CHARACTERIZING THE X-RAY PROPERTIES AND EVOLUTION
OF DISTANT GALAXIES USING DEEP EXTRAGALACTIC
SURVEYS

A Thesis in
Astronomy and Astrophysics

by
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Abstract

With the advent of deep extragalactic X-ray surveys conducted using the Chandra X-ray Observatory (Chandra), it has now become possible to investigate the X-ray properties and evolution of distant populations of “normal” galaxies. Normal galaxies have X-ray emission that originates primarily from X-ray binary populations, supernovae, supernova remnants, hot interstellar gas, and O-stars; these galaxies are not heavily influenced by the presence of luminous active galactic nuclei (AGNs). In this thesis, I study the X-ray properties and evolution of normal galaxy populations over significant fractions of cosmic history, which for some populations extends from the present day to cosmic look-back times that correspond to $\approx 85-95\%$ of the age of the Universe (i.e., $z \approx 3-6$). These studies have been carried out using two of the most well-studied extragalactic multiwavelength survey fields: the $\approx 2$ Ms Chandra Deep Field-North (CDF-N) and the Extended Chandra Deep Field-South (E-CDF-S), which is composed of the central $\approx 1$ Ms Chandra Deep Field-South (CDF-S) and four flanking $\approx 250$ ks Chandra observations (see Chapter 2 for an extensive discussion of these observations). These Chandra Deep Fields (CDFs) are the most sensitive X-ray surveys yet conducted and are complemented by extensive multiwavelength coverage (e.g., through Galex, HST, Spitzer, Keck, NOAO, SCUBA, VLA, VLT). The combination of the deep Chandra data from the CDFs and their coincident multiwavelength observations have allowed for effective investigations of galaxy populations selected via morphological type, physical properties, and environment.

It is predicted that as galaxy populations assembled (via star-formation and galaxy/galaxy interactions) and aged passively (e.g., through dynamical relaxation, aging of stellar populations, and cooling of hot gas) into the diverse galaxy population that we observe in the local universe, the dominant X-ray properties (e.g., X-ray binaries and hot gas) of normal galaxies correspondingly evolved dramatically. In this thesis, I provide significant new constraints and insight into how the global X-ray properties evolved in response to the physical changes that the galaxy populations underwent. This is achieved through investigations of (1) the X-ray properties and evolution of early-type (E–S0) galaxies over the last half of cosmic time (i.e., since $z \approx 0.7$; Chapter 3), (2) the demographics and properties of intermediate-redshift ($z \approx 0.05-0.3$) off-nuclear X-ray sources within normal galaxies (Chapter 4), (3) the X-ray properties and evolution of late-type (Sa–Irr) galaxies over the last $\approx 70\%$ of cosmic history (i.e., since $z \approx 1.4$; Chapter 5), and (4) the average X-ray properties of distant ($z \approx 3, 4, 5, \text{ and } 6$) Lyman break galaxies and their AGN content (Chapter 6).
Table of Contents

List of Tables .................................................................................................................. vii
List of Figures .................................................................................................................. viii
Acknowledgments ......................................................................................................... xi

Chapter 1. Introduction .................................................................................................... 1
  1.1 Historical Perspective ............................................................................................ 1
  1.2 The Deepest Chandra Surveys ............................................................................. 2
  1.3 Normal Galaxies in the Local Universe ................................................................. 4
  1.4 Overview of this Thesis: Studying Normal Galaxies in the Distant Universe ........ 6

Chapter 2. The Extended Chandra Deep Field-South Survey. Chandra Source Catalogs 8
  2.1 Introduction .......................................................................................................... 8
  2.2 Observations and Data Reduction ....................................................................... 10
    2.2.1 Instrumentation and Observations ................................................................. 10
    2.2.2 Data Reduction ............................................................................................. 13
  2.3 Production of the Point-Source Catalogs ............................................................. 13
    2.3.1 Image and Exposure-Map Creation ............................................................... 14
    2.3.2 Point-Source Detection ................................................................................ 15
    2.3.3 Point-Source Catalogs ................................................................................ 17
      2.3.3.1 Main Chandra Source Catalog ................................................................. 17
      2.3.3.2 Supplementary Optically Bright Chandra Source Catalog 30
  2.4 Background and Sensitivity Analysis .................................................................... 36
  2.5 Number Counts for Main Chandra Catalog ........................................................ 37
  2.6 Extended Sources ................................................................................................. 42
  2.7 Summary ............................................................................................................... 45

Chapter 3. The X-ray Evolution of Early-Type Galaxies in the Extended Chandra Deep
Field-South ....................................................................................................................... 47
  3.1 Introduction .......................................................................................................... 47
    3.1.1 X-ray Properties of Early-Type Galaxies ....................................................... 47
    3.1.2 Physical Properties of the X-ray Emitting Components ............................... 48
    3.1.3 Observations of the X-ray Emission from Distant Early-Type Galaxies .......... 51
  3.2 Data Analysis ........................................................................................................ 52
    3.2.1 Sample Selection ......................................................................................... 52
      3.2.1.1 Removing AGN Contamination .............................................................. 52
      3.2.1.2 Normal Early-Type Galaxy Samples ..................................................... 54
    3.2.2 X-ray Stacking Technique .......................................................................... 57
  3.3 Results .................................................................................................................... 61
    3.3.1 Individually Detected X-ray Sources ......................................................... 61
3.3.2 X-ray Stacking Results ................................. 65
  3.3.2.1 Stacked Properties ............................. 65
  3.3.2.2 Assessing Remaining AGN Contamination .... 75
3.4 Discussion .............................................. 78
  3.4.1 Optically Luminous Early-Type Galaxies ...... 78
  3.4.2 Optically Faint Early-Type Galaxies .......... 80
  3.4.3 Future Work ...................................... 81
3.5 Summary ................................................. 82

Chapter 4. The Properties and Redshift Evolution of Intermediate-Luminosity Off-Nuclear X-ray Sources in the Chandra Deep Fields ........................................ 84
  4.1 Introduction .......................................... 84
  4.2 Off-Nuclear Source Sample Construction ........ 85
    4.2.1 Sample Selection ................................ 85
    4.2.2 X-ray and Optical Properties of Off-Nuclear Sources and Host Galaxies .... 88
  4.3 Analysis and Results ................................. 96
    4.3.1 The Observed Fraction ($f_O$) .................. 97
    4.3.2 The True Fraction ($f_T$) ....................... 99
    4.3.3 Consistency Check .............................. 105
  4.4 Summary and Future Work ............................ 106

Chapter 5. The X-ray Evolution of Late-Type Galaxies in the Chandra Deep Fields .......... 108
  5.1 Introduction .......................................... 108
  5.2 Late-Type Galaxy Sample Selection ............... 109
    5.2.1 Galaxy Selection Footprint .................... 110
    5.2.2 Redshifts ....................................... 110
    5.2.3 Rest-Frame Color and Morphological Selection .......... 112
  5.3 Physical Properties and Redshift Evolution of Late-Type Galaxies ............ 114
    5.3.1 Optical Luminosity ............................. 115
    5.3.2 Stellar Mass .................................... 115
    5.3.3 Star-Formation Rates ........................... 117
  5.4 Analysis .............................................. 118
    5.4.1 X-ray–Detected Late-Type Galaxies ............ 118
    5.4.2 X-ray Stacking Analyses of Normal Late-Type Galaxy Populations ....... 126
  5.5 Results ............................................... 129
    5.5.1 Stacking Results ................................ 129
    5.5.2 AGN Contribution to Stacked Signals .......... 132
  5.6 Extension to Distant Lyman Break Galaxies .............................................. 138
  5.7 Summary .............................................. 140

Chapter 6. The X-ray Properties of Distant Lyman Break Galaxies .................. 142
  6.1 Introduction .......................................... 142
  6.2 Analysis .............................................. 143
    6.2.1 Samples ......................................... 143
List of Tables

2.1 Journal of Extended *Chandra* Deep Field-South Observations .......................... 12
2.2 Main *Chandra* Catalog Source Properties .................................................. 19
2.3 Main *Chandra* Catalog Cross-Field Source Properties ................................. 26
2.4 Summary of *Chandra* Source Detections ..................................................... 28
2.5 Sources Detected In One Band But Not Another ............................................ 29
2.6 Supplementary Optically Bright *Chandra* Catalog ........................................ 34
2.7 Background Parameters ..................................................................................... 38
2.8 Extended-Source Properties ............................................................................... 44

3.1 X-ray Detected Early-Type Galaxies: Source Properties ................................. 63
3.2 Stacked Early-Type Normal Galaxies: Basic Properties ..................................... 66
3.3 Stacked Early-Type Normal Galaxies: Mean X-ray Properties ......................... 67

4.1 Off-Nuclear Sources: X-ray Properties ............................................................... 89
4.2 Off-Nuclear Sources: Additional Properties ...................................................... 90

5.1 X-ray Detected Late-Type Galaxies: Source Properties .................................... 124
5.2 Stacked Late-Type Normal Galaxies: Mean Properties ..................................... 125
5.3 Parametric Fitting Results For Stacked Samples ............................................. 132

6.1 X-ray Properties of Individually Detected LBGs ............................................... 146
6.2 Stacking Results For Normal LBGs ................................................................. 150
## List of Figures

1.1 False-color images of the \( \approx 2 \) Ms CDF-N and \( \approx 1 \) Ms CDF-S. ......................................................... 2  
1.2 Cumulative 0.5–2 keV and 2–8 keV number counts versus flux for extragalactic point-sources. ........................................ 3  
1.3 Chandra images of local galaxies with different optical morphologies. ....... 5  

2.1 0.5–2 keV sensitivity versus solid angle for several deep X-ray surveys conducted by Chandra ROSAT, and XMM-Newton. ....................... 9  
2.2 Chandra and HST covered regions of the Extended Chandra Deep Field-South (E-CDF-S) ............................................................... 11  
2.3 0.5–8 keV raw and smoothed images of the E-CDF-S. .................. 15  
2.4 0.5–8 keV exposure map of the E-CDF-S. .................................. 16  
2.5 Solid angle versus effective exposure time for the E-CDF-S. ........ 17  
2.6 Chandra false-color X-ray image of the E-CDF-S. ........................ 18  
2.7 Cross-band (optical/X-ray) offset versus off-axis angle for E-CDF-S sources. .......................................................... 21  
2.8 Distribution of net X-ray counts and fluxes for E-CDF-S sources. ...... 29  
2.9 Optical (R-band) postage-stamp images of E-CDF-S X-ray sources. 31  
2.10 Distribution map of X-ray sources in the E-CDF-S. ....................... 32  
2.11 X-ray band ratios versus 0.5–8 keV count-rates for E-CDF-S sources. 33  
2.12 R-band magnitude versus 0.5–2 keV flux for E-CDF-S sources. ....... 33  
2.13 0.5–8 keV background map of the E-CDF-S. ............................ 39  
2.14 0.5–8 keV sensitivity map of the E-CDF-S. ............................... 40  
2.15 Solid angle versus flux limit for the E-CDF-S. ............................. 41  
2.16 Number counts for E-CDF-S sources. .................................. 42  
2.17 Optical (R-band) images of regions coincident with E-CDF-S extended X-ray sources. ......................................................... 43  

3.1 X-ray SEDs for NGC 1600 and NGC 4697. ........................................ 49  
3.2 B-band luminosity versus redshift for the early-type galaxy sample. ...... 56  
3.3 Results of optimization procedure used for stacking analyses. .......... 59  
3.4 0.5–2.0 keV image with early-type galaxy positions indicated. ......... 60  
3.5 Optical (R-band) magnitude versus 0.5–8 keV flux for X-ray-detected early-type galaxies. ....................................................... 62  
3.6 Cumulative AGN fraction of early-type galaxies at \( z_{\text{median}} = 0.65 \) and 0.42. .................. 64  
3.7 Stacked, adaptively-smoothed 0.5–2 keV images of early-type galaxy samples. .......................................................... 68  
3.8 0.5–2 keV luminosity versus B-band luminosity for local galaxies and our galaxy samples. ....................................................... 69  
3.9 0.5–2 keV luminosity versus redshift for our early-type galaxies. ....... 71  
3.10 0.5–2 keV–to–B-band luminosity ratio versus redshift for our early-type galaxies. .......................................................... 73  
3.11 Best-fit residuals to the local 0.5–2 keV to B-band luminosity relation versus redshift for our early-type galaxies. ...................... 74  
3.12 Analysis of AGN contamination to stacked samples using the AGN fraction. 76
3.13 Mean 2–8 keV AGN luminosity versus redshift for early-type galaxies.

4.1 X-ray–to–optical flux ratio versus off-nuclear source X-ray/optical offset.

4.2 $V_{606}$-band postage-stamp images of each off-nuclear source host galaxy.

4.3 X-ray and optical luminosity versus redshift for each off-nuclear source and host galaxy, respectively.

4.4 Relative color difference between optical knot and host galaxy.

4.5 $B-V$ color versus $V_{606}$ magnitude for field galaxies and off-nuclear source host galaxies.

4.6 Histograms of 0.5–2 keV luminosity limits and detections for field and off-nuclear source host galaxies, respectively.

4.7 Observed fraction of galaxies hosting off-nuclear sources versus 0.5–2 keV luminosity.

4.8 Optical luminosity distribution of intermediate-redshift and local field galaxies.

4.9 Galactic radial distribution of intermediate-luminosity X-ray sources in local hosts.

4.10 Fraction of host galaxies in which and off-nuclear source is observable and the fraction of off-nuclear sources expected to be observed as a function of nuclear offset.

4.11 True fraction of galaxies hosting an off-nuclear source versus 0.5–2 keV luminosity.

4.12 Ratio of off-nuclear source fraction at intermediate-redshift to that observed in the local universe versus 0.5–2 keV luminosity.

5.1 Rest-frame $U-V$ color versus $M_V$ in redshift bins for galaxies at $z \approx 0–1.4$

5.2 Fraction of galaxy sample with blue-cloud and red-sequence colors versus sersic index.

5.3 Examples of misclassified blue-cloud and red-sequence galaxies.

5.4 $L_B, M_*,$ and SFR versus redshift for late-type galaxy sample.

5.5 Count-rate ratio of X-ray–detected sources.

5.6 $R$-band magnitude versus log $f_{0.5–8 \text{ keV}}$ for X-ray–detected late-type galaxies.

5.7 0.5–8 keV luminosity versus SFR for X-ray–detected late-type galaxies.

5.8 0.5–8 keV luminosity versus redshift for X-ray–detected late-type galaxies.

5.9 Effective photon index versus X-ray–to–optical flux ratio for stacked samples of $z \approx 0–1.4$ late-type galaxies.

5.10 $L_X/L_B, L_X/M_*$, and $L_X/$SFR for stacked late-type galaxy samples.

5.11 SFR versus $L_X$ for both local and stacked $z \approx 0–1.4$ late-type galaxy samples.

5.12 Cumulative X-ray luminosity dependent AGN fraction versus $L_{2–8 \text{ keV}}$.

5.13 Cumulative redshift-dependent AGN fraction versus redshift.

5.14 Cumulative physical property dependent AGN fraction versus physical property.

5.15 $L_X/L_B$ for local galaxies, $z = 0–1.4$ late-type galaxies and $z \sim 3$ LBGs.

6.1 Lyman break galaxy mean $z_{850}$-band magnitude versus redshift.

6.2 Results of optimization procedure used for stacking analyses.

6.3 Histograms of count distributions and Monte Carlo estimates for both $U$-dropouts and $B_{435}$-dropouts.
6.4 Stacked 0.5–2 keV images of $U$-dropouts and $B_{435}$-dropouts. . . . . . . . . . . 151
6.5 X-ray–to–$B$-band luminosity ratio ($L_X/L_B$) versus redshift for normal galaxies and $L_X/L_B$ versus $L_X$ for detected and stacked LBGs. . . . . . . . . . . . . . . . . 153
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Who are we? We find that we live on an insignificant planet of a humdrum star lost in a galaxy tucked away in some forgotten corner of a universe in which there are far more galaxies than people.

–Carl Sagan
Chapter 1

Introduction

In this thesis, I utilize deep extragalactic X-ray surveys to study the evolution of X-ray activity from normal galaxy populations (i.e., those that are not dominated by luminous active galactic nuclei [AGNs]) over a significant fraction of cosmic time ($\sim 90\%$). These normal galaxies have X-ray emission primarily from X-ray binaries and hot interstellar gas (see discussion below). The study of the X-ray properties of normal galaxies in the high-redshift universe (i.e., $z \gtrsim 0.1$) has only recently been enabled through deep extragalactic X-ray surveys with the advent of new world-class space-borne X-ray observatories *Chandra* and *XMM-Newton*. As a consequence, much of the material presented in this thesis is exploratory in nature and often represents a preliminary look into the high-redshift X-ray universe.

1.1 Historical Perspective

In the early-1960s, the first observations of the X-ray sky, through short-lived rocket flights, revealed that the sky was glowing with X-ray emission (Giacconi et al. 1962). The near isotropy of this cosmic X-ray background (CXR) suggested an extragalactic origin, which we now know to be due largely to the collective emission from distant discrete X-ray point-sources. From the early-1960s to the present-day, X-ray telescopes and their detectors underwent major technological improvements, including improvements in sensitivity and imaging resolution of $\approx 8-9$ and $\approx 6-7$ orders of magnitude, respectively (Giacconi 2003). These technological advances allowed astronomers to study the demographics and nature of the underlying CXRB point-sources through deep extragalactic X-ray surveys, which consisted of long observational exposures over small areas of the sky (see, e.g., Brandt & Hasinger 2005 for a review). One of the most important findings of these surveys was that the majority of the point-sources that constitute the CXRB originates from accreting supermassive black holes (i.e., AGNs) that are seen over a significant fraction of cosmic look-back times ($\approx 95\%$). Through these surveys it became possible to study in detail the history of the growth of supermassive black holes in the universe, and for the deepest X-ray surveys, less luminous X-ray activity from more common normal galaxies could be studied (i.e., X-ray binaries, supernovae, hot gas, etc.).

The most notable X-ray missions contributing to advances in deep extragalactic survey work are the *Chandra* X-ray Observatory (hereafter, *Chandra*) and *XMM-Newton*. These observatories were launched in 1999 and are presently (as of Fall 2007) in operation, continuously returning new views of the X-ray universe. Owing to its unprecedented imaging capabilities (0.492 arcsec pixel$^{-1}$; a factor of $\approx 6$ times sharper than *XMM-Newton*) and large collecting area ($\approx 400$ cm$^2$ at 1 keV for the ACIS-I camera), *Chandra* is the most well-suited X-ray observatory for deep extragalactic surveys. Furthermore, due to its overall relevance to this thesis, I hereafter restrict discussions to results from *Chandra*. 
1.2 The Deepest Chandra Surveys

In the nearly eight years of Chandra operations, several deep extragalactic surveys have now been conducted (see, e.g., Brandt & Hasinger 2005 for a comprehensive list). The two deepest surveys yet performed are the $\approx 2$ Ms Chandra Deep Field-North (CDF-N; Alexander et al. 2003) and $\approx 1$ Ms Chandra Deep Field-South (CDF-S; Giacconi et al. 2002). These Chandra deep fields (hereafter, CDFs) reach 0.5–2 keV flux limits of $\approx 2–5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$, corresponding to sources with Chandra count rates of $\approx 1$ X-ray–detected photon per 2–4 days! These flux limits are a factor of $\approx 10–100$ times more sensitive than the deepest X-ray surveys from other X-ray missions. In total, $\sim 1000$ X-ray sources are detected in these fields over an area of the sky that is roughly the size of the full moon. In Figure 1.1, I show false-color X-ray images of the $\approx 2$ Ms CDF-N (Fig. 1.1a) and $\approx 1$ Ms CDF-S (Fig. 1.1b).

To gain a more complete understanding of the nature of the extragalactic sources in these regions, the CDFs were proposed to coincide with areas of the sky that were targeted with other multiwavelength observatories. The multiwavelength coverage that is available over these regions is quite extensive; some of the highlights include observations from space-borne observatories such as Hubble, Spitzer, and Galex, as well as ground-based observations from ATCA, SCUBA, VLA, and the VLT. These observations have helped to establish distances, morphologies, multiwavelength energetics, and demographics for the $\approx 50,000$ galaxies observed in the CDFs.

Through the use of the multiwavelength observations in the CDFs, the numerous X-ray populations that make up the CXRB have become better understood. As mentioned previously, the majority of the CXRB emission is the result of distant luminous ($L_X \gtrsim 10^{42}$ erg s$^{-1}$) AGNs. However, luminous AGNs are generally present in only a minority fraction ($\lesssim 10\%$) of galaxies in the universe. Since the majority of the X-ray sources detected in deep extragalactic X-ray

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**Fig. 1.1:** False-color images of the $\approx 2$ Ms CDF-N (a) and $\approx 1$ Ms CDF-S (b). Each color image was constructed using adaptively-smoothed images from the 0.5–2 keV (red), 2–4 keV (green) and 4–8 keV (blue) bandpasses.
surveys are AGNs, this implies that the incredibly numerous X-ray population of normal galaxies has remained largely undetected.

The X-ray sensitivity limits of the CDFs allows for the X-ray detection of normal galaxies that are energetic in the X-ray band. Statistical analyses of the X-ray number counts of CDF sources show that at such depths, normal galaxies begin to make up a significant fraction ($\approx 25\%$) of the sources with $0.5$–$2$ keV fluxes below $\approx 10^{-16}$ erg cm$^{-2}$ s$^{-1}$. To illustrate this point, I have presented Figure 1.2, which shows the cumulative $0.5$–$2$ keV (Fig. 1.2a) and $2$–$8$ keV (Fig. 1.2b) number counts [i.e., the number of sources with X-ray flux greater than $S$, $N(>S)$] versus flux $S$ for extragalactic sources, broken into contributions from normal galaxies (green dashed curves) and AGNs (red dashed curves). This figure was originally presented in Brandt & Hasinger (2005), and was constructed using number-count data from a variety of sources (Hasinger et al. 1998, 2005; Ueda et al. 1999; Miyaji & Griffiths 2002; Bauer et al. 2004; Kim et al. 2004; see caption). Based on number-count and fluctuation analyses, it has been predicted that the cumulative X-ray number counts from normal galaxies will rise quickly below the CDF sensitivity limits and eventually outnumber the AGN population around $0.5$–$2$ keV fluxes of $S \approx 2–8 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ (e.g., Ptak et al. 2001; Miyaji & Griffiths 2002; Bauer et al. 2004; Kim et al. 2004; Hickox & Markevitch 2007). However, studies of the average X-ray emission from normal galaxies that are below the X-ray detection limit for an individual source...
can already be performed via the X-ray stacking technique. This technique allows for the detection and analysis of the average X-ray properties of a galaxy population via the “stacking” of X-ray cutouts, which are centered on regions where normal galaxies are known to be present based on observations at other wavelengths (e.g., optical). This technique has powerful utility in the CDFs, where the deep Chandra imaging allows for the detection and removal of luminous AGNs from stacked samples of normal galaxies, thus enabling investigations of these populations out to significant cosmological look-back times. As mentioned above, the goal of this thesis is to study the nature and evolution of the X-ray activity from normal galaxy populations. Throughout this thesis X-ray stacking analyses is used extensively to place average constraints on normal galaxy populations (see, e.g., Chapters 3, 5, and 6 for details).

1.3 Normal Galaxies in the Local Universe

In addition to the improved extragalactic X-ray survey data, Chandra has enabled revolutionary new views of the X-ray characteristics of normal galaxies in the local universe. In normal galaxies, X-ray emission originates primarily from X-ray binaries, supernovae, supernova remnants, hot (≈0.2–1 keV) interstellar gas, and O-stars (see, e.g., Fabbiano 1989, 2006 for reviews).

The most prominent X-ray–emitting point-source populations in normal galaxies are the X-ray binaries. Studies of X-ray binaries in the Milky Way (see Verbunt & van den Heuvel 1995 for a review) have found two basic flavors: high-mass X-ray binaries (HMXBs) and low-mass X-ray binaries (LMXBs). HMXBs are young stellar binaries composed of a neutron star or black hole primary and a mass-losing O/B-star secondary. The stellar winds from the secondary provide fuel for an accretion disk, which forms around the primary compact object and heats up to X-ray temperatures. Since HMXBs consist of relatively massive secondary stars, these systems form on short timescales following a star-formation event and are typically short-lived (≈10⁶–10⁷ yr). By contrast, LMXBs consist of older (e.g., K-stars) that are orbiting a neutron star or black hole. Through stellar evolution, the envelope of the secondary star expands and overfills its Roche lobe thus forming an X-ray–emitting accretion disk around the compact primary. Since these systems form on the timescale of the less massive secondary star, LMXBs first appear ≈10⁸–10⁹ yr after the binary system formed; however, in globular clusters, where the stellar densities are large, LMXBs can form effectively through dynamical interactions of normal stars and compact objects. Generally, LMXB populations will persist as X-ray-luminous objects for ≈10⁸–10⁹ yr.

Since HMXBs and LMXBs both emit X-rays via the accretion of matter onto a compact object, these sources have similar X-ray spectra, which can often be described well as a power-law with photon index Γ = 1−2 (e.g., Church & Balucinska-Church 2001; Irwin et al. 2003; Sasaki et al. 2003; Liu & Mirabel 2005; Liu et al. 2006). However, as a result of physical differences in the donor secondary star, the variability and statistical properties of these source populations are somewhat different. HMXBs tend to be more persistent X-ray sources versus LMXBs, which are often transient sources in the X-ray band. Also, the X-ray luminosity functions (N ∝ L^α, where N is the number of sources with luminosities of L or larger and α is a power-law index) of HMXBs are flatter and reach larger X-ray luminosity cut-offs than LMXBs (e.g., Grimm et al. 2002). Furthermore, the most luminous HMXBs can reach LX ≈ 2–100 × 10³⁹ erg s⁻¹, which implies masses of ≈10–1000 M☉ for the accreting compact objects if they are...
Fig. 1.3: Chandra images of low-SSFR (M31; a) and high-SSFR (M82; b) normal late-type galaxies and low-mass (NGC 4697; c) and high-mass (M87; d) early-type galaxies. These images were obtained from the Chandra X-ray Observatory at http://chandra.harvard.edu (see also references in the text) and highlight the salient X-ray–emitting populations in these galaxies, including LMXBs in M31 and NGC 4697, hot gas and HMXBs in M82, and hot gas in M87.
accreting isotropically at the Eddington limit; these sources are commonly referred to as ultraluminous X-ray sources (ULXs). However, the true nature of ULXs is not well understood and whether these sources are indeed massive black holes or anisotropically-radiating sources is a topic of much debate (e.g., King et al. 2001; Miller & Colbert 2004).

Another important X-ray–emitting mechanism at soft (∼2 keV) X-ray energies is hot (∼0.5–1.5 keV) interstellar gas. The gas generally arises due to stellar winds that are heated by high-velocity stars, supernovae, and kinetic outflows from AGNs (see, e.g., Mathews & Brighenti 2003 for a review). Hot gas is present in most galaxies; however, it is most conspicuous in massive early-type galaxies. For the most massive ellipticals, the gas can dominate the total 0.5–2 keV emission (e.g., O’Sullivan et al. 2001).

The dominant X-ray–emitting mechanisms for galaxy populations can be divided roughly by optical morphology, as well as star-formation activity and stellar mass content. For late-type galaxies (Sa–Irr), the X-ray emission is often dominated by HMXBs and LMXBs, and each respective fractional contribution depends primarily on the star-formation activity per unit stellar mass. Normal late-type galaxies with large star-formation rates per unit stellar mass (hereafter, specific star-formation rates [SSFRs]) have 0.5–2 keV emission dominated by HMXBs, while galaxies with low SSFRs are dominated by LMXB. By contrast, the X-ray spectra of early-type galaxies (E–S0) are mainly dominated by hot interstellar gas and LMXBs, and their relative dominance is dependent on galaxy stellar mass. For normal early-type galaxies, LMXBs contribute most of the X-ray emission for low-mass galaxies, while hot gas and LMXBs dominate the X-ray emission for high-mass galaxies in the 0.5–2 keV and 2–8 keV energy bands, respectively. In Figure 1.3, we show Chandra images for galaxies representing each of the four “extremes” discussed above; these include (1) M31, a late-type galaxy with a low SSFR (Fig. 1.3a; e.g., Kong et al. 2002), (2) M82, a late-type galaxy with a large SSFR (Fig. 1.3b; e.g., Griffiths et al. 2000), (3) NGC 4697, a low-mass early-type galaxy (Fig. 1.3c; e.g., Sarazin et al. 2001), and (4) M87 a massive elliptical galaxy (Fig. 1.3d; e.g., Forman et al. 2005).

