 established that the ULXs in this galaxy are likely to be accreting compact objects (Matsumoto *et al.* 2001). The *Chandra* observations of NGC 3628 (Strickland *et al.* 2001) show the re-appearance of the 10^{40} ergs s^{-1} variable ULX first discovered with *ROSAT* (Dahlem, Heckman & Fabbiano 1995). A new transient ULX was discovered in M74 (NGC 628) with (Soria & Kong 2002). *Chandra* observations of MF 16 in NGC 6946, formerly identified as an extremely luminous supernova remnant (Schlegel 1994), reveal instead a point-like source with the typical X-ray spectrum of a black-hole binary (Holt *et al.* 2003; Roberts & Colbert 2003). Similarly, M81 X-6, which is positionally coincident with a supernova remnant, is identified as a XRB by its X-ray spectrum (Swartz *et al.* 2003). *Chandra* observations of the nucleus of M33 have revealed a two-component (power-law and disk) spectrum and have established luminosity-spectral variability patterns in this ULX, reminiscent of the black hole binary LMC X-3 (La Parola *et al.* 2003; see also Long, Charles & Dubus 2002); Dubus & Rutledge (2002) compare this source with the Galactic microquasar GRS 1915+105.

High/hard-low/soft variability was found in M51 X-7, together with a possible 2.1 hr period (but the time coverage is scant) by Liu *et al.* (2002). Both Cyg X-1 like high/soft-low/hard as well as high/hard-low/soft variability was detected in the population of nine ULXs discovered with *Chandra* in the Antennae galaxies (Fabbiano ; Fig. 11.10). The latter type of variability can also be found in a few Galactic XRBs (1E 1740.7-2942, GRS 1758-258, GX 339-4, Smith *et al.* 2002; see also the *XMM-Newton* results on GRS 1758-258, Miller *et al.* 2002). This spectral variability may be indicative of the competition between the relative dominance of the accretion disk versus the innermost hot accretion flow; several scenarios for spectral variability are discussed in Fabbiano *et al.* 2003a and references therein.

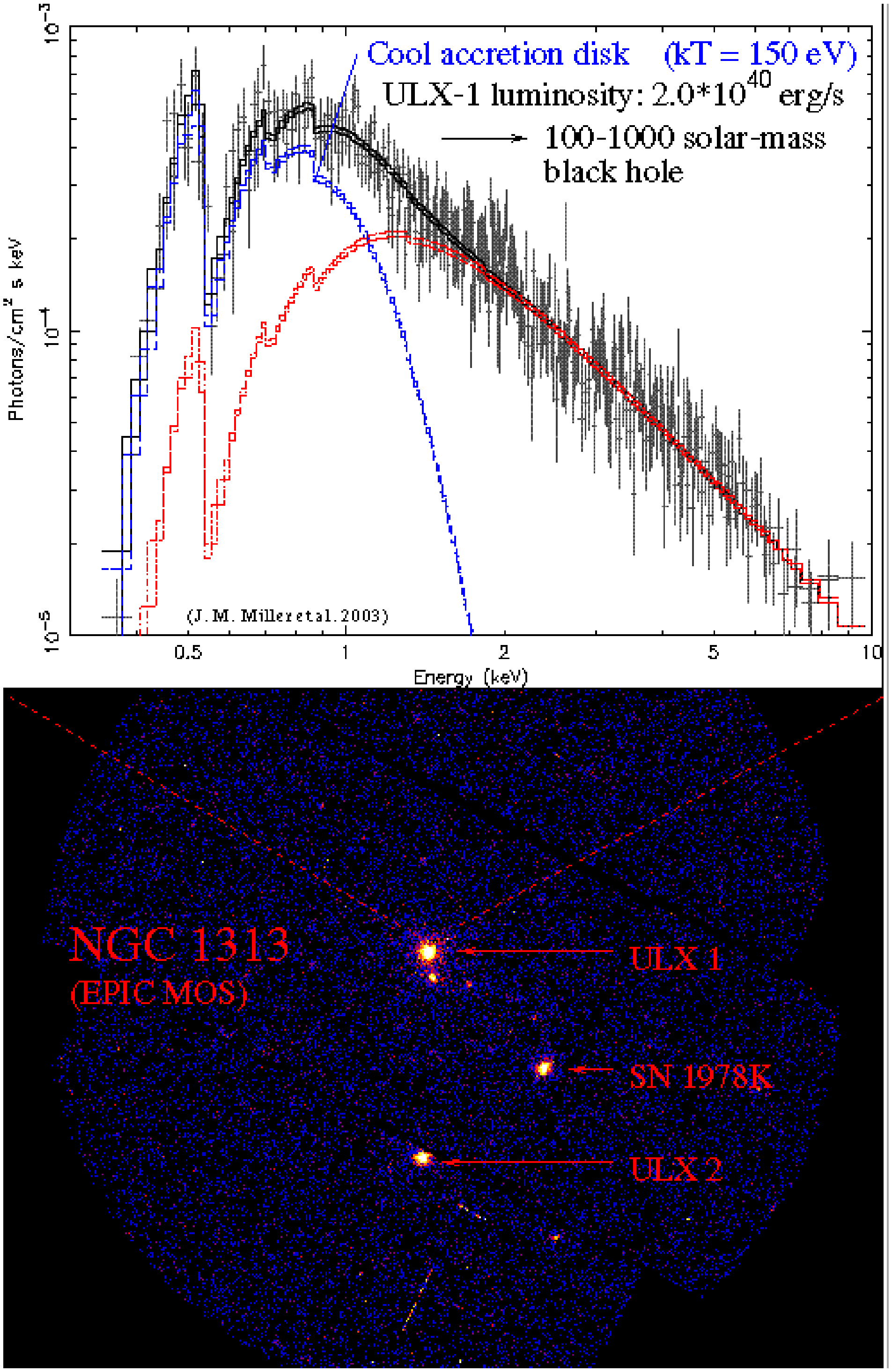

Fig. 11.8. Bottom: the *XMM-Newton* image of NGC 1313, showing the position of the two ULXs. Top: X-ray spectrum of ULX-1, compared with best-fit model requiring a cool accretion disk component (Miller *et al.* 2003).

