The Challenge to Large Optical Telescopes from X-ray Astronomy

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ABSTRACT

In the ROSAT era of the mid-1990s, the problems facing deep X-ray surveys could be largely solved with 10 m class telescopes. In the first decade of this new millennium, with X-ray telescopes such as the Chandra X-ray Observatory and XMM-Newton in operation, deep X-ray surveys are challenging 10 m telescopes. For example, in the Chandra Deep Field surveys, \( \approx 30\% \) of the X-ray sources have optical counterparts fainter than \( R = 25 \) \((I = 24)\).

This paper reviews current progress with 6–10 m class telescopes in following up sources discovered in deep X-ray surveys, including results from several X-ray surveys which have depended on telescopes such as Keck, VLT and HET. Topics include the prospects for detecting extreme redshift \( (z > 6) \) quasars and the first detections of normal and starburst galaxies at cosmologically interesting distances in the X-ray band.

X-ray astronomy can significantly bolster the science case for the next generation of large aperture (30–100 m) ground-based telescopes and has already provided targets for these large telescopes through the Chandra and XMM-Newton surveys. The next generation of X-ray telescopes will continue to challenge large optical telescopes; this review concludes with a discussion of prospects from new X-ray missions coming into operation on a 5–30 year timescale.

Keywords: Deep X-ray surveys, Galaxies, AGN, stars

1. INTRODUCTION

X-ray astronomy has made great strides in the past several years with the larger effective areas and greatly improved spatial resolutions of Chandra and XMM-Newton (both launched in 1999). However, the science results from deep X-ray surveys even before these missions relied heavily on the information obtained from large ground-based optical telescopes. For example, those who carried out the optical follow-up of the ROSAT Ultra Deep Survey (UDS) sources broke through major barriers only when 10 m telescopes became available.

The purpose of this contribution is to describe the science coming from deep X-ray surveys, including the nature of the first supermassive black holes in the Universe and the evolution of the high-energy emission from normal and starburst galaxies since \( z \approx 1 \). These scientific results have relied critically on ground-based optical follow-up with large telescopes such as Keck, VLT, and the HET, fitting well with this conference’s theme of “science with 6–10 m class telescopes.”

1.1. An X-ray Astronomy Primer

X-ray astronomy utilizes much smaller aperture optics than in the optical band (the Wolter-type Chandra mirrors have diameters between 0.6–1.2 m and effective area \( \approx 100–600 \text{ cm}^2 \) over 0.5–8 keV), but these “small” X-ray telescopes are revolutionizing our understanding of the high-energy Universe. This section covers some general terms and definitions in X-ray astronomy for those who observe outside the X-ray band.

The X-ray surveys discussed here cover the 0.5–10.0 keV band, a dynamic range of frequency as large as that from the near-infrared to the ultraviolet. There is generally a division made between the “soft” and “hard”
X-ray bands, largely due to the nature of X-ray detectors. The soft band is typically $0.25 \lesssim E \lesssim 2 \text{ keV}$ and the hard band is $2 \lesssim E \lesssim 10 \text{ keV}$. Many non-thermal X-ray sources are described empirically as a power law of the form $F_E = N_E E^{-\Gamma}$ where $N_E$ is the normalization at 1 keV in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$. The parameter $\Gamma$ is called the photon index. The shape of a source’s X-ray spectrum is often described by its “hardness”: an object with a flat X-ray spectrum (smaller $\Gamma$) is referred to as “hard”.

X-rays are an important way to study supermassive black holes as they are thought to be a universal property of accretion. Throughout this paper “accreting supermassive black holes” is synonymous with “active galactic nucleus” (AGN). Energetically X-rays are significant, comprising between 2–20% of the radiant power of AGN. The AGN X-ray emission at energies up to $\sim 100 \text{ keV}$ is believed to originate as ultraviolet and optical photons from the accretion disk that illuminate a hot ($\sim 10^7$–$10^9 \text{ K}$) corona. The corona, or ionized plasma surrounding the black hole, reprocesses this radiation, perhaps via inverse Compton scattering, and results in a non-thermal X-ray spectrum (a power-law). Though there is significant scatter in its value, $\Gamma$ typically ranges from 1.7–2.3 for radio-quiet luminous AGN.