1.4 Overview of this Thesis: Studying Normal Galaxies in the Distant Universe

Observations of galaxy populations over significant cosmological look-back times have provided significant insight into how galaxies formed and evolved into the systems and structures that we observe in the local universe. These observations have been conducted over many different wavebands, each of which reveals new physical information about the nature of galaxy evolution. Thanks largely to the CDFs (see § 1.3), it has now become possible to study in detail the evolution of distant normal galaxy populations in the X-ray band. Of particular interest is the evolution of X-ray binary populations and the hot gas content (see § 1.4) of normal galaxies. For example, it has been predicted that as the global star-formation rate density increases over the redshift range z ≈ 0–2 (e.g., Colbert et al.2006), a corresponding increase in the mean normal-galaxy X-ray luminosity should also be observable due to the evolution of HMXB and LMXB populations (e.g., Ghosh & White 2001). Using the CDFs, observational constraints can be placed on the X-ray evolution of normal late-type galaxy populations, which dominate the star-formation content of the Universe (e.g., Bell et al. 2007). Additionally, for the relatively massive early-type galaxies that have X-ray emission dominated by hot interstellar gas, the CDFs can provide new insight into the role that feedback (e.g., from AGNs) plays in keeping the gas hot, which prevents further star-formation.
In this thesis, I present new investigations of the X-ray properties and evolution of normal galaxies and their source constituents. These studies have made extensive use of the CDFs and their multiwavelength data. Each chapter is in itself a self-contained work, and therefore detailed comprehensive introductions and motivations are provided at the beginning of each chapter. Beginning in chapter 2, I present new deep (∼250 ks) Chandra observations of a region flanking the ∼1 Ms CDF-S known as the Extended Chandra Deep Field-South (E-CDF-S), which I use extensively throughout the rest of the thesis. In chapter 3, I discuss the X-ray evolution of normal early-type galaxies over the last ∼1/2 of cosmic history. Chapter 4 has been dedicated to studying the physical and statistical properties of off-nuclear X-ray point sources (primarily ULXs) in optically-bright galaxies over the redshift range z ∼ 0–0.3. In chapter 5, I investigate the X-ray properties and evolution of normal late-type galaxies over the last ∼70% of cosmic history. Finally, in chapter 6, I extend the study of normal galaxies to distant Lyman break galaxies (LBGs) at z ∼ 3, 4, 5, and 6.

At the time of writing this thesis, several of the chapters presented below had been published; below, I have provided the references to the journals in which these chapters were published.


Chapter 2

The Extended Chandra Deep Field-South Survey.

Chandra Source Catalogs

2.1 Introduction

Deep and wide X-ray surveys indicate that the cosmic X-ray background is largely due to accretion onto supermassive black holes (SMBHs) integrated over cosmic time (e.g., see Brandt & Hasinger 2005 for a review). Follow-up studies of deep-survey sources with 8–10 m optical telescopes as well as multiwavelength correlative studies have shown that most of the X-ray sources are active galactic nuclei (AGNs), many of which are obscured (e.g., Bauer et al. 2004; Szokoly et al. 2004; Barger et al. 2005). X-ray surveys have found the highest density of AGNs on the sky (up to \( \approx 7200 \) deg\(^{-2} \)). In addition to AGNs, the deepest X-ray surveys have also detected respectable numbers of starburst and normal galaxies out to cosmologically interesting distances (\( z \approx 1 \); e.g., Hornschemeier et al. 2003; Bauer et al. 2004; Norman et al. 2004).

Presently, the two deepest X-ray surveys are the \( \approx 2 \) Ms Chandra Deep Field-North (CDF-N; Brandt et al. 2001, hereafter B01; Alexander et al. 2003, hereafter A03) and the \( \approx 1 \) Ms Chandra Deep Field-South (CDF-S; Giacconi et al. 2002, hereafter G02). These \( \approx 400 \) arcmin\(^2 \) surveys have been performed in regions of sky with extensive multiwavelength coverage. They have provided 50–250 times the sensitivity of surveys by previous X-ray missions, detecting large numbers of point sources (584 for the CDF-N and 346 for the CDF-S; G02; A03) and about a dozen extended groups and poor clusters (Bauer et al. 2002; G02).

The X-ray surveys performed to date have explored an impressive amount of the sensitivity versus solid angle “discovery space” (see Fig. 2.1 and Brandt & Hasinger 2005). However, one limitation of the present surveys is that there is only a relatively small amount of sky probed to 0.5–2 keV flux levels of \( (2–50) \times 10^{-17} \) erg cm\(^{-2} \) s\(^{-1} \), a flux regime where many obscured AGNs are observed (e.g., Bauer et al. 2004). As a result, our understanding of the X-ray universe at these faint fluxes suffers from limited source statistics and field-to-field variance. To mitigate this limitation, the Extended Chandra Deep Field-South (E-CDF-S) survey was undertaken as part of the Chandra Cycle 5 guest observer program. The E-CDF-S is composed of four 250 ks Chandra ACIS-I pointings flanking the original CDF-S; these are arranged in a contiguous two-by-two pattern and cover a total solid angle of \( \approx 1100 \) arcmin\(^2 \).\(^1 \) The pointings have sufficient sensitivity to detect the X-ray emission from moderate-luminosity AGNs (\( L_X = 10^{43–10^{44}} \) erg s\(^{-1} \)) to \( z \approx 3–6 \) as well as X-ray luminous starburst galaxies to \( z \approx 1 \). The E-CDF-S therefore can significantly improve understanding of SMBH accretion at high redshift where the source statistics are still limited. The contiguous nature of the E-CDF-S will allow

\(^1\)The \( \approx 1 \) Ms CDF-S data cover \( \approx 35\% \) of the E-CDF-S; much of this coverage, however, has limited sensitivity due to point spread function (PSF) broadening and vignetting at large off-axis angles (see § 2.3 for details). The same effects limit the sensitivity and positions derived from the XMM-Newton data (Streblyanska et al. 2004) extending outside the region with Chandra coverage.
Fig. 2.1: Distributions of some well-known extragalactic surveys by Chandra (blue), XMM-Newton (green), and ROSAT (red) in the 0.5–2 keV flux-limit versus solid angle, $\Omega$, plane. Circled dots denote surveys that are contiguous. Each of the surveys shown has a range of flux limits across its solid angle; we have generally shown the most sensitive flux limit. This plot has been adapted from Figure 1 of Brandt & Hasinger (2005) to show the part of parameter space most relevant for the E-CDF-S; see Table 1 of Brandt & Hasinger (2005) for references to descriptions of many of the surveys plotted here.

wider field studies of the remarkable AGN clustering already found in the CDF-S (e.g., Gilli et al. 2003, 2005), and comparisons with other surveys of comparable depth (e.g., Stern et al. 2002; Harrison et al. 2003; Wang et al. 2004a,b; Nandra et al. 2005) will allow further assessment of the field-to-field variance of X-ray source populations.

The E-CDF-S field was selected for this program primarily due to its superb and growing multiwavelength coverage over a $\approx 900 \text{ arcmin}^2$ area, which ensures that it will remain a prime survey field in coming decades (see Fig. 2.2). For example, the E-CDF-S has been imaged intensively with the HST Advanced Camera for Surveys (ACS) via the Galaxy Evolution from Morphology and Spectral Energy Distributions (GEMS; Rix et al. 2004; 117 HST orbits) and Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004; 199 HST orbits)
projects. Excellent ground-based imaging is also available (e.g., Arnouts et al. 2001; Renzini et al. 2003; Giavalisco et al. 2004; Wolf et al. 2004; Gawiser et al. 2005), and several spectroscopic campaigns are underway to identify sources in the E-CDF-S, most notably with the Very Large Telescope (VLT; e.g., Le Fevre et al. 2004; Szokoly et al. 2004; Vanzella et al. 2005). The E-CDF-S has been targeted by Spitzer via the GOODS (M. Dickinson et al., in preparation), the Spitzer Wide-Area Infrared Extragalactic Survey (SWIRE; Lonsdale et al. 2003), guaranteed time (e.g., Papovich et al. 2004), and guest observer (PI: P. van Dokkum) programs. Radio observations of the E-CDF-S have been made with the Australia Telescope Compact Array (ATCA; J. Afonso et al., in preparation) and the Very Large Array.

In this paper, we present Chandra point-source catalogs and data products derived from the E-CDF-S data set along with details of the observations, data reduction, and technical analysis. The observational procedures and data processing were similar in nature to those presented in B01 and A03. Detailed follow-up investigations and scientific interpretation of the E-CDF-S sources will be presented in subsequent papers.

The Galactic column density along the line of sight to the E-CDF-S is remarkably low: $N_H = 8.8 \times 10^{19}$ cm$^{-2}$ (e.g., Stark et al. 1992). The coordinates throughout this paper are J2000. Cosmological parameters of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ are adopted.

2.2 Observations and Data Reduction

2.2.1 Instrumentation and Observations

The Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) was used for all of the Chandra observations. ACIS is composed of ten CCDs (each 1024 $\times$ 1024 pixels) designed for efficient X-ray source detection and spectroscopy. ACIS-I consists of four CCDs (CCDs I0–I3) arranged in a 2 $\times$ 2 array with each CCD tipped slightly to approximate the curved focal surface of the Chandra High Resolution Mirror Assembly (HRMA). The aim-point of ACIS-I lies on CCD I3. The remaining six CCDs (ACIS-S; CCDs S0–S5) reside in a linear array and are tipped to approximate the Rowland circle of the objective gratings that can be inserted behind the HRMA.

The ACIS-I full field of view is 16.9 $\times$ 16.9 ($\approx$285 arcmin$^2$), and the sky-projected ACIS pixel size is $\approx$0.492. The PSF is smallest at the lowest photon energies and for sources at small off-axis angles. For example, the 95% encircled-energy radius at 1.5 keV for off-axis angles of $0^\circ$–$8^\circ$ is $\approx$1.8–7.5 (Feigelson, Broos, & Gaffney 2000; Jerius et al. 2000). The PSF is approximately circular at small off-axis angles, broadens and elongates at intermediate off-axis angles, and becomes complex at large off-axis angles.

The entire Chandra observation program consisted of nine separate Chandra observations taken between 2004 February 29 and 2004 November 20 and is described in Table 2.1. The four ACIS-I CCDs were operated in all of the observations; the ACIS-S CCD S2 was in operation for observations 5019–5022 and 6164. Due to the large off-axis angle of ACIS-S, and consequently its low sensitivity, these data were not used in this analysis. All observations were taken in Very Faint mode to improve the screening of background events and thus increase

\footnote{For additional information on ACIS and Chandra see the Chandra Proposers’ Observatory Guide at http://cxc.harvard.edu/proposer/CfP/.
Feigelson et al. (2000) is available at http://www.astro.psu.edu/xray/acis/memos/memoindex.html.}
Fig. 2.2: Coverage map of the E-CDF-S area showing the various Chandra (dashed lines) and HST (solid lines) observational regions. The E-CDF-S Chandra observational fields are shown as four 16.9 × 16.9 regions (colored black in the electronic edition) which flank the CDF-S (central polygon [colored blue in the electronic edition]). Each observational field is labeled in text, and the corresponding aim points are indicated as “+” signs within the fields. The HST coverage includes the 63, 202″ × 202″ square regions (colored green in the electronic edition) from GEMS (Rix et al. 2004), the central rectangle (colored orange in the electronic edition) from GOODS (Giavalisco et al. 2004), and the central 202″ × 202″ (colored red in the electronic edition) region of the Hubble Ultra Deep Field (UDF; PI: S. Beckwith). The Spitzer GOODS coverage coincides with the HST GOODS region (central rectangle), and there is a substantial amount of wider field Spitzer coverage either executed or approved (see § 2.1).
Table 2.1. Journal of Extended *Chandra* Deep Field-South Observations

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Obs. Start (UT)</th>
<th>Exposure Time (ks)</th>
<th>$\alpha_{2000}$</th>
<th>$\delta_{2000}$</th>
<th>Roll Angle ($^\circ$)</th>
<th>Field Number</th>
<th>Pipeline Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>5015…</td>
<td>2004-02-29, 21:21</td>
<td>162.9</td>
<td>03 33 05.61</td>
<td>–27 41 08.84</td>
<td>270.2</td>
<td>1</td>
<td>7.1.1</td>
</tr>
<tr>
<td>5016…</td>
<td>2004-03-03, 12:09</td>
<td>77.2</td>
<td>03 33 05.61</td>
<td>–27 41 08.84</td>
<td>270.2</td>
<td>1</td>
<td>7.2.0</td>
</tr>
<tr>
<td>5017…</td>
<td>2004-05-14, 01:09</td>
<td>155.4</td>
<td>03 31 51.43</td>
<td>–27 41 38.80</td>
<td>181.5</td>
<td>2</td>
<td>7.2.1</td>
</tr>
<tr>
<td>5018…</td>
<td>2004-05-16, 13:44</td>
<td>72.0</td>
<td>03 31 51.43</td>
<td>–27 41 38.80</td>
<td>181.5</td>
<td>2</td>
<td>7.2.1</td>
</tr>
<tr>
<td>5019…</td>
<td>2004-11-17, 14:43</td>
<td>163.1</td>
<td>03 31 49.94</td>
<td>–27 57 14.56</td>
<td>0.2</td>
<td>3</td>
<td>7.3.2</td>
</tr>
<tr>
<td>5020…</td>
<td>2004-11-15, 23:25</td>
<td>77.6</td>
<td>03 31 49.94</td>
<td>–27 57 14.56</td>
<td>0.2</td>
<td>3</td>
<td>7.3.2</td>
</tr>
<tr>
<td>5021…</td>
<td>2004-11-13, 03:26</td>
<td>97.8</td>
<td>03 33 02.93</td>
<td>–27 57 16.08</td>
<td>0.2</td>
<td>4</td>
<td>7.3.2</td>
</tr>
<tr>
<td>5022…</td>
<td>2004-11-15, 00:51</td>
<td>79.1</td>
<td>03 33 02.93</td>
<td>–27 57 16.08</td>
<td>0.2</td>
<td>4</td>
<td>7.3.2</td>
</tr>
<tr>
<td>6164….</td>
<td>2004-11-20, 21:08</td>
<td>69.1</td>
<td>03 33 02.93</td>
<td>–27 57 16.08</td>
<td>0.2</td>
<td>4</td>
<td>7.3.2</td>
</tr>
</tbody>
</table>

*a* All observations were continuous. The short time intervals with bad satellite aspect are negligible and have not been removed.

*b* Roll angle describes the orientation of the *Chandra* instruments on the sky (see Figure 2.2). The angle is between 0–360°, and it increases to the West of North (opposite to the sense of traditional position angle).
the sensitivity of ACIS in detecting faint X-ray sources.\textsuperscript{4} The observations were made in four
distinct observational fields (hereafter, fields 1, 2, 3, and 4; see Table 2.1 for more observational
details) and cover a total solid angle of 1128.4 arcmin\textsuperscript{2}. The focal-plane temperature was kept
at $\approx -120^\circ$ C for all of the nine observations.

Background light curves for all nine observations were inspected using EVENT BROWSER
in the Tools for ACIS Real-time Analysis (TARA; Broos et al. 2000) software package.\textsuperscript{5} All but
two are free from significant flaring and are stable to within $\approx 20\%$. The two observations with
significant flaring are 5015 and 5017. The background was $\gtrsim 1.5$ times higher than nominal
for two $\approx 1$ ks intervals of observation 5015, and during observation 5017 the background rose
to $\gtrsim 1.5$ times the nominal rate and remained above this level for $\approx 10$ ks near the end of the
observation. Intervals with flaring were retained because the flaring strengths were not strong
enough to have significant negative effects on our analyses.

2.2.2 Data Reduction

\textit{Chandra} X-ray Center (hereafter CXC) pipeline software was used for basic data pro-
cessing, and the pipeline versions are listed in Table 2.1. The reduction and analysis of the data
used \textit{Chandra} Interactive Analysis of Observations (CIAO) Version 3.2 tools whenever possible;\textsuperscript{6}
however, custom software, including the TARA package, was also used extensively.

All data were corrected for the radiation damage sustained by the CCDs during the first
few months of \textit{Chandra} operations using the Charge Transfer Inefficiency (CTI) correction pro-
cedure of Townsley et al. (2000, 2002).\textsuperscript{7} In addition to correcting partially for the positionally
dependent grade distribution due to CTI effects, this procedure also partially corrects for qua-
tum efficiency losses (see Townsley et al. 2000, 2002 for further details).

All bad columns, bad pixels, and cosmic ray afterglows were removed using the “status”
information in the event files, and we only used data taken during times within the CXC-
generated good-time intervals. The CIAO tool ACIS_PROCESS_EVENTS was used to remove the
standard pixel randomization.

2.3 Production of the Point-Source Catalogs

By design, the four 250 ks E-CDF-S observations have their regions of highest sensitivity located
where the sensitivity of the original $\approx 1$ Ms CDF-S observation is poorest (see Table 2.1 and
Figs. 2.2 and 2.17). The loss of sensitivity is due to the combination of substantial degradation of
the \textit{Chandra} PSF at large off-axis angles and vignetting. In fact, most of the area where the
E-CDF-S observations have their highest sensitivity lack any \textit{Chandra} coverage in the $\approx 1$ Ms
CDF-S. We experimented with source searching utilizing the addition of the $\approx 1$ Ms CDF-S
and the 250 ks E-CDF-S images; such searching was done with WAVDETECT (Freeman et al. 2002) runs that did not utilize detector-specific PSF information (i.e., the “DETNAME” keyword

\textsuperscript{4}For more information on the Very Faint mode see http://cxc.harvard.edu/cal/Acis/Cal_prods/vfbkgrnd/

\textsuperscript{5}TARA is available at http://www.astro.psu.edu/xray/docs.

\textsuperscript{6}See http://cxc.harvard.edu/ciao/ for details on CIAO.

\textsuperscript{7}The software associated with the correction method of Townsley et al. (2000, 2002) is available at
http://www.astro.psu.edu/users/townsley/cti/.
in the image files was deleted). However, such searching did not find a substantial number of new sources compared to those presented below combined with those from the original ≈1 Ms CDF-S (G02; A03); these results were verified via inspection of adaptively smoothed images. Therefore, our basic approach here is to present just the sources detected in the new 250 ks E-CDF-S observations. The X-ray sources in the ≈1 Ms CDF-S catalog of A03 were processed using the same techniques presented here with two main differences:

1. Our main Chandra catalog includes sources detected by running WAVDETECT at a false-positive probability threshold of $10^{-6}$, somewhat less conservative than the $10^{-7}$ value adopted by A03; see § 2.3.2 for details.

2. The E-CDF-S consists of four ACIS-I observational fields and subtends a larger solid angle than the fields presented in A03. Therefore, our main Chandra catalog of the entire E-CDF-S exposure was generated by merging sub-catalogs created in each of the four observational fields; see § 2.3.2, Table 2.1, and Figure 2.2 for details.

2.3.1 Image and Exposure-Map Creation

We constructed images of each of the four E-CDF-S fields using the standard ASCA grade set (ASCA grades 0, 2, 3, 4, 6) for three standard bands (i.e., 12 images in total): 0.5–8 keV (full band; FB), 0.5–2 keV (soft band; SB), and 2–8 keV (hard band; HB). These images have $0''$.492 per pixel. For each of the standard bands, the images from all four observational fields were merged into a single image using the CIAO script MERGE_ALL. In Figures 2.3a and 2.3b we display the full-band raw and exposure-corrected adaptively smoothed images (see discussion below), respectively. Our point-source detection analyses have been restricted to the raw images constructed for each of the four observational fields so that the Chandra PSF is accounted for correctly (see § 2.3.2).

We constructed exposure maps for each of the four observational fields in the three standard bands. These were created following the basic procedure outlined in § 3.2 of Hornschemeier et al. (2001) and are normalized to the effective exposures of sources located at the aim points. Briefly, this procedure takes into account the effects of vignetting, gaps between the CCDs, bad column filtering, and bad pixel filtering. Also, with the release of CIAO version 3.2, the spatially dependent degradation in quantum efficiency due to contamination on the ACIS optical blocking filters is now incorporated into the generation of exposure maps. A photon index of $\Gamma = 1.4$, the slope of the X-ray background in the 0.5–8 keV band (e.g., Marshall et al. 1980; Gendreau et al. 1995), was assumed in creating the exposure maps. For each standard band, a total exposure map, covering the entire E-CDF-S, was constructed by merging the exposure maps of the four observational fields using the CIAO script DMREGRID. The resulting full-band exposure map is shown in Figure 2.4. Figure 2.5 displays the survey solid angle as a function of full-band exposure.

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8See http://cxc.harvard.edu/ciao/threads/merge_all/

9Raw and adaptively smoothed images for all three standard bands are available at the E-CDF-S website (see http://www.astro.psu.edu/users/niel/ecdfs/ecdfs-chandra.html). Furthermore, equivalent images obtained by merging the E-CDF-S and CDF-S are also available at the E-CDF-S website.

10See http://cxc.harvard.edu/ciao/why/acisqedeg.html
effective exposure for both the total E-CDF-S exposure (Fig. 2.5a) and the four individual observational fields (Fig. 2.5b). Each observational field has comparable coverage with the majority of the solid angle coverage ($\approx 900$ arcmin$^2$) having at least $200$ ks of effective exposure.

Using the exposure maps and adaptively smoothed images discussed above, we produced exposure-corrected images following the prescription outlined in § 3.3 of Baganoff et al. (2003). Figure 2.6 shows a “false-color” composite image made using exposure-corrected adaptively smoothed 0.5–2 keV (red), 2–4 keV (green), and 4–8 keV (blue) images.

2.3.2 Point-Source Detection

Point-source detection was performed in each band with WAVDETECT using a “$\sqrt{2}$ sequence” of wavelet scales (i.e., $1$, $\sqrt{2}$, $2\sqrt{2}$, $4\sqrt{2}$, and 8 pixels). Our key criterion for source detection, and inclusion in the main Chandra catalog, is that a source must be found with a given false-positive probability threshold in at least one of the three standard bands. The false-positive probability threshold in each band was set to $1 \times 10^{-6}$; a total of 762 distinct sources met this criterion. We also ran WAVDETECT using false-positive probability thresholds of $1 \times 10^{-7}$ and $1 \times 10^{-8}$ to evaluate the significance of each detected source.

If we conservatively treat the 12 images (i.e., the three standard bands over the four observational fields) as being independent, it appears that $\approx 50$ (i.e., $\approx 6\%$) false sources are expected
Fig. 2.4: Full-band exposure map of the E-CDF-S. The grayscales are linear with the darkest areas corresponding to the highest effective exposure times (the high effective exposure times between fields is due to overlap of observations). Note the chip gaps in white running between the four ACIS-I CCDs. Symbols and regions have the same meaning as those shown in Figure 2.3a.
in our total Chandra source catalog for the case of a uniform background over \( \approx 5.0 \times 10^7 \) pixels. However, since WAVDETECT suppresses fluctuations on scales smaller than the PSF, a single pixel usually should not be considered a source detection cell, particularly at large off-axis angles. Hence, our false-source estimates are conservative. As quantified in § 3.4.1 of A03 and by new source-detection simulations (P. E. Freeman 2005, private communication), the number of false-sources is likely \( \approx 2–3 \) times less than our conservative estimate, leaving only \( \approx 15–25 \) (i.e., \( \lesssim 3\% \)) false sources. In § 2.3.3.1 below we provide additional source-significance information that a user can utilize to perform more conservative source screening if desired.

2.3.3 Point-Source Catalogs

2.3.3.1 Main Chandra Source Catalog

We ran WAVDETECT with a false-positive probability threshold of \( 1 \times 10^{-6} \) on all of the 12 images. The resulting source lists were then merged to create the point-source catalog given in Table 2.2. For cross-band matching, a matching radius of 2\('\) was used for sources within 6\('\) of the average aim point. For larger off-axis angles, a matching radius of 4\('\) was used. These matching radii were chosen based on inspection of histograms showing the number of matches obtained as a function of angular separation (e.g., see §2 of Boller et al. 1998); with these radii the mismatch probability is \( \lesssim 1\% \) over the entire field.

We improved the WAVDETECT source positions using a matched-filter technique (A03). This technique convolves the full-band image in the vicinity of each source with a combined PSF. The combined PSF is automatically generated as part of the ACIS_EXTRACT procedure (Broos
Fig. 2.6: Chandra “false-color” image of the E-CDF-S. This image has been constructed from the 0.5–2 keV (red), 2–4 keV (green), and 4–8 keV (blue) exposure-corrected adaptively smoothed images discussed in § 2.3.1.
### Table 2.2. Main Chandra Catalog Source Properties

<table>
<thead>
<tr>
<th>No.</th>
<th>$\alpha_{2000}$ (2)</th>
<th>$\delta_{2000}$ (3)</th>
<th>Pos Err (4)</th>
<th>Off-Axis (5)</th>
<th>FB (6)</th>
<th>FB Upp Err (7)</th>
<th>FB Low Err (9)</th>
<th>SB (10)</th>
<th>SB Upp Err (11)</th>
<th>SB Low Err (12)</th>
</tr>
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<td>03 31 11.40</td>
<td>−27 33 38.5</td>
<td>2.6</td>
<td>11.95</td>
<td>29.0</td>
<td>11.7</td>
<td>10.6</td>
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<td>−1</td>
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<td>8.29</td>
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<td>19.8</td>
<td>152.1</td>
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<td>13.2</td>
</tr>
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<td>−28 04 20.3</td>
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<td>10.63</td>
<td>27.1</td>
<td>−1</td>
<td>−1</td>
<td>21.3</td>
<td>7.6</td>
<td>6.4</td>
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<td>−27 47 07.3</td>
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<td>9.87</td>
<td>99.2</td>
<td>13.4</td>
<td>12.3</td>
<td>76.5</td>
<td>10.7</td>
<td>9.7</td>
</tr>
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<td>03 31 14.64</td>
<td>−28 01 44.3</td>
<td>0.8</td>
<td>9.00</td>
<td>73.3</td>
<td>11.9</td>
<td>10.8</td>
<td>27.4</td>
<td>7.5</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Note. — Table 2.2 is presented in its entirety in the electronic edition of Lehmer et al. (2005a). An abbreviated version of the table is shown here for guidance as to its form and content. The full table contains 39 columns of information on the 762 X-ray sources.
et al. 2002) within TARA (see Footnote 5) and is produced by combining the “library” PSF of a source for each observation, weighted by the number of detected counts. This technique takes into account the fact that, due to the complex PSF at large off-axis angles, the X-ray source position is not always located at the peak of the X-ray emission. The matched-filter technique provides a small improvement ($\approx 0''1$ on average) in the positional accuracy for sources further than $6'$ from the average aim-point. For sources with off-axis angles ($\theta < 6'$, we found that the off-axis-angle-weighted combination of centroid and matched-filter positions returned the most significant improvement to source positions. Algebraically, this can be written as:

$$(6' - \theta)/6' \times \text{centroid position} + \theta/6' \times \text{matched-filter position} \quad (2.1)$$

This method is similar to that employed by A03.

Manual correction of the source properties was required in some special cases: (1) There were 11 close doubles (i.e., sources with overlapping PSFs) and one close triple. These sources incur large photometric errors due to the difficulty of the separation process. (2) A total of eight sources were located close to bright sources, in regions of high background, in regions with strong gradients in exposure time, or partially outside of an observational field. The properties of these sources have been adjusted manually and are flagged in column 39 of Table 2.2 (see below).

For each observational field, we refined the absolute X-ray source positions by matching X-ray sources from the main point-source catalog to $R$-band optical source positions from deep observations ($R_{lim,6\sigma} \approx 27$ [AB] over the entire E-CDF-S) obtained with the Wide Field Imager (WFI) of the MPG/ESO telescope at LaSilla (see § 2 of Giavalisco et al. 2004). X-ray sources from each of the four observational fields were matched to optical sources using a $2''5$ matching radius. Using this matching radius, a small number of sources were observed to have more than one optical match; the brightest of these sources was selected as the most probable counterpart. Under these criteria, 640 ($\approx 84\%$) X-ray sources have optical counterparts. We also note that in a small number of cases the X-ray source may be offset from the center of the optical source even though both are associated with the same galaxy (e.g., a galaxy with bright optical emission from starlight that also has an off-nuclear ultraluminous X-ray binary with $L_X \approx 10^{38-40}$ erg s$^{-1}$; see e.g., Hornschemeier et al. 2004). The accuracy of the X-ray source positions was improved by centering the distribution of offsets in right ascension and declination between the optical and X-ray source positions; this resulted in small ($< 1''0$) field-dependent astrometric shifts for all sources in each field. We also checked for systematic offsets as a function of right ascension and declination that may arise from differing “plate scales” and rotations between the X-ray and optical images. These investigations were performed by plotting the right ascension and declination offsets (between optical and X-ray sources) as functions of right ascension and declination; no obvious systematic offsets were found.