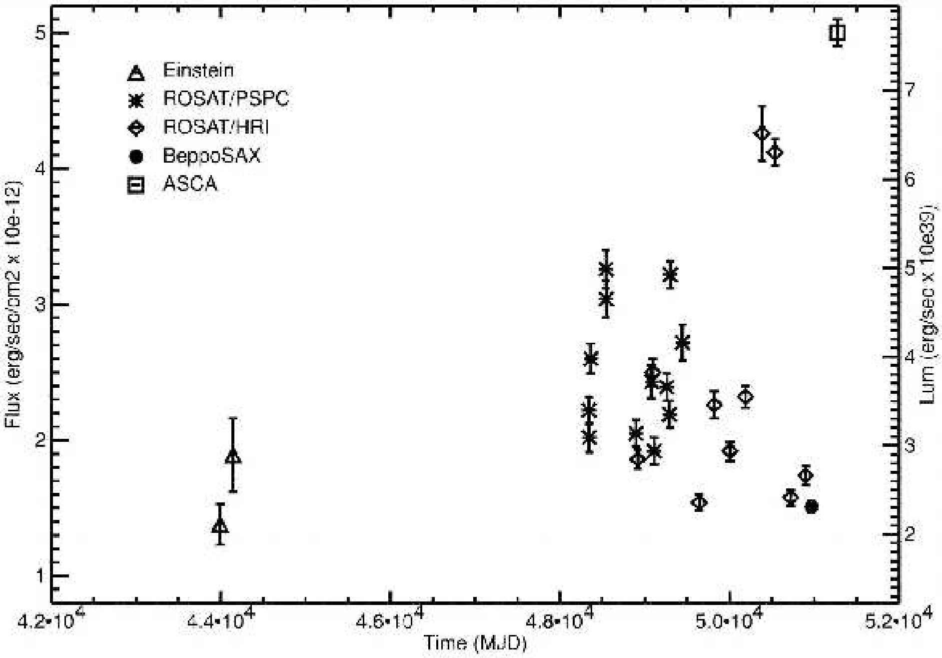

Fig. 11.9. Light-curve of M81 X-9, covering $\sim$ 20 yrs of observations (La Parola *et al.* 2001).

11.3.2 Intermediate Mass Black Holes or Beamed XRBs?

Although there is clear evidence pointing towards an XRB nature for ULXs, the presence of IMBHs in these systems is by no means universally accepted, and it may be quite possible that ULXs are indeed a heterogeneous population. As discussed above, the *ASCA* spectra were interpreted by Makishima *et al.* (2000) as evidence for rotating Kerr IMBH, to reconcile the high accretion disk temperature suggested by the model fitting of these spectra with the large black hole masses implied by the bolometric luminosity of the ULXs, which would require much cooler disks for a non-rotating IMBH. Colbert & Mushotzky (1999) suggested that these cooler accretion disk components may be present in their *ASCA* survey of ULXs, but the statistical significance of these early claims is not very high. The *Chandra* detections of super-soft ULXs (e.g., Swartz *et al.* 2002, in M81; Di Stefano *et al. 2003* in M104; see also later in this Section) could be interpreted as evidence for IMBHs. More important, low-temperature components vere discovered in the *XMM-Newton* spectra of 'normal' ULXs: in the NGC 1313 ULXs, which do not require a Kerr black hole, and are entirely consistent with emission from an IMBH accretion disk (Miller *et al.* 2003a; Fig. 11.8); and in at least one of the ULXs in the Antennae galaxies (kT$\sim$0.13 keV) (Miller *et al.* 2003b).

Considerable attention has been devoted to an extremely luminous variable 10^{40} ergs s^{-1} ULX detected with *Chandra* near the dynamical center of M82. In the picture of spherical accretion onto an IMBH, the luminosity of this source would imply masses

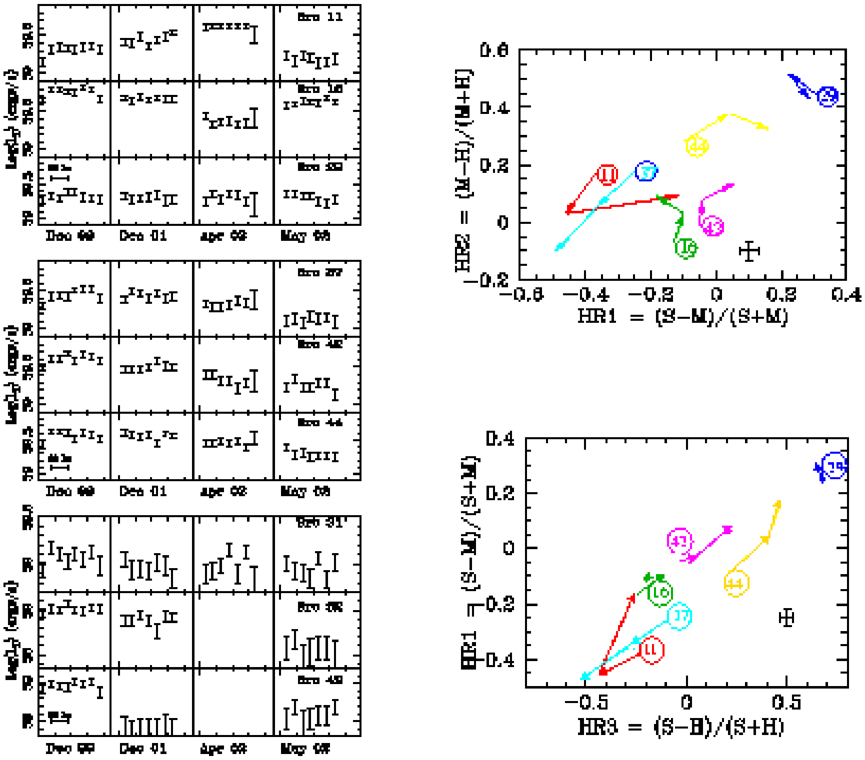

Fig. 11.10. Left: *Chandra* light curves of the ULXs of The Antennae. Right: color-color diagrams of the most luminous sources (Fabbiano *et al.* 2003a).

in excess of 100 $M_\odot$ for the accretor. This ULX appears to be at the center of an expanding molecular superbubble with 200 pc diameter (Matsushita *et al.* 2000). Based on its accurate *Chandra* position, which is not at the nucleus, Kaaret *et al.* (2001) set an upper limit of $10^5 - 10^6 M_\odot$ to its mass. Strohmayer & Mushotzky (2003) report quasi periodic oscillations (QPOs) in the *XMM-Newton* data of this source. They argue that their discovery suggests emission from an accretion disk and is incompatible with the radiation being beamed, and therefore implying a less extreme emitted luminosity, as in King *et al.* (2001; see below). On the assumption that the highest QPO frequency is associated with the Kepler frequency at the innermost circular orbit around a Schwarzschild black hole, these authors set an upper limit of $1.87{\times}10^4 M_\odot$ to the black hole mass: this source could therefore be an IMBH, with masses in the 100-10,100 $M_\odot$ range. However, as noted by Strohmayer & Mushotzky (2003), the crowded M82 field cannot be spatially resolved with *XMM-Newton*, making the association of the QPO with the most luminous ULX in the field not entirely proven. Moreover, the spectral fit of these data suggests a temperature kT∼ 3 keV, much higher than the one expected from an IMBH accretion disk.

As we will discuss below, some results are hard to explain in the IMBH scenario. Two other models have been advanced, which do not require IMBH masses. The large number of ULXs found in The Antennae led to the suggestion that they may represent a normal stage of XRB evolution (King *et al.* 2001). In the King *et al.* (2001) model, the apparent (spherical) accretion luminosity is boosted because of geometrical collimation of the emitting area in thick accretion disks, resulting from the large thermal-timescale mass transfer characterizing the later stages of a massive XRB (see Chapter by King in this book). Exploiting the similarity with Galactic microquasars, the jet emission model of Körding *et al.* (2002) produces enhanced luminosity via relativistic beaming. In at least one case, the variable luminous ULX 2E1400.2-4108 in NGC 5408, there is observational evidence pointing to this relativistic jet model: Kaaret *et al.* (2003) find weak radio emission associated with the X-ray source, and argue that the both the multi-wavelength spectral energy distribution, and the X-ray spectrum are consistent with the Körding *et al.* (2002) scenario.