Radio-quiet luminous AGN have X-ray luminosities in the range $10^{42} – 10^{45} \text{ erg s}^{-1}$ (0.5–8 keV); below this range AGN are referred to as low-luminosity AGN (LLAGN), as they have much lower luminosity than expected for accretion via a geometrically thin, optically thick accretion disk onto a supermassive black hole. AGN are generally classified, both in the optical and X-ray bands, by the level of obscuration toward the accretion activity. The classification of “obscured/unobscured” refers to the X-ray spectral classification of an AGN’s spectrum, where the obscuration is described by the hydrogen column density, $N_H$. Optical classification is split into “Type I” and “Type II” where Type I objects demonstrate broad ($> 1000 \text{ km s}^{-1}$) emission lines and Type II objects only show narrow lines. Generally, X-ray obscured AGN are also Type II objects, although obscuration in the X-ray is not necessarily concordant with obscuration in the optical.

The “normal” galaxies discussed here are much less X-ray luminous than typical AGN; the most luminous normal galaxies have $L_X \approx 10^{42} \text{ erg s}^{-1}$ (typical X-ray luminosities are $L_X \approx 10^{39} – 10^{40} \text{ erg s}^{-1}$). X-ray emission is an important way to study star formation in galaxies, revealing stellar endpoints (i.e., compact objects in binaries, supernovae) that are often much less visible in other wavebands. Significant amounts of matter may be found in the hot phase of the interstellar media (ISM) of galaxies, representing another key physical property of quiescent galaxies that requires X-ray observation to be accurately measured.

While the dominant X-ray emission from AGN is generally confined to the central part of the galaxy, the X-ray emission from normal galaxies is more spatially extended as it arises from accreting binary star systems, supernova remnants, and hot ISM. An LLAGN component may also be present, although these rarely dominate the X-ray emission (LLAGN may have X-ray luminosities as low as $\approx 10^{38} – 10^{39} \text{ erg s}^{-1}$).

X-rays break degeneracies concerning the origin of far-infrared/submillimeter emission from high-redshift dusty starbursts, providing another independent diagnostic of the evolution of star-formation processes over cosmic time. X-rays are also more penetrating than ultraviolet emission which has been used to diagnose levels of current star-formation.

1.2. Deep X-ray Surveys and the X-ray Background
The imprint of every physical process over the history of the Universe is present in the extragalactic background radiation (EBR; for a review, see Hasinger & Gilli). The spectrum of the EBR is shown in Figure 1 and is clearly dominated by the Cosmic Microwave Background (CMB), which is the signature of the very early Universe at the epoch where matter and radiation decouple. At far-infrared wavelengths, we are likely observing the re-radiation of emission from physical processes such as accretion or star-formation obscured by dust; however the precise nature of the relative contribution of the two is still under study. In the optical and ultraviolet, starlight is thought to dominate the total sky. Finally, at X-ray energies, the sky is thought to be dominated by emission from accreting supermassive black holes. We refer to the X-ray portion of the EBR as the cosmic X-ray background (CXB).
The cosmic energy density spectrum from radio waves to high-energy gamma rays in a $\nu I_\nu$ representation. This figure is adapted from Hasinger & Gilli\cite{Hasinger} with permission; the references for the data are contained within this article. The Cosmic Microwave Background (CMB) clearly dominates the EBR. The other three distinct components are the Cosmic Far-Infrared Background (CIB), the Cosmic Optical/Ultraviolet Background (COB), and the Cosmic X-ray/Gamma-Ray Background (CXB).

The spectrum of the CXB peaks at high energies ($kT \approx 40$ keV), and the energy range over which it may be observed is quite large ($\approx 0.1$ keV–1 MeV) representing a span of four decades in frequency. In the intervening years since the discovery of the CXB (in the 1960’s\cite{Hasinger}), more progress has generally been made towards resolving the background at other wavelengths than in the X-ray band. This is largely due to the technical difficulty of building X-ray optics with spatial resolution $\lesssim 30''$.