Figure 2.7 shows the positional offset between the X-ray and optical sources versus off-axis angle after applying the positional corrections discussed above. Here, the off-axis angles are computed for each observational field appropriately; this allows for the consistent analysis of Chandra positional uncertainties as a function of off-axis angle. The median offset is $\approx 0''35$;
Fig. 2.7: Positional offset vs. off-axis angle (computed in each observational field) for sources in the main Chandra catalog that were matched to optical sources from the WFI $R$-band image to within 2′′.5. Open circles are Chandra sources with < 50 full-band counts, and filled circles are Chandra sources with ≥ 50 full-band counts. The dotted curve shows the running median for all sources. These data were used to determine the positional uncertainties of the Chandra sources; see § 2.3.3.1.

however, there are clear off-axis angle and source-count dependencies. The off-axis angle dependence is due to the HRMA PSF becoming broad at large off-axis angles, while the count dependency is due to the difficulty of centroiding a faint X-ray source. The median offset of the bright X-ray sources (≥ 50 full-band counts) is only ≈0′′25, while the median offset of the faint X-ray sources (< 50 full-band counts) is ≈0′′47. The positional uncertainty of each source is estimated following equations 2.2 and 2.3.

The main Chandra source catalog is presented in Table 2.2, and the details of the columns are given below.

- Column 1 gives the source number. Sources are listed in order of increasing RA.

- Columns 2 and 3 give the RA and Dec of the X-ray source, respectively. Note that more accurate positions are available for sources detected near the aim-point of the ≈1 Ms CDF-S through the catalogs presented in A03; see columns 19–21. To avoid truncation error, we quote the positions to higher precision than in the International Astronomical Union (IAU) registered names beginning with the acronym “CXO ECDFS” for “Chandra X-ray Observatory Extended Chandra Deep Field-South.” The IAU names should be truncated after the tenths of seconds in RA and after the arcseconds in Dec.

- Column 4 gives the positional uncertainty. As shown above, the positional uncertainty is dependent on off-axis angle and the number of detected counts. For the brighter X-ray sources (≥ 50 full-band counts) the positional uncertainties are given by the empirically determined equation:
\[
\Delta = \begin{cases} 
0.6 & \theta < 5' \\
0.6 + \left( \frac{\theta - 5'}{20} \right) & \theta \geq 5' 
\end{cases}
\tag{2.2}
\]

where \( \Delta \) is the positional uncertainty in arcseconds and \( \theta \) is the off-axis angle in arcminutes (compare with Fig. 2.7).

For the fainter X-ray sources (< 50 full-band counts) the positional uncertainties are given by the empirically determined equation:

\[
\Delta = \begin{cases} 
0.85 & \theta < 5' \\
0.85 + \left( \frac{\theta - 5'}{4} \right) & \theta \geq 5' 
\end{cases}
\tag{2.3}
\]

The stated positional uncertainties are somewhat conservative, corresponding to the \( \approx 80–90\% \) confidence level.

- Column 5 gives the off-axis angle for each source in arcminutes. This is calculated using the source position given in columns 2 and 3 and the aim point (see Table 2.1) for the corresponding field in which it was detected (column 37).

- Columns 6–14 give the source counts and the corresponding 1\( \sigma \) upper and lower statistical errors (from Gehrels 1986), respectively, for the three standard bands. All values are for the standard ASCA grade set, and they have not been corrected for vignetting. Source counts and statistical errors have been calculated using circular aperture photometry; extensive testing has shown that this method is more reliable than the WAVDETECT photometry. The circular aperture was centered at the position given in columns 2 and 3 for all bands.

The local background is determined in an annulus outside of the source-extraction region. The mean number of background counts per pixel is calculated from a Poisson model using \( \frac{n_1}{n_0} \), where \( n_0 \) is the number of pixels with 0 counts and \( n_1 \) is the number of pixels with 1 count. Although only the numbers of pixels with 0 and 1 counts are measured, this technique directly provides the mean background even when \( n_1 \gg n_0 \). Furthermore, by ignoring all pixels with more than 1 count, this technique guards against background contamination from sources. We note that relatively bright nearby sources may contribute counts to nearby pixels where the background is estimated. Since the number density of relatively bright sources in the E-CDF-S is low, we estimate that only \( \approx 10–20 \) of these sources are thereby contaminated; the majority of these sources have been corrected via manual photometry of close doubles (see above). The principal requirement for using this Poisson-model technique is that the background is low and follows a Poisson distribution; in §4.2 of A03 it has been shown that the ACIS-I background matches this criterion for exposures as long as \( \approx 2 \) Ms. The total background for each source is calculated and subtracted to give the net number of source counts.

For sources with fewer than 1000 full-band counts, we have chosen the aperture radii based on the encircled-energy function of the Chandra PSF as determined using the CXC’s
MKPSF software (Feigelson et al. 2000; Jerius et al. 2000). In the soft band, where the background is lowest, the aperture radius was set to the 95% encircled-energy radius of the PSF. In the other bands, the 90% encircled-energy radius of the PSF was used. Appropriate aperture corrections were applied to the source counts by dividing the extracted source counts by the encircled-energy fraction for which the counts were extracted.

For sources with more than 1000 full-band counts, systematic errors in the aperture corrections often exceed the expected errors from photon statistics when the apertures described in the previous paragraph are used. Therefore, for such sources we used larger apertures to minimize the importance of the aperture corrections; this is appropriate since these bright sources dominate over the background. We set the aperture radii to be twice those used in the previous paragraph and inspected these sources to verify that the measurements were not contaminated by neighboring objects.

We have performed several consistency tests to verify the quality of the photometry. For example, we have checked that the sum of the counts measured in the soft and hard bands does not differ from the counts measured in the full band by an amount larger than that expected from measurement error. Systematic errors that arise from differing full-band counts and soft-band plus hard-band counts are estimated to be $\lesssim 4\%$.

When a source is not detected in a given band, an upper limit is calculated; upper limits are indicated as a "−1" in the error columns. All upper limits are determined using the circular apertures described above. When the number of counts in the aperture is $\leq 10$, the upper limit is calculated using the Bayesian method of Kraft, Burrows, & Nousek (1991) for 99% confidence. The uniform prior used by these authors results in fairly conservative upper limits (see Bickel 1992), and other reasonable choices of priors do not materially change our scientific results. For larger numbers of counts in the aperture, upper limits are calculated at the 3$\sigma$ level for Gaussian statistics.

- Columns 15 and 16 give the RA and Dec of the optical source centroid, which was obtained by matching our X-ray source positions (columns 2 and 3) to WFI R-band positions using a matching radius of 1.5 times the positional uncertainty quoted in column 4. For a small number of sources more than one optical match was found, and for these sources the brightest match was selected as the most probable counterpart. Using these criteria, 594 ($\approx 78\%$) of the sources have optical counterparts. Note that the matching criterion used here is more conservative than that used in the derivation of our positional errors discussed in § 2.3.3.1. Sources with no optical counterparts have RA and Dec values set to "00 00 00.00" and "+00 00 00.0".

- Column 17 gives the measured offset between the optical and X-ray sources (i.e., $O−X$) in arcseconds. Sources with no optical counterparts have a value set to "0".

- Column 18 gives the R-band magnitude (AB) of each X-ray source. Sources with no optical counterparts have a value set to "0".

- Column 19 gives the $\approx 1$ Ms CDF-S source number from the main Chandra catalog presented in A03 (see column 1 of Table 3a in A03) for E-CDF-S sources that were matched to A03 counterparts. We used a matching radius of 1.5 times the sum of the positional
errors of the E-CDF-S and A03 source positions. We note that for each matched source only one match was observed; E-CDF-S sources with no A03 match have a value of “0”.

- Columns 20 and 21 give the RA and Dec of the corresponding ≈1 Ms CDF-S A03 source indicated in column 19. Sources with no A03 match have RA and Dec values set to “00 00 00.00” and “+00 00 00.0”.

- Column 22 gives the ≈1 Ms CDF-S source number from the main Chandra catalog presented in G02 (see “ID” column of Table 2 in G02) for E-CDF-S sources that were matched to G02 counterparts. When matching our E-CDF-S source positions with G02 counterparts, we removed noted offsets to the G02 positions of −1′′2 in RA and +0′′8 in Dec (see § A3 of A03); these positions are corrected in the quoted source positions in columns 23 and 24. We used a matching radius of 1.5 times the E-CDF-S positional error plus the G02 quoted positional error for each source position. We note that for each matched source only one match was observed; E-CDF-S sources with no G02 match have a value of “0”.

- Columns 23 and 24 give the RA and Dec of the corresponding ≈1 Ms CDF-S G02 source indicated in column 22. Note that the quoted positions have been corrected by the noted offsets described in column 22 (see § A3 of A03). Sources with no G02 match have RA and Dec values set to “00 00 00.00” and “+00 00 00.0”.

- Columns 25–27 give the effective exposure times derived from the standard-band exposure maps (see §2.3.1 for details on the exposure maps). Dividing the counts listed in columns 6–14 by the corresponding effective exposures will provide vignetting-corrected and quantum efficiency degradation-corrected count rates.

- Columns 28–30 give the band ratio, defined as the ratio of counts between the hard and soft bands, and the corresponding upper and lower errors, respectively. Quoted band ratios have been corrected for differential vignetting between the hard band and soft band using the appropriate exposure maps. Errors for this quantity are calculated following the “numerical method” described in §1.7.3 of Lyons (1991); this avoids the failure of the standard approximate variance formula when the number of counts is small (see §2.4.5 of Eadie et al. 1971). Note that the error distribution is not Gaussian when the number of counts is small. Upper limits are calculated for sources detected in the soft band but not the hard band and lower limits are calculated for sources detected in the hard band but not the soft band. For these sources, the upper and lower errors are set to the computed band ratio.

- Columns 31–33 give the effective photon index (Γ) with upper and lower errors, respectively, for a power-law model with the Galactic column density. The effective photon index has been calculated based on the band ratio in column 28 when the number of counts is not low.

A source with a low number of counts is defined as being (1) detected in the soft band with < 30 counts and not detected in the hard band, (2) detected in the hard band with < 15 counts and not detected in the soft band, (3) detected in both the soft and hard bands, but with < 15 counts in each, or (4) detected only in the full band. When the number of counts
is low, the photon index is poorly constrained and is set to $\Gamma = 1.4$, a representative value for faint sources that should give reasonable fluxes. Upper and lower limits are indicated by setting the upper and lower errors to the computed effective photon index.

- Columns 34–36 give observed-frame fluxes in the three standard bands; quoted fluxes are in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$. Fluxes have been computed using the counts in columns 6, 9, and 12, the appropriate exposure maps (columns 25–27), and the spectral slopes given in column 31. The fluxes have not been corrected for absorption by the Galaxy or material intrinsic to the source. For a power-law model with $\Gamma = 1.4$, the soft-band and hard-band Galactic absorption corrections are $\approx 2.1\%$ and $\approx 0.1\%$, respectively. More accurate fluxes for these sources would require direct fitting of the X-ray spectra for each observation, which is beyond the scope of this paper.

- Column 37 gives the observational field number corresponding to the detected source. The observational fields overlap in a few areas (see Figs. 2.4 and 2.5a) over $\approx 50$ arcmin$^2$, which allowed for duplicate detections of a single source. Fourteen sources in the Chandra catalog were detected in more than one observational field; these sources are flagged in column 39 (see below). The data from the observation that produced the greatest number of full-band counts for these sources is included here; properties derived from the cross-field observations are provided in Table 2.3.

- Column 38 gives the logarithm of the minimum false-positive probability run with WAVDETECT in which each source was detected (see § 2.3.2). A lower false-positive probability indicates a more significant source detection. Note that 655 ($\approx 86\%$) and 596 ($\approx 78\%$) of our sources are detected with false-positive probability thresholds of $1 \times 10^{-7}$ and $1 \times 10^{-8}$, respectively.

- Column 39 gives notes on the sources. “D” denotes a source detected in more than one of the four observational fields. “U” denotes objects lying in the UDF (see Fig. 2.2). “G” denotes objects that were identified as Galactic stars through the optical spectrophotometric COMBO-17 survey (Wolf et al. 2004). “O” refers to objects that have large cross-band (i.e., between the three standard bands) positional offsets ($> 2''$); all of these sources lie at off-axis angles of $> 8'$. “M” refers to sources where the photometry was performed manually. “S” refers to close-double or close-triple sources where manual separation was required. “C” refers to sources detected within the boundary of the $\approx 1$ Ms CDF-S exposure that have no A03 or G02 counterparts. Several of these sources are located in low-sensitivity regions of the $\approx 1$ Ms CDF-S, and a few of these sources may be variable. For further explanation of many of these notes, see the above text in this section on manual correction of the WAVDETECT results.

In Table 2.3 we summarize the cross-field source properties of the 14 sources detected in more than one observational field; none of these sources were detected in more than two fields. These properties were derived from the observation not included in the main Chandra catalog (see columns 37 and 39 of Table 2.2) and are included here for comparison. The columns of Table 2.3 are the same as those in Table 2.2; the source number for each source corresponds to its duplicate listed in the main Chandra catalog. In Table 2.4 we summarize the source detections in the three standard bands for each of the observational fields and the main Chandra catalog.
Table 2.3. Main *Chandra* Catalog Cross-Field Source Properties

<table>
<thead>
<tr>
<th>No. (1)</th>
<th>α<em>2000</em> (2)</th>
<th>δ<em>2000</em> (3)</th>
<th>Pos Err (4)</th>
<th>Off-Axis (5)</th>
<th>FB (6)</th>
<th>FB Upp Err (7)</th>
<th>FB Low Err (8)</th>
<th>SB (9)</th>
<th>SB Upp Err (10)</th>
<th>SB Low Err (11)</th>
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<td>−27 42 19.4</td>
<td>0.8</td>
<td>9.02</td>
<td>62.7</td>
<td>11.2</td>
<td>10.1</td>
<td>38.0</td>
<td>8.1</td>
<td>7.1</td>
</tr>
<tr>
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<td>03 32 25.62</td>
<td>−27 43 05.8</td>
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<td>9.06</td>
<td>81.1</td>
<td>12.1</td>
<td>11.0</td>
<td>53.4</td>
<td>9.2</td>
<td>8.1</td>
</tr>
<tr>
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<td>03 32 25.91</td>
<td>−28 00 46.7</td>
<td>1.8</td>
<td>8.90</td>
<td>22.3</td>
<td>8.7</td>
<td>7.6</td>
<td>14.4</td>
<td>−1</td>
<td>−1</td>
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<tr>
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<td>03 32 26.18</td>
<td>−27 37 12.1</td>
<td>2.0</td>
<td>9.58</td>
<td>35.1</td>
<td>10.3</td>
<td>9.2</td>
<td>22.0</td>
<td>7.3</td>
<td>6.1</td>
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<td>7.84</td>
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<td>95.3</td>
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<td>12.7</td>
<td>72.8</td>
<td>10.9</td>
<td>9.9</td>
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<td>16.0</td>
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<td>425.9</td>
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<td>865.2</td>
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<td>32.7</td>
<td>622.5</td>
<td>27.2</td>
<td>26.1</td>
</tr>
<tr>
<td>383 ...</td>
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<td>−27 41 44.9</td>
<td>0.8</td>
<td>8.02</td>
<td>63.6</td>
<td>11.0</td>
<td>9.8</td>
<td>20.3</td>
<td>6.8</td>
<td>5.7</td>
</tr>
<tr>
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<td>−27 57 30.3</td>
<td>0.8</td>
<td>8.63</td>
<td>72.2</td>
<td>11.2</td>
<td>10.1</td>
<td>55.4</td>
<td>9.1</td>
<td>8.0</td>
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<td>03 32 29.25</td>
<td>−28 01 46.0</td>
<td>2.0</td>
<td>9.79</td>
<td>12.0</td>
<td>9.2</td>
<td>8.1</td>
<td>12.3</td>
<td>−1</td>
<td>−1</td>
</tr>
<tr>
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<td>03 33 38.54</td>
<td>−27 49 42.3</td>
<td>2.4</td>
<td>11.24</td>
<td>28.7</td>
<td>11.3</td>
<td>10.2</td>
<td>19.9</td>
<td>−1</td>
<td>−1</td>
</tr>
</tbody>
</table>

Note. — Basic source properties for the 14 objects detected in more than one observational field. These properties are derived from the observation not included in the main *Chandra* catalog. Columns follow the same format as those presented in Table 2.2; all 39 columns of this table are available via the electronic version of Lehmer et al. (2005a).
In total 776 point sources are detected in one or more of the three standard bands; 14 of these sources are detected in more than one of the four observational fields (see columns 37 and 39 of Tables 2.2 and 2.3) leaving a total of 762 distinct point sources. Out of these 762 distinct point sources, we find that 173 are coincident with sources included in the main Chandra catalog for the ≈1 Ms CDF-S presented in A03 (see columns 19–24 of Table 2.2). For these sources, we find reasonable agreement between the derived X-ray properties presented here and in A03. A total of 589 new point sources are thus detected here, which brings the total number of E-CDF-S plus ≈1 Ms CDF-S sources to 915.

In Table 2.5 we summarize the number of sources detected in one band but not another. All but two of the detected sources are detected in either the soft or full bands. From Tables 2.4 and 2.5, the fraction of hard-band sources not detected in the soft band is 96/453 ≈ 21%. The fraction is somewhat higher than for the Chandra Deep Fields, where it is ≈ 14%. Some of this difference is likely due to differing methods of cross-band matching (i.e., compare § 3.4.1 of A03 with our § 2.3.3.1). Furthermore, this fraction is physically expected to vary somewhat with sensitivity limit. We have also attempted comparisons with X-ray surveys of comparable depth (Stern et al. 2002; Harrison et al. 2003; Wang et al. 2004a,b; Nandra et al. 2005) to the E-CDF-S. Such comparisons are not entirely straightforward due to varying energy bands utilized, source-selection techniques, and source-searching methods. However, the “hard-band but not soft-band” fractions for these surveys appear plausibly consistent (≈15–25%) with that for the E-CDF-S.

In Figure 2.8a we show the distributions of detected counts in the three standard bands. There are 154 sources with > 100 full-band counts, for which basic spectral analyses are possible; there are eight sources with > 1000 full-band counts. In Figure 2.8b we show the distributions of X-ray flux in the three standard bands. The X-ray fluxes in this survey span roughly four orders of magnitude with ≈50% of the sources having soft band fluxes less than 50 × 10^{-17} erg cm^{-2} s^{-1}, a flux regime that few X-ray surveys have probed with significant areal coverage.

In Figure 2.9 we show “postage-stamp” images from the WFI R-band with adaptively-smoothed full-band contours overlaid for sources included in the main Chandra catalog. The wide range of X-ray source sizes observed in these images is largely due to PSF broadening with off-axis angle. In Figure 2.10 we plot the positions of sources detected in the main Chandra catalog. Sources that are also included in the A03 CDF-S source catalog are indicated as open circles, and new X-ray sources detected in this survey are indicated as filled circles; the circle sizes depend upon the most significant false-positive probability run with WAVDETECT for which each source was detected (see column 38 of Table 2.2). The majority of the sources lie in the vicinities of the aim points where the fields are most sensitive. In Figure 2.11 we show the band ratio as a function of full-band count rate for sources in the main Chandra catalog. This plot shows that the mean band ratio for sources detected in both the soft and hard bands hardens for fainter fluxes, a trend observed in other studies (e.g., della Ceca et al. 1999; Ueda et al. 1999; Mushotzky et al. 2000; B01; Tozzi et al. 2001; A03). This trend is due to the detection of more absorbed AGNs at low flux levels, and it has been shown that AGNs will dominate the number counts down to 0.5–2 keV fluxes of ≈1 × 10^{-17} erg cm^{-2} s^{-1} (e.g., Bauer et al. 2004).

Figure 2.12a shows the R-band magnitude versus the soft band flux for sources included in the main Chandra catalog. The approximate X-ray to R-band flux ratios for AGNs and galaxies (e.g., Maccacaro et al. 1998; Stocke et al. 1991; Hornschemeier et al. 2001; Bauer et al. 2004) are
Table 2.4. Summary of *Chandra* Source Detections

<table>
<thead>
<tr>
<th>Band (keV)</th>
<th>Observational Field</th>
<th>Number of Sources</th>
<th>Detected Counts Per Source</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Median</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full (0.5–8.0)</td>
<td>1</td>
<td>191</td>
<td>2509.4</td>
<td>3.9</td>
<td>43.4</td>
<td>123.2</td>
<td></td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
<td>1</td>
<td>167</td>
<td>1715.7</td>
<td>3.7</td>
<td>28.4</td>
<td>91.3</td>
<td></td>
</tr>
<tr>
<td>Hard (2–8)</td>
<td>1</td>
<td>128</td>
<td>787.7</td>
<td>3.9</td>
<td>29.0</td>
<td>60.8</td>
<td></td>
</tr>
<tr>
<td>Full (0.5–8.0)</td>
<td>2</td>
<td>165</td>
<td>2346.5</td>
<td>5.2</td>
<td>37.7</td>
<td>110.2</td>
<td></td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
<td>2</td>
<td>144</td>
<td>1689.4</td>
<td>4.4</td>
<td>25.5</td>
<td>77.4</td>
<td></td>
</tr>
<tr>
<td>Hard (2–8)</td>
<td>2</td>
<td>109</td>
<td>735.2</td>
<td>4.3</td>
<td>25.2</td>
<td>59.2</td>
<td></td>
</tr>
<tr>
<td>Full (0.5–8.0)</td>
<td>3</td>
<td>187</td>
<td>1078.3</td>
<td>6.0</td>
<td>39.3</td>
<td>85.4</td>
<td></td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
<td>3</td>
<td>156</td>
<td>756.6</td>
<td>4.6</td>
<td>24.3</td>
<td>61.1</td>
<td></td>
</tr>
<tr>
<td>Hard (2–8)</td>
<td>3</td>
<td>128</td>
<td>324.5</td>
<td>3.7</td>
<td>26.1</td>
<td>45.8</td>
<td></td>
</tr>
<tr>
<td>Full (0.5–8.0)</td>
<td>4</td>
<td>160</td>
<td>1771.6</td>
<td>4.2</td>
<td>37.1</td>
<td>115.7</td>
<td></td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
<td>4</td>
<td>142</td>
<td>1312.0</td>
<td>4.2</td>
<td>25.8</td>
<td>85.0</td>
<td></td>
</tr>
<tr>
<td>Hard (2–8)</td>
<td>4</td>
<td>98</td>
<td>514.8</td>
<td>4.7</td>
<td>28.2</td>
<td>60.9</td>
<td></td>
</tr>
<tr>
<td>Full (0.5–8.0)</td>
<td>1,2,3,4</td>
<td>689</td>
<td>2509.4</td>
<td>3.9</td>
<td>38.6</td>
<td>104.8</td>
<td></td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
<td>1,2,3,4</td>
<td>598</td>
<td>1715.7</td>
<td>3.7</td>
<td>25.9</td>
<td>75.7</td>
<td></td>
</tr>
<tr>
<td>Hard (2–8)</td>
<td>1,2,3,4</td>
<td>453</td>
<td>787.7</td>
<td>3.7</td>
<td>27.8</td>
<td>55.0</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.5. Sources Detected In One Band But Not Another

<table>
<thead>
<tr>
<th>Detection Band (keV)</th>
<th>Non-detection Energy Band</th>
<th>Full (0.5–8.0)</th>
<th>Soft (0.5–2.0)</th>
<th>Hard (2–8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full (0.5–8.0)</td>
<td></td>
<td>...</td>
<td>149</td>
<td>251</td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
<td></td>
<td>58</td>
<td>...</td>
<td>241</td>
</tr>
<tr>
<td>Hard (2–8)</td>
<td></td>
<td>15</td>
<td>96</td>
<td>...</td>
</tr>
</tbody>
</table>

Fig. 2.8: (a) Histograms showing the distributions of detected source counts for sources in the main Chandra catalog in the full (top), soft (middle), and hard (bottom) bands. Sources with upper limits have not been included in this plot. The vertical dotted lines indicate median numbers of counts (see Table 4). (b) Histograms showing the distributions of X-ray fluxes for sources in the main Chandra catalog in the full (top), soft (middle), and hard (bottom) bands. Sources with upper limits have not been included in this plot. The vertical dotted lines indicate the median fluxes of 26.3, 6.8, and $34.6 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ for the full, soft, and hard bands, respectively.
indicated with dark and light shading, respectively. The majority of the sources in this survey appear to be AGNs. Sixty-one of the sources were reliably classified as AGNs and seventeen sources have been identified as Galactic stars (see column 39 of Table 2.2) in the COMBO-17 survey (Wolf et al. 2004). A significant minority of the sources appear to have X-ray-to-optical flux ratios characteristic of normal or starburst galaxies.

### 2.3.3.2 Supplementary Optically Bright Chandra Source Catalog

The density of optically bright \((R < 23)\) sources on the sky is comparatively low. Therefore, we can search for X-ray counterparts to optically bright sources at a lower X-ray significance threshold than that used in the main catalog without introducing many false sources (see §5.3 of Richards et al. 1998 for a similar technique applied at radio wavelengths). We ran WAVDETECT with a false-positive probability threshold of \(1 \times 10^{-5}\) on images created in the three standard bands. A basic lower significance Chandra catalog was produced containing 323 X-ray sources not present in the main Chandra source catalog.

In our matching of these lower significance Chandra sources to optically bright sources, we used the WFI \(R\)-band source catalog described in §2.3.3. We searched for X-ray counterparts to these optical sources using a matching radius of \(1\arcsec\). Based upon offset tests, as described below, we found empirically that we could match to sources as faint as \(R = 23\) without introducing an unacceptable number of false matches; this \(R\)-band cutoff provides an appropriate balance between the number of detected sources and the expected number of false sources.

In total 26 optically bright X-ray sources were found via our matching. We estimated the expected number of false matches by artificially offsetting the X-ray source coordinates in RA and Dec by both \(5\arcsec\) and \(10\arcsec\) (using both positive and negative shifts) and then re-correlating with the optical sources. On average \(\approx 3\) matches were found with these tests, demonstrating that the majority of the 26 X-ray matches are real X-ray sources; only about 12\% of these sources are expected to be spurious matches.

We also included seven \(R < 21\) sources where the X-ray source lay \(1\arcsec 3–10\arcsec 0\) from the centroid of the optical source but was still within the extent of the optical emission. Using optical spectrophotometric redshift information from COMBO-17, we required that our off-nuclear sources have \(0.5–2\) keV luminosities of \(\lesssim 10^{40}\) erg s\(^{-1}\). This restriction was intended to remove obvious sources not associated with their host galaxies; this led to the removal of one candidate source (J033210.9−280230) when forming our sample of seven plausible off-nuclear X-ray sources. Of the seven selected off-nuclear sources included in the supplementary catalog, we found that six of the host galaxies have COMBO-17 redshift information available. These galaxies were found to have \(z \approx 0.10 – 0.25\) and \(0.5–2\) keV luminosities in the range of \(\approx 10^{39–40}\) erg s\(^{-1}\). These derived luminosities are consistent with these sources being off-nuclear X-ray binaries or star-forming regions associated with bright host galaxies. Since these seven sources were identified in a somewhat subjective manner, it is not meaningful to determine a false-matching probability for them. These sources are indicated in column 33 of Table 2.6. Thus, in total, the supplementary optically bright Chandra source catalog contains 33 sources.

The format of Table 2.6 is similar to that of Table 2.2. Details of the columns in Table 2.6 are given below.

- Column 1 gives the source number (see column 1 of Table 2.2 for details).
Fig. 2.9: WFI $R$-band postage-stamp images for the sources in the main Chandra catalog with full-band adaptively smoothed X-ray contours overlaid. The contours are logarithmic in scale and range from $\approx0.03$–$30\%$ of the maximum pixel value. Note that for sources with few full-band counts, CSMOOTH has suppressed the observable emission in the adaptively smoothed images and therefore no X-ray contours are observed for these sources. The label at the top of each image gives the source name, which is composed of the source coordinates, while numbers at the bottom left and right hand corners correspond to the source number (see column 1 of Table 1) and full-band source counts, respectively. Each image is $\approx 24''/6$ on a side, and the source of interest is always located at the center of the image. Only one of the thirteen pages of cutouts is included here; all thirteen pages are available at the E-CDF-S website (http://www.astro.psu.edu/users/niel/ecdfs/ecdfs-chandra.html).
Fig. 2.10: Positions of the sources in the main Chandra catalog. The regions have the same meaning as those given in Figure 2.3a. New X-ray sources are shown here as filled circles while sources that were previously detected in the \( \approx 1 \) Ms CDF-S are shown as open circles. Large, medium, and small circles correspond to sources with WAVDETECT false-positive probability \( \leq 1 \times 10^{-8} \), \( \leq 1 \times 10^{-7} \), and \( \leq 1 \times 10^{-6} \), respectively.
**Fig. 2.11:** Band ratio as a function of full-band count rate for the sources in the main *Chandra* catalog. Small solid dots show sources detected in both the soft and hard bands. Plain arrows show sources detected in only one of these two bands with the arrows indicating upper and lower limits; sources detected in only the full band cannot be plotted. The open stars show average band ratios as a function of full-band count rate. Horizontal dotted lines are labeled with the photon indices that correspond to a given band ratio assuming only Galactic absorption (these were determined using the CXC’s Portable, Interactive, Multi-Mission Simulator; PIMMS).