In some cases at least the IMBH hypothesis is supported by the association of the ULX with diffuse Hα nebulae, suggesting isotropic illumination of the interstellar medium by the ULX, and therefore absence of beaming (e.g. Pakull & Mirioni 2002 in the case of the NGC 1313 sources, see Miller *et al.* 2003). M81 X-9 is also associated with an optical nebula, which also contains hot gas (La Parola *et al.* 2001; Wang 2002). Wang (2002) considers the possibility that this nebula may be powered by the ULX and also speculates that it may be the remnant of the formation of the ULX. Weaver *et al.* (2002) discuss a heavily absorbed ULX in the nuclear starburst of NGC 253; this source appears to photoionize the surrounding gas. Weaver *et al.* speculate that it may be an IMBH, perhaps connected with either the beginning or the end of AGN activity. However, in at least one case (IC 342 X-1, Roberts *et al.* 2003), there is a suggestion of anisotropic photoionization, that may indicate beamed emission from the ULX.

In The Antennae, comparison with *HST* data shows that the ULXs are offset from starforming stellar clusters. While coincidence with a stellar cluster may be due to happenstance because of the crowded fields, the absence of an optical counterpart is a solid result and suggests that the ULXs may have received kicks at their formation (Zezas & Fabbiano 2002), which would be highly unlikely in the case of a massive IMBH forming in a dense stallar cluster (e.g. Miller & Hamilton 2002). An alternate IMBH scenario, discussed by Zezas & Fabbiano, is that of primordial IMBHs drifting through stellar clusters after capturing a companion (Madau & Rees 2001).

Other optical studies find counterparts to ULXs, and set indirect constraints on the nature of the accretor. A blue optical continuum counterpart to the variable ULX NGC 5204 X-1 was found by Roberts *et al.* (2001), and subsequently resolved by Goad *et al.* (2002) with *HST*. These authors conclude that the stellar counterpart points to an early-type binary. Similarly, Liu, Bregman & Seizer (2002) find an 08V star conterpart for M81 X-1, a ULX with average $L_X \sim 2 \times 10^{39}$ ergs s^{-1}. These counterparts may be consistent with the picture of King *et al.* (2001), of ULXs as XRBs experiencing thermal timescale mass transfer.

Recent results on supersoft variable ULXs suggest that the emitting region may not be associated with the inner regions of IMBH accretion disks in these sources, but may be due to Eddington-driven outflows from a stellar mass black hole. The spectral variability (at constant bolometric luminosity) of the soft ULX P098 in

M101 (detected with *Chandra*; Mukai *et al.* 2003) led to the suggestion of an optically thick outflow from a 15-25 $M_\odot$ black hole, regulated by the Eddington limit. *Chandra* time monitoring observations of The Antennae have led to the discovery of a variable super-soft source (kT = 90 - 100 eV for a blackbody spectrum), reaching ULX luminosities of 2.4×10^{40} ergs s^{-1} (Fabbiano *et al.* 2003b). The assumption of unbeamed emission would suggest a black hole of $\geq 100M_\odot$. However the radiating area would have to vary by a factor ~ 1000 in this case, inconsistent with gravitational energy release from within a few Schwarzschild radii of a black hole. As discussed in (Fabbiano *et al.* 2003b), a surprising possible solution is a white dwarf with $M \sim 1M_\odot$, at the Eddington limit, with a variable beaming factor (up to a beaming factor $b \sim 10^{-2}$). A second possible solution involves outflows from a stellar–mass black hole, accreting near the Eddington limit (as in Mukai *et al.* 2002) but with mildly anisotropic radiation patterns ($b \sim 0.1$, as in King *et al.* 2001). Similar sources are reported in M81 (Swartz *et al.* 2002), NGC 300 (Kong & Di Stefano 2003), and other nearby spiral galaxies (Di Stefano & Kong 2003; see also Di Stefano *et al* (2003) for SSSs in M31).

Transient behavior has been shown to be an important observational diagnostic that could allow us to distinguish between beamed models and IMBH accretion for the origin of ULXs in young, star-forming regions (Henninger et al. 2003). Accretion onto IMBH black holes can lead to unstable disks and hence transient behavior whereas beamed binary systems have transfer rates that are high enough for the disks to be stable and X-ray emission to be persistent. Therefore long-term monitoring can prove a valuable and possibly unique tool in unraveling the nature of ULXs.

11.4 XRBs in Elliptical and S0 Galaxies

As discussed in the 1995 chapter (Fabbiano 1995), XRBs could not be directly detected in E and S0 galaxies with pre-*Chandra* telescopes, because of the distance of these galaxies and the limited angular resolution of the telescopes. The presence of XRBs in E and S0 galaxies was predicted by Trinchieri & Fabbiano (1985), based on an analogy with the bulge of M31, for which such a population could be detected (Van Speybroeck *et al.* 1979; see also Fabbiano, Trinchieri & Van Speybroeck 1987). This early claim was reinforced by differences in the average spectral properties of E and S0 galaxies with different X-ray-to-optical luminosity ratios, that suggested a baseline X-ray faint XRB emission (Kim, Fabbiano & Trinchieri 1992; Fabbiano, Kim & Trinchieri 1994), and by the *ASCA* discovery of a hard spectral component in virtually all E and S0 galaxies (Matsushita *et al.* 1994), which, however, could also have been due, at least in part, to accreting massive nuclear black holes (Allen, Di Matteo & Fabian, 2000).

The *Chandra* images (Fig. 11.11) leave no doubt about the presence of rich populations of point-like sources in E and S0 galaxies. Published results, of which the first one is the paper on NGC 4697 by Sarazin, Irwin & Bregman (2000), include point-source detections in a number of galaxies. These source populations have been detected with varying low-luminosity detection thresholds (a function of galaxy distance and observing time). While most of the detected sources have luminosities in the $10^{37}-10^{39}$ ergs s^{-1} range, some were detected at luminosities above 10^{39} ergs s^{-1}, in the Ultra-Luminous-X-ray (ULX) source range (see Section 11.3). A representa-