The photon index of the CXB ($\Gamma = 1.4$ from 1–10 keV\cite{Iwasawa}) is much harder than the $\Gamma \approx 1.7$–2.3 typical of unobscured AGN in the nearby Universe. AGN synthesis models\cite{Iwasawa, Bautz} can reproduce the CXB spectrum from 1–20 keV but require the existence of a substantial obscured AGN population (column densities in the range $N_H = 10^{21}$–$10^{25}$ cm$^{-2}$). The hardness of the CXB stands in contrast to the types of AGN turned up in many of the deep X-ray surveys prior to the Chandra–XMM-Newton era (mainly Type I AGN), creating the so-called “spectral paradox.” As will be described in the following sections, this paradox is now partially solved.

2. SCIENCE RESULTS FROM OPTICAL FOLLOW-UP PROGRAMS BEFORE CHANDRA AND XMM-NEWTON

2.1. The Soft ($<2$ keV) Background

A large fraction of the soft ($<2$ keV) CXB was identified prior to Chandra and XMM-Newton through the combined sensitivity and imaging quality ($\lesssim 5.0''$) of ROSAT. The deepest ROSAT survey performed was the UDS\cite{Hasinger} of the Lockman Hole, chosen for its extremely low Galactic absorption ($N_H \approx 5 \times 10^{19}$ cm$^{-2}$). The
UDS sample includes 94 X-ray sources with \( f_X > 1.2 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\)(0.5–2.0 keV) that were detected in a 1112 ks \textit{ROSAT} High Resolution Imager (HRI) observation. At this flux level \( \approx 70–80\% \) of the X-ray background in the 0.5–2.0 keV band is resolved. The HRI observations were critical for optical identifications as they as they produced positions accurate to \( \approx 2'' \).

Ground-based optical observations identified \( \approx 90\% \) of the UDS sources.\(^7\) The optically brightest counterparts were observed with the 5 m Hale telescope, but the majority of the sources required a larger aperture. The 10 m Keck telescope was used for this program as early as February 1995,\(^7\) showing that the marriage between deep X-ray surveys and large telescopes goes back to the beginning of the era of 10 m class telescopes.

Of these identified UDS sources, Type I (generally unobscured) AGN comprised \( \approx 61\% \) of the sources and Type II (generally obscured) AGN comprised \( \approx 14\% \). The Type I AGN were detected up to \( z = 4.45 \),\(^6\) enabling the X-ray QSO luminosity function to be constructed over a large interval of cosmic time.\(^7\) Interestingly, the number density of luminous QSOs as measured in the X-ray band did not demonstrate the decline seen above \( z \sim 2 \) in the optical band.\(^7\) One possible interpretation for this difference between X-ray and optical selection of high-redshift QSOs is a difference in the bolometric luminosities being sampled. Bolometric luminosity may be correlated with the mass of the accreting black hole, indicating possible differences in AGN evolution based on black hole mass.\(^7\)

The UDS Type II AGN were typically found at lower redshifts (and lower X-ray luminosities). The median redshift of the Type II AGN in the UDS survey was \( z \approx 0.6 \).\(^7\) Recall (§1.2) that AGN synthesis models of the CXB predict a high fraction of obscured AGN at high redshift.\(^7\) Note also that at \( z > 3 \) the \textit{ROSAT} band samples energies \( > 2 \) keV; at these hard energies X-ray photons can easily penetrate column densities as high as \( N_H \approx 10^{22} \) cm\(^{-2}\)(and higher columns at even higher redshift). The observations thus presented a puzzle in that the population of luminous, obscured AGN predicted by some CXB synthesis models\(^7\) were not being found.

One of the results of the \textit{ROSAT} UDS that is also relevant to this contribution was the confirmation that AGN tend to exist in a certain range of X-ray-to-optical flux ratio \( (f_X/f_V) \). The X-ray to optical flux ratio had been found to be a useful discriminator of object type in the \textit{Einstein} Medium-Sensitivity Survey (EMSS\(^7\)), where AGN were noted to have \( -1.0 < \log f_X/f_V < 1.2 \) whereas normal galaxies were found to have values of \( \log f_X/f_V < -1.0 \). Schmidt et al.\(^7\) extended this to the greater depths of the \textit{ROSAT} UDS, showing that 97\% of the UDS AGN had \( \log f_X/f_V > -1.0 \).

The second most abundant class of objects in soft X-ray surveys (after AGN) are clusters of galaxies. There were 10 extended objects (the majority of which were groups of galaxies) detected in the UDS over the \( \sim 30' \) \textit{ROSAT} field of view.\(^7\) The clusters included one which is double-peaked in the X-ray image and is possibly two merging clusters of galaxies \((z = 1.26, \text{RXJ105343+5735}^\text{?})\).