**Fig. 2.12:** (a) WFI R-band magnitude versus soft-band flux for sources in the main *Chandra* catalog. Open-star symbols indicate Galactic stars identified using the optical spectrophotometric COMBO-17 survey (Wolf et al. 2004). Diagonal lines indicate constant flux ratios. Sources that were not detected in the soft band that were detected in at least one of the full and hard bands are plotted here as upper limits. The shaded regions show the approximate flux ratios for AGNs and galaxies (dark and light, respectively); the sixty-one AGNs with reliable COMBO-17 identifications are plotted as squares. (b) WFI R-band magnitude versus soft-band flux for sources in the optically bright supplementary catalog. Note that many of these sources have X-ray-to-optical flux ratios expected for normal and starburst galaxies.
<table>
<thead>
<tr>
<th>No. (1)</th>
<th>$\alpha_{2000}$ (2)</th>
<th>$\delta_{2000}$ (3)</th>
<th>Pos Err (4)</th>
<th>Off-Axis (5)</th>
<th>FB (6)</th>
<th>FB Upp Err (7)</th>
<th>FB Low Err (8)</th>
<th>SB (9)</th>
<th>SB Upp Err (10)</th>
<th>SB Low Err (11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ...</td>
<td>03 31 16.20</td>
<td>−27 50 30.9</td>
<td>1.2</td>
<td>10.04</td>
<td>17.9</td>
<td>5.3</td>
<td>4.2</td>
<td>12.3</td>
<td>−1</td>
<td>−1</td>
</tr>
<tr>
<td>2 ...</td>
<td>03 31 22.00</td>
<td>−27 36 20.1</td>
<td>1.2</td>
<td>8.41</td>
<td>17.0</td>
<td>5.2</td>
<td>4.1</td>
<td>11.5</td>
<td>−1</td>
<td>−1</td>
</tr>
<tr>
<td>3 ...</td>
<td>03 31 28.87</td>
<td>−27 53 29.9</td>
<td>1.2</td>
<td>5.97</td>
<td>12.1</td>
<td>4.6</td>
<td>3.4</td>
<td>9.1</td>
<td>−1</td>
<td>−1</td>
</tr>
<tr>
<td>4 ...</td>
<td>03 31 35.14</td>
<td>−27 58 08.6</td>
<td>1.2</td>
<td>3.39</td>
<td>10.0</td>
<td>−1</td>
<td>−1</td>
<td>2.8</td>
<td>2.9</td>
<td>1.6</td>
</tr>
<tr>
<td>5 ...</td>
<td>03 31 39.05</td>
<td>−28 02 21.1</td>
<td>1.2</td>
<td>5.65</td>
<td>14.6</td>
<td>−1</td>
<td>−1</td>
<td>1.5</td>
<td>2.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Note. — Table 2.6 is presented in its entirety in the electronic edition Lehmer et al. (2005a). An abbreviated version of the table is shown here for guidance as to its form and content. The full table contains 33 columns of information on the 33 X-ray sources.
Columns 2 and 3 give the RA and Dec of the X-ray source, respectively. The WAVDETECT positions are given for these faint X-ray sources. Whenever possible, we quote the position determined in the full band; when a source is not detected in the full band we use, in order of priority, the soft-band position and then the hard-band position. The priority ordering of position choices above was designed to maximize the signal-to-noise of the data being used for positional determination.

Column 4 gives the positional uncertainty in arcseconds. For these faint X-ray sources, the positional uncertainty is taken to be 1\arcsec \text{, the 90th percentile of the average optical-X-ray positional offsets given in column 17.}

Column 5 gives the off-axis angle for each source in arcminutes (see column 5 of Table 2.2 for details).

Columns 6–14 give the counts and the corresponding 1\(\sigma\) upper and lower statistical errors (using Gehrels 1986), respectively, for the three standard bands. The photometry is taken directly from WAVDETECT for these faint X-ray sources.

Columns 15 and 16 give the RA and Dec of the optical source centroid, respectively.

Column 17 gives the measured offset between the optical and X-ray sources (i.e., \(O - X\)) in arcseconds.

Column 18 gives the \(R\)-band magnitude (AB) of the optical source.

Column 19 gives the \(\approx 1\) Ms CDF-S source number from the main Chandra catalog presented in A03 (see column 1 of Table 3a in A03) for supplementary sources that were matched to A03 counterparts. We used a matching radius of 1.5 times the sum of the positional errors of the E-CDF-S and A03 source positions. We note that for each matched source only one match was observed; supplementary sources with no A03 match have a value of “0”.

Columns 20 and 21 give the RA and Dec of the corresponding \(\approx 1\) Ms CDF-S A03 source indicated in column 19. Sources with no A03 match have RA and Dec values set to “00 00 00.00” and “+00 00 00.0”.

Column 22 gives the \(\approx 1\) Ms CDF-S source number from the main Chandra catalog presented in G02 (see “ID” column of Table 2 in G02) for supplementary sources that were matched to G02 counterparts. When matching our supplementary source positions with G02 counterparts, we removed noted offsets to the G02 positions of \(-1\"2\) in RA and \(+0\"8\) in Dec (see \(\S\) A3 of A03); these positions are corrected in the quoted source positions in columns 23 and 24. We used a matching radius of 1.5 times the E-CDF-S positional error plus the G02-quoted positional error for each source position. We note that for each matched source only one match was observed; supplementary sources with no G02 match have a value of “0”.

Columns 23 and 24 give the RA and Dec of the corresponding \(\approx 1\) Ms CDF-S G02 source indicated in column 22. Note that the quoted positions have been corrected by the noted
offsets described in column 22 (see § A3 of A03). Sources with no G02 match have RA and Dec values set to “00 00 00.00” and “+00 00 00.0”.

- Columns 25–27 give the effective exposure times derived from the standard-band exposure maps (see columns 25–27 of Table 2.2 for details).
- Column 28 gives the photon index used to calculate source fluxes (columns 26–28). We used a constant photon index of $\Gamma = 2.0$ since our source-selection technique preferentially selects objects with flux ratios $f_{0.5-2.0 \text{ keV}}/f_R < 0.1$, which are observed to have effective photon indices of $\Gamma \approx 2$ (e.g., § 4.1.1 of Bauer et al. 2004).
- Column 29–31 give observed-frame fluxes in the three standard bands; quoted fluxes are in units of $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ and have been calculated assuming $\Gamma = 2.0$. The fluxes have not been corrected for absorption by the Galaxy or material intrinsic to the sources (see columns 34–36 of Table 2.2 for details).
- Column 32 gives the observational field number corresponding to the detected source (see column 37 of Table 2.2 for details).
- Column 33 gives notes on the sources. With the exception of the additional note given below, the key for these notes is given in column 39 of Table 2.2. “L” refers to objects where the X-ray source lies $>1''3$ from the centroid of the optical source but is still within the extent of the optical emission (see the text above for further discussion).

The $R$-band magnitudes of the supplementary sources span $R = 16.6–22.9$. In Figure 2.12b we show the $R$-band magnitude versus soft-band flux. All of the sources lie in the region expected for starburst and normal galaxies. Three of these sources have been classified as Galactic stars via optical classifications from COMBO-17 (see column 33 of Table 2.6). Some of these sources may be low-luminosity AGNs; the small number of hard-band detections ($\approx 6\%$) indicates that few of these are absorbed AGNs. Due to the low number of counts detected for these sources, we do not provide postage-stamp images as we did for sources in the main catalog (i.e., Fig. 2.9).

The addition of the optically bright supplementary sources increases the number of extragalactic objects in the E-CDF-S with $f_{0.5-2.0 \text{ keV}}/f_R < 0.1$ and $f_{0.5-2.0 \text{ keV}}/f_R < 0.01$ by $\approx 20\%$ and $\approx 50\%$, respectively. However, the optically bright supplementary sources are not representative of the faintest X-ray sources as a whole since our selection criteria preferentially select optically bright and X-ray faint non-AGNs (e.g., A03; Hornschemeier et al. 2003).

### 2.4 Background and Sensitivity Analysis

The faintest sources in the main Chandra catalog have $\approx 4$ counts (see Table 2.4). For a $\Gamma = 1.4$ power law with Galactic absorption, the corresponding soft-band and hard-band fluxes at the aim points are $\approx 8.9 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $\approx 4.4 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively. This gives a measure of the ultimate sensitivity of this survey, however, these numbers are only relevant for a small region close to the aim point. To determine the sensitivity across the field it is necessary to take into account the broadening of the PSF with off-axis angle, as well as changes in the effective exposure and background rate across the field. We estimated the sensitivity across the field by employing a Poisson model, which was calibrated for sources detected in the main Chandra catalog. Our resulting relation is
\[
\log(N) = \alpha + \beta \log(b) + \gamma \log(b)^2 + \delta \log(b)^3
\]  

(2.4)

where \(N\) is the required number of source counts for detection, and \(b\) is the number of background counts in a source cell; \(\alpha = 0.967, \beta = 0.414, \gamma = 0.0822,\) and \(\delta = 0.0051\) are fitting constants. The only component within this equation that we need to measure is the background. For the sensitivity calculations here we measured the background in a source cell using the background maps described below and assumed an aperture size of 70% of the encircled-energy radius of the PSF; the 70% encircled energy-radius was chosen as a compromise between having too few source counts and too many background counts. The total background includes contributions from the unresolved cosmic background, particle background, and instrumental background (e.g., Markevitch 2001; Markevitch et al. 2003). For our analyses we are only interested in the total background and do not distinguish between these different components.

To create background maps for all of the twelve images, we first masked out the point sources from the main Chandra catalog using apertures with radii twice that of the \(\approx 90\%\) PSF encircled-energy radius. The resultant images should include minimal contributions from detected point sources. They will, however, include contributions from extended sources (e.g., Bauer et al. 2002; see § 2.6), which will cause a slight overestimation of the measured background close to extended sources. Extensive testing of background-count distributions in all three standard bands has shown that the X-ray background follows a nearly Poisson count distribution (see § 4.2 of A03). We filled in the masked regions for each source with a local background estimate by making a probability distribution of counts using an annulus with inner and outer radii of 2 and 4 times the \(\approx 90\%\) PSF encircled-energy radius, respectively. The background properties are summarized in Table 2.7, and the full-band background map is shown in Figure 2.13. The majority of the pixels have no background counts (e.g., in the full band \(\approx 97\%\) of the pixels are zero) and the mean background count rates for these observations are broadly consistent with those presented in A03.

Following equation 2.4, we generated sensitivity maps using the background and exposure maps; we assumed a \(\Gamma = 1.4\) power-law model with Galactic absorption. In Figure 2.14 we show the full-band sensitivity map, and in Figure 2.15 we show plots of flux limit versus solid angle for the full, soft, and hard bands. The \(\approx 1\) arcmin\(^2\) regions at the aim points has average 0.5–2 keV and 2–8 keV sensitivity limits of \(\approx 1.1 \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\) and \(\approx 6.7 \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\), respectively. Since we do not filter out detected sources with our sensitivity maps, a number of sources have fluxes below these sensitivity limits (4 sources in the soft band and 17 sources in the hard band). Approximately 800 arcmin\(^2\) of the field (i.e., \(\approx 3\) times the size of a single ACIS-I field) has a soft-band sensitivity limit of \(\approx 3 \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\), well into the flux range where few X-ray surveys have probed (see Fig. 2.1).

### 2.5 Number Counts for Main Chandra Catalog

We have calculated cumulative number counts, \(N(> S)\), for the soft and hard bands using sources presented in our main Chandra catalog (see Table 2.2). We restricted our analyses to flux levels where we expect to be mostly complete based on our sensitivity maps and simulations performed by Bauer et al. (2004); this also helps to guard against Eddington bias at low flux levels. We empirically set our minimum flux levels to \(3.0 \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\) in the soft band and \(1.2 \times 10^{-15}\)
Table 2.7. Background Parameters

<table>
<thead>
<tr>
<th>Band (keV)</th>
<th>Observational Field</th>
<th>Mean Background (counts pixel(^{-1}))(^a)</th>
<th>Mean Background (counts Ms(^{-1}) pixel(^{-1}))(^b)</th>
<th>Total Background(^c) (10(^4) counts)</th>
<th>Count Ratio(^d) (background/source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full (0.5–8.0)</td>
<td>1</td>
<td>0.033</td>
<td>0.169</td>
<td>14.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Soft (0.5–2.0)</td>
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<td>0.009</td>
<td>0.044</td>
<td>3.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Hard (2–8)</td>
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<td>0.024</td>
<td>0.128</td>
<td>10.8</td>
<td>12.7</td>
</tr>
<tr>
<td>Full (0.5–8.0)</td>
<td>2</td>
<td>0.036</td>
<td>0.192</td>
<td>15.8</td>
<td>8.6</td>
</tr>
<tr>
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<td>0.066</td>
<td>4.1</td>
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<tr>
<td>Hard (2–8)</td>
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<td>11.7</td>
<td>16.9</td>
</tr>
<tr>
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<td>0.181</td>
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<td>10.1</td>
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<td>4.2</td>
</tr>
<tr>
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<td>0.140</td>
<td>12.1</td>
<td>19.5</td>
</tr>
<tr>
<td>Full (0.5–8.0)</td>
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<td>0.228</td>
<td>17.4</td>
<td>9.4</td>
</tr>
<tr>
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<td>0.048</td>
<td>4.4</td>
<td>3.6</td>
</tr>
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<td>0.148</td>
<td>13.1</td>
<td>20.6</td>
</tr>
<tr>
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<td>0.192</td>
<td>63.9</td>
<td>8.5</td>
</tr>
<tr>
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<td>0.051</td>
<td>16.3</td>
<td>3.5</td>
</tr>
<tr>
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<td>0.027</td>
<td>0.140</td>
<td>47.7</td>
<td>17.4</td>
</tr>
</tbody>
</table>

\(^a\)The mean numbers of counts per pixel. These are measured from the masked background images described in § 2.4.

\(^b\)The mean numbers of counts per pixel divided by the mean effective exposure. These are measured from the exposure maps and masked background images described in § 2.4.

\(^c\)Total number of background counts.

\(^d\)Ratio of the total number of background counts to the total number of source counts.
Fig. 2.13: Full-band background map of the E-CDF-S. This background map has been created following §2.4. Symbols and regions have the same meaning as those given in Figure 2.3a.
Fig. 2.14: Full-band sensitivity map of the E-CDF-S. This sensitivity map has been created following §2.4. Symbols and regions have the same meaning as those given in Figure 2.3a. Black, dark gray, light gray, and white areas correspond to flux-limits of $<3 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, $3-7.8 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, $7.8-20 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, and $>20 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, respectively. The central dashed circle ($\approx 6'$ radius) shows the approximate region of the $\approx 1$ Ms CDF-S where the full band flux-limit is $<3 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$. Note the most sensitive regions of the E-CDF-S exposure lie just outside the $\approx 1$ Ms CDF-S exposure.
Fig. 2.15: Solid angle vs. flux limit for the full (top), soft (middle), and hard (bottom) bands, determined following §2.4. The average flux limits (averaged over the four observational fields) at the aim points are $3.5 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ (full-band), $1.1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ (soft-band), and $6.7 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ (hard-band).
erg cm$^{-2}$ s$^{-1}$ in the hard band, which correspond to the minimum detected fluxes for sources with $\gtrsim 15$ counts in each respective band.

Assuming completeness to the flux levels quoted above, the cumulative number of sources, $N(>S)$, brighter than a given flux, $S$, weighted by the appropriate aerial coverage, is

$$N(>S) = \sum_{S_i > S} \Omega_i^{-1}$$

(2.5)

where $\Omega_i$ is the maximum solid angle for which a source with measured flux, $S_i$, could be detected. Each maximum solid angle was computed using the profiles presented in Figure 2.15. In Figure 2.16 we show the cumulative number counts for the main Chandra catalog. Number counts derived for the $\approx 1$ Ms CDF-S from Rosati et al. (2002) have been plotted for comparison. The E-CDF-S number counts appear to be consistent with those from the $\approx 1$ Ms CDF-S to within $\approx 1\sigma$ over the overlapping flux ranges. We note, however, that the hard-band number counts appear to be generally elevated with respect to those from the $\approx 1$ Ms CDF-S; this effect is likely a signature of field-to-field variance from the $\approx 1$ Ms CDF-S where a smaller solid angle is surveyed. Even with the conservative flux constraints used in our number-counts analysis we reach source densities exceeding $\approx 2000$ deg$^{-2}$; as noted in § 2.3.3.1, a large majority of these sources are AGNs. For comparison, the number density of COMBO-17 sources with reliable AGN identifications is $\approx 300$ deg$^{-2}$ (Wolf et al. 2004).

### 2.6 Extended Sources

We searched the standard-band images for extended sources using the Voronoi Tessellation and Percolation algorithm VTPDETECT (Ebeling & Wiedenmann 1993; Dobrzycki et al. 2002). In our VTPDETECT searching, we adopted a false-positive probability threshold of $1 \times 10^{-7}$ and a "coarse" parameter of 50. Following the source-detection criteria presented in Bauer et al. (2002),
we further required that VTPDETECT-detected sources have (1) average VTPDETECT radii (i.e., average of the 3σ major and minor axes estimated by VTPDETECT) ≥ three times the 95% encircled-energy radius of a point source at the given position and (2) visible evidence for extended emission in the adaptively smoothed, exposure-corrected images (see § 2.3.3.1 and Fig. 2.3b). Application of these somewhat conservative selection criteria yielded three extended X-ray sources, all of which are detected only in the soft band. The soft emission from the most significant of these three extended sources, CXOECDFS J033320.3–274836, is clearly visible as an extended red “glow” near the left-hand side of Figure 2.6.

The X-ray properties of these three extended sources are presented in Table 2.8; our analysis was limited to the soft band where we find all of our detections. The counts for extended
Table 2.8. Extended-Source Properties

<table>
<thead>
<tr>
<th>No.</th>
<th>$\alpha_{2000}$</th>
<th>$\delta_{2000}$</th>
<th>Region$^a$</th>
<th>Angle$^b$</th>
<th>SB Counts$^c$</th>
<th>S-to-B Ratio$^d$</th>
<th>$\xi$</th>
<th>SB Flux$^f$</th>
<th>$L_X^g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 . . .</td>
<td>03 32 09.62</td>
<td>$-27 42 42.2$</td>
<td>$100'' \times 60''$</td>
<td>335$^\circ$</td>
<td>$44.1 \pm 16.5$</td>
<td>0.22</td>
<td>0.7</td>
<td>2.2</td>
<td>4.8</td>
</tr>
<tr>
<td>2 . . .</td>
<td>03 32 57.94</td>
<td>$-28 01 55.4$</td>
<td>$90'' \times 60''$</td>
<td>35$^\circ$</td>
<td>$50.5 \pm 16.3$</td>
<td>0.28</td>
<td>0.7</td>
<td>1.7</td>
<td>4.1</td>
</tr>
<tr>
<td>3 . . .</td>
<td>03 33 20.32</td>
<td>$-27 48 36.2$</td>
<td>$380'' \times 230''$</td>
<td>10$^\circ$</td>
<td>$901.0 \pm 60.4$</td>
<td>0.34</td>
<td>0.1</td>
<td>27.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

$^a$Extraction region given as major axis and minor axis in arcseconds.
$^b$Position angle of the extraction region.
$^c$Net 0.5–2.0 keV background-subtracted source counts. These counts have been measured using the specified extraction regions.
$^d$Ratio of the 0.5–2.0 keV source counts to the total number of expected 0.5–2.0 keV background counts.
$^e$Redshift of candidate group or poor cluster associated with the extended source. All redshifts were inferred from galaxies with optical spectrophotometric redshifts from the COMBO-17 survey with the exception of source number 1, which was previously identified spectroscopically by Szokoly et al. (2004).
$^f$Integrated 0.5–2.0 keV X-ray flux in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$, derived for each source assuming a Raymond-Smith thermal plasma spectral energy distribution with $kT = 1.0$ keV at the given redshift.
$^g$Integrated 0.5–2.0 keV X-ray luminosity in units of $10^{42}$ erg s$^{-1}$. 
sources were determined using manual aperture photometry; point sources were masked out using circular apertures with radii of twice the 95% encircled-energy radii (see Footnote 3). We extracted extended-source counts using elliptical apertures with sizes and orientations that most closely matched the apparent extent of X-ray emission (> 10% above the background level) as observed in the adaptively smoothed images (see Table 2.8). The local background was estimated using elliptical annuli with inner and outer sizes of 1 and 2.5 times those used for extracting source counts. In order to calculate properly the expected numbers of background counts in our source extraction regions, we extracted total exposure times from the source and background regions (with point sources removed) and normalized the extracted background counts to the source exposure times. That is, using the number of background counts \( b_m \) and total background exposure time \( T_m \) as measured from the elliptical annuli, we calculated the expected number of background counts \( b_s \) in a source extraction region with total exposure time \( T_s \) as being \( b_s = b_m T_s / T_m \). This technique was used to account for extended emission from sources that are spatially distributed over more than one observational field, which was the case for CXOECDFS J033320.3−274836.

Figure 2.17 shows WFI R-band images of the extended sources with adaptively smoothed soft-band contours overlaid. Inspection of the spectrophotometric redshifts of optical sources (from COMBO-17) in these regions suggests that the extended X-ray emission for all three sources may originate from low-to-moderate redshift groups or poor clusters. The most conspicuous of these is the apparent clustering of galaxies at \( z \approx 0.1 \) in the area of CXOECDFS J033320.3−274836, an \( \approx 20 \) arcmin\(^2\) extended X-ray source. CXOECDFS J033209.6−274242 lies in the \( \approx 1 \) Ms CDF-S and was previously detected as an extended source by G02. Optical spectroscopic follow-up observations using the VLT have shown that this source is associated with a galaxy cluster at \( z = 0.73 \) (Szokoly et al. 2004). Suggestive evidence for clustering at \( z \approx 0.7 \) is also observed for CXOECDFS J033257.9−280155; this may be an extension of the large-scale structures observed in the \( \approx 1 \) Ms CDF-S (Gilli et al. 2003, 2005). Under the assumption that these sources are indeed groups or poor clusters at the discussed redshifts, we computed the expected soft-band fluxes and luminosities assuming a Raymond-Smith thermal plasma (Raymond & Smith 1977) with \( kT = 1.0 \) keV (see Table 2.8). We find that these sources would have rest-frame 0.5–2 keV luminosities of \( \approx 1–5 \times 10^{42} \) erg s\(^{-1}\). Further optical spectroscopic observations and analyses beyond the scope of this paper are required for confirmation of the nature of these sources.

### 2.7 Summary

We have presented catalogs and basic analyses of point sources detected in the 250 ks \( \approx 0.3 \) deg\(^2\) Extended Chandra Deep Field-South (E-CDF-S). The survey area consists of four observational fields, of similar exposure, with average on-axis flux limits in the 0.5–2 keV and 2–8 keV band-passes of \( \approx 1.1 \times 10^{-16} \) erg cm\(^{-2}\) s\(^{-1}\) and \( \approx 6.7 \times 10^{-16} \) erg cm\(^{-2}\) s\(^{-1}\), respectively. We have presented two catalogs: a main Chandra catalog of 762 sources (589 of these are new), which was generated by running WAVDETECT with a false-positive probability threshold of \( 1 \times 10^{-6} \), and a supplementary catalog of 33 lower-significance (false-positive probability threshold of \( 1 \times 10^{-5} \)) X-ray sources with optically bright (\( R < 23 \)) counterparts. The X-ray spectral properties and optical fluxes of sources in our main Chandra catalog indicate a variety of source types, most of
which are absorbed AGNs that dominate at lower X-ray fluxes. The X-ray and optical properties of sources in the supplementary optically bright *Chandra* catalog are mostly consistent with those expected for starburst and normal galaxies. We have presented basic number-count results for point sources in our main *Chandra* catalog and find overall consistency with number counts derived for the $\approx$1 Ms CDF-S in both the 0.5–2 keV and 2–8 keV bandpasses. We have also presented three 0.5–2 keV extended sources, which were detected using a conservative detection criterion. These sources are likely associated with groups or poor clusters at $z \approx 0.1 – 0.7$ with $L_X \approx 1 – 5 \times 10^{42}$ erg s$^{-1}$. 
Chapter 3

The X-ray Evolution of Early-Type Galaxies in the Extended Chandra Deep Field-South

3.1 Introduction

Distant ($z \approx 0.1–3$), isolated early-type galaxies have been studied extensively at optical and near-IR wavelengths. The optical luminosities of early-type galaxies with rest-frame red-sequence colors have faded by $\approx 1$ magnitude since $z = 1$ (e.g., Bell et al. 2004a; McIntosh et al. 2005; Treu et al. 2005, 2006; van der Wel et al. 2005). Furthermore, little star-formation activity is observed within these galaxies out to at least $z \approx 0.7$ (e.g., Bell et al. 2005) indicating that this observed evolution is consistent with the passive aging of old stars. However, the luminosity density of red-sequence galaxies has been observed to remain approximately constant over $z \approx 0.1–0.7$ (e.g., Bell et al. 2004a; Faber et al. 2006), and since these galaxies appear to be fading passively with cosmic time, this suggests that an important fraction ($\approx 1/2$) of the current $z = 0$ stellar-mass content of the early-type galaxy population has emerged since $z = 1$. One explanation for these observations is that relatively young, lower-mass galaxies continuously populate the red-sequence (e.g., van der Wel et al. 2004; Thomas et al. 2005) through either a downsizing mass-assembly scenario (e.g., Cowie et al. 1996; Bundy et al. 2005; Cimatti et al. 2006; De Lucia et al. 2006; Lee et al. 2006) and/or a scenario where lower-mass early-type galaxies have different merging histories than their higher-mass counterparts (e.g., Khochfar & Burkert 2003).

At $z \gtrsim 1$, distant red galaxies (DRGs; selected using $J-K$ colors) and extremely red objects (EROs; $R-K$ or $I-K$ selected), some of which are likely progenitors to early-type galaxies, appear to have large star-formation rates and inferred dynamical masses similar to those observed for massive local ellipticals (e.g., Förster–Schreiber et al. 2004; McCarthy 2004; van Dokkum et al. 2004; Papovich et al. 2006). These analyses suggest that the majority of the stellar mass within many massive early-type galaxies formed at $z \gtrsim 1.5$, possibly during a dust-obscured far-infrared-luminous phase (e.g., Chapman et al. 2005; Swinbank et al. 2006).

3.1.1 X-ray Properties of Early-Type Galaxies

X-ray investigations of local early-type galaxies have revealed that the total X-ray luminosity is correlated with optical luminosity (e.g., Trinchieri & Fabbiano 1985; Canizares et al. 1987; Brown & Bregman 1998; O’Sullivan et al. 2001; Ellis & O’Sullivan 2006). X-ray emission from local early-type galaxies originates primarily from a combination of hot interstellar gas and low mass X-ray binaries (LMXBs), and due to their relatively low star-formation rates (SFRs) per unit stellar mass (typically SFR/$M_\ast \approx 10^{-3}–10^{-1}$ Gyr$^{-1}$ for $z \approx 0.0–0.7$ galaxies with $M_\ast \gtrsim 10^{10}$ $M_\odot$; e.g., Feulner et al. 2006), these galaxies are expected to have negligible contributions from high mass X-ray binaries (HMXBs; e.g., Grimm et al. 2002). Two fairly distinct classes of early-type galaxies, which can be divided by optical luminosity at $L_{B, \text{crit}} \approx 10^{10} L_{B, \odot}$,
have been identified. Early-type galaxies with $L_B \gtrsim L_{B,\text{crit}}$ are referred to as “optically luminous” and those with $L_B \lessgtr L_{B,\text{crit}}$ are referred to as “optically faint.”

Optically luminous early-type galaxies in the local universe are generally observed to have X-ray emission powered largely by hot ($kT \approx 0.3\text{–}1$ keV) interstellar gas at soft ($0.5\text{–}2.0$ keV) X-ray energies and LMXBs at hard ($2\text{–}10$ keV) X-ray energies (e.g., Matsumoto et al. 1997). Figure 3.1a illustrates the X-ray spectrum of NGC 1600 (Sivakoff et al. 2004), a representative optically luminous early-type galaxy; the hot-gas and LMXB components have been separated for illustrative purposes. The X-ray luminosities for optically luminous early-type galaxies are correlated with their optical luminosities following $L_X \propto L_B^2$. Stellar winds generate the gas and high-velocity interactions and Type Ia supernovae heat it to X-ray temperatures (e.g., Sarazin 1997). Galaxies with larger stellar masses and deeper gravitational potential wells generally have higher stellar velocity dispersions and thus provide more significant heating of the gas. Therefore, the $L_X-L_B$ relation is manifested as a result of proportionalities between the stellar mass in a particular galaxy (traced by $L_B$) and the stellar velocity dispersion of that galaxy (traced by $L_X$; e.g., Mahdavi & Geller 2001).