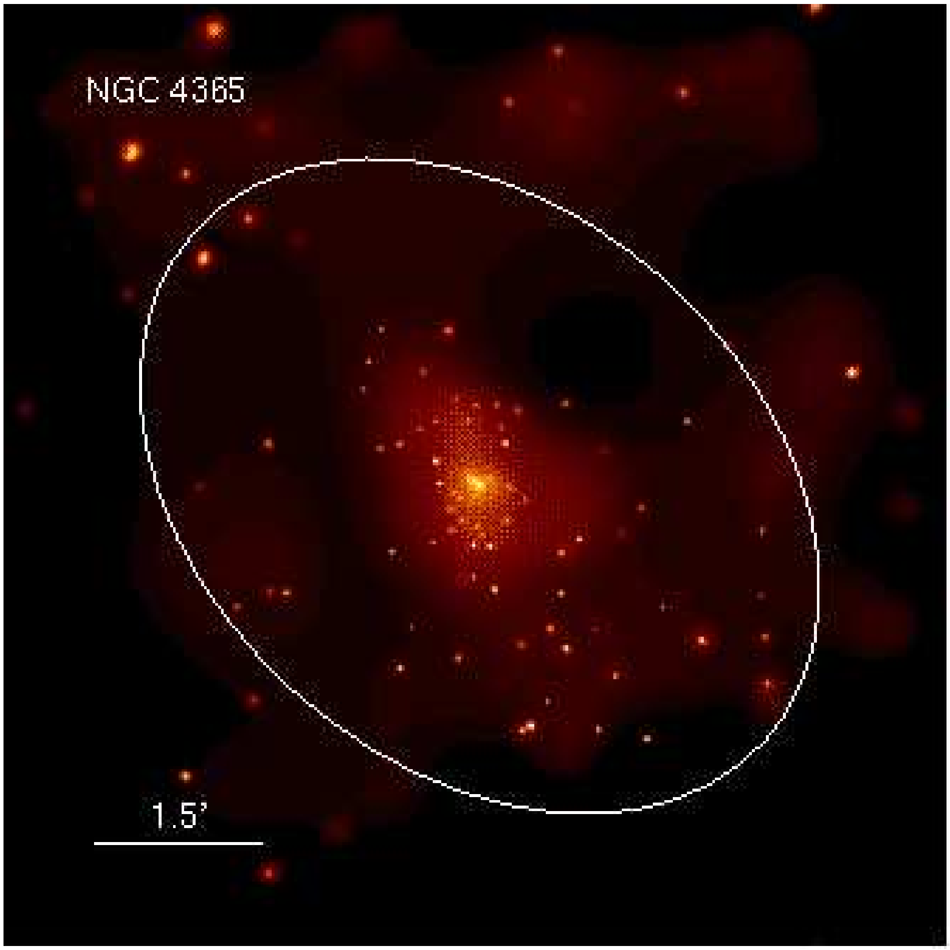

Fig. 11.11. *Chandra* ACIS image of the Virgo elliptical NGC 4365, using archival data. The white ellipse is the D_{25} isophote, from de Vaucouleurs *et al.* (1991).

tive summary (limited to papers published or in press as of May 2003) in given in Table 11.1.

The X-ray colors or co-added spectra of these sources are consistent with those of LMXBs (see above references, and Irwin, Athey & Bregman 2003); however, a variety of spectral properties have been reported in some cases, similar to the spectral variety of Galactic and Local Group XRBs, including a few instances of very soft and supersoft (i. e., all photons below ~ 1 keV) sources (e.g., NGC 4697, Sarazin, Irwin & Bregman 2000; M84, Finoguenov & Jones 2002; NGC 1399, Angelini, Loewenstein & Mushotzky 2001; NGC 1316, Kim & Fabbiano 2002). The overall spatial distribution of these sources follows that of the stellar light, but there are exceptions, such as in NGC 720, where the most luminous sources follow arcs (Jeltema *et al.* 2003), NGC 4261 and NGC 4697, where the X-ray source distributions are highly asymmetric (Zezas *et al.* 2003), and NGC 4472, where the X-ray source distribution

Table 11.1. *E & S0 Galaxies: Representative Summary of Chandra Results*

Name	No. of sources	L_X (ergs s^{-1}) band (keV)	Comment
NGC 720	42	$4 \times 10^{38} - 1 \times 10^{40}$ 0.3-7	9 ULX in 'arc' pattern 12 associations with GCs (Jeltema *et al.* 2003)
NGC 1291	∼50	$< 3 \times 10^{38}$ 0.3-10	3 associations with GCs (Irwin *et al.*. 2002)
NGC 1316	81	$2 \times 10^{37} - 2 \times 10^{39}$ 0.3-8	kT∼5 keV average spectrum 5 associations with GCs (Kim & Fabbiano 2003)
NGC 1399	∼ 140	$5 \times 10^{37} - 5 \times 10^{39}$ 0.3-10	70% associated with GCs (Angelini *et al.*. 2001)
NGC 1553	49	$1.6 \times 10^{38} - \sim \times 10^{40}$ 0.3-10	X-ray colors consistent with NGC 4697 3 associations with GCs (Blanton *et al.*. 2001)
NGC 4374 (M84)	∼ 100	$3 \times 10^{37} - \sim 2 \times 10^{39}$ 0.4-10	spectra consistent with Galactic LMXB (Finoguenov & Jones 2002)
NGC 4472	∼ 120	$1 \times 10^{37} - \sim 1.5 \times 10^{39}$ 0.5-8	40% associated with CGs (Kundu *et al.*. 2002)
NGC 4697	∼80	$5 \times 10^{37} - 2.5 \times 10^{39}$ 0.3-10	average spectrum kT∼8 keV 7 (20%) in GCs (Sarazin *et al.*. 2001)
NGC 5128 (CenA)	246	$2 \times 10^{36} - 1 \times 10^{39}$ 0.4-10	9 identifications with GCs (Kraft *et al.* 2001)
NGC 5846	∼ 40	$3 \times 10^{38} - 2 \times 10^{39}$ 0.3-10	(Trinchieri & Goudfrooij 2002)

may be more consistent with that of Globular Clusters (GCs) than of the general field stellar light (Kundu, Maccarone & Zepf 2002; Maccarone, Kundu & Zepf 2003). No firm conclusion on the origin and evolution of these sources exists. Given the old stellar population of the parent galaxies, and the life-times of LMXBs, it has ben suggested that these sources may be outbursting transients (Piro & Bildsten 2002). Alternatively, more recent formation and evolutions in GCs may result in steady sources (Maccarone, Kundu & Zepf 2003). With the exception of NGC 5128, which is near enough to allow detection of sources in the 10^{36} ergs s^{-1} luminosity range, and for which multiple observations demonstrate widespread source variability (Kraft *et al.* 2001), the *Chandra* observations performed so far typically only give a single snapshot of the most luminous part of the XRB population in a given galaxy. In NGC 5128, a comparison of the two *Chandra* observations reveals at least five transients (sources that disappear with a dimming factor of at least 10), supporting the Piro & Bildsten scenario.

Chandra observations of highly significant asymmetries in the spatial distribution of X-ray sources in otherwise regular old elliptical galaxies (Zezas *et al.* 2003) may suggest rejuvenation of the stellar population of these galaxies. In NGC 4261, the most significant example, all the detected sources are luminous, above the Eddington limit for a neutron star accretor. If the X-ray sources were standard LMXBs belonging to the dominant old stellar population, we would expect their spatial distribution to be consistent (within statistics) with that of the stellar light. However this is not so, as indicated by Kolmogorov-Smirnov tests and Bayesian block analysis. On the basis of simulations of galaxy interactions (Hernquist & Spergel 1992; Mihos & Hernquist 1996), this result suggests that the luminous XRBs may belong to a younger stellar component, related to the rejuvenating fall-back of material in tidal tails onto a relaxed merger remnants.