Thus, the basic picture of the soft CXB prior to \textit{Chandra} was that it was mostly resolved, and most of the extragalactic X-ray point sources were Type I AGN. The Type II AGN were found preferentially at lower redshifts and lower X-ray luminosities.

### 2.2. The Hard \((> 2 \) keV\)) Background

The greatest progress in understanding the CXB at \( E > 2 \) keV before \textit{Chandra} and \textit{XMM-Newton} was made with the \textit{ASCA} (e.g., Akiyama et al.\(^7\)) and \textit{Beppo-SAX} (e.g., Fiore et al.\(^7\)) satellites. Due to space constraints I have focused on soft-band surveys; this section is in no way a comprehensive review of hard-band surveys. Before these missions, only \( \sim 3\% \) of the \( > 2 \) keV background was resolved into individual point sources by \textit{HEAO-1}\(^7\). \textit{ASCA} and \textit{Beppo-SAX} were able to identify the hard CXB sources to 2–10 keV fluxes of \( \approx 1 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). The expected range of X-ray-to-optical flux ratios for AGN, calculated at this limit, resulted in expected optical magnitudes of \( V \approx 16–21 \) for the counterparts. The positional accuracy of

\(^7\)The decline in luminous QSO number density at high redshift as measured in the optical band has been extended to higher redshift recently by Fan et al.\(^7\) This work confirms the decline.
Figure 2. Some extragalactic X-ray surveys in the 0.5–2 keV band, displayed as limiting sensitivity versus solid angle. The dashed vertical line indicates coverage of the full sky. The larger circles mark current Chandra and XMM-Newton surveys. Note that in 100 ks of observation with Chandra one is already able to go significantly deeper than the previous generation of X-ray surveys. This figure is adapted from Brandt et al.; references for these surveys are given there.

ASCA and Beppo-SAX are comparable, typically ≈ 30″. In some cases, observations with other X-ray observatories at softer energies allowed more precise positioning, but generally multiple objects had to be observed spectroscopically to determine the correct optical counterpart. ASCA and Beppo-SAX were able to resolve and identify ≈ 20–30% of the hard CXB to 2–10 keV fluxes of ≈ 1 × 10⁻¹³ erg cm⁻² s⁻¹. At this level the number counts (log N–log S, N is the number of sources per unit solid angle brighter than a given flux, S) in the hard band are still consistent with a Euclidean slope. A significant fraction of the hard CXB, although not the majority, was thus resolved before Chandra and XMM-Newton and while AGN dominated this resolved fraction, there still was not a large population of high-redshift obscured AGN found.

3. SCIENCE RESULTS FROM OPTICAL FOLLOW-UP OF X-RAY SOURCES

Chandra has allowed soft band X-ray fluxes as low as 1 × 10⁻¹⁶ erg cm⁻² s⁻¹ and hard band X-ray fluxes as low as 6 × 10⁻¹⁶ erg cm⁻² s⁻¹ to become attainable with moderately deep (∼ 200 ks) observations. These fluxes are ≈ 10× fainter in the soft band and ≈ 100× fainter in the hard band than the previous generation of deep surveys. Chandra’s sub-arcsecond spatial resolution also allows for the first unambiguous matching to optical counterparts at hard energies. Some example Chandra and XMM-Newton surveys are compared with other X-ray surveys in Figure 2. Note that this figure is just a representative sample as the X-ray surveys carried out so far are too numerous to plot.

The science covered here includes results from the Chandra Deep Field (CDF) Surveys, which have reached 2 Ms of coverage in the North (hereafter CDF-N) and 1 Ms of coverage in the South (hereafter CDF-S), representing the deepest X-ray views of the Universe to date. Among the XMM-Newton surveys, the Lockman
Figure 3. $R$-band magnitude versus soft-band X-ray flux for Chandra Deep Field-North sources within the high exposure area, from Hornschemeier et al.\textsuperscript{7}; the CDF-N sources are marked with open symbols. The triangles mark upper limits, these sources are potential $z > 6$ AGN. For comparison, the filled circles show the X-ray sources detected in the ROSAT UDS.\textsuperscript{7} The shaded regions indicate typical values of X-ray-to-optical flux ratio for different classes of objects. The sources located in the lowest shaded region have X-ray-to-optical flux ratios well below those expected for AGN; this is the regime of the normal and starburst galaxies.
Hole continues to be an important field for X-ray surveys\(^1\). Also discussed are some wide-field X-ray surveys, including the 5 deg\(^2\) Chandra Multiwavelength Project\(^2\) (ChaMP) and the “An XMM-Newton International Survey” (AXIS\(^2\),\(^7\)). Results are included from the 100 ks Chandra Spectroscopic Photometric Infrared-Chosen Extragalactic Survey (SPICES\(^2\)) survey. Briefly discussed also is X-ray follow-up of sources discovered in optical surveys such as the Sloan Digital Sky Survey (SDSS).