Optically faint early-type galaxies in the local universe have soft X-ray emission characterized by a power-law ($\Gamma \approx 1.8$) component from LMXBs and a mild contribution from hot interstellar gas (i.e., a thermal plasma with $kT \approx 0.1$ keV). At hard X-ray energies, the emission is completely dominated by LMXBs. The total X-ray luminosities of optically faint early-type galaxies are observed to be linearly correlated with their optical luminosities (i.e., $L_X \propto L_B$). This linear correlation is thought to arise largely as a result of the number of LMXBs in a given galaxy being proportional to the stellar mass within that galaxy (e.g., Gilfanov 2004). Due to their low luminosities, few optically faint early-type galaxies have been studied in detail in the X-ray band, and the presently available data for these galaxies are plagued by large scatter due to small numbers of LMXBs per galaxy and varying contributions from hot interstellar gas (e.g., David et al. 2006). Therefore, much of what is known about LMXBs in these galaxies comes from studying optically luminous early-type galaxies that have little contamination from hot interstellar gas (i.e., X-ray faint early-type galaxies). Figure 3.1b shows the X-ray spectrum of NGC 4697 (e.g., Sarazin et al. 2001), an X-ray faint (yet optically luminous) early-type galaxy, which is expected to be representative of the typical optically faint early-type galaxy X-ray spectrum.

### 3.1.2 Physical Properties of the X-ray Emitting Components

The two early-type galaxy classes discussed above (optically luminous and faint) generally differ in their relative spectral contributions from hot interstellar gas and LMXBs. An important component of the X-ray emission from early-type galaxies, most notably in optically luminous sources, is the hot interstellar gas. Detailed observations of the gas have shown that it radiates strongly but does not appear to be cooling as expected (e.g., Xu et al. 2002; § 7.1 of Mathews & Brighenti 2003 and references therein; Tamura et al. 2003; Bregman et al. 2005). The observed gas temperatures and densities of the central regions of optically luminous early-type galaxies (e.g., Fukazawa et al. 2006) imply short radiative cooling times of $\approx 10^8$ yr on average. Simple cooling-flow models, which include heating from stellar winds and Type Ia supernovae, vastly overpredict the amount of cooled gas observed in the central regions of these galaxies (see, e.g., § 8 of Mathews & Brighenti 2003); this suggests some additional form of
Fig. 3.1: Rest-frame X-ray spectral energy distributions (SEDs) for (a) NGC 1600 (Sivakoff et al. 2004) and (b) NGC 4697 (Sarazin et al. 2001). These are normal early-type galaxies with X-ray emission dominated by hot interstellar gas (NGC 1600) and discrete LMXBs (NGC 4697) and have X-ray spectra representative of optically luminous and faint galaxies, respectively. These SEDs (solid curves) were separated into LMXB (dashed curves) and hot gas (dotted curves) components (see § 3.2.2 for further details). The X-ray emission from NGC 1600 was best fit using a power-law ($\Gamma \approx 1.8$) for the discrete component and a MEKAL plasma ($kT \approx 1$ keV; $Z \approx 0.2Z_\odot$) for the unresolved component. NGC 4697 was best fit by a thermal bremsstrahlung ($kT \approx 5.2$ keV) for the LMXB component and a MEKAL plasma ($kT \approx 0.3$ keV; $Z \approx 0.1Z_\odot$) for the hot interstellar gas. For reference, we have shown the energy ranges of our adopted bandpasses redshifted to $z = 0.55$ and $z = 0.39$, the median redshifts of our optically luminous and faint samples, respectively. We note that for X-ray luminous (optically luminous) early-type galaxies within the redshift ranges considered in this study, the 0.5–1.0 keV (SB1) and 0.5–2.0 keV (SB) bandpasses primarily trace hot interstellar gas and the 2–8 keV (HB) bandpass is primarily dominated by LMXBs. However, for X-ray faint (optically faint) early-type galaxies, all bandpasses are generally dominated by LMXB emission.
heating must be present. Attempts to mitigate this problem by including additional heating components in these models, such as transient heating from active galactic nuclei (AGNs), have been unsuccessful in reproducing the observed properties of the gas (e.g., the radial profiles of electron temperature, density, and metallicity; see, e.g., Brighenti & Mathews 2003). Despite these modelling difficulties, both observational and theoretical studies have suggested that energy feedback from transient AGNs must be important (e.g., Binney & Tabor 1995; Ciotti & Ostriker 1997, 2001; Birzan et al. 2004; Best et al. 2005, 2006; Churazov et al. 2005; Di Matteo et al. 2005; Scannapieco et al. 2005; Bower et al. 2006; Brighenti & Mathews 2006; Croton et al. 2006; Hopkins et al. 2006; McNamara et al. 2006); these studies maintain that AGN feedback plays a crucial role in regulating the growth of early-type galaxies and their central supermassive black holes. Observations of giant elliptical galaxies in the local universe have revealed significant X-ray cavities filled with radio lobes that are inferred to have been driven by nuclear AGN outbursts (e.g., Churazov et al. 2001, 2002; Jones et al. 2002, 2005; Forman et al. 2005; Nulsen et al. 2005a, 2005b; Allen et al. 2006); these observations suggest significant energy transfer and recurrence timescales much shorter than the average cooling time. One of the goals of this paper is to characterize the evolution of the hot X-ray-emitting gas in normal early-type galaxies and to place constraints on the role of feedback by transient AGNs.

LMXBs provide another important contribution to the X-ray emission from early-type galaxies (both optically luminous and faint), and many investigations have been dedicated to understanding their nature. Observations in the optical band, most notably from the Hubble Space Telescope (HST), have shown that many of the LMXBs in early-type galaxies are coincident with globular clusters (e.g., Sarazin et al. 2003), and the number of LMXBs observed in a given galaxy appears to be linearly correlated with the globular-cluster specific frequency, $S_N$ (i.e., the number of globular clusters per unit optical luminosity; e.g., White et al. 2002; Kim & Fabbiano 2004; Irwin 2005; Juett 2005). White et al. (2002) examined several optically luminous, LMXB-dominated early-type galaxies with stellar populations having ages ranging from $\approx5$–13 Gyr (as measured via spectroscopy), and found that their X-ray–to–optical luminosity ratios ($L_X/\text{LMXB}/L_{\text{opt}}$) have no dependence on galaxy age; $L_X/\text{LMXB}/L_{\text{opt}}$ was observed to be linearly proportional to $S_N$. Again using optically luminous early-type galaxies, Irwin (2005) found that details of the $L_X/\text{LMXB}/L_{\text{opt}}$–$S_N$ relation imply that a significant number of LMXBs were formed in the fields of the early-type galaxies and that the field LMXB contribution to $L_X/\text{LMXB}/L_{\text{opt}}$ is most significant, and even dominates over the globular cluster LMXB emission, for galaxies with smaller values of $S_N$. In the optically luminous galaxies studied by White et al. (2002) and Irwin (2005) $S_N$ is large, and LMXBs are mainly formed in the high-density central regions of globular clusters through tidal interactions between normal stars and either neutron stars or black holes. In optically faint low-mass systems, however, $S_N$ is typically small (e.g., Ashman & Zepf 1998), and it is therefore likely that LMXBs that formed within the galactic fields of these systems dominate $L_X/\text{LMXB}/L_{\text{opt}}$ (see, e.g., Fig. 3 of Irwin 2005); these LMXBs are thought to have formed via the evolution of primordial binaries on timescales of $\approx1$–10 Gyr following a star-formation event (e.g., Verbunt & van den Heuvel 1995). Furthermore, if the downsizing mass-assembly scenario discussed above is correct, field LMXBs within optically faint galaxies could evolve significantly over cosmic time, as LMXB populations emerge in the wake of relatively recent bursts of star formation and eventually fade after $\approx1$ Gyr (e.g., Ghosh & White 2001). Therefore, another goal of this paper is to measure the
X-ray properties of normal optically faint early-type galaxies over a significant range of redshift to place constraints on the evolution of the LMXB activity in these systems.

### 3.1.3 Observations of the X-ray Emission from Distant Early-Type Galaxies

At present, there have been few investigations of the redshift evolution of the X-ray properties of isolated early-type galaxies, which contrasts with the case for late-type galaxies (e.g., Hornschemeier et al. 2002; Norman et al. 2004; Laird et al. 2005; Kim et al. 2006; Lehmer et al. 2006). Brand et al. (2005) used X-ray stacking analyses (see also, e.g., Brandt et al. 2001; Nandra et al. 2002; Lehmer et al. 2005b) to investigate the evolution of optically luminous red galaxies within the Boötes field of the NOAO Deep Wide-Field Survey (NDWFS) over the redshift range $z \sim 0.3–0.9$. The *Chandra* observations used in these analyses were $\approx 5$ ks in duration (e.g., Murray et al. 2005) and covered an area of $\approx 1.4$ deg$^2$. Brand et al. (2005) found that the average X-ray luminosities of these galaxies mildly increase with redshift, which is primarily due to a rise in AGN activity with redshift. Due to its relatively large sample size (3316 red galaxies), the Brand et al. (2005) investigation provided useful statistical constraints on the X-ray activity from distant powerful AGNs; however, the X-ray sensitivity of this study was too low (i.e., the luminosity detection limit was $L_X \approx 10^{43.2}$ erg s$^{-1}$ at $z \approx 0.7$) to distinguish effectively galactic X-ray emission (i.e., hot interstellar gas and LMXBs) from that of luminous AGNs. Deep X-ray surveys, which utilize long X-ray exposures with *Chandra* or XMM-Newton (see, e.g., Brandt & Hasinger 2005 for a review), are required to investigate the X-ray emission from distant “normal” (i.e., not predominantly powered by luminous AGNs) early-type galaxies. An ideally suited field for such an investigation is the Extended *Chandra* Deep Field-South (E-CDF-S). The E-CDF-S is a $\approx 0.3$ deg$^2$, multiwavelength survey field composed of the central $\approx 1$ Ms *Chandra* Deep Field-South (CDF-S; Giacconi et al. 2002; Alexander et al. 2003) and four flanking, contiguous $\approx 250$ ks *Chandra* observations (Lehmer et al. 2005a). The 0.5–2.0 keV sensitivity limits (for detecting an individual unresolved X-ray point source) over the E-CDF-S are $\approx 5.2 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ in the most sensitive regions and $\approx 3.0 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ over the majority of the field; these levels correspond to 0.5–2.0 keV luminosity detection limits of $\approx 10^{41.0}$ and $\approx 10^{41.5}$ erg s$^{-1}$, respectively, at $z = 0.7$. Such sensitivity limits are sufficient to detect moderately-powerful AGNs and normal, X-ray luminous early-type galaxies (e.g., NGC 1600; Sivakoff et al. 2004) out to $z = 0.7$.

Recently, McIntosh et al. (2005; hereafter, M05) isolated a sample of 728 optically selected early-type galaxies within the E-CDF-S from the GEMS (Galaxy Evolution from Morphologies and SEDs; Rix et al. 2004) and COMBO-17 (Classifying Objects by Medium-Band Observations in 17 Filters; Wolf et al. 2004) surveys, which overlap with $\approx 0.23$ deg$^2$ ($\approx 77\%$) of the E-CDF-S. The M05 sample spans a redshift range of $z \approx 0.2–1.0$, and due to its depth and relatively large comoving volume, it is ideal for investigating the evolution of early-type galaxies over the last half of cosmic history. In this paper, we utilize the M05 sample and a supplementary sample of 64 additional $z \approx 0.1–0.2$ early-type galaxies located within the E-CDF-S (selected using the same techniques discussed in M05) to characterize the redshift evolution of the X-ray properties of early-type galaxies. Our aim is to measure the average X-ray emission, via stacking techniques (applied to X-ray detected and X-ray undetected sources), from distant normal early-type galaxy populations. We investigate separately the cosmic-time evolution of
(1) the hot interstellar gas content through optically luminous galaxy samples and (2) the LMXB populations through optically faint galaxy samples.

The Galactic column density is $N_H \approx 8.8 \times 10^{19}$ cm$^{-2}$ for the E-CDF-S (Stark et al. 1992). All of the X-ray fluxes and luminosities quoted throughout this paper have been corrected for Galactic absorption. Unless stated otherwise, we make reference to optical magnitudes using the Vega magnitude system. $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ are adopted throughout this paper (e.g., Spergel et al. 2003), which imply a look-back time of 6.3 Gyr at $z = 0.7$.

3.2 Data Analysis

3.2.1 Sample Selection

We started with the M05 sample of 728, $z \approx 0.2$–1.0 early-type galaxies and a supplementary sample of 64 $z \approx 0.1$–0.2 galaxies within the E-CDF-S field (i.e., 792 total galaxies), which were selected following the same methods outlined in M05 using the same data. The total sample was selected using (1) rest-frame $U - V$ red-sequence colors derived from COMBO-17 and (2) quantitative optical morphologies (via the Sérsic indices; $n \geq 2.5$) as observed from HST imaging through GEMS (see § 2.3 of M05 for details). The sample generated using these criteria is representative of the early-type galaxy population as a whole and is highly complete down to the selection limit of $R \approx 24$. Photometric redshifts for these early-type galaxies were provided by COMBO-17 and are used throughout this paper. Using secure redshifts from various spectroscopic surveys in the E-CDF-S region (e.g., Le Fevre et al. 2004; Szokoly et al. 2004; Mignoli et al. 2005; Vanzella et al. 2005, 2006; Silverman et al. 2006), which were available for $\approx 20\%$ of the M05 sample, we confirmed that the photometric redshifts for our sample are highly accurate (i.e., $\approx 50\%$ of the galaxies have $\delta z/[1 + z_{\text{spec}}] < 0.02$ and $\approx 75\%$ have $\delta z/[1 + z_{\text{spec}}] < 0.03$). The selection of early-type galaxies via these quantitative methods isolates galaxies with visual morphologies ranging from E–Sa galaxies, and a large majority of these are E/S0 galaxies (Bell et al. 2004b). We note that the X-ray properties of E and S0 galaxies are observed to be similar (e.g., Forman et al. 1985; Blanton et al. 2001; Xu et al. 2005).

Our primary goal was to investigate the redshift evolution of the X-ray properties of normal early-type galaxies. To achieve this better, we filtered our original sample to include 539 galaxies within the redshift range $z \approx 0.1$–0.7. This range was chosen to optimize our use of the E-CDF-S X-ray sensitivity to allow for the detection and identification of low-luminosity AGNs over a broad range of cosmic look-back times ($\approx 6.3$ Gyr). As discussed in § 3.1.3, the Chandra observations of the E-CDF-S are sufficiently sensitive to detect AGNs with $0.5$–$2.0$ keV luminosities $L_X \approx 10^{41.5}$ erg s$^{-1}$ over this entire redshift range ($z \approx 0.7$). Furthermore, given that the X-ray luminosities of AGN-hosting optically luminous ($L_B > L_{B,\text{crit}}$) early-type galaxies in the local universe span $L_X \approx 10^{40.3}$–$42.9$ erg s$^{-1}$ (mean $L_X \approx 10^{42.0}$ erg s$^{-1}$; O’Sullivan et al. 2001), this limit should adequately prevent powerful AGNs from dominating stacked photon counts (assuming the AGN activity is not widespread).

3.2.1.1 Removing AGN Contamination

We utilized multiwavelength observations of the E-CDF-S region to obtain a census of the X-ray-detected AGNs and normal galaxies within our sample. We matched galaxies in our
sample to X-ray sources in the catalogs presented in Alexander et al. (2003)\(^1\) for the \(\approx 1\) Ms CDF-S observations and Lehmer et al. (2005a)\(^2\) for the \(\approx 250\) ks E-CDF-S observations. For a successful match, we required that the optical and X-ray centroids be displaced from each other by less than \(1.5 \times \) the radius of the \(\text{Chandra}\) positional error circles (80–90% confidence), which are given in each respective X-ray catalog. We note that investigations of luminous off-nuclear X-ray sources, which may lie outside our matching radius, have shown that there is a dearth of such sources within early-type galaxies (e.g., Irwin et al. 2004; Lehmer et al. 2006). The \(\text{Chandra}\) source catalogs were generated using \texttt{wavdetect} (Freeman et al. 2002) at false-positive probability thresholds of \(1 \times 10^{-7}\) and \(1 \times 10^{-6}\) for the \(\approx 1\) Ms CDF-S and the \(\approx 250\) ks E-CDF-S, respectively. However, as demonstrated in § 3.4.2 of Alexander et al. (2003) and § 3.3.2 of Lehmer et al. (2005a), legitimate lower significance X-ray sources, detected by running \texttt{wavdetect} at a false-positive probability threshold of \(1 \times 10^{-5}\), can be isolated by matching with relatively bright optical sources. Since the sky surface density of \(z < 0.7, R < 24\) early-type galaxies is relatively low (\(\approx 0.65\) galaxies \(\text{arcmin}^{-2}\)), we can effectively use this technique to isolate X-ray sources within our sample. We estimate that when using \texttt{wavdetect} at a false-positive probability threshold of \(1 \times 10^{-5}\), we expect \(\approx 0.5\) spurious sources. In total, we detected 49 early-type galaxies in at least one of the 0.5–2.0 keV, 2–8 keV, or 0.5–8.0 keV bandpasses.

1. **Hard X-ray Emission.**—Our best discriminator of obscured (\(N_H \gtrsim 10^{22}\) cm\(^{-2}\)) AGN activity is the presence of a hard X-ray spectrum, which is characterized by a relatively shallow effective X-ray spectral slope (i.e., \(\Gamma_{\text{eff}} \lesssim 1.5\)). We classified X-ray sources that were detected only in the 2–8 keV bandpass as potential AGN candidates. For sources detected in both the 0.5–2.0 keV and 2–8 keV bandpasses, we required that the hardness ratio measured using these bandpasses, \(\Phi_{2-8\text{ keV}}/\Phi_{0.5-2.0\text{ keV}}\) (where \(\Phi\) is the observed count-rate in each respective bandpass), be greater than 0.5 (corresponding to an effective photon index of \(\Gamma_{\text{eff}} \lesssim 1.5\)); these sources would have spectral slopes shallower than those expected for a pure LMXB population (e.g., Church & Balucinska-Church 2001; Irwin et al. 2003). We found that all sources with 2–8 keV detections were classified as AGN candidates. Furthermore, there were a few sources that were detected in only the 0.5–8.0 keV bandpass. We argue that since these sources were not detected in the 0.5–2.0 keV bandpass, our most sensitive bandpass, then there must be a significant contribution from the 2–8 keV bandpass such that \(\Phi_{2-8\text{ keV}}/\Phi_{0.5-2.0\text{ keV}} > 0.5\). These sources were flagged as AGN candidates and removed from our stacking analyses. Using criterion 1, we identified a total of 29 AGN candidates.

2. **X-ray–to–Optical Flux Ratio.**—Spectral hardness is a good indicator of obscured AGN activity; however, powerful unobscured AGNs with steep spectral slopes (\(\Gamma \approx 2\)) could still be missed if this were our only means for identifying candidate AGNs. Another useful discriminator of AGN activity, which aids in the identification of luminous unobscured AGN candidates, is the 0.5–8.0 keV X-ray–to–optical flux ratio, \(f_{0.5-8.0\text{ keV}}/f_R\) (e.g., Maccacaro et al. 1988; Hornschemeier et al. 2000; Bauer et al. 2004). We use the criterion \(\log(f_{0.5-8.0\text{ keV}}/f_R) > -1\) (see § 4.1.1 of Bauer et al. 2004 for justification) to identify unobscured AGN candidates in our

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\(^1\)See http://www.astro.psu.edu/users/niel/hdf/hdf-chandra.html for the relevant source catalogs and data products for the \(\approx 1\) Ms CDF-S.

\(^2\)See http://www.astro.psu.edu/users/niel/ecdfs/ecdfs-chandra.html for the relevant source catalogs and data products for the \(\approx 250\) ks E-CDF-S.
sample; two candidates, which were not identified by criterion 1 above, were found using this criterion. We note that 16 out of the 29 AGNs that satisfied criterion 1 (≈55%) also satisfied criterion 2.

3. Radio–to–Optical Flux Ratio.—We used radio maps (1.4 GHz; limiting 1σ depth of ≈14µJy) from the Australia Telescope Compact Array (ATCA; PI: A. Koekemoer; Afonso et al. 2006), which cover the entire E-CDF-S region, to identify additional potential AGNs. We matched the positions of radio-detected sources to those of our early-type galaxies using a 2″ matching radius and found 18 matches. Of the 18 radio-detected sources in our sample, we find that three are detected in the X-ray bandpass. Of the three X-ray-detected sources, only CXOECDFS J033228.81–274355.6 was not previously identified as an AGN candidate using criteria 1 and 2; however, visual inspection of the radio source coincident with CXOECDFS J033228.81–274355.6 reveals that it has a clear FR II radio morphology. We find that the three AGN-like X-ray-detected radio sources have relatively large radio–to–optical flux ratios, \( \log(\nu f_\nu[1.4\,\text{GHz}]/\nu f_\nu[5000\,\text{Å}]) \), as expected for AGNs (e.g., Kinney et al. 1996). Out of the remaining 15 radio-detected sources, 13 sources that were not detected in the X-ray bandpass were found to have uncharacteristically high radio–to–optical flux ratios for early-type galaxies, \( \log(\nu f_\nu[1.4\,\text{GHz}]/\nu f_\nu[5000\,\text{Å}]) > -4 \). These 13 sources were classified as potential AGNs and were excluded from our stacking analyses described below. We note that in addition to AGNs, star-forming galaxies (e.g., edge-on dusty galaxies) that were misclassified as early-type galaxies may also satisfy this criterion (see, e.g., Fig. 8 of Barger et al. 2006); therefore, this criterion also helps to guard against the inclusion of such sources.

To summarize, we have detected 49 early-type galaxies in the X-ray band and have identified 32 X-ray-detected AGN candidates: 29 from criterion 1, two additional sources from criterion 2, and one additional source from criterion 3. Finally, using criterion 3 we identified an additional 13 AGN candidates that were not detected in the X-ray band. Therefore, we identified a total of 45 AGN candidates from our sample of 539 early-type galaxies. The remaining 17 X-ray-detected sources that we do not classify as AGN candidates are considered to be normal early-type galaxies. These normal galaxies are included in our stacking analyses, and as we discuss in § 3.2.2 below, including these galaxies does not significantly affect our results. A more detailed discussion of the X-ray properties of our X-ray-detected sources is presented in § 3.3.1 below. We note that the three criteria discussed above may not be completely sufficient to classify all X-ray-detected sources that are truly AGNs as AGN candidates (see, e.g., Peterson et al. 2006). Such a misclassification is possible for low-luminosity AGNs that are only detected in the more sensitive 0.5–2.0 keV bandpass, which have 2–8 keV emission too weak for an accurate classification. Furthermore, we also expect there to be AGNs that lie below the X-ray detection threshold that are not identified here. However, in § 3.3.2.2, we use the 2–8 keV AGN fraction as a function of X-ray luminosity to argue quantitatively that we do not expect misclassified AGNs (detected only in the 0.5–2.0 keV bandpass) and low-luminosity AGNs below the X-ray detection limit to have a serious impact on our results.

3.2.1.2 Normal Early-Type Galaxy Samples

A large majority of the normal galaxies in our sample were not detected individually in the deep Chandra observations over the E-CDF-S. We therefore implemented stacking analyses
(see § 3.2.2 for a description) of galaxy samples, which were constructed to cover two optical luminosity ranges in multiple redshift bins. We first divided the original sample of 539 early-type galaxies by luminosity into optically luminous \((L_B \approx 10^{10-11} L_{B,\odot})\) and optically faint \((L_B \approx 10^{9.3-10} L_{B,\odot})\) samples. The two luminosity ranges were motivated by the observed physical differences between local early-type galaxies within these two luminosity ranges (see discussion in § 3.1.1) and optical completeness limitations of the M05 sample (i.e., the \(R < 24\) completeness limit). As mentioned in § 3.1.1 and displayed in Figure 3.1, the optically luminous galaxies have soft X-ray spectra dominated by hot interstellar gas, while the optically faint early-type galaxies have X-ray spectra powered mainly by LMXBs with a small contribution from hot interstellar gas. Galaxies from both luminosity classes have hard X-ray emission dominated by LMXBs.

We divided the optically luminous sample into four redshift bins of equal comoving volume \((z \approx 0.10-0.41, 0.41-0.53, 0.53-0.62, \text{ and } 0.62-0.70)\), and due to optical completeness limitations, we divided our optically faint sample into two redshift bins \((z \approx 0.10-0.41 \text{ and } 0.41-0.53)\). Although the E-CDF-S subtends a relatively small solid angle, we note that each redshift bin has a radial depth that exceeds 500 Mpc, which is a factor of \(\sim 5\) times larger than the extent of the largest structures in the Universe (e.g., Springel et al. 2006). We created histograms of the galaxy luminosity-distance distributions on scales of \(\sim 100\) Mpc and did not observe any dominating density “spikes.” This suggests that our samples are not being significantly affected by cosmic variance. Furthermore, provided the physical properties of field early-type galaxies are not strongly affected by their environments in a systematic way, we suggest that cosmic variance should not affect our results even if present. In Figure 3.2a, we show rest-frame \(B\)-band luminosity, \(L_B\) (in solar units; \(L_{B,\odot} = 5.2 \times 10^{32} \text{ erg s}^{-1}\)), versus redshift for the 539 galaxies (dots and crosses) that make up our “general sample”; we indicate the divisions of the sample by optical luminosity (shaded regions) and redshift (vertical dotted lines). Sources highlighted by large circles (both open and filled) are those that are individually detected in X-rays; the open circles indicate X-ray-detected AGN candidates, and the filled circles indicate the remaining detected sources, which are classified as normal early-type galaxies.

In addition to the general sample, we have created “faded samples” of early-type galaxies. The faded samples were constructed using the general sample discussed above; however, we have corrected the rest-frame \(B\)-band luminosities for passive evolution. These corrections take into account the fact that the optical power output of early-type galaxies has been fading with cosmic time due to stellar evolution (see § 3.1). For each galaxy, we have computed an evolved, \(z = 0\) \(B\)-band luminosity \((L_{B,0})\) following the best-fit optical-size-dependent solutions for optical fading presented in Tables 1 and 2 of M05. M05 present eight best-fit relations for \(\Delta M_V(z)\) (i.e., the difference between the absolute \(V\)-band magnitude at redshifts \(z\) and \(z = 0\)) versus \(z\), which differ in their evolutionary scenarios (based upon formation scenarios and the PEGASE models of Fioc & Rocca-Volmerange 1997) and whether or not the fit is constrained to \(\Delta M_V(z = 0) = 0\). Throughout this paper we quote results based upon the best-fit solution that assumes \(\Delta M_V(z = 0) = 0\) and a single-burst evolutionary model with a formation redshift of \(z_{\text{form}} = 3\) and a metallicity of \([\text{Fe/H}] = -0.2\) (see § 3.2 of M05 for details). We converted the \(V\)-band relation to the \(B\)-band following \(\Delta M_B \approx 1.1 \times \Delta M_V\). Additional X-ray analyses, using the seven alternative evolutionary scenarios presented in M05, were also performed, but no material differences were observed in our results. Figure 3.2b shows \(L_{B,0}\) versus \(z\) for our faded sample; symbols, lines, and shaded regions have the same meaning as in Figure 3.2a. In generating samples for stacking, we made the same sample divisions (of both luminosity and redshift) as we
Fig. 3.2: (a) Rest-frame $B$-band luminosity versus redshift for our general sample of 539 early-type galaxies. Larger circles indicate X-ray-detected AGN candidates (open) and normal galaxies (filled). Sources denoted with crosses are (1) in close proximity ($<10''$) to an X-ray-detected source, (2) within the boundaries of extended X-ray sources, (3) at large off-axis angles (i.e., $>7''$ from all aimpoints), and/or (4) found to have relatively large radio–to–optical flux ratios (see § 3.2.1.1); these sources have been removed from our stacking analyses (see § 3.2.2 for details). The shaded bands show the luminosity ranges of our optically luminous and faint samples; vertical dotted lines indicate the evenly-spaced comoving volume intervals chosen in constructing our stacking samples. (b) Evolved, $z = 0$, $B$-band luminosity of our sample (see discussion in § 3.2.1.2), which constitutes our faded sample. Symbols and boundaries are the same as in Figure 3.3a. Using a Chabrier initial mass function (Chabrier 2003), we estimate that the luminosity ranges $L_{B,0} = 10^{9.3-10}$ and $10^{10-11}$ $L_{B,\odot}$ correspond roughly to stellar mass ranges of $\approx 10^{9.9-10.6}$ and $\approx 10^{10.6-11.6}$ $M_\odot$, respectively.
did for the general sample, except we used $L_{B,0}$ to discriminate between optically luminous and faint galaxies. This approach allows us to place constraints on the evolution of the X-ray activity from distant galaxies selected from the optical band as they would appear today. Furthermore, based on local estimates of stellar mass-to-light ratios, we can use $L_{B,0}$ to estimate the stellar masses of these systems. Using a Chabrier initial mass function (Chabrier 2003), we estimate that the luminosity ranges $L_{B,0} = 10^{9.3-10}$ and $10^{10-11}$ $L_{\odot}$ correspond roughly to stellar-mass ranges of $\approx 10^{9.9-10.6}$ and $\approx 10^{10.6-11.6} M_{\odot}$, respectively. In the presentation below, we focus our attention on results drawn from the faded samples since these are expected to be the most physically meaningful.