11.4.1 ULXs in Early-Type Galaxies

As can be seen from Table 11.1, in early-type galaxies the occurrence of sources with $L_X = 1 - 2 \times 10^{39}$ ergs s^{-1} is common, although generally limited to a few sources per galaxy. These sources could easily be explained with normal black hole binaries or moderately beamed neutron star binaries (King 2002). In their mini-survey of 14 galaxies observed with *Chandra* (which include some of the ones listed in Table 11.1), Irwin, Athey & Bregman (2003) find that of the four sources with X-ray luminosities in the $1 - 2 \times 10^{39}$ ergs s^{-1} range for which they can derive spectra, three have soft spectra, similar to those of black hole binaries in high state (see also Finoguenov & Jones 2002).

Not much can be said about the variability of ULXs in early-type galaxies, because repeated *Chandra* observations of a given galaxy are not generally available. In the case of NGC 5128, comparison with previous *ROSAT* images (see Colbert and Ptak 2002) shows considerable flux variability in these very luminous sources: two ULXs were detected in *ROSAT* observations, both have considerable lower luminosities in the *Chandra* data (Kraft *et al.* 2001), and one of them may have disappeared.

While, in general, sources with $L_X > 2 \times 10^{39}$ ergs s^{-1} are relatively rare in early-type galaxies as compared to actively star-forming galaxies (see Section 11.3), and may be preferentially associated with GCs (e.g. Angelini, Loewenstein & Mushotzky 2001; see Irwin, Athey & Bregman 2003), this is not always the case, as exemplified by NGC 720. This galaxy (Jeltema *et al.* 2003) is peculiar in possessing nine ULXs (this number is of course dependendent on the assumed distance, 35 Mpc), a population as rich as that of the actively starforming merger galaxies The Antennae (Fabbiano, Zezas & Murray 2001, Zezas & Fabbiano 2002). Only three of these ULXs can be associated with GCs. The sources in NGC 720 are also peculiar in their spatial distribution, which does not follow the distribution of the optical light, as it would be expected from LMXBs evolving from low-mass bulge binaries: these sources are distributed in arcs. Their large number and their spatial distribution may suggest that they are younger systems, perhaps the remnants of a recent merger event.

The associations of some ULXs in early-type galaxies with GCs may support the possibility that a subset of these sources may be associated with IMBH ($> 10M_\odot$) (see Fabbiano 1989 and refs. therein; Irwin, Athey & Bregman 2003). However, most of the ULXs in early-type galaxies are likely to be lower mass binaries, given the stellar population of the parent galaxy. King (2002; see also Piro & Bildsten 2002) suggests that they may be a class of ULXs associated with outbursts of soft X-ray transients, resulting in moderately beamed emission from the inner regions of a thick accretion disk. In the case of NGC 720 they may be related to a 'hidden' younger stellar population (Jeltema *et al.* 2003).

11.4.2 X-ray sources and Globular Clusters

The association of X-ray sources in early type-galaxies with GCs has been widely discussed. As can be seen from Table 11.1, associations with GCs range from $\leq 10\%$ in most galaxies, $\sim 40\%$ in some Virgo galaxies (NGC 4472, NGC 4649), to 70% in NGC 1399, the dominant galaxy in a group . The statistics are somewhat fraught with uncertainty, since lists of GCs from *HST* are not available for all the galaxies studied with *Chandra*, and the detection thresholds differ in different galaxies. However, this association is interesting and has led to the suggestion that perhaps all the LMXBs in early-type galaxies may form in GCs, from whence they may be expelled if they receive strong enough kicks at their formation, or may be left behind if the GC is tidally disrupted. This suggestion was first advanced by Sarazin, Irwin & Bregman (2000), and was more recently elaborated by White, Sarazin & Kulkarni (2002), on the basis of a correlation of the specific GC frequency with the ratio of the integrated LMXB luminosity to the optical luminosity of eleven galaxies. Kundu, Maccarone & Zepf (2002) explore the LMXB-GC connection in NGC 4472, where they find that 40% of the sources detected at $L_X > 1 \times 10^{37}$ ergs s^{-1} are associated with GCs. In this galaxy, the fraction of GCs hosting an X-ray source is 4%, the same as in the Galaxy and M31. More luminous, more metal rich, and more centrally located GCs are more likely to host LMXBs, reflecting both an increased probability of binary formation with the numbers of stars in a GC, and also an effect of metallicity in aiding binary formation (Kundu, Maccarone & Zepf 2002).

While the possibility of LMXB formation in GCs is intriguing, this is still an open question, since evolution of bulge stars may also produce LMXBs (e.g., Kalogera & Webbink 1998; Kalogera 1998). The spatial distribution of the LMXBs, if it follows the optical stellar light (e.g. in NGC 1316, Kim & Fabbiano 2003; Fig. 11.12), would be consistent with this hypothesis. However, in NGC4472 at least, no differences are found in the distributions of X-ray luminosities of the GC sources and the other LMXBs (Maccarone, Kundu & Zepf 2003). Moreover, in the inner bulge of M31, at radii that even with *Chandra* cannot be explored in elliptical galaxies because of their distances, the distribution of LMXBs appears more peaked than that of the optical light (Kaaret 2002).

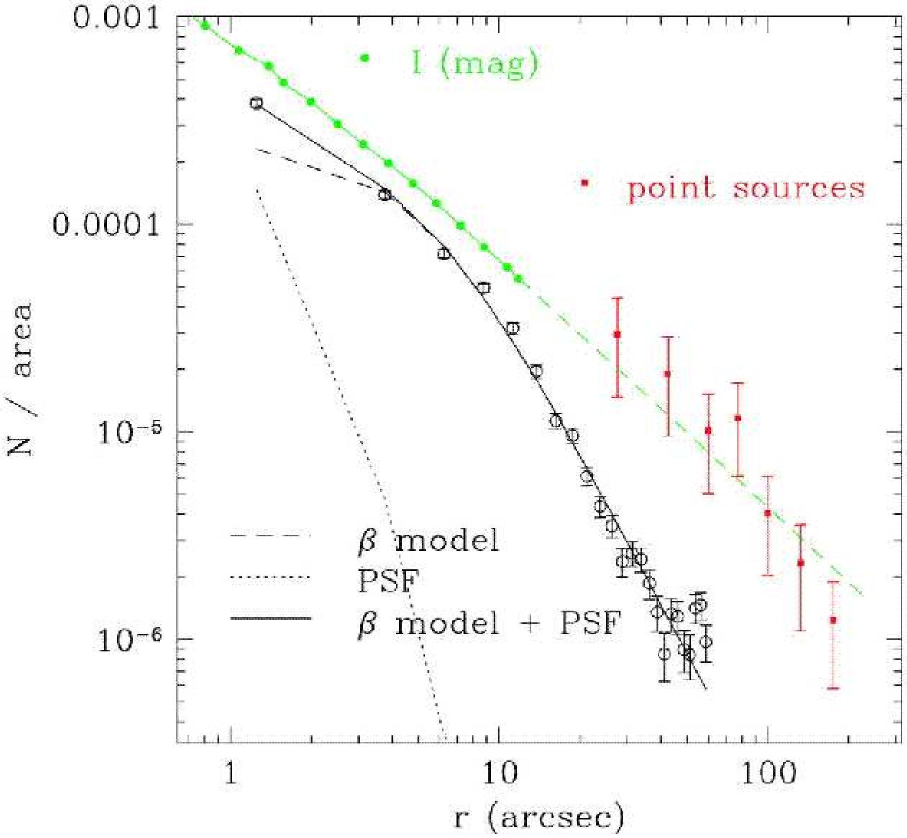

Fig. 11.12. Radial distributions of the emission components of NGC 1316. The gaseous component (hot ISM) is represented by the inner distribution of points. The cumulative XRB contribution is given by the outer set of points; the dashed line through these points is the extrapolation of the stellar (I) surface brightness (Kim & Fabbiano 2003).