For the overall nature of optical follow-up of X-ray point sources\(^3\), refer to the plot of R-band magnitude versus 0.5–2 keV X-ray flux shown in Figure 3 for the CDF-N survey. The range of X-ray-to-optical flux ratio typical of AGN is marked, and we see that it continues to hold for a large number of sources down to (extremely!) faint optical magnitudes. Attention should be drawn to the faintest limits in both optical flux and X-ray flux. At very faint optical fluxes (upper left of diagram), the sources are still consistent with the expected values for AGN, and this is where we expect high redshift (possibly even \(z > 6\)) AGN to exist. At very faint X-ray fluxes (left side), we find quite a few sources whose optical counterparts are brighter than expected for AGN—these sources are fairly “normal” galaxies, with their X-ray emission dominated by processes associated with, among others, active star-formation and accreting binary systems. We are now able to detect these normal galaxies in the X-ray band at cosmologically interesting distances (i.e. \(z > 0.1\)).

### 3.1. X-ray Selected AGN at High Redshift (\(z > 3\))

Many of the X-ray sources detected in deep Chandra and XMM-Newton surveys are optically faint (\(I > 24\)).\(^7\) This presents a real challenge to ground-based optical observatories, and exceeds the practical limit for optical spectroscopy even with the largest (10 m) telescopes. The properties of the optically faint X-ray population (X-ray hardness, X-ray-to-optical flux ratio) indicate that many are luminous obscured AGN at \(z > 1\),\(^?,\(^?,\(^?,\(^?,\(^?,\(^?)\) meaning that these sources provide an important window into the evolution of obscured accretion power in the earlier Universe and may contain the elusive population of luminous obscured AGN at high redshift.

Already there has been remarkable success in selecting AGN at very high redshifts (\(z > 5\)) with Chandra. At the time of writing two very high redshift AGN have been selected in deep X-ray surveys; \(z = 4.93\) (discovered through ChaMP\(^7\)) and \(z = 5.18\) (discovered in the CDF-N\(^2\),\(^7\)). The optical spectra of these two highest redshift X-ray selected AGN are shown in Figure 4. Chandra is also able to detect Seyfert-luminosity objects at \(z > 4\), as evidenced by the detection of a lower-luminosity AGN at \(z = 4.424\) in the CDF-N.\(^7\)

It is still the case that the vast majority of known \(z > 4\) AGN\(^5\) have been discovered in the optical band. This is largely an effect of the relative size of the areas surveyed. For example, if we could reach the X-ray depth of the CDF surveys over the SDSS early data release area\(^2\) (\(\approx 500\) deg\(^2\)), we would expect to find \(\approx 15,000\) AGN at \(z > 4\).\(^7\) There are \(\approx 45\) optically-selected AGN at \(z > 4\) in this area.\(^7\) The highest redshift quasars known to date were discovered in the SDSS\(^2\) (\(z = 5.74, 5.82, 5.99, 6.28\)) and all four of these have been detected with Chandra or XMM-Newton.\(^7\) Interestingly, despite the large change in the number density of optically luminous QSOs,\(^?,\(^?,\(^?)\) there has not been strong evolution in certain properties, including the optical-to-X-ray spectral index, \(\alpha_{ox}\), in optically selected (radio-quiet) AGN from \(z \approx 3\) to the present.