3.2.2 X-ray Stacking Technique

In order to address the fact that the X-ray emission from early-type galaxies is dominated by different physical processes in different energy bands, we performed stacking analyses in three bandpasses: 0.5–1.0 keV (SB1), 0.5–2.0 keV (soft band; SB), and 2–8 keV (hard band; HB). The shaded bars in the panels of Figure 3.1 show the spectral coverage of these bandpasses at the median redshifts of our optically luminous ($z_{\text{median}} \approx 0.55$) and faint ($z_{\text{median}} \approx 0.39$) samples for the X-ray spectral energy distributions (SEDs) of NGC 1600 (top panel) and NGC 4697 (bottom panel), respectively. For optically luminous galaxies, the SB1 and SB will effectively sample X-ray emission dominated by hot interstellar gas, which produces $\approx 80\%$ and $\approx 70\%$ of the total emission in each respective bandpass. In contrast, 90\% of the HB flux originates from LMXB emission. For optically faint galaxies, SB and HB will effectively sample the X-ray emission from LMXBs; however, the X-ray emission observed in SB1 has roughly equal contributions from hot gas and LMXB emission. In our analyses, we used data products from Alexander et al. (2003) for the $\approx 1$ Ms CDF-S and Lehmer et al. (2005a) for the $\approx 250$ ks E-CDF-S (see footnotes 1 and 2). The data products are publicly available for all energy bands except for SB1 in the $\approx 250$ ks E-CDF-S regions, which were generated specifically for the analyses here using the same methods described in Lehmer et al. (2005b). The methodology of our stacking procedure was similar to that outlined in Lehmer et al. (2005b); for completeness, we describe this procedure below.

We maximized our stacked signal by optimizing our choices of circular stacking aperture radius (from which we extract photon counts for both sources and their backgrounds) and inclusion radius (i.e., the maximum off-axis angle within which we include sources for stacking). This process is needed because the Chandra point spread function (PSF) increases in size with off-axis angle, which degrades the sensitivity for those sources that are far off-axis. For the optimization process, we stacked all early-type galaxies in our sample that were not detected individually in the X-ray band. In order to obtain a clean X-ray signal, we excluded galaxies that were located $\lesssim 10''$ from unrelated sources in the X-ray source catalogs and within the extent of extended X-ray sources, which are likely associated with galaxy groups or poor clusters (see § 3.4 of Giacconi et al. 2002 and § 6 of Lehmer et al. 2005a). Sources that lie within both the $\approx 1$ Ms CDF-S and $\approx 250$ ks E-CDF-S were stacked using both observations, as long as the off-axis angle for each observation was within our chosen inclusion radius.

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3 The 0.5–1.0 keV bandpass was originally defined as SB1 in § 3.1 of Alexander et al. (2003).
Our optimization procedure was a two-step iterative process that was performed using the SB, the bandpass in which our signal was maximized. In the first step of the optimization process (step one) we held the inclusion radius ($R_{\text{incl}}$) fixed and stacked sources using a variety of circular stacking apertures of constant radii (i.e., we did not vary the aperture radius as a function of off-axis angle). We used 15 different circular stacking apertures with radii in the range of $0.5''-3.0''$ to obtain a relation for how the signal-to-noise ratio (S/N) varied as a function of aperture size. For a given aperture, we stacked the photon counts and effective exposure times from each galaxy position and summed them to obtain total source-plus-background counts, S, and a total exposure time, T, respectively. We estimated total background counts, B, using Monte Carlo simulations and the background maps described in §4.2 of Alexander et al. (2003) for the $\approx1$ Ms CDF-S and §4 of Lehmer et al. (2005a) for the $\approx250$ ks E-CDF-S. We shifted our aperture from each galaxy position randomly within a circular region of radius $\approx25''$, extracted background counts from each relevant background map, and summed the counts to obtain an estimate of the total background counts. This procedure was repeated 10,000 times to obtain an estimate of the local background and its dispersion. Our best estimate of the total background counts, B, was approximated by taking the mean background calculated from the 10,000 Monte Carlo trials. For each of the 15 circular apertures, we computed the relevant signal-to-noise ratio (S/N) using the equation, $S/N \equiv (S-B)/\sqrt{B}$. After performing the stacking procedure for all 15 different apertures, we identified the aperture radius that produced the maximal S/N. In the second step of the optimization process (step two), we held the optimized aperture determined from step one fixed, but this time we stacked sources using 15 different inclusion radii ranging from 1''5–11.0 to obtain S/N as a function of inclusion radius. After performing the stacking procedure for all 15 different inclusion radii, we identified the optimal inclusion radius. For a clean stacking signal, we expect that S/N will be proportional to the inclusion radius (i.e., $S/N \propto [\text{Number of sources}]^{1/2} \propto \pi R_{\text{incl}}^2 \propto R_{\text{incl}}$), and therefore we chose the optimal inclusion radius based on where the S/N–$R_{\text{incl}}$ relation appears to deviate significantly from linear. This method helps to guard against the inclusion of contaminating AGNs in the low-sensitivity regions at large off-axis angles. Using the optimal inclusion radius determined with this method, we repeated step one. This two-step process was run iteratively until a converged solution was obtained. We found that a stacking aperture of $\approx1.5''$ and an inclusion radius of $\approx7.0''$ produced the optimal signal; we note that this choice of optimized $R_{\text{incl}}$ is somewhat smaller than that determined in Lehmer et al. (2005b) due to differing X-ray exposures and the more conservative approach that we have adopted for choosing the optimal $R_{\text{incl}}$. Hereafter, we utilize these values for stacking aperture and inclusion radius in our analyses. In Figure 3.3, we show S/N as a function of inclusion radius (Fig. 3.3a) and aperture size (Fig. 3.3b), which were obtained by holding the aperture radius constant at 1.5'' and the inclusion radius constant at 7.0, respectively.

After excluding sources that were (1) classified as AGN candidates (via the three criteria outlined in §3.2.1.1), (2) located at off-axis angles greater than $7.0''$, (3) within regions of extended X-ray emission, and (4) within $10''$ of an unrelated X-ray-detected sources, we were left with general and faded samples of 276 and 229 galaxies, respectively; in both samples, 13 galaxies were X-ray-detected sources. Using these samples, we stacked the X-ray properties following the procedure described above. The sizes of the general and faded samples differ most notably because of the fading of high-redshift optically luminous galaxies out of the selected luminosity range. We stacked samples both with and without X-ray-detected normal galaxies included, and no material differences were observed in our results; therefore, X-ray-detected sources that were
Fig. 3.3: (a) Soft-band (0.5–2.0 keV) signal-to-noise ratio (S/N) versus inclusion radius (i.e., the maximum off-axis angle within which a source is included in stacking) for a fixed aperture size of 1.5; the solid line indicates the expected linear increase in S/N versus inclusion radius. (b) Soft-band S/N versus aperture radius for a fixed inclusion radius of 7.0. The above plots were generated using corresponding optimized stacking parameters (i.e., stacking aperture size and inclusion radius), which were determined iteratively (see § 3.2.2 for details); the optimized parameters are indicated by vertical dashed lines in each plot.

classified as normal galaxies were included in our stacking analyses. Figure 3.4 shows the spatial distribution of the 229 stacked sources in our faded sample over the E-CDF-S region. Sources stacked using the ≈1 Ms and ≈250 ks observations are shown as circles and diamonds, respectively; the sources indicated with filled circles were stacked using both observations. For each stacked sample, we required the S/N be greater than or equal to 3 (i.e., ≃99.9% confidence) for a detection. For stacked samples without significant detections, 3σ upper-limits were placed on the source counts.

Using net counts (i.e., S−B) from our stacked samples and adopted X-ray SEDs (see below), we calculated absorption-corrected fluxes and rest-frame luminosities. Due to the fact that our 1.5 radius stacking aperture encircles only a fraction of the PSF4 for sources at relatively large off-axis angle, we calculated aperture corrections ξ_{i} for each stacked source i.

Since we are calculating average X-ray counts from the summed emission of many sources of differing backgrounds and exposure times, we used a single, representative exposure-time-weighted aperture correction, ξ. This factor, which was determined for each stacked sample, was calculated following:

4For SB and SB1, the encircled-energy fraction of a 1.5 radius circular aperture varies from ≃100% at off-axis angle θ ≃ 3' to ≃45% at θ ≃ 7'. For the HB, this fraction varies from ≃80% at θ ≃ 3' to ≃40% at θ ≃ 7'.
Fig. 3.4: Adaptively smoothed 0.5–2.0 keV image of the combined \( \approx 1 \) Ms CDF-S and \( \approx 250 \) ks E-CDF-S. Positions of stacked sources from our faded sample are shown as open circles (\( \approx 1 \) Ms CDF-S) and open diamonds (\( \approx 250 \) ks E-CDF-S); filled circles represent galaxy positions that have been stacked using both the \( \approx 1 \) Ms CDF-S and \( \approx 250 \) ks E-CDF-S observations (see § 3.2.2 for additional details). Aim points of each Chandra observation are indicated as plus signs, and the surrounding 7.0 inclusion radii are indicated with dashed circles. The apparent lack of sources in the north-eastern corner (i.e., the upper left-hand corner) of the image is partially due to missing HST coverage from the GEMS imaging. For reference, we have outlined the \( \approx 160 \) arcmin\(^2\) GOODS-S region (solid rotated rectangle; Giavalisco et al. 2004).
\[ \xi = \frac{\sum_i \xi_i \times T_i}{\sum_i T_i}, \]  

(3.1)

where \( T_i \) is the effective exposure time for each stacked source. The average aperture corrections \((\xi)\) for our samples were \( \approx 1.5 \) and \( \approx 1.8 \) for the 0.5–2.0 keV and 2–8 keV bands, respectively. We note that at the mean redshifts of our samples, the \( \approx 1'5 \) radius aperture corresponds to projected physical radii in the range of 5.8–10.5 kpc. For early-type galaxies in the local universe, extended X-ray emission originating outside of these radii varies considerably among galaxies and generally represents only a small fraction (\( \approx 1–10\% \)) of the total flux (e.g., Fukazawa et al. 2006). Therefore, we do not make additional aperture corrections to account for extended X-ray emission. We estimated mean observed count rates \((\Phi)\) using the following equation:

\[ \Phi = \xi (S - B)/T, \]  

(3.2)

where \( S, B, \) and \( T \) are defined above. To convert count rate to flux, we used the Galactic column density given in § 3.1.3 and the best-fit X-ray spectral energy distribution (SED) for NGC 1600 for the optically luminous galaxies (see Fig. 3.1a) and a power-law SED with \( \Gamma = 1.8 \) for the optically faint galaxies (see § 3.1.1 for justification). We note that for a range of reasonable SED choices, we find systematic fractional uncertainties in the count-rate to flux conversion of \( \approx 10\% \) for SB and HB and \( \approx 50\% \) for SB1. Mean rest-frame X-ray luminosities \( L_{X,R} \) were calculated following:

\[ \langle L_{X,R} \rangle \approx 4\pi \langle d_L^2 \rangle \langle f_{X,O} \rangle K, \]  

(3.3)

where \( d_L \) is the luminosity distance, \( \langle f_{X,O} \rangle \) is the mean observed-frame X-ray flux, and \( K \) is a unitless conversion factor, which relates the observed-frame X-ray flux to the rest-frame luminosity using our adopted SEDs. The fractional errors on \( \langle L_{X,R} \rangle \) due to uncertainties in \( \langle d_L^2 \rangle \) range from \( \approx 10\% \) to \( \approx 1\% \) for our optically luminous \( z \approx 0.10–0.41 \) and \( z \approx 0.62–0.70 \) samples, respectively. Due to the relatively broad energy ranges our bandpasses encompass and the relatively small spectral shifts observed over the redshifts of sources in our samples, we used observed-frame fluxes to compute rest-frame luminosities. For our adopted SEDs, we found that values of \( K \) varied between 0.8 and 1.1, depending on the bandpass and redshift of the source. For all bandpasses, SED choice contributes small systematic uncertainties in \( K \), which range from \( \approx 10–20\% \) depending on redshift. We note that the mean X-ray luminosity is expected to be closely representative of a typical galaxy within the confined optical luminosity ranges used here. Moreover, using the O’Sullivan et al. (2001) sample of local early-type galaxies, we find that \( L_{X,\text{mean}}/L_{X,\text{median}} \approx 1.7 \) and 1.2 for optically luminous and faint samples respectively. Since we are only able to calculate mean quantities via the X-ray stacking used here, we utilize mean quantities throughout. Results from our stacking analyses are presented below in § 3.3.2.

### 3.3 Results

#### 3.3.1 Individually Detected X-ray Sources

In Table 3.1, we present the properties of the X-ray-detected early-type galaxies. X-ray source properties were determined following the methods outlined in Alexander et al. (2003) and Lehmer et al. (2005a) for the CDF-S and E-CDF-S, respectively. Using the matching criterion
**Fig. 3.5:** Optical $R$-band magnitude versus 0.5–8.0 keV flux for X-ray-detected early-type galaxies in our sample. AGN candidates and normal galaxies are plotted as open symbols (circles and stars) and filled circles, respectively; sources with upper limits were detected in either the 0.5–2.0 keV or 2–8 keV bandpasses. Diagonal dotted lines represent lines of constant X-ray–to–optical flux ratio (i.e., $\log f_{0.5-8.0 \text{ keV}} / f_R = +1, -1, \text{ and } -2$); luminous AGNs generally have $\log f_{0.5-8.0 \text{ keV}} / f_R > -1$ (shaded region). AGN-candidates were classified following the three criteria discussed in §3.2.1.1. The sources marked with five-pointed stars are radio-detected AGN candidates, including the FR II source CXOECDFS J033228.81–274355.6. Furthermore, mean $R$-band magnitudes and 0.5–8.0 keV fluxes for our stacked optically luminous (large filled squares) and faint (large filled triangles) faded samples are plotted with varying grayscale levels to indicate redshift; darker levels indicate larger redshift values.

As discussed in §3.2.1.1, we matched 39 of our early-type galaxies to sources that were included in the main *Chandra* catalogs of either Alexander et al. (2003) or Lehmer et al. (2005a), and an additional ten matches were identified using X-ray sources detected using wavdetect at a false-positive probability threshold of $1 \times 10^{-5}$ (i.e., 49 total detected sources). Figure 3.5 shows the $R$-band magnitude (from COMBO-17) versus 0.5–8.0 keV flux for all 49 X-ray detected early-type galaxies in our sample; normal galaxies and AGN candidates are indicated as filled and open circles, respectively. As discussed in §3.2.1.1, we classified 32 ($\approx 65\%$) X-ray-detected sources as AGN candidates. We note that the majority of the AGN candidates have $\log f_{0.5-8.0 \text{ keV}} / f_R > -1$; however, a few of these candidates have $\log f_{0.5-8.0 \text{ keV}} / f_R < -2$, including the FR II source CXOECDFS J033228.81–274355.6. AGNs with $\log f_{0.5-8.0 \text{ keV}} / f_R < -2$ are either significantly obscured or relatively X-ray-weak AGNs.
### Table 3.1. X-ray Detected Early-Type Galaxies: Source Properties

<table>
<thead>
<tr>
<th>Chandra Name (J2000.0)</th>
<th>z</th>
<th>Flux (log erg cm(^{-2}) s(^{-1}))</th>
<th>Hardness Ratio</th>
<th>(\log f_{0.5-8.0,\text{keV}}/f_{0.5-2.0,\text{keV}})</th>
<th>(\Gamma)</th>
<th>(L_R) (log(L_{B,0}))</th>
<th>(L_{2-8,\text{keV}}) (log erg s(^{-1}))</th>
<th>Survey</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>J033121.17–275857.7</td>
<td>0.68</td>
<td>-15.5</td>
<td>-14.7</td>
<td>1.26</td>
<td>-0.94</td>
<td>0.7</td>
<td>11.1</td>
<td>42.3</td>
<td>E-CDF-S 03 A</td>
</tr>
<tr>
<td>J033132.81–280115.9</td>
<td>0.15</td>
<td>-15.4</td>
<td>&lt; -14.9</td>
<td>&lt;0.78</td>
<td>-2.63</td>
<td>1.4</td>
<td>10.4</td>
<td>&lt; 40.8</td>
<td>E-CDF-S 03 N</td>
</tr>
<tr>
<td>J033137.72–273843.3</td>
<td>0.22</td>
<td>&lt; -15.5</td>
<td>-14.6</td>
<td>&gt;1.46</td>
<td>-1.93</td>
<td>1.4</td>
<td>10.4</td>
<td>41.4</td>
<td>E-CDF-S 02 A</td>
</tr>
<tr>
<td>J033138.05–280312.2</td>
<td>0.49</td>
<td>&lt; -15.6</td>
<td>&lt; -14.9</td>
<td>~1</td>
<td>-1.04</td>
<td>1.4</td>
<td>10.2</td>
<td>&lt; 42.0</td>
<td>E-CDF-S 03 A</td>
</tr>
<tr>
<td>J033143.42–274248.6</td>
<td>0.47</td>
<td>-15.8</td>
<td>-14.6</td>
<td>2.31</td>
<td>-0.77</td>
<td>0.1</td>
<td>10.3</td>
<td>42.0</td>
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<tr>
<td>J033151.15–275051.5</td>
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<td>-15.3</td>
<td>-14.9</td>
<td>0.57</td>
<td>-0.31</td>
<td>1.2</td>
<td>10.3</td>
<td>42.3</td>
<td>CDF-S A,R</td>
</tr>
<tr>
<td>J033156.00–273942.4</td>
<td>0.58</td>
<td>-15.2</td>
<td>-14.9</td>
<td>0.51</td>
<td>-1.11</td>
<td>1.5</td>
<td>10.8</td>
<td>42.1</td>
<td>E-CDF-S 02 A</td>
</tr>
<tr>
<td>J033158.13–274459.4</td>
<td>0.58</td>
<td>-15.3</td>
<td>-14.8</td>
<td>-0.83</td>
<td>-1.36</td>
<td>1.4</td>
<td>10.4</td>
<td>41.5</td>
<td>CDF-S 02 A</td>
</tr>
<tr>
<td>J033200.42–275228.6</td>
<td>0.63</td>
<td>-15.9</td>
<td>-15.6</td>
<td>0.54</td>
<td>-1.13</td>
<td>1.4</td>
<td>10.4</td>
<td>41.8</td>
<td>CDF-S A</td>
</tr>
<tr>
<td>J033200.83–275954.6</td>
<td>0.43</td>
<td>&lt; -15.6</td>
<td>&lt; -14.9</td>
<td>&gt;1.07</td>
<td>-0.67</td>
<td>1.4</td>
<td>9.6</td>
<td>41.8</td>
<td>E-CDF-S 03 A</td>
</tr>
<tr>
<td>J033202.13–275621.6</td>
<td>0.61</td>
<td>&lt; -15.6</td>
<td>-14.8</td>
<td>1.49</td>
<td>-0.54</td>
<td>1.4</td>
<td>10.0</td>
<td>42.2</td>
<td>E-CDF-S 03 A</td>
</tr>
<tr>
<td>J033203.65–274603.7</td>
<td>0.59</td>
<td>-15.1</td>
<td>-13.7</td>
<td>3.74</td>
<td>0.01</td>
<td>-0.3</td>
<td>10.8</td>
<td>43.0</td>
<td>E-CDF-S 02 A</td>
</tr>
<tr>
<td>J033205.90–275449.7</td>
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<td>-16.2</td>
<td>&lt; -15.0</td>
<td>3.18</td>
<td>&lt; -1.32</td>
<td>1.4</td>
<td>10.9</td>
<td>&lt; 42.1</td>
<td>E-CDF-S 03 N,S</td>
</tr>
<tr>
<td>J033206.27–274536.7</td>
<td>0.66</td>
<td>-15.9</td>
<td>&lt; -15.3</td>
<td>0.67</td>
<td>-1.35</td>
<td>1.4</td>
<td>10.7</td>
<td>&lt; 41.8</td>
<td>CDF-S N</td>
</tr>
<tr>
<td>J033209.52–273634.1</td>
<td>0.23</td>
<td>-15.8</td>
<td>&lt; -14.9</td>
<td>1.85</td>
<td>&lt; -1.99</td>
<td>1.4</td>
<td>10.2</td>
<td>&lt; 41.2</td>
<td>E-CDF-S 02 N</td>
</tr>
</tbody>
</table>

Note. — Col.(1): *Chandra* source name. Col.(2): Source redshift as determined by COMBO-17. Col.(3)–(4): Flux for the 0.5–2.0 keV and 2–8 keV bandpasses. Col.(5): Hardness ratio of the 2–8 keV and 0.5–2.0 keV count rates (\(\Phi_{2-8\,\text{keV}}/\Phi_{0.5-2.0\,\text{keV}}\)). Col.(6): Logarithm of the 0.5–8.0 keV to R-band flux ratio. Col.(7): Effective photon index (\(\Gamma\)). Here a value of 1.4 was assumed when photon statistics were too limited to determine accurate values. Col.(8): Logarithm of the rest-frame B-band luminosity. Col.(9): Logarithm of the rest-frame 2–8 keV luminosity. Col.(10): Survey field in which each source was identified. For E-CDF-S identifications, the associated field number (i.e., 01–04) indicates the *Chandra* pointing within which the source was detected (see Lehmer et al. 2005a for details). Col.(11): Source notes. Here an “N” denotes normal galaxies, an “A” denotes candidate AGNs, an “R” denotes sources with radio detections, and an “S” denotes sources that were detected in the supplementary catalogs (i.e., using wavdetect at a false-positive probability threshold of \(1 \times 10^{-5}\)). *Please see Lehmer et al. (2007) for all 49 rows of this table.*
As discussed in § 3.1.2, transient AGN feedback may play an important role in heating the hot gas in normal early-type galaxies. In order to understand and constrain the influence of transient AGN activity within early-type galaxies, we computed the X-ray-luminosity-dependent cumulative AGN fraction, \( f_C \) (i.e., the fraction of early-type galaxies harboring an AGN with a 2–8 keV luminosity of \( L_{2-8} \) keV or greater). We made use of the 2–8 keV bandpass because of its ability to probe relatively unattenuated X-ray emission in a regime of the X-ray spectrum where we expect there to be minimal emission from normal galaxies (see also § 3.2.1.1 for more details). Figure 3.2 illustrates that the majority of the AGNs in our samples (open circles) originate within optically luminous (\( L_B > \sim 10^{10} L_B^{\odot} \)) early-type galaxies, and therefore when computing \( f_C \), we used only optically luminous galaxies; we note that the number of AGNs within our optically faint samples is too low to obtain a respectable constraint on \( f_C \). In order to quantify the redshift evolution of \( f_C \), we split our optically luminous samples into two redshift intervals of roughly equal size (\( z \approx \sim 0.10-0.55 \) \([z_{\text{median}} = 0.42]\) and \( z \approx 0.55-0.70 \) \([z_{\text{median}} = 0.65]\)). Only two redshift intervals were chosen due to statistical limitations on the number of detected AGNs. We computed \( f_C \) by taking the number of candidate AGNs with a 2–8 keV luminosity of \( L_{2-8} \) keV or greater and dividing it by the number of early-type galaxies in which we could have detected an AGN with luminosity \( L_{2-8} \) keV. The latter number was computed by considering the redshift of each galaxy and its corresponding sensitivity limit, as obtained from spatially dependent sensitivity maps (see § 4.2 of Alexander et al. 2003 and § 4 of Lehmer et al. 2005a); these sensitivity maps were calibrated empirically using sources detected by wavdetect at a false-positive probability threshold of \( 1 \times 10^{-5} \). Figure 3.6 shows \( f_C \) as a function of \( L_{2-8} \) keV for the two redshift bins considered here. We find suggestive evidence for evolution in \( f_C \) between
\[ z \approx 0.42 \text{ and } z \approx 0.65, \] which is consistent with the global trend observed for luminous AGNs in general (e.g., Brandt & Hasinger 2005). At \[ L_{2-8 \text{ keV}} \gtrsim 10^{42.2} \text{ erg s}^{-1} \], where \( f_C \) is most tightly constrained, we find that \( f_C(z = 0.65) = [2.1^{+10.5}_{-2.0}] \times f_C(z = 0.42) \). We note that although this value is poorly constrained, it is consistent with the \((1+z)^3\) evolution observed for X-ray luminosity functions of X-ray-selected AGNs (e.g., Ueda et al. 2003; Barger et al. 2005; Hasinger et al. 2005), and is in agreement with the stacked constraints on optically-selected early-type galaxies set by Brand et al. (2005). We return to the discussion of X-ray-detected AGNs in § 3.3.2.2 when discussing the undetected AGN contribution to our stacked samples and in § 4.1 when discussing the transient AGN contribution to heating the hot interstellar gas in optically luminous early-type galaxies.

### 3.3.2 X-ray Stacking Results

#### 3.3.2.1 Stacked Properties

In Tables 3.2 and 3.3, we summarize the average properties of our stacked samples of normal early-type galaxies. For illustrative purposes, we created Figure 3.7, which shows 0.5–2.0 keV (SB) adaptively-smoothed stacked images of our faded samples. We detect the average X-ray emission from all of our samples in SB, several in SB1, and only two in HB. The two samples from which we detect HB emission (the \( z \approx 0.65 \) optically luminous general sample and the \( z \approx 0.58 \) optically luminous faded sample) have HB–to–SB1 and HB–to–SB count-rate ratios (i.e., \( \Phi_{2-8 \text{ keV}}/\Phi_{0.5-1.0 \text{ keV}} \) and \( \Phi_{2-8 \text{ keV}}/\Phi_{0.5-2.0 \text{ keV}} \)) that are broadly consistent with our adopted X-ray SED. Furthermore, all of our stacked samples have mean X-ray–to–optical flux ratios \( (f_{0.5-8.0 \text{ keV}}/f_R) \) that are consistent with those expected for normal galaxies (see col.[5] of Table 3.3 and Fig. 3.5). In Figure 3.5, we have plotted mean quantities from our samples as large filled squares and triangles, which represent our optically luminous and faint faded samples, respectively; these symbols have been shaded with varying grayscale levels to indicate redshift, such that darker shading represents higher redshift samples.

For the purpose of comparing our results with local early-type galaxies, we utilize the O'Sullivan et al. (2001; hereafter OS01) sample. The OS01 sample was selected from the Lyon-Meudon Extragalactic Data Archive (LEDA) using morphological type \((T < -1.5; \ E–\text{S0 Hubble types})\), distance \((V \leq 9000 \text{ km s}^{-1})\), and apparent magnitude \((B_T \leq 13.5)\). The LEDA catalog is known to be \( \approx 90\% \) complete down to \( B_T = 14 \). X-ray observations of these galaxies were available mainly from the ROSAT PSPC with a significant minority of the data originating from the Einstein IPC. We also utilized Chandra data from David et al. (2006) for six of the OS01 galaxies having only X-ray upper limits. Figure 3.8 shows the 0.5–2.0 keV luminosity versus \( B \)-band luminosity for galaxies included in the OS01 sample with \( D < 70 \text{ kpc} \); X-ray luminosities have been normalized to the 0.5–2.0 keV bandpass using the X-ray SED adopted in OS01 (i.e., a MEKAL plasma SED with solar metallicity and a plasma temperature of 1 keV). We have denoted field, central-cluster, brightest-group, and AGN-hosting early-type galaxies as identified from the OS01 sample; several well-studied examples have been highlighted (M32, M87, NGC 1399, NGC 1600, NGC 4697, and NGC 5102) for reference.