11.4.3 X-ray Luminosity Functions

The XLFs of the early-type galaxies observed with *Chandra* are generally steeper than those of star-forming galaxies (see Section 11.2.4), i.e. with a relative lack of luminous HMXBs. These XLFs are generally well fitted with power-laws or broken power laws with (cumulative) slopes ranging from -1.0 to -1.8, and breaks have been reported both at 2-3$\times10^{38}$ ergs s^{-1}, the Eddington luminosity of an accreting neutron star (Sarazin, Irwin & Bregman 2000; Blanton, Sarazin & Irwin 2001; Finoguenov & Jones 2002; Kundu, Maccarone & Zepf 2002), and at higher luminosities (10^{39} ergs s^{-1}) (Jeltema *et al.* 2003, in NGC 720). While the former break may be related to a transition between neutron star and black hole binaries (Sarazin, Irwin & Bregman 2000), the latter, high luminosity break, could be produced by a decaying (aging) starburst component from binaries formed in past merging and star bursting episodes (Wu 2001). This possibility was suggested in the case of NGC 720 (Jeltema *et al.* 2003). The XLFs of NGC 5128 (Kraft *et al.* 2001), obtained at different times and reflecting source variability, are well fitted with single power-laws in the luminosity range of $10^{37} - 10^{39}$ ergs s^{-1}. In NGC 1291 (Irwin, Sarazin & Bregman 2002), no super-Eddington sources are detected.

The effects of detection incompleteness have been considered by Finoguenov & Jones (2002), and have been recently explored extensively by Kim & Fabbiano (2003) in their derivation of the XLF of NGC 1316. Low-luminosity sources may be missed because of higher background/diffuse emission levels in the inner parts of galaxies, and also because of the widening of the *Chandra* beam at larger radii. Correcting for these effects with an extensive set of simulations, Kim & Fabbiano (2003) found that an apparent 2-3$\times 10^{38}$ ergs s^{-1} break in the XLF of NGC 1316 disappeared when incompleteness was taken into account, and the XLF of this galaxy could be represented by an unbroken power-law down to luminosities of $\sim 3 \times 10^{37}$ ergs s^{-1} (Fig. 11.13). This result shows that caution must be exercised in the derivation of XLFs, and that perhaps some of the previous reports should be reconsidered. If the XLFs extend unbroken to lower luminosities, the amount of X-ray emission from undetected LMXBs in early-type galaxies can be sizeable, as it is the case in NGC 1316. This result is important not only for our understanding of the XRB populations, but also for the derivations of the parameters of the hot interstellar medium in these system (see Kim & Fabbiano 2003). Ignoring the contribution to the emission of hidden XRBs results in biases and erroneous results and may give the wrong picture of the overall galaxy dynamics and evolution. Moreover, the dominance at large radii of XRB emission over the hot ISM (see Fig. 11.12) in some (X-ray faint) ellipticals, does also affect adversely mass measurements of these galaxies from low-resolution X-ray data (Kim & Fabbiano 2003).

11.5 Multi-wavelength Correlations

Although this chapter is focussed on the XRB populations that we can now resolve and study with *Chandra* in galaxies as distant as ~ 20 Mpc, the study of the integrated emission properties of samples of galaxies (either more distant, or observed at lower resolution) can also give useful information on the average properties of their XRB components. We will summarize here some of these studies, that were pursued mostly by using the samples of galaxies observed with *Einstein* and *ROSAT*.

Most of the early work in this area was done by Fabbiano and collaborators, using the first sample of galaxies ever observed in X-rays, the *Einstein* sample (see reviews in Fabbiano 1989; 1995). Besides suggesting the baseline XRB emission in E and S0 galaxy, that is now confirmed with *Chandra* (Section 11.4), these results suggested a general scaling of the integrated X-ray emission with the optical luminosity (and therefore stellar population) of the galaxies, and pointed to a strong association of the XRB populations of disk/arm-dominated spirals with the far-IR emission, i.e. the younger component of the stellar population (e.g., Fabbiano, Gioia & Trinchieri 1988; see also David, Jones and Forman 1992). More recent work on the *Einstein* sample (Shapley, Fabbiano & Eskridge 2001; Fabbiano & Shapley 2002*), on *ROSAT*-observed galaxies (Read & Ponman 2001), and on *Beppo-SAX* and *ASCA* data (Ramalli, Comastri & Setti 2003) has examined some of these correlations afresh. Given the different pass-bands of these observatories, these studies have a varied

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* probably the last paper to be published on the *Einstein* data

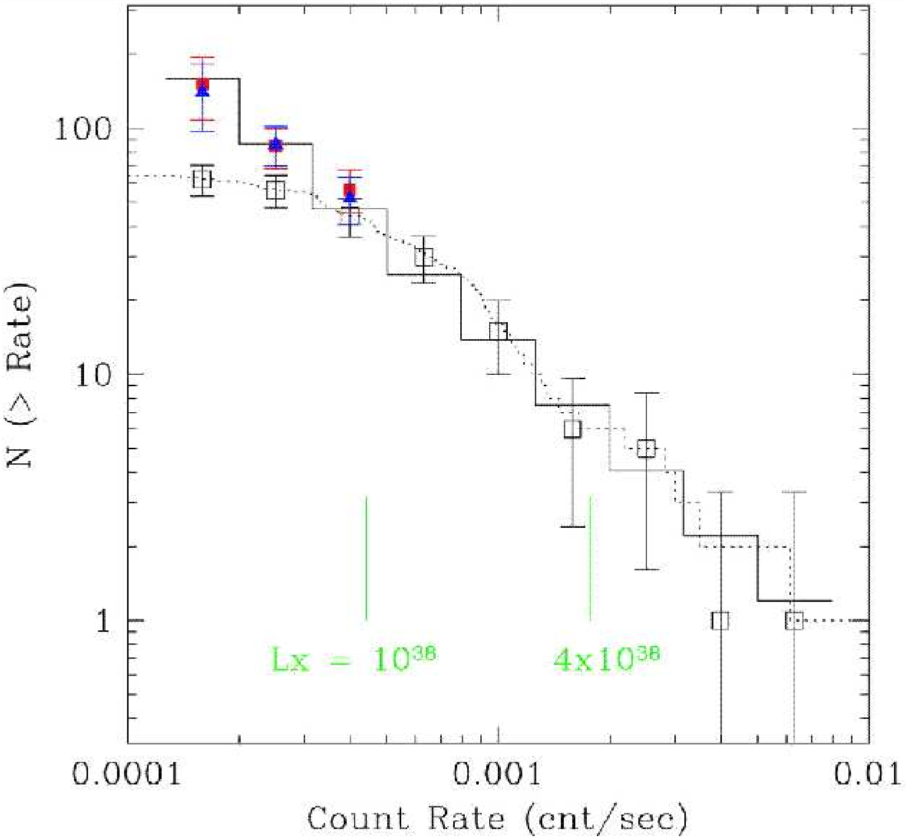

Fig. 11.13. Observed (empty squares) and corrected (filled points) XLFs of NGC 1316 (Kim & Fabbiano (2003).

sensitivity to the effect of hard XRB emission and soft hot ISM emission in the galaxies.