Optical selection of quasars of course carries a bias against heavily absorbed objects that is less significant in the X-ray band, in particular for high-redshift objects where the observed X-ray emission comes from hard-to-absorb high-energy photons. It has been found that X-ray selected quasars at \(z > 4\) have flatter values of \(\alpha_{ox}\)\(^7\) (are more X-ray bright) than optically selected \(z > 4\) quasars, as expected from optical selection effects. Among the optically selected, X-ray faint \(z > 4\) AGN\(^7\) are those which tend to exhibit signs of absorption, including strong ultraviolet absorption features.\(^7\) XMM-Newton has found some strange absorbed AGN: \(\approx 10\%\) of the

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\(^1\)Space prohibits additional discussion of the results from the Lockman Hole survey, covered in \(\S 2.1\). The reader is referred to Hasinger et al.\(^7\) for more discussion.

\(^2\)Diffuse X-ray sources are not discussed here; these are clusters and groups of galaxies. The reader is referred to Bauer et al.\(^7\) and references therein for discussion of extended X-ray sources.

\(^3\)There are \(\approx 400\) \(z > 4\) AGN as of mid-2002. http://www.astro.caltech.edu/~george/z4.qsos
AXIS sources exhibit strong ultraviolet absorption but not photoelectric absorption in the X-ray. It is clear that X-rays are an efficient means for selecting rare AGN populations which will provide critical information on the nature of obscured activity in the Universe.

Pursuing the nature of ultraviolet absorption may be the key to understanding the early growth of supermassive black holes. Are the material outflows which possibly give rise to these absorption features much stronger at the higher accretion rates which may be present in nascent black holes? Pursuing questions of this type requires sensitive near-infrared spectroscopic observations. An excellent example of this is the observation of the $z = 5.74$ XMM-Newton-detected QSO by two groups. This object has $K \approx 17$ and a high signal-to-noise spectrum was obtained with NIRSPEC in 2.7 hours of observation. If we are to unambiguously identify all of the optically faint Chandra population (many of which are Extremely Red Objects with $I - K > 4$), high signal-to-noise spectroscopy will be needed at $K \gtrsim 24$. This is clearly in the realm of large-aperture (30–100 m) telescopes.

As mentioned in §2.2, X-ray background synthesis models required a substantial population of highly obscured luminous AGN at hard X-ray energies. Sources with the expected hard X-ray spectra have been found in deep X-ray exposures, but the spectroscopic identification of these potentially high-redshift obscured AGN is still far from complete (both due to optical faintness and to the large size of the areas surveyed). There have been a few instances of successful optical spectroscopic observations of interesting obscured AGN. The Chandra Deep Field-South team has found one convincing case for a luminous, high-redshift Type 2 QSO for which they were able to obtain a VLT optical spectrum (see Figure 4) and another object was found in the SPICES survey with Keck. Perhaps there are more such objects lurking in the unidentified X-ray source population, but it already appears that the X-ray background synthesis models may need major revision, as a significant fraction of the hard X-ray background flux is identified with sources at fairly low redshift. Of course, the final answer awaits the positive identification of the remaining $\approx 30\%$ of the hard XRB flux density (and possibly for the higher energy capability of future X-ray missions, see §4).

Ultradeep ($\gtrsim 1$ Ms) Chandra surveys may have already achieved the sensitivity to detect of the first supermassive black holes (SMBHs) to form in the Universe at $z \approx 8–20$. X-ray surveys represent one of the few ways that such objects might be found. These SMBHs are thought to play a crucial role in galaxy formation. Such $\approx 10^{5–7} M_\odot$ “proto-quasars” are expected to have X-ray luminosities comparable to those of local Seyfert galaxies.

### 3.2. Starburst/normal Galaxies at Moderate Redshift ($z \gtrsim 1$)

While many of the sources with the high X-ray-to-optical flux ratios typical of AGN are extremely optically faint, other populations are arising in deep X-ray surveys which are well-matched to the capabilities of 10 m telescopes. One of these is the normal and starburst galaxy population, whose X-ray emission is thought to originate from accreting binary star systems, supernova remnants, and the hot ISM. What is new in the Chandra and XMM-Newton era is that we are detecting normal galaxies at cosmologically interesting distances (look-back times of billions of years).