As noted in § 3.1.1, the X-ray and \( B \)-band luminosities of local early-type galaxies are observed to be correlated, and these correlations follow a power law:

\[ \log L_X = \alpha \log L_B + \beta, \]  
(3.4)
Table 3.2. Stacked Early-Type Normal Galaxies: Basic Properties

<table>
<thead>
<tr>
<th>$z_{\text{mean}}$</th>
<th>$N_{\text{total}}$</th>
<th>$N_{\text{detected}}$</th>
<th>$E_{0.5-3.0 \text{ keV}}$ (Ms)</th>
<th>$S-B$ (0.5–1.0 keV)</th>
<th>$S-B$ (0.5–2.0 keV)</th>
<th>$S-B$ (2–8 keV)</th>
<th>$S/N$ (0.5–1.0 keV)</th>
<th>$S/N$ (0.5–2.0 keV)</th>
<th>$S/N$ (2–8 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 ± 0.08</td>
<td>45</td>
<td>5</td>
<td>15.0</td>
<td>30.5 ± 7.4</td>
<td>94.5 ± 11.9</td>
<td>&lt; 27.0</td>
<td>9.8</td>
<td>19.7</td>
<td>0.9</td>
</tr>
<tr>
<td>0.47 ± 0.03</td>
<td>52</td>
<td>2</td>
<td>20.4</td>
<td>15.6 ± 6.6</td>
<td>31.4 ± 9.1</td>
<td>&lt; 32.4</td>
<td>4.1</td>
<td>5.5</td>
<td>2.1</td>
</tr>
<tr>
<td>0.58 ± 0.02</td>
<td>51</td>
<td>2</td>
<td>18.2</td>
<td>12.9 ± 6.2</td>
<td>33.5 ± 9.0</td>
<td>&lt; 31.2</td>
<td>3.6</td>
<td>6.2</td>
<td>2.2</td>
</tr>
<tr>
<td>0.66 ± 0.02</td>
<td>74</td>
<td>3</td>
<td>30.0</td>
<td>16.6 ± 7.3</td>
<td>40.7 ± 10.6</td>
<td>34.4 ± 13.4</td>
<td>3.5</td>
<td>5.7</td>
<td>3.2</td>
</tr>
</tbody>
</table>

General Sample; $L_B \approx 10^{10-11} L_B, \odot$

<table>
<thead>
<tr>
<th>$z_{\text{mean}}$</th>
<th>$N_{\text{total}}$</th>
<th>$N_{\text{detected}}$</th>
<th>$E_{0.5-3.0 \text{ keV}}$ (Ms)</th>
<th>$S-B$ (0.5–1.0 keV)</th>
<th>$S-B$ (0.5–2.0 keV)</th>
<th>$S-B$ (2–8 keV)</th>
<th>$S/N$ (0.5–1.0 keV)</th>
<th>$S/N$ (0.5–2.0 keV)</th>
<th>$S/N$ (2–8 keV)</th>
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</thead>
<tbody>
<tr>
<td>0.24 ± 0.11</td>
<td>27</td>
<td>1</td>
<td>11.9</td>
<td>10.1 ± 5.4</td>
<td>25.5 ± 7.8</td>
<td>&lt; 27.1</td>
<td>3.4</td>
<td>5.7</td>
<td>2.9</td>
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<tr>
<td>0.46 ± 0.03</td>
<td>27</td>
<td>0</td>
<td>9.9</td>
<td>&lt; 14.5</td>
<td>12.7 ± 6.5</td>
<td>&lt; 22.0</td>
<td>2.7</td>
<td>3.2</td>
<td>0.5</td>
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</table>

Faded Sample; $L_{B,0} \approx 10^{10-11} L_B, \odot$

<table>
<thead>
<tr>
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<th>$N_{\text{total}}$</th>
<th>$N_{\text{detected}}$</th>
<th>$E_{0.5-3.0 \text{ keV}}$ (Ms)</th>
<th>$S-B$ (0.5–1.0 keV)</th>
<th>$S-B$ (0.5–2.0 keV)</th>
<th>$S-B$ (2–8 keV)</th>
<th>$S/N$ (0.5–1.0 keV)</th>
<th>$S/N$ (0.5–2.0 keV)</th>
<th>$S/N$ (2–8 keV)</th>
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</thead>
<tbody>
<tr>
<td>0.25 ± 0.08</td>
<td>41</td>
<td>4</td>
<td>14.1</td>
<td>26.3 ± 7.0</td>
<td>75.3 ± 10.9</td>
<td>&lt; 26.2</td>
<td>8.7</td>
<td>16.2</td>
<td>1.0</td>
</tr>
<tr>
<td>0.47 ± 0.03</td>
<td>44</td>
<td>2</td>
<td>16.5</td>
<td>&lt; 17.0</td>
<td>25.4 ± 8.3</td>
<td>&lt; 30.0</td>
<td>2.9</td>
<td>4.9</td>
<td>2.3</td>
</tr>
<tr>
<td>0.58 ± 0.02</td>
<td>30</td>
<td>2</td>
<td>9.5</td>
<td>12.5 ± 5.5</td>
<td>28.0 ± 7.6</td>
<td>21.9 ± 8.8</td>
<td>4.9</td>
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<td>3.6</td>
</tr>
<tr>
<td>0.66 ± 0.02</td>
<td>55</td>
<td>3</td>
<td>20.5</td>
<td>17.6 ± 6.7</td>
<td>42.2 ± 9.8</td>
<td>&lt; 33.5</td>
<td>4.6</td>
<td>7.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Faded Sample; $L_{B,0} \approx 10^{9.3-10} L_B, \odot$

<table>
<thead>
<tr>
<th>$z_{\text{mean}}$</th>
<th>$N_{\text{total}}$</th>
<th>$N_{\text{detected}}$</th>
<th>$E_{0.5-3.0 \text{ keV}}$ (Ms)</th>
<th>$S-B$ (0.5–1.0 keV)</th>
<th>$S-B$ (0.5–2.0 keV)</th>
<th>$S-B$ (2–8 keV)</th>
<th>$S/N$ (0.5–1.0 keV)</th>
<th>$S/N$ (0.5–2.0 keV)</th>
<th>$S/N$ (2–8 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22 ± 0.09</td>
<td>28</td>
<td>2</td>
<td>11.2</td>
<td>14.3 ± 5.8</td>
<td>43.5 ± 8.9</td>
<td>&lt; 26.3</td>
<td>4.9</td>
<td>10.1</td>
<td>2.6</td>
</tr>
<tr>
<td>0.46 ± 0.03</td>
<td>31</td>
<td>0</td>
<td>12.5</td>
<td>11.9 ± 5.7</td>
<td>15.3 ± 7.1</td>
<td>&lt; 24.2</td>
<td>3.9</td>
<td>3.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Note. — Col.(1): Mean redshift and standard deviation of the redshift for each stacked sample. Col.(2): Number of sources being stacked. Col.(3): Number of stacked sources that were detected individually in the X-ray bandpass. Col.(4): Total vignetting-corrected effective exposure time measured from the 0.5–2.0 keV exposure maps. Col.(5)–(7): Net 0.5–1.0 keV, 0.5–2.0 keV, and 2–8 keV source counts. Col.(8)–(10): S/N for the 0.5–1.0 keV, 0.5–2.0 keV, and 2–8 keV bandpasses.
Table 3.3. Stacked Early-Type Normal Galaxies: Mean X-ray Properties

| $z_{\text{mean}}$ | $f_{0.5-1.0\text{ keV}}$ (log cgs) | $f_{0.5-2.0\text{ keV}}$ (log cgs) | $f_{2-8\text{ keV}}$ (log cgs) | $\log f_{0.5-8.0\text{ keV}}/f_R$ (5) | $L_{0.5-1.0\text{ keV}}$ (log erg s$^{-1}$) (6) | $L_{0.5-2.0\text{ keV}}$ (log erg s$^{-1}$) (7) | $L_{2-8\text{ keV}}$ (log erg s$^{-1}$) (8) | $L_B^a$ (log $L_{B,\odot}$) (9) | $L_{0.5-2.0\text{ keV}}/L_B^a$ (log erg s$^{-1}$ $L_{B,\odot}^{-1}$) (10) |
|-------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 0.25 ± 0.08       | -16.5 ± 0.6                    | -16.2 ± 0.2                    | < -16.0                        | -3.00                           | 39.7 ± 0.6                      | 40.2 ± 0.2                      | < 40.4                          | 10.5                            | 29.7 ± 0.1                      |
| 0.47 ± 0.03       | -16.9 ± 0.7                    | -16.8 ± 0.4                    | < -16.1                        | -2.63                           | 39.9 ± 0.8                      | 40.1 ± 0.4                      | < 40.8                          | 10.4                            | 29.7 ± 0.1                      |
| 0.58 ± 0.02       | -17.0 ± 0.8                    | -16.8 ± 0.3                    | < -16.1                        | -2.29                           | 40.1 ± 0.8                      | 40.4 ± 0.4                      | < 41.1                          | 10.5                            | 29.9 ± 0.1                      |
| 0.66 ± 0.02       | -17.1 ± 0.8                    | -16.9 ± 0.3                    | -16.4 ± 0.5                    | -2.21                           | 40.1 ± 0.8                      | 40.4 ± 0.4                      | 40.8 ± 0.6                      | 10.6                            | 29.9 ± 0.1                      |

| 0.24 ± 0.11       | -17.1 ± 0.9                    | -16.7 ± 0.4                    | < -15.9                        | -2.70                           | 39.4 ± 0.9                      | 39.6 ± 0.4                      | < 40.5                          | 9.8                             | 29.9 ± 0.2                      |
| 0.46 ± 0.03       | < -16.8                       | -17.0 ± 0.7                    | < -16.0                        | < -1.79                         | < 40.5                          | 40.0 ± 0.7                      | < 41.0                          | 9.6                             | 30.4 ± 0.2                      |

| 0.25 ± 0.08       | -16.5 ± 0.6                    | -16.3 ± 0.2                    | < -16.0                        | -3.08                           | 39.7 ± 0.6                      | 40.1 ± 0.2                      | < 40.4                          | 10.4                            | 29.7 ± 0.1                      |
| 0.47 ± 0.03       | < -16.6                       | -16.8 ± 0.4                    | < -16.1                        | -2.67                           | < 40.2                          | 40.1 ± 0.4                      | < 40.9                          | 10.4                            | 29.8 ± 0.2                      |
| 0.58 ± 0.02       | -16.7 ± 0.7                    | -16.5 ± 0.3                    | -16.1 ± 0.5                    | -2.21                           | 40.3 ± 0.8                      | 40.6 ± 0.4                      | 41.0 ± 0.6                      | 10.5                            | 30.2 ± 0.1                      |
| 0.66 ± 0.02       | -16.9 ± 0.7                    | -16.7 ± 0.3                    | < -16.1                        | -2.22                           | 40.3 ± 0.7                      | 40.6 ± 0.4                      | < 41.2                          | 10.5                            | 30.1 ± 0.1                      |

| 0.22 ± 0.09       | -17.0 ± 0.7                    | -16.4 ± 0.3                    | < -15.9                        | -2.71                           | 39.5 ± 0.7                      | 39.8 ± 0.3                      | < 40.4                          | 9.8                             | 30.0 ± 0.1                      |
| 0.46 ± 0.03       | -17.1 ± 0.8                    | -17.0 ± 0.6                    | < -16.0                        | < -1.96                         | 40.1 ± 0.8                      | 40.0 ± 0.6                      | < 40.9                          | 9.8                             | 30.2 ± 0.2                      |

*aFor the faded samples, quoted $B$-band luminosities indicate faded ($z = 0$) luminosities, $L_{B,0}$.

Note. — Col.(1): Mean redshift and standard deviation of the redshift for each stacked sample. Col.(2)–(4): Logarithm of the mean 0.5–1.0 keV, 0.5–2.0 keV, and 2–8 keV flux in units of erg cm$^{-2}$ s$^{-1}$. Col.(5): Logarithm of the 0.5–8.0 keV to $R$-band flux ratio. Col.(6)–(8): Logarithm of the mean 0.5–1.0 keV, 0.5–2.0 keV, and 2–8 keV rest-frame luminosity. Col.(9): Logarithm of the mean rest-frame $B$-band luminosity. Col.(10): Logarithm of the 0.5–2.0 keV–to–$B$-band mean luminosity ratio.
Fig. 3.7: Stacked, adaptively-smoothed 0.5–2.0 keV images of our early-type, faded samples for each redshift bin. The top panels show our optically luminous \((L_{B,0} \approx 10^{10.1-11} L_{B,⊙})\) samples, and the bottom panels show our optically faint \((L_{B,0} \approx 10^{9.3-10} L_{B,⊙})\) samples. These images were generated using the CIAO tool CSMOOTH with a minimum significance of 2.5\(\sigma\). The images are \(\approx 15''\) \((\approx 30.5\) pixels\) per side, and each pixel is \(0''492\). Our circular stacking aperture of radius \(1''5\) is shown in each image centered on the optical centroid of our stacked sources. Additional sample information, including the number of stacked galaxies, total Chandra exposure, signal-to-noise ratio (S/N), and logarithm of the mean \(z = 0\) \(B\)-band luminosity \((L_{B,0})\) are annotated on each smoothed image.
**Fig. 3.8:** Logarithm of the 0.5–2.0 keV luminosity ($L_X$) versus the logarithm of the $B$-band luminosity, $L_B$, for $D < 70$ kpc local ellipticals with the average properties of our faded samples plotted. Small symbols and upper limits are sources from the OS01 local sample, and the different symbols correspond to field galaxies (circles), central-cluster galaxies (upward-pointing open triangles), brightest-group galaxies (downward-pointing open triangles), and AGNs (crosses). The best-fit relations for the luminosity intervals $L_B \gtrsim 10^{10} L_{B,\odot}$ and $L_B \lesssim 10^{10} L_{B,\odot}$ are shown as solid and dashed lines, respectively; the shaded region shows the expected discrete-source contribution (Kim & Fabbiano 2004; see also the discussion in § 3.3.2.1). The local ellipticals M32, M87, NGC 1399, NGC 1600, NGC 4697, and NGC 5102 have been marked, for reference. Large shaded symbols represent our optically luminous (squares) and faint (triangles) faded samples and have grayscale levels corresponding to the mean redshift of each sample, such that darker shading represents higher redshifts. Error bars in $L_X$ represent 1σ errors on the mean. We quote $B$-band luminosities as $L_{B,0}$ to illustrate any potential evolution of the mean X-ray luminosities.
where \(\alpha\) and \(\beta\) are fitting constants. Using the OS01 sample, we performed linear-regression analyses for galaxies with \(L_B \gtrsim 10^{10} \, L_{B,\odot}\) and \(L_B \lesssim 10^{10} \, L_{B,\odot}\) separately to determine \(\alpha\) and \(\beta\) for each luminosity regime. When doing these calculations, we excluded (1) sources at \(D > 70\) kpc, (2) sources with X-ray emission that may be significantly influenced by X-ray-emitting gas associated with galaxy clusters or groups such as central-cluster and brightest-group galaxies, (3) AGN-hosting galaxies, (4) NGC 5102, due to its anomalously low X-ray luminosity and evidently recent star-formation activity (e.g., OS01; Kraft et al. 2005; see Fig. 3.8), and (5) NGC 4782, which has an anomalously large \(L_B\) that drives the correlation (i.e., \(L_B = 10^{11.4} \, L_{B,\odot}\); see, e.g., OS01). We utilized Kendall’s tau (Kendall 1938) to measure the correlation strengths and Buckley-James regression (Buckley & James 1979; Isobe et al. 1986) to calculate the best-fit correlation parameters (i.e., \(\alpha\) and \(\beta\)) for each luminosity regime. These tools were available through the Astronomy SURVival Analysis software package (\textsc{asurv} Rev. 1.2; Isobe & Feigelson 1990; LaValley et al. 1992). We found correlation significances of \(\approx 6.8\sigma\) and \(\approx 2.8\sigma\) for the \(L_B \gtrsim 10^{10} \, L_{B,\odot}\) and \(L_B \lesssim 10^{10} \, L_{B,\odot}\) galaxy samples, respectively. We found that for the optically luminous sample \(\alpha = 2.61 \pm 0.61\) and \(\beta = 12.77\) (solid line in Fig. 3.8), and for the optically faint sample \(\alpha = 1.05 \pm 0.27\) and \(\beta = 29.36\) (dashed line in Fig. 3.8). We note that the \(L_X-L_B\) relation for optically faint galaxies is poorly constrained with \(\approx 75\%\) of the galaxies having only X-ray upper limits; however, since these galaxies are thought to be dominated by LMXBs, investigations of the LMXB luminosity per unit \(B\)-band luminosity can offer a consistency check for this relation. Using \textit{Chandra} observations of 14 E/S0 galaxies, Kim & Fabbiano (2004) found that for LMXBs with \(L_X > 10^{37}\) erg s\(^{-1}\), \(\beta = 29.5 \pm 0.25\) using a fixed slope of \(\alpha = 1\). This value is the most tightly constrained \(L_X(\text{LMXB})-L_B\) relation available at present and is consistent with other investigations of the discrete-source contribution (e.g., Sarazin 1997; OS01 and references therein; Gilfanov 2004) and our calculated \(L_X-L_B\) relation for local optically faint early-type galaxies. For reference, the expected discrete-source contribution from LMXBs is presented in Figure 3.8 as a shaded region, which represents the dispersion of the relation. We note that the \(L_X-L_B\) relation for local optically faint early-type galaxies (dashed line) is consistent with that expected for X-ray emission originating strictly from LMXBs.

In Figure 3.8, we have plotted mean quantities from our samples using the same symbols and symbol-shading schemes that were adopted in Figure 3.5. The plotted error bars for our stacked samples were computed by propagating (1) Poisson errors on the source counts (Gehrels 1986), (2) 1 \(\sigma\) errors on \(\langle n_f^2 \rangle\), and (3) systematic errors on the SED-dependent parameters (i.e., count-rate to flux conversion and \(K\)); these errors were propagated following the “numerical method” described in §1.7.3 of Lyons (1991). In an initial evaluation of these results, we find that the average X-ray properties of our optically luminous samples appear to follow the local relation at all redshifts. In contrast, our optically faint samples deviate from the local relation significantly (1.5\(\sigma\) at \(z \approx 0.46\) over the redshift range \(z \approx 0.1-0.5\), suggesting there may be some evolution in the LMXB populations within these galaxies.

Figures 3.9a and 3.9b show the mean 0.5–2.0 keV luminosities \((L_X)\) of our stacked general and faded samples, respectively; optically luminous and faint samples are indicated as dark filled squares and triangles, respectively. X-ray-detected sources are shown as circles, which represent both normal galaxies (filled circles) and AGN candidates (open circles). We have included the corresponding mean X-ray luminosities for local early-type galaxies from the OS01 optically luminous and faint samples in matched optical-luminosity ranges; as before, these samples were filtered to exclude galaxies classified as AGNs, central-cluster galaxies, brightest-group galaxies,
Fig. 3.9: Logarithm of the 0.5–2.0 keV luminosity $L_X$ versus redshift for our general (a; see Figure 3.2a) and faded (b; see Figure 3.2b) samples; filled and open circles indicate X-ray-detected normal galaxies and AGN candidates, respectively. Black squares and triangles with error bars show the stacking results for our optically luminous ($L_B \approx 10^{10-11} \text{ erg s}^{-1}$) and faint ($L_B \approx 10^{9.3-10} \text{ erg s}^{-1}$) samples, respectively. Error bars in redshift represent the standard deviation of the redshift for sources in each stacked sample. For comparison, we have plotted the corresponding mean X-ray luminosities (and errors on the means computed with ASURV) of normal early-type galaxies from the OS01 local sample (gray filled square and triangle). All mean values (ours and those of OS01) were calculated after excluding AGNs, central-cluster galaxies, and brightest-group galaxies, and should reflect the average properties of isolated field early-type galaxies. The solid curve illustrates the median X-ray detection limit (using the median sensitivity limit of $\approx 1.6 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ for our total sample). For reference, the X-ray luminosities of the local ellipticals M32, M87, NGC 1399, NGC 1600, NGC 4697, and NGC 5102 have been indicated.
NGC 5102, and NGC 4782. Mean optical and X-ray luminosities for the OS01 samples were computed using the Kaplan-Meier estimator (e.g., Feigelson & Nelson 1986) within ASURV, which appropriately handles censored data. When calculating these mean luminosities, we filtered the OS01 sample to include only sources with distances < 40 Mpc and < 20 Mpc for the optically luminous and faint samples, respectively; these distances represent approximate completeness limits for the optical-luminosity ranges used here. We calculated mean X-ray luminosities of \( \log(L_X) \approx 40.2 \pm 0.2 \) and \( \approx 39.2 \pm 0.2 \) for the optically luminous and faint samples, respectively; error bars here represent 1σ errors on the means (computed with ASURV). These calculations were made using 102 optically luminous galaxies (60 upper limits) and 48 optically faint galaxies (36 upper limits). We attempted to improve the X-ray-detection fractions of these samples by using subsamples of galaxies that were created with distance limits smaller than the completeness limits quoted above; however, we found no improvement in these fractions.

Figures 3.10a and 3.10b show the X-ray–to–B-band mean luminosity ratio \( (L_X/L_B) \) for our general and faded samples, respectively (symbols have the same meaning as they did in Fig. 3.9); the expected local discrete-source contribution and its dispersion are shown as a horizontal dotted line and the surrounding shaded region, respectively. As observed in Figure 3.8, we find little evidence for evolution in our optically luminous samples (both general and faded). Using the available data, we find that \( (L_X/L_B)_{z=0.7} = [1.0 \pm 0.5] \) and \( [1.7 \pm 0.8] \times (L_X/L_B)_{z=0} \) for our optically luminous general and faded samples, respectively. In order to constrain further the allowed redshift evolution of \( L_X/L_B \), we utilized the \( \chi^2 \) statistic and a simple evolutionary model, \( (L_X/L_B)_z = (1+z)^\eta (L_X/L_B)_{z=0} \). For this single-parameter model, we constrained \( \eta \) using 90% confidence errors (\( \Delta \chi^2 = 2.7 \)). We found best-fit parameters of \( \eta = -0.4^{+0.6}_{-0.7} (\chi^2 = 3.4 \) for 4 degrees of freedom) and \( \eta = 0.4^{+0.6}_{-0.7} (\chi^2 = 11.3 \) for 4 degrees of freedom) for our optically luminous general and faded samples, respectively. For the optically faint early-type samples, we observe suggestive redshift evolution in \( L_X/L_B \), and by \( z \approx 0.5 \) it has increased above the local relation by a factor of \( \approx 5.3 \pm 4.1 \) and \( \approx 5.6 \pm 4.1 \) for our general and faded samples, respectively. Using the \( \chi^2 \) statistic and the same simple model for redshift evolution presented above, we find best-fit values of \( \eta = 4.4 \pm 1.7 (\chi^2 = 1.1 \times 10^{-3} \) for 2 degrees of freedom) and \( \eta = 5.4 \pm 1.5 (\chi^2 = 1.0 \) for 2 degrees of freedom) for our optically faint general and faded samples, respectively. We note that the evolution observed for optically faint early-type galaxies is largely driven by the value of \( L_X/L_B \) at \( z = 0 \). Due to the fact that the \( z = 0 \) value for \( L_X/L_B \) is based on 48 sources, with 36 (75%) having only X-ray upper limits, we cannot rule out the possibility that \( L_X/L_B \) at \( z = 0 \) is significantly affected by systematic errors. Moreover, the total X-ray emission from optically faint galaxies is expected to vary significantly between galaxies due to low numbers of LMXBs and variable amounts of hot gas, and therefore large fractional errors are expected for \( L_X/L_B \). We therefore consider this result to be only marginal at present.

As noted above, the local relation between \( L_X \) and \( L_B \) is nonlinear for optically luminous early-type galaxies. In order to investigate whether such nonlinearities have an effect on our overall results, we created Figure 3.11, which illustrates residuals to the local best-fit relations, \( \log L_X = \alpha \log L_B + \beta \), for optically luminous (\( \alpha = 2.61; \beta = 12.77 \)) and faint (\( \alpha = 1.05; \beta = 29.36 \)) samples. Figure 3.11 shows that the nonlinearities observed in the local \( L_X-L_B \) relation do not affect our conclusions drawn from using \( L_X/L_B \) as a proxy for evolution. Furthermore, due to the approximate equality of the mean values of \( L_B \) for all samples of a given luminosity class, quantitative analyses that account for nonlinearities in the \( L_X-L_B \) relations yield roughly identical results to those quoted using simply \( L_X/L_B \).
Fig. 3.10: Logarithm of the X-ray–to–$B$-band mean luminosity ratio ($L_X/L_B$) versus redshift for our general (a; see Figure 3.2a) and faded (b; see Figure 3.2b) samples. Symbols have the same meaning as in Figure 3.9; the dotted line and shaded region represent the expected local discrete-source contribution and its dispersion (from Kim & Fabbiano 2004). For the faded sample, we used $L_{B,0}$ when computing the X-ray–to–$B$-band mean luminosity ratios. For reference, the local ellipticals M32, M87, NGC 1399, NGC 1600, NGC 4697, and NGC 5102 have been plotted.
Fig. 3.11: Residuals to the local best-fit relation, $\log L_X - \alpha \log L_B - \beta$ for our general (a; see Figure 3.2a) and faded (b; see Figure 3.2b) samples. For optically luminous galaxies ($L_B \approx 10^{10-11} L_{B,\odot}$) we used $\alpha = 2.61$ and $\beta = 12.77$, and for optically faint galaxies ($L_B \approx 10^{9.3-10} L_{B,\odot}$), we adopted $\alpha = 1.05$ and $\beta = 29.36$. Symbols have the same meaning as in Figure 3.9, and the redshifts of the local samples have been offset from $z = 0$ for viewing ease. The dotted horizontal line indicates the zero residual. For reference, the local ellipticals M32, M87, NGC 1399, NGC 1600, NGC 4697, and NGC 5102 have been plotted.
3.3.2.2 Assessing Remaining AGN Contamination

In this section we assess whether the stacked properties presented above suffer from contamination by AGNs with 2–8 keV luminosities below our detection threshold. In § 3.3.1 (see also Fig. 3.6), we presented the cumulative AGN fraction, $f_C$, the fraction of early-type galaxies harboring an AGN with a 2–8 keV luminosity of $L_{2–8\text{ keV}}$ or greater. To first order, we can use the functional form of $f_C$ to generate a census of the AGN population that we expect to be missing due to sensitivity limitations. As noted in § 3.3.1, there is evidence that $f_C$ evolves with redshift. We modelled this redshift evolution of $f_C$ using the functional form, $f_C(z) = (1+z)^{3}f_C(z=0)$ (see § 3.3.1 for justification). We also assumed that the dependence of $f_C$ upon $L_{2–8\text{ keV}}$ was similar at all redshifts over the range $z \approx 0.1–0.7$. Using our faded sample of optically luminous early-type galaxies we computed $\langle f_C \rangle_z$, the average cumulative AGN fraction over the redshift range $z \approx 0.1–0.7$ ($z_{\text{median}} = 0.55$), following the procedure outlined in § 3.3.1; this was done to obtain a better understanding of the overall shape of the $f_C(L_{2–8\text{ keV}})$ curve. Figure 3.12a (filled circles with error bars) shows our computed values of $\langle f_C \rangle_z$ as a function of $\log L_{2–8\text{ keV}}$. We fit the $\langle f_C \rangle_z$ data points using a quadratic relation (i.e., $\log \langle f_C \rangle_z = a_0 + a_1 \log L_{2–8\text{ keV}} + a_2 (\log L_{2–8\text{ keV}})^2$, where $a_0 = -1.36$, $a_1 = 7.1$, and $a_2 = -0.1$; thick solid curve in Fig. 3.12a) over the luminosity range $\log L_{2–8\text{ keV}} = 40–44$; this covers the same luminosity range for AGNs as the OS01 local sample. Using our best-fit relation for $\langle f_C \rangle_z$ and our model for the redshift evolution of $f_C$, we calculated $f_C(z, \log L_{2–8\text{ keV}})$ for each of our optically luminous faded samples following:

$$f_C = \left(\frac{1+z}{1+z_{\text{median}}}\right)^3 \langle f_C \rangle_z,$$

where $z$ is the median redshift of each sample, $z_{\text{median}} = 0.55$ is the median redshift of our best-fit redshift-averaged relation, $\langle f_C \rangle_z$. In Figure 3.12a, we show our estimates of $f_C$ for each of our optically luminous faded samples; these curves are annotated on the figure. For comparison, we have shown the AGN fraction measured for DRGs (see § 3.1) at $z \approx 2.5$ by Rubin et al. (2004; open diamond) and have extrapolated our model for $f_C$ out to $z \approx 2.5$ (dot-dashed curve). We note that even at $z \approx 2.5$ our model agrees reasonably well with observations.