The *Einstein* sample is the largest, consisting of 234 S0/a-Irr galaxies observed in the 0.2-4. keV band. The X-ray luminosities are compared with B, H, 12 μm, 60 μm, 100 μm, global FIR, and 6 cm luminosities (Shapley, Fabbiano & Eskridge 2001; Fabbiano & Shapley 2002). Both fluxes and upper limits were used in this work, to avoid obvious selection biases. This work provides baseline distributions of L_X and of L_X/L_B for the entire Hubble sequence (including E and S0 galaxies), and a critical compilation of distances for the sample. Multi-variable correlation analysis shows clear dependencies of the emission properties on the morphological type of the galaxies (and therefore indirectly on the stellar population and star formation activity). In Sc-Irr galaxies, all the emission properties (including the X-rays) are tightly correlated, suggesting a strong connection to the stellar population. This is not true for S0/a-Sab, where there is a general connection of the X-ray luminosity with the B and H-band emission (stellar population), but not with either radio or FIR. In Sc-Irr galaxies the strongest link of the X-ray emission is a linear correlation with the FIR, suggesting a connection with the star-forming stellar component. This conclusion is reinforced by a correlation between L_X/L_B and L_{60}/L_{100}, which associates more intense X-ray emission with hotter IR colors.

The X-ray emission / star-formation connection is also discussed as a result of the analysis of a small sample (17 nearby spirals) observed with ROSAT in a softer energy band (0.1-2.0 keV; Read & Ponman 2001), and more recently from the analysis of another small sample (also 17 galaxies) observed in the 2-10 keV band (Ranalli, Comastri & Setti 2003). The advantage of this harder band is that the emission is predominantly due to the XRB population (if the sample does not include AGNs). These authors suggest that the hard X-ray emission can be used as a clean indicator of star formation, because extinction is not a problem at these energies.

These correlation analyses are now being extended to the XRB populations detected with *Chandra*. Colbert *et al.* (2003) report good correlations between the total point source X-ray luminosity in a sample of 32 galaxies of different morphological type extracted from the *Chandra* archive and the stellar luminosity (both B and K bands). While correlations are still present in the spiral and merger/irregular galaxies with FIR and UV luminosities, the ellipticals do not follow this trend and show a clear lack of FIR and UV emission, consistent with their older stellar populations. This results is consistent with the conclusions of Fabbiano & Shapley (2002; see above), which were however based on the analysis of the integrated x-ray luminosity of bulge dominated and disk/arm dominated spiral and irregular galaxies.

In summary, there is a correlation between X-ray emission and SFR in star-forming galaxies, that may lead to a new indicator of the SFR. However, one has to exercise caution, because this conclusion is only true for star-forming galaxies. In old stellar systems (bulges, gas-poor E and S0s), the X-ray emission is connected with the older stellar population of these systems. This conclusion is also in agreement with the recent studies of XLFs (Section 11.2; Section 11.4.3)

11.6 The X-ray Evolution of Galaxies

X-ray images of the extragalactic sky routinely taken with *Chandra* and *XMM-Newton* do not typically detect normal galaxies as serendipitous sources in the field. Instead the images reveal a relativity sparse population of point sources, the majority of which are Active Galatic Nuclei (AGN) with a space density of order a thousand per square degree. Normal galaxies are not detected because the X-ray luminosity of normal galaxies is relatively low and the predicted fluxes very faint. However, in the deepest few million second or more exposures made with *Chandra* (the *Chandra* Deep Fields – CDFs; Giacconi *et al.* 2002, Alexander *et al.* 2003) faint X-ray emission has been detected from optically bright galaxies at redshifts of 0.1 to 0.5 (Hornschemeier *et al.* 2001). These are amongst the faintest X-ray sources in the CDF, with fluxes of $\sim 10^{-16}$ erg cm^{-2} s^{-1} , corresponding to a luminosity of 10^{39} to 10^{41} erg s^{-1} – the range seen from nearby galaxies (e.g. see Shapley, Fabbiano & Eskridge 2001). Some of these might be galaxies containing a low luminosity AGN, but most are likely to be part of an emerging population of normal galaxies at faint X-ray fluxes.

The detection sensitivity of *Chandra* can be increased by 'stacking' analysis, i. e. by 'stacking' sub-images centered on the positions of galaxies in comparable redshift ranges. This can push the threshold of *Chandra* to $\sim 10^{-18}$ erg cm^{-2} s^{-1} – equivalent to an effective exposure time of several months or more. Brandt *et al.* (2001) used this technique for 24 Lyman Break galaxies at z $\sim$ 3 in the Hubble Deep Field North (Steidel *et al.* 1996) and detected a signal with an average luminosity of 3×10^{41} erg s^{-1} – similar to that of nearby starburst galaxies. Nandra *et al.* (2002) confirmed this result by increasing the number of Lyman Break galaxies to 144 and then extended it to also include 95 Balmer Break galaxies at $z \sim 1$. The Balmer Break galaxies were detected with a lower average luminosity of 7×10^{40} erg s^{-1} , but a similar X-ray to optical luminosity ratio as the Lyman Break galaxies. Hornschemeier *et al.* (2002) report 'stacking' detections of optically luminous spiral galaxies at $0.4 < z < 1.5$.

These *Chandra* X-ray Observatory detections of normal galaxies at high redshifts have initiated the study of the X-ray evolution of normal galaxies over cosmologically interesting distances. Evolution of the X-ray properties of galaxies is to be expected because the star formation rate (SFR) of the universe was at least a factor of 10 higher at redshifts of 1–3 (Madau *et al.* 1996). Since the X-ray luminosity of galaxies scales with the infra-red and optical luminosity (see Section 11.5; Fabbiano, Gioia & Trinchieri 1988; David, Jones and Forman 1992; Shapley, Fabbiano & Eskridge 2001; Fabbiano & Shapley 2002) the increased star formation will have a corresponding impact on the X-ray properties of galaxies at high redshift (White and Ghosh 1998). For spiral galaxies without an AGN, the overall X-ray luminosity in the 1–10 keV band will typically be dominated by the galaxy's X-ray binary population. There is expected to be a corresponding increase in the number of high mass X-ray binaries associated with the increased star formation rate. The 'detection' of the Balmer and Lyman Break galaxies by Nanda *et al.* (2001) and the factor of 5 increase in the X-ray luminosity from redshift 1 to 3 is consistent with an increasing star formation rate. Nandra *et al.* (2001) point out that the X-ray luminosity of galaxies provides a new 'dust free' method to estimate the star formation rate, as also pointed in the *Beppo-Sax* study of Ranalli, Comastri & Setti (2003), and by Grimm, Gilfanov & Sunyaev (2003).