Prior to Chandra and XMM-Newton studies of galaxies in the X-ray band had not reached far beyond $z \approx 0.05$. In the CDF surveys, galaxies with $0.1 \lesssim z \lesssim 1.0$ are detected in appreciable numbers at $0.5–2$ keV fluxes below $1 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (see Figure 3). The bulk of the energy density of the CXB is certainly explained by AGN (see the preceding sections), but the investigation of the “typical” galaxy, whether its X-ray emission is dominated by a population of X-ray binaries, hot interstellar gas, or even a low-luminosity AGN, is an equally important function of deep X-ray surveys. Normal galaxies are likely to be the most numerous extragalactic X-ray sources in the Universe and are expected to dominate the number counts at $0.5–2$ keV fluxes below $\approx 1 \times 10^{-17}–1 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$. It is only with Chandra that it has been possible to measure the normal and starburst galaxy X-ray number counts. The number counts of the X-ray-detected normal galaxy population are much steeper than that of the rest of the X-ray sources discovered in deep surveys (see Figure 5), and to resolve the last few percent of the X-ray background requires the presence of this large population.
Reaching larger look-back times at high energies presents the exciting possibility of detecting the bulk X-ray response to the heightened star-formation rate at $z \approx 1.5–3$. One expects the X-ray luminosity per unit $B$-band luminosity to be larger at $z \approx 0.5–1$ due to the increased production of X-ray binary progenitors at $z \approx 1.5–3$; this X-ray emission represents a “fossil record” of past epochs of star formation. Therefore, measurements of the X-ray luminosities of typical galaxies can constrain models of X-ray binary production in galaxies.

Even with 1 Ms of X-ray coverage, many normal/starburst galaxies are individually undetected in the X-ray band. X-ray stacking analyses, possible because of the extremely low Chandra background, allow for the study of these individually undetected objects. One such Chandra study (to $z \approx 1$) has found that the average spiral galaxy is detected at $0.5–2$ keV X-ray fluxes of $\approx (3–5) \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$. The X-ray to $B$-band luminosity ratio is found to be relatively constant to $z \approx 1$, but some upwards evolution is detected by $z \approx 2$. Since different global star-formation rates can lead to very different X-ray luminosity evolution profiles (e.g. Ghosh & White), these constraints on the evolution of galaxies in the X-ray band are a useful independent probe of the cosmic star-formation history.

At higher redshift still ($z \approx 2–4$), the Lyman break technique has been used extensively to isolate actively star-forming galaxies and hence observe galaxies near the peak of the cosmic star-formation rate. Lyman break galaxies have been stacked in the X-ray to find an average rest-frame 2–8 keV luminosity of...
Figure 5. Number counts for the X-ray detected “normal” galaxies in the CDF-N 2 Ms survey as compared to other studies. The black filled circles are the CDF-N 1 Ms data. The open squares indicate ROSAT UDS data. The dashed and solid black lines at faint X-ray fluxes show two predictions of the galaxy number counts from Ptak et al. The open cross marks the constraint from the 1 Ms stacking analysis of individually undetected field spirals. The arrow indicates the number density of field galaxies at $I = 24$. This figure adapted from Hornschemeier et al. with permission.

\[ \approx 3.2 \times 10^{41} \text{ erg s}^{-1}, \] comparable to that of the most X-ray luminous starbursts in the local Universe. The observed ratio of X-ray to $B$-band luminosity for these higher redshift galaxies is consistent with that seen from local starbursts. This technique of statistical X-ray analysis to survey objects selected in the optical may also be useful at intermediate redshifts to determine the properties of $z \approx 1$ “Balmer-Break” galaxies. The Balmer-Break galaxies are found to have X-ray luminosities approximately five times lower than the Lyman-Break galaxies, but the connection between the X-ray emission and the ultraviolet emission of these galaxies is unclear. What is clear is that there is a new body of information on the evolution of star-formation that remains to be fully exploited.

Deep X-ray surveys have also reached the sensitivity to detect individual non-nuclear point sources within galaxies to appreciable distances ($z \approx 0.3$). These sources are Ultra-luminous X-ray (ULX) sources with luminosities tens of hundreds of times higher than expected for Eddington-limited accretion onto a stellar-mass black hole (see Figure 6). ULX sources represent either an intermediate-mass ($\approx 100$–$500 M_\odot$) class of black holes, or a beamed, relatively brief phase of more normal stellar mass black hole binary evolution. Intermediate-mass black holes are of particular interest as they may be the seeds for the growth of supermassive black holes. Several candidate ULX sources within nearby galaxies have already been detected in the CDF-N, and continued follow-up of X-ray surveys promises many more.

Deep X-ray surveys with Chandra and XMM-Newton cover roughly square fields of side length $\sim 18$–$30$ arcminutes, requiring the wide-field capabilities of instruments such as the VLT’s Virmos (see Giampaolo Vettolani’s contribution in this same proceedings) and the Keck’s DEIMOS (see Marc Davis’ contribution in this
The location of the X-ray emission is marked by a circle of radius $1''$, somewhat larger than the expected X-ray positional error. The X-ray source appears to be located along a spiral arm and is coincident with a region of slightly enhanced optical emission. From X-ray variability analysis, this source is determined to be a black hole candidate.

same proceedings). The required depth of coverage to complement $\gtrsim 1$ Ms Chandra surveys is $R \approx 23$ over these large fields; since many of these normal galaxies are absorption-dominated, 10 m telescopes are clearly required.

4. THE NEXT GENERATION OF OBSERVATORIES

In the late 1990’s, it was demonstrated that 10 m telescopes and deep ROSAT surveys were well matched; $\approx 96\%$ of the ROSAT UDS sources were successfully identified though optical ground-based observations. In the early 2000’s, $\approx 30\%$ of the sources detected in X-ray surveys with Chandra and XMM-Newton are beyond the reach of optical spectroscopic observations with 10 m optical telescopes but populations such as X-ray detected normal and starburst galaxies are found to be well-matched with 10 m telescopes. Within the optically faint population lies the answer to the question of how much of the accretion activity of the Universe is obscured and key parameters concerning the growth of the first supermassive black holes of the Universe. Within the X-ray detected galaxy population is crucial information on the growth of stellar and intermediate-mass black holes and new physical measures of star-formation processes. The identification of many of the optically faint sources must necessarily wait for the light-collecting power of 30–100 m telescopes. The normal and starburst galaxies will be well-studied for the first time now that wide-field multi-object spectrographs are available on 10 m class telescopes (e.g., VLT Virmos and Keck DEIMOS).

What does the next generation of X-ray telescopes have in store? An excellent description of NASA’s future missions in X-ray astronomy is given in White et al. and in a review of new X-ray missions is presented in SPIE conference 4835 by Richard Mushotzky. The reader is also referred to the proceedings of the SPIE conference on X-ray missions (4851). Here I give a brief summary of what is to come in the next few decades.
The Constellation-X mission, which is planned for launch around 2010, will provide X-ray spectroscopy down to the faint limits of the CDF surveys, where formerly we have relied upon broad-band X-ray photometry. Recall that the collecting area of Chandra’s mirrors is \( \approx 100-600 \text{ cm}^2 \) over 0.5–8 keV (the collecting area of XMM-Newton is higher at \( \approx 400-1300 \text{ cm}^2 \) over 0.5–10 keV). Constellation-X is planned to have 15,000 \text{ cm}^2 effective area at 1 keV and spectroscopic coverage up to 40 keV \(^\dagger\). This large collecting area will allow for detailed emission-line analysis, we will be able to physically constrain the nature of the material near accreting supermassive black holes at \( z \approx 8 \) and resolve the emission lines in normal and starburst galaxies up to \( z \approx 1 \). X-ray spectroscopy of individual stellar-mass black holes up to \( z \approx 0.3 \) will also become possible.

The XEUS and Generation-X observatories are currently being planned on longer timescales (10–20 years) to study X-ray sources down to 0.5–2 keV fluxes of \( \approx 4 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \approx 5 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively. It can be expected that the optical counterparts to many of these X-ray sources will be extremely faint (\( R > 30 \) if the trend of X-ray-to-optical flux ratio continues to these X-ray fluxes!). At this level, every quiescent and starburst galaxy in the Universe will be detected in the X-ray band to at least \( z \approx 3 \) and deep X-ray surveys shall closely resemble the optical Hubble Deep Field observations as far as areal density of sources. So, in addition to depth, high quality imaging will be needed, possibly only attainable with space-based near-infrared imagers such as NGST. It is clear that X-ray astronomy will continue to present many challenges for future generations of optical telescopes.

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\(^\dagger\)The reader is referred to the Constellation-X web page for the latest details on the mission design, http://constellation.gsfc.nasa.gov/