In order to estimate the amount of AGN contamination that may be contributing to our stacked signals, it is desirable to convert the cumulative AGN fractions to differential forms (i.e., the fraction of galaxies harboring AGNs within discrete X-ray luminosity bins). Using the model for $f_C$ presented above, we estimated the fractions of galaxies harboring an AGN within luminosity bins of width $\Delta \log L_{2–8\text{ keV}} = 0.5$ for each of our optically luminous faded samples; we refer to these as differential AGN fractions, $f_D$. The histograms in Figure 3.12b show our estimates of $f_D$. Due to the deep Chandra coverage in the E-CDF-S region, a large fraction of the luminous AGNs ($L_{2–8\text{ keV}} \gtrsim 10^{41.5}$ erg s$^{-1}$) would have been removed from our samples before stacking (see § 3.2.1.1). We are therefore only interested in the fraction of galaxies falling below our sensitivity limit. Using the sensitivity maps described in § 3.3.1, we determined the fraction of optically luminous galaxies within each of our stacked faded samples for which we could not have detected an AGN of luminosity $L_{2–8\text{ keV}}$ if present; we refer to these fractions as $f_U$ (i.e., the fractions of galaxies below our sensitivity limit) and show them in Figure 3.12c. For each of our optically luminous faded samples we calculated the fraction of sources that harbor an undetected AGN with 2–8 keV luminosity $L_{2–8\text{ keV}}$ (in bins of width $\Delta \log L_{2–8\text{ keV}} = 0.5$), $f_U$, ...
Fig. 3.12: (a) Cumulative AGN fraction (i.e., the fraction of galaxies harboring an AGN with a 2–8 keV luminosity of \(L_{2-8}\) or greater), \(f_C\), versus \(\log L_{2-8}\) for our optically luminous faded samples. The cumulative AGN fraction computed over the entire redshift range, \(\langle f_C \rangle\), is indicated as filled circles with 1\(\sigma\) error bars, and the thick solid curve represents our best-fit quadratic relation to the data (see § 3.3.2.2 for details). This relation was used to estimate \(f_C\) for our optically luminous faded samples (annotated curves). For reference, we have plotted the observed AGN fraction for \(z \approx 2.5\) DRGs (Rubin et al. 2004; open diamond) and our model extrapolated out to \(z = 2.5\) (dot-dashed curve). (b) Differential AGN fractions (i.e., the fraction of galaxies harboring an AGN in discrete bins of width \(\Delta \log L_{2-8} = 0.5\)), \(f_D\), versus \(\log L_{2-8}\). (c) Fraction of early-type galaxies for which we could not have detected an AGN with a 2–8 keV luminosity of \(L_{2-8}\), \(f_B\), versus \(\log L_{2-8}\). (d) Fraction of galaxies harboring AGNs in our optically luminous faded samples that would remain undetected due to sensitivity limitations, \(f_U = f_D \times f_B\), versus \(\log L_{2-8}\); these galaxies would not have been removed from our stacking analyses.
by multiplying \( f_D \) by \( f_B \). In Figure 3.12d, we show \( f_U \) as a function of \( \log L_{2-8 \, \text{keV}} \). Using \( f_U \), we computed the approximate AGN contamination with the following summation:

\[
L_{2-8 \, \text{keV}}(\text{contam}) = \sum f_{U,i} \times L_{2-8 \, \text{keV},i},
\]

where the summation is over all bins of \( \Delta \log L_{2-8 \, \text{keV}} = 0.5 \). We find \( L_{2-8 \, \text{keV}}(\text{contam}) \approx 10^{39.5-40.5} \, \text{erg s}^{-1} \) for our samples. For our samples with \( z \approx 0.45 \), AGNs with \( L_{2-8 \, \text{keV}} \approx 10^{41} \, \text{erg s}^{-1} \) contribute \( > 70\% \) of the total \( L_{2-8 \, \text{keV}}(\text{contam}) \) estimate. Furthermore, when extrapolating our model for \( f_C \) down to much lower values of \( L_{2-8 \, \text{keV}} \), we find no significant difference in our estimates of \( L_{2-8 \, \text{keV}}(\text{contam}) \). We note that this result is mildly dependent on our extrapolation of \( f_C \) to values of \( L_{2-8 \, \text{keV}} \approx 10^{39-40.5} \, \text{erg s}^{-1} \). If there exists a large population of radiatively-inefficient low-luminosity AGNs in early-type galaxies that radiate within this X-ray luminosity range (e.g., advection-dominated accretion flows [ADAFs]), then we may be underestimating \( L_{2-8 \, \text{keV}}(\text{contam}) \). However, \textit{Chandra} observations of \( \approx 50 \) early-type galaxies in the local universe have revealed that the majority of the central supermassive black holes in these galaxies are radiating at extremely low efficiencies and typically have observed \( L_X \approx 10^{39} \, \text{erg s}^{-1} \) (e.g., Loewenstein et al. 2001; David et al. 2005; Pellegrini 2005). Therefore a change in the shape of \( f_C \) at \( L_{2-8 \, \text{keV}} \approx 10^{39-40.5} \, \text{erg s}^{-1} \) is not expected.

We converted \( L_{2-8 \, \text{keV}}(\text{contam}) \) to a 0.5–2.0 keV luminosity assuming a power-law model with an effective photon index \( \Gamma_{\text{eff}} \), which was determined by stacking all 24 AGN candidates in our optically luminous faded sample; in this calculation we purposely made no attempt to correct for intrinsic absorption. For these 24 AGN candidates, we find that the mean band ratio \( \Phi_{2-8 \, \text{keV}} / \Phi_{0.5-2.0 \, \text{keV}} = 1.12 \pm 0.09 \), which corresponds to an effective photon index of \( \Gamma_{\text{eff}} = 0.77 \pm 0.08 \); this effective photon index is in agreement with the effective photon indices measured for sources in the \textit{Chandra} Deep Field-North (CDF-N; see Fig. 14 of Alexander et al. 2003) with similar fluxes. If we assume \( \Gamma_{\text{eff}} = 0.8 \) is a characteristic effective photon index for the AGNs we expect to be missing, then we find that AGN contamination can account for \( \approx 4\% \) and \( \approx 11\% \) of the observed 0.5–2.0 keV emission from our optically luminous faded samples at \( z \approx 0.25 \) and \( z \approx 0.66 \), respectively; this amount does not significantly affect the results presented in § 3.3.2.1 above. We note that the X-ray SED used in this calculation has an important effect on the overall estimate of the AGN contamination. Since our estimate for contamination decreases as \( \Gamma_{\text{eff}} \) decreases, the amount of contamination in our samples may be affected if our choice of \( \Gamma_{\text{eff}} \) is too flat. However, if we choose a steeper effective photon index such as \( \Gamma_{\text{eff}} = 1.4 \) (the observed spectrum of the X-ray background), we still find that the estimated AGN contribution to our 0.5–2.0 keV signal is too low (\( \lesssim 25\% \) at \( z \approx 0.66 \)) to make a substantive difference to our results. Furthermore, as discussed in § 3.2.1.1, we have taken additional precautions to eliminate several AGN candidates that were not detected in the 2–8 keV bandpass; these sources would not be taken into account in this estimate for AGN contamination. We also note that similar results are found when performing the above analyses using our optically luminous general samples.

Due to poor statistical constraints on AGN activity in optically faint early-type galaxies, an estimate of \( f_C \) could not be determined reliably using the present data. Studies of the AGN fraction as a function of galactic stellar mass have found that AGNs are much more commonly observed in massive galaxies than lower-mass galaxies (e.g., Kauffmann et al. 2003). We therefore approximated a strict upper limit to the AGN contribution to the X-ray emission from our optically faint early-type samples by using the same model for \( f_C \) presented above for the more
massive optically luminous galaxies. Using this model, we estimate that AGNs contribute < 20% and < 40% of the X-ray emission from our optically faint samples (both general and faded) assuming $\Gamma_{\text{eff}} = 0.8$ and $\Gamma_{\text{eff}} = 1.4$, respectively. These limits slightly reduce the significance of the quoted evolution for our optically faint faded samples such that $(L_X/L_B)_{z=0.5}$ is estimated to be $[4.5 \pm 3.3]$ and $[3.4 \pm 2.5] \times (L_X/L_B)_{z=0}$ for $\Gamma_{\text{eff}} = 0.8$ and $\Gamma_{\text{eff}} = 1.4$, respectively; however, we note that these limits should be regarded as very conservative.

3.4 Discussion

The above results suggest differing evolutionary histories for optically luminous and faint early-type galaxies. As shown in § 3.3.2.2, our results are not expected to be significantly affected by an undetected population of AGNs. Therefore, changes in the X-ray emission with redshift are likely the result of global changes in the emission from hot interstellar gas and/or LMXBs. In the sections below, we discuss possible interpretations of the results for our optically luminous and faint early-type galaxies in turn.

3.4.1 Optically Luminous Early-Type Galaxies

As discussed in § 3.2.2, we chose the SB for our stacking analyses to sample directly the X-ray emission from hot interstellar gas. Therefore, the near constancy of $L_X/L_B$ with redshift can be largely explained as a general balance between the energy losses from the hot gas ($\Delta E_{\text{gas}}$) and the energy deposition from heating mechanisms ($\Delta E_{\text{heating}}$) over each cooling time, $t_{\text{cool}}$. Here we investigate the relative contributions from feedback mechanisms to constrain physical models of the heating of the hot gas in early-type galaxies. As noted in § 3.1.2, the typical inferred radiative cooling time for the central regions of an optically luminous early-type galaxy is $t_{\text{cool}} \approx 10^8$ yr. Since each of our optically luminous early-type galaxy redshift bins are larger than the cooling timescale (i.e., our redshift bins have temporal widths in the range of $\approx 0.5–4.4 \times 10^9$ yr), we can estimate the redshift-dependent energy components following:

$$\Delta E_{\text{gas}} = L_{\text{gas}}t_{\text{cool}}$$

$$\Delta E_{\text{heating}} = \epsilon_{\text{rad}}\gamma_{\text{BC}}L_{2-8 \text{ keV,AGN}}t_{\text{cool}} + L_{\text{mech,AGN}}t_{\text{cool}} + \Delta E_{\text{other}}.$$  \hspace{1cm} (3.7)

(3.8)

Here, $L_{\text{gas}}$ is the redshift-dependent globally-averaged power output from the gaseous component of our optically luminous early-type galaxies. The first two terms of equation 3.8 represent AGN heating from both radiative and mechanical feedback power, respectively. The radiative feedback power is represented as the product of the average 2–8 keV AGN luminosity per galaxy ($L_{2-8 \text{ keV,AGN}}$), its bolometric correction factor ($\gamma_{\text{BC}} \approx 30$; e.g., Marconi et al. 2004; Barger et al. 2005), and the efficiency factor describing the coupling between radiation and the hot interstellar gas ($\epsilon_{\text{rad}}$). We note that in cases where the Compton temperature of the AGN SED falls below the temperature of the hot interstellar gas, radiation from the central AGN may effectively cool the gas and thereby drive $\epsilon_{\text{rad}}$ to negative values (see, e.g., § 6 of Nulsen & Fabian 2000; Ciotti & Ostriker 2001). Mechanical power (e.g., through AGN jets) is likely to be a very important feedback mechanism, and we have indicated its contribution as $L_{\text{mech,AGN}}$. Finally, $\Delta E_{\text{other}}$ represents additional energy input from alternative forms of heating over each cooling time (see below).
Using the hot-gas component of the X-ray SED for NGC 1600 (see dotted curve in Fig. 3.1a), we estimate \( L_{\text{gas}} \approx 3 \times L_{\text{O.5-2.0 keV}} \) for our optically luminous samples, this amounts to a mean value of \( \langle L_{\text{gas}} \rangle \approx 8 \times 10^{40} \text{ erg s}^{-1} \). We measured \( L_{2-8 \text{ keV,AGN}} \) using our redshift-dependent model for the differential fraction, \( f_D \), which was presented in § 3.3.2.2 (see also Fig. 3.12b). Duty cycles for AGN activity in any given galaxy are expected to be shorter than the timescales represented by each of our redshift bins; however, since we are considering large populations of early-type galaxies, we do not expect significant variations in the AGN fraction (as measured from the E-CDF-S “snapshot”) at any given time within each redshift bin. Therefore using this model, we can calculate \( L_{2-8 \text{ keV,AGN}} \) following:

\[
L_{2-8 \text{ keV,AGN}} \approx \sum_i f_{D,i} \times L_{2-8 \text{ keV,i}},
\]

where the summation is over bins of \( \Delta \log L_{2-8 \text{ keV}} = 0.5 \) and covers the luminosity range \( L_{2-8 \text{ keV}} = 10^{40-44} \text{ erg s}^{-1} \). We found \( L_{2-8 \text{ keV,AGN}} \approx 9.1 \) and \( \approx 21 \times 10^{40} \text{ erg s}^{-1} \) per galaxy at \( z \approx 0.25 \) and \( z \approx 0.66 \), respectively. In Figure 3.13, we show \( L_{2-8 \text{ keV,AGN}} \) as a function of redshift for our optically luminous faded samples (filled squares). For comparison, we also show stacking results from the Brand et al. (2005) samples of \( z \approx 0.4-0.9 \) early-type galaxies (open diamonds), which have mean \( R \)-band absolute magnitudes that are well matched to those of our optically luminous faded samples; these mean luminosities are dominated by X-ray emission from AGNs and therefore provide a good estimate of \( L_{2-8 \text{ keV,AGN}} \) (\( \approx 80-90\% \) of the emission is from AGNs). Using these data and our model for the evolution of the X-ray emission from transient AGNs, \( L_{2-8 \text{ keV,AGN}} = L_{2-8 \text{ keV,AGN},z=0} (1+z)^3 \), we found \( L_{2-8 \text{ keV,AGN},z=0} \approx 5 \times 10^{40} \text{ erg s}^{-1} \) (see the dotted curve in Fig. 3.13).

Using the above relations and the assumption that \( \Delta E_{\text{gas}} = \Delta E_{\text{heating}} \), we arrive at the following relation:

\[
L_{\text{gas}} = \epsilon_{\text{rad}} \gamma_{\text{BC}} L_{2-8 \text{ keV,AGN},z=0} (1+z)^3 + L_{\text{mech,AGN}} + \Delta E_{\text{other}}/t_{\text{cool}}
\]

As discussed in § 3.1.2, transient AGN feedback is expected to play a significant role in the heating of the hot interstellar gas. If we assume that AGN feedback is largely responsible for keeping the gas hot, then we can neglect the last term of equation 3.10 (i.e., \( \Delta E_{\text{other}}/t_{\text{cool}} \ll L_{\text{gas}} \)). With this assumption and the observed constancy of \( L_{\text{gas}} \) with redshift, we infer that the strongly-evolving radiative power must be poorly coupled to the hot interstellar gas, such that \( \epsilon_{\text{rad}} \ll 0.05 \). This suggests that mechanical AGN power (i.e., \( L_{\text{mech}} \)) dominates the feedback over the redshift range \( z \approx 0.0-0.7 \) and does not evolve in the same way as the radiative power. We note that it is also possible that \( \Delta E_{\text{other}} \) may play some non-negligible role in the heating of the hot gas. Additional heating sources may include inward thermal conduction from the large reservoirs of hot gas found in the outer regions of early-type galaxies (e.g., Narayan & Medvedev 2001; Brighenti & Mathews 2003), Type Ia supernovae and stellar winds (e.g., Loewenstein & Mathews 1987, 1991), and infalling circumgalactic gas (e.g., Brighenti & Mathews 1998); however, the influence of these heating sources is presently not well constrained.
Fig. 3.13: Mean 2–8 keV AGN luminosity per early-type galaxy, $L_{2–8 \text{ keV, AGN}}$, versus redshift for our optically luminous faded samples (filled squares); these luminosities were derived following equation 3.9. Error bars on $L_{2–8 \text{ keV, AGN}}$ are 1σ errors, which were derived by propagating errors on the fit to $\langle f_C \rangle_z$ (solid curve in Fig. 3.12) through to equation 3.9. For comparison, we have plotted the Brand et al. (2005) stacking constraints for their early-type galaxy samples (open diamonds), which have mean $R$-band absolute magnitudes similar to those of our optically luminous faded samples. The dotted curve represents the $(1+z)^3$ model fit to our data.

3.4.2 Optically Faint Early-Type Galaxies

For our optically faint early-type galaxy samples, we found suggestive evidence for redshift evolution in $L_X/L_B$ over the redshift range $z \approx 0.0–0.5$ (see § 3.3.2.1 and Figs. 3.10 and 3.11). Although some of the observed emission may be due to AGN activity (§ 3.3.2.2), there remains suggestive evidence that normal X-ray activity is evolving with redshift, and we discuss possible scenarios explaining this evolution below.

One possible driver of $L_X/L_B$ evolution may come from global changes in the LMXB populations within optically faint early-type galaxies. As discussed in § 3.1.2, LMXBs from primordial binaries within the galactic field are expected to dominate the overall LMXB emission from optically faint early-type galaxies; this differs from the LMXB emission from optically luminous early-type galaxies, which originates primarily from globular clusters. LMXBs from primordial binaries emerge in the wake of star-formation epochs $\approx 1–10$ Gyr following a major star-formation event. Therefore, changes in the mean early-type galaxy stellar age with redshift should result in observed changes in the mean X-ray emission from these systems. Furthermore, these changes are expected to be most conspicuous $\approx 1$ Gyr after major star-formation events (e.g., White & Ghosh 1998; Ghosh & White 2001). Galaxy formation scenarios that favor a more recent emergence of the optically faint early-type galaxy population onto the red-sequence such as downsizing or mass-dependent merging histories (see discussion and references in § 3.1) would predict significant evolution of the LMXB emission from these systems.
A second source of evolution of the X-ray emission from optically faint early-type galaxies could in principle come from cooling of the hot X-ray-emitting gas. However, studies of optically faint early-type galaxies in the local universe have shown that the hot gas emission generally makes up a minority fraction (typically \(\approx 40\%\)) of the total X-ray emission (e.g., David et al. 2006) and is therefore less likely to be completely responsible for the observed evolution than LMXBs.

### 3.4.3 Future Work

Understanding the evolution of the X-ray properties of early-type galaxies could be greatly improved by (1) constraining better the X-ray properties of local optically faint early-type galaxies and making a census of their AGN populations, (2) performing additional investigations using other deep Chandra fields that have complementary HST coverage, and (3) conducting deeper observations using Chandra or future X-ray missions. These possibilities are discussed in more detail below.

In Figure 3.8, we showed the values of \(L_X\) and \(L_B\) for local early-type galaxies from the OS01 sample, which is the largest, uniformly-selected sample available for studying the \(L_X-L_B\) correlations of local early-type galaxies. The majority (\(\approx 75\%\)) of the isolated optically faint early-type galaxies have only X-ray upper limits, which has restricted our interpretation of the redshift evolution of these galaxies. New Chandra observations of the galaxies having only X-ray upper limits could not only improve the characterization of the \(L_X-L_B\) correlation at lower \(L_B\), but could also provide useful insight into the role of hot interstellar gas and LMXBs within the galactic field, which are presently not well constrained. Furthermore, stacking analyses of well-chosen samples of these galaxies could provide useful statistical insight into the mean X-ray properties of these galaxies and mitigate the effects of poor source statistics for individual galaxies.

Chandra stacking analyses using additional samples of early-type galaxies could effectively reduce the sizes of the errors on mean quantities and/or allow for the analyses of samples in more finely partitioned bins of redshift and optical luminosity. An important requirement for such studies is to obtain an adequate census of the underlying AGN population, which may significantly influence the stacking results. In order to remove effectively AGNs from stacked signals at \(z \approx 0.7\), relatively deep Chandra observations are necessary. Using the luminosity-dependent AGN fractions determined in § 3.3.2.2, we suggest that AGNs will provide significant contamination for Chandra exposures of \(\approx 100\) ks. Therefore, studies of distant early-type galaxies using multiwavelength data (including HST coverage) from already existing Chandra fields such as the \(\approx 2\) Ms CDF-N or the \(\approx 200\) ks All-wavelength Extended Groth Strip International Survey (AEGIS; Nandra et al. 2005; Davis et al. 2006) would improve the present situation.

Finally, deeper Chandra observations of already existing fields (most notably the CDF-N) would provide an improved census of the low-to-moderate luminosity AGN population at higher redshifts and connect the X-ray properties of these relatively passive early-type populations with those of their higher redshift progenitors (e.g., DRGs, EROs, and distant submillimeter-emitting galaxies; e.g., Alexander et al. 2005). In addition to the improvement that additional Chandra observations could provide, it is also worth noting that future X-ray missions such as XEUS...
and *Generation-X*\textsuperscript{5} should allow the first investigations of the evolution of the normal early-type galaxy X-ray luminosity function with redshift.

### 3.5 Summary

Using X-ray stacking analyses, we have investigated the X-ray evolution of 539, $z \approx 0.1–0.7$ early-type galaxies located in the E-CDF-S. These galaxies were selected using a combination of red-sequence colors and Sérsic indices as a part of the COMBO-17 and GEMS surveys (M05). We classified our original early-type galaxy sample as the “general sample” and generated an additional “faded sample,” which was corrected for the passive fading of old stellar populations. Using these samples, we analyzed separately optically luminous ($L_B \approx 10^{10–11} L_{B,\odot}$) and faint ($L_B \approx 10^{9.3–10} L_{B,\odot}$) populations, which are expected to have soft X-ray spectra dominated by hot interstellar gas and LMXBs, respectively. Our primary goal was to use stacking analyses to measure and constrain the redshift evolution of the average X-ray emission from normal early-type galaxies. To achieve this, we used a variety of techniques to identify powerful AGNs, which we removed from our stacking analyses. Our key results are as follows:

1. We detected 49 early-type galaxies in the X-ray band and classified 32 of these as AGN candidates based on their X-ray, optical, and radio properties (see §3.2.1.1 for details); the remaining 17 X-ray-detected sources had multwavelength properties consistent with normal galaxies. In addition to the 32 X-ray-detected AGN candidates, we identified 13 galaxies with AGN-like radio–to–optical flux ratios, which we characterized as potential AGNs. We found that the majority of the AGN candidates were coincident with optically luminous early-type hosts. The inferred AGN fraction for our optically luminous galaxies shows evidence for evolution with redshift in a manner consistent with the $(1+z)^3$ evolution expected from other studies of AGN evolution.

2. When stacking the X-ray counts from our normal optically luminous early-type galaxy samples, we found that the X-ray–to–optical mean luminosity ratio, $L_X/L_B$, stays roughly constant over the redshift range $z \approx 0.0–0.7$, which indicates that the X-ray-emitting gas has not significantly evolved over the last $\approx 6.3$ Gyr (i.e., since $z \approx 0.7$). Using the data available, we found that $(L_X/L_B)_{z=0.7} = [1.0 \pm 0.5]$ and $[1.7 \pm 0.8] \times (L_X/L_B)_{z=0}$ for our general and faded samples, respectively. We interpret the lack of X-ray evolution of optically luminous early-type galaxies to be due to an energy balance between the heating and cooling of the hot gas over each cooling time. When assuming that the heating is largely due to transient AGN activity, we found that mechanical feedback dominates the heating out to $z \approx 0.7$ versus radiative power, which we inferred to be very poorly coupled to the gas. Furthermore, this result suggests that the radiative and mechanical AGN power evolve differently with cosmic time.

3. For our optically faint early-type galaxy samples, we found suggestive evidence that $L_X/L_B$ increases with redshift. By $z \approx 0.5$, $L_X/L_B$ is measured to be $5.3 \pm 4.1$ and $5.6 \pm 4.1$ times larger than that measured at $z = 0$ for our general and faded samples, respectively;

\textsuperscript{5}For further information regarding the future X-ray missions *XEUS* and *Generation-X*, see http://www.rssd.esa.int/XEUS/ and http://genx.cfa.harvard.edu, respectively.
however, due to poor statistical constraints on the local relation and the undetected AGN population, we could not confidently rule out the null hypothesis. We hypothesized that evolution of the optically faint early-type galaxy X-ray emission may be due to the evolution of LMXBs in galaxies that have recently joined the red-sequence and/or the cooling of hot gas within these galaxies.
Chapter 4

The Properties and Redshift Evolution of Intermediate-Luminosity Off-Nuclear X-ray Sources in the Chandra Deep Fields

4.1 Introduction

Intermediate-luminosity X-ray objects (IXOs) in the local universe are off-nuclear X-ray sources having 0.5–8.0 keV luminosities exceeding $\sim 10^{39}$ erg s$^{-1}$ (e.g., Colbert & Ptak 2002). X-ray sources making up the high-luminosity end (i.e., $\gtrsim 2 \times 10^{39}$ erg s$^{-1}$) of the IXO population are commonly referred to as ultraluminous X-ray sources (ULXs); they are referred to as “ultraluminous” because their inferred isotropic luminosities exceed that expected for an $\approx 10 M_{\odot}$ black hole accreting at the Eddington limit. Investigations of this enigmatic population suggest that many IXOs may be intermediate-mass black holes (IMBHs) with masses exceeding $\approx 10 M_{\odot}$ (e.g., Colbert & Miller 2004; Miller et al. 2004) and/or normal high mass X-ray binaries (HMXBs) anisotropically beaming X-rays into our line-of-sight (e.g., King et al. 2001). Recent observations indicate IXOs may be a natural high-luminosity extension of the HMXB X-ray luminosity function, suggesting that these sources trace relatively young stellar populations (e.g., Gilfanov et al. 2004). Indeed, analyses of the physical and environmental properties of IXOs have shown that the number and cumulative X-ray luminosities of IXOs are correlated with star-formation rate (e.g., Kilgard et al. 2002; Swartz et al. 2004). As a consequence of this, IXOs are more commonly observed in late-type spiral and irregular galaxies than in early-type ellipticals. Furthermore, investigations of X-ray populations in early-type galaxies find that luminous ($L_X \gtrsim 2 \times 10^{39}$ erg s$^{-1}$) IXOs (i.e., ULXs) are generally absent (e.g., Irwin et al. 2003); however, exceptions have been noted (e.g., Loewenstein et al. 2005).

Recently, the fraction of galaxies in the local universe containing IXOs (as a function of X-ray luminosity) has been constrained statistically using ROSAT observations of a sample of 766 relatively nearby ($D < 66.7$ Mpc) galaxies (Ptak & Colbert 2004; hereafter PC04) from the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs et al. 1991). PC04 report that, after correcting for expected background sources, $\approx 12\%$ and $\approx 1\%$ of all local RC3 spiral and irregular galaxies have one or more IXOs with 2–10 keV luminosities $L_X > 10^{39}$ erg s$^{-1}$ and $L_X > 10^{40}$ erg s$^{-1}$, respectively. Here, 2–10 keV luminosities were estimated from the 0.2–2.4 keV flux with an assumed IXO power-law photon index of $\Gamma = 1.7$.

At increasing redshifts, it is plausibly expected that the fraction of galaxies hosting IXOs will increase as a result of the observed rise in global star-formation density with redshift (e.g., Madau et al. 1998; Ghosh & White 2001). Evidence for the global evolution of star-formation activity has also been observed as an increase in the average X-ray luminosity from normal galaxies out to $z \approx 1$ (e.g., Hornschemeier et al. 2002); IXOs likely play an important role in this evolution. Thus far, low X-ray flux levels and limited angular resolution have restricted the
study of relatively distant \((z \gtrsim 0.05; \ D \gtrsim 200 \ \text{Mpc})\) IXOs. However, deep multiwavelength extragalactic surveys that combine the optical imaging capabilities of the *Hubble Space Telescope* (HST) and the sub-arcsecond X-ray imaging of the *Chandra X-ray Observatory* (Chandra) have made the detection and classification of intermediate-redshift \((z \approx 0.05 - 0.3; \text{lookback times of} \ \approx 0.7-3.4 \ \text{Gyr})\) off-nuclear sources possible. Hornschemeier et al. (2004; hereafter H04) isolated and characterized ten off-nuclear source candidates in optically-bright field galaxies with redshifts in the range \(z = 0.04 - 0.23 \ (z_{\text{median}} \approx 0.1)\). This investigation utilized HST observations with Advanced Camera for Surveys (ACS) filters \(B_{435}, V_{606}, i_{775}, \text{and} \ z_{850}\) from the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) and deep Chandra observations coincident with these fields through the \(\approx 2 \ \text{Ms} \ Chandra \ \text{Deep Field-North (CDF-N; Alexander et al. 2003) and} \approx 1 \ \text{Ms} \ Chandra \ \text{Deep Field-South (CDF-S; Giacconi et al. 2002) surveys. H04 found that the fraction of field galaxies with detectable off-nuclear X-ray sources \(L_{\text{X, 0.5-2.0 keV}} \gtrsim 10^{38.9} \ \text{erg s}^{-1}\) at \(z \approx 0.1\) is \(36^{+24}_{-15}\), suggestively larger than that observed for galaxies in the local universe. Moreover, due to an angular-resolution bias, this “observed” fraction was only considered to be a lower limit to the true fraction, which would include off-nuclear sources with offsets smaller than the *Chandra* positional error circles. Unfortunately, a study of the dependence of this fraction upon off-nuclear source X-ray luminosity fraction was not possible due to limited source statistics, most notably for sources with \(0.5-2.0 \ \text{keV luminosities} \ L_{\text{X}} \gtrsim 10^{39.5} \ \text{erg s}^{-1}\).

In this investigation, we estimate the true fraction of intermediate-redshift field galaxies hosting off-nuclear X-ray sources as a function of \(0.5-2.0 \ \text{keV luminosity} \) and compare it with that observed for local galaxies (from PC04). We improve the source statistics available for intermediate-redshift, off-nuclear sources by combining the multiwavelength data within the \(\approx 2 \ \text{Ms} \ CDF-N \text{and} \approx 1 \ \text{Ms} \ CDF-S\) with new HST and *Chandra* observations of the Extended *Chandra* Deep Field-South (E-CDF-S; Lehmer et al. 2005a). The E-CDF-S is composed of four contiguous \(\approx 250 \ \text{ks} \ Chandra \