The low mass X-ray binary (LMXB) population created by the burst in star formation at z > 1 may not emerge as bright X-ray sources until several billion years later (White and Ghosh 1998; Ghosh and White 2001). This is due to the fact that the evolutionary timescales of LMXBs, their progenitors, and their descendants are thought be significant fractions of the time-interval between the SFR peak and the present epoch. In addition to an enhancement near the peak ($z \approx 1.5$) of the SFR due to the prompt turn-on of the relatively short-lived massive X-ray binaries, there may be a second enhancement, by up to a factor ~ 10, at a redshift between ~ 0.5 and ~ 1 due to the delayed turn-on of the LMXB population (Ghosh and White 2001). This second enhancement will not be associated with an overall increase in the optical or infrared luminosity of the galaxy, resulting in an increase in the X-ray to optical luminosity ratio. Hornschemeier *et al.* (2001) using the 'stacking' technique detected X-ray emission from L_* redshift 0.4 to 1.5 spiral galaxies in the HDF-N. The X-ray to optical luminosity ratios are consistent with those of galaxies in the local universe (e.g., Shapley, Fabbiano & Eskridge 2001), although the data indicate a possible increase in this ratio by a factor of 2–3.

Ptak *et al.* (2001) discuss the observable consequences of the increased SFR at high redshifts for the X-ray detection of galaxies at redshift > 1 in the HDF-N. To do this Ptak *et al.* (2001) used the Ghosh and White (2001) models for the evolution of the underlying X-ray binary populations for several different possible SFR models (the SFR with redshift is not well known). Depending on the SFR model used, the average X-ray luminosity of galaxies in the HDF-N can be an order of magnitude higher than in the local universe. These model predictions can be translated into a prediction of the number counts verses flux. Fig. 11.14 taken from Hornschemeier *et al.* (2003) shows the number counts from the CDF-N (which are dominated by AGN), along with the predictions from Ptak *et al.* (2001) for two different SFR models. The emerging population of optically bright, X-ray faint (OBXF) galaxies detected in the CDF-N is also shown, along with the extension of the source counts to fainter fluxes using a fluctuation analysis of the CDF-N (Miyaji & Griffiths 2002) . The predictions are that emission from normal galaxies, largely at redshift of 1–3, will start to dominate the source counts somewhere between fluxes of 10^{-17} and 10^{-18} erg cm^{-2} s^{-1} . The cross on Fig. 11.14 shows the constraint from the stacking analysis of Hornschemeier *et al.* (2002) for relatively nearby spiral galaxies (z<1.5), which is in agreement with the predictions from Ptak *et al.* (2001) for the lower SFR models.

Much deeper *Chandra* exposures of several months or even a year long will be able to eventually reach fluxes of 10^{-18} erg cm^{-2} s^{-1} and directly test the models for the X-ray evolution of galaxies – given the projected long lifetime of *Chandra* and good luck, these very deep exposures will hopefully will eventually happen as the mission matures. To obtain spectra of these galaxies, which are typically at a redshift of 1–3, and to see higher redshift objects at a similar faint flux level, will require 100-1000 times more collecting area with 1 arc sec angular resolution to avoid confusion (e.g., Fabbiano 1995, 2000; Elvis & Fabbiano 1997; Fabbiano & Kessler 2001). Even more challenging, to resolve an AGN or an offset ULX from more extended emission from the galaxy will require an angular resolution of order 0.1 arc sec. Such mission parameters are technologically extremely challenging, but nonetheless are being pursued by NASA, ESA and ISAS as a long term goal for X-ray astronomy (Parmar *et al.* 2002, Zhang *et al.* 2002).

11.7 Conclusions

As we have shown in this review, X-ray studies of galaxies are now yielding copious information on the properties of their XRB populations. The classification and study of these different populations is providing a unique tool for understanding the origin and evolution of XRBs, and for relating these sources to the evolution of the stellar populations of the parent galaxies, both in the nearby and the far-away universe.

This work would not have happened without the vision of Riccardo Giacconi, who pushed forward the high resolution X-ray telescope concept, and the work of Leon Van Speybroeck, who designed the *Chandra* optics. We thank the colleagues that have provided figures and comments (Martin Elvis, Albert Kong, Ann Hornschemeier, Vicky Kalogera, Jon Miller, Doug Swartz, Andreas Zezas, Harvey Tananbaum, Phil Kaaret, Jeff McClintock, Andrew King). This work benefitted by the

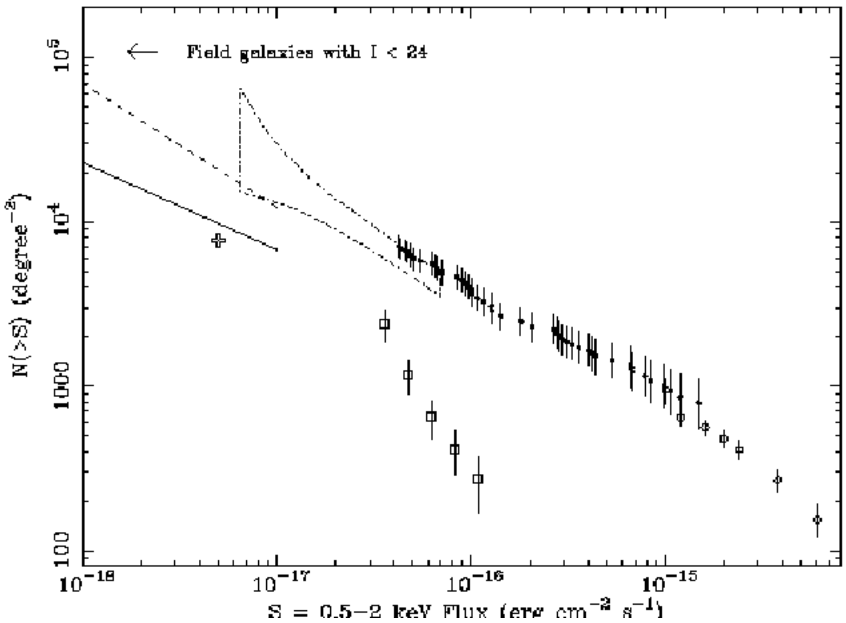

Fig. 11.14. CDF-N number counts, with predictions (ar the faint end) based on different SRF at high redshift. The open boxes are the counts from the optically bright, X-ray faint sources - these are mainly normal and starburst galaxies, but some low-luminosity AGN may be present -. The cross is the result of the 'stacking' analysis using $z \leq 1.4$ galaxies in the CDF-N field. The solid and dashed lines at the lowest fluxes are the the predictions of the galaxy number counts from Ptak et al 2001 (from Hornschemeier et al 2003). The leftward pointing arrow indicates the number density of field galaxies at $I = 24$ mag.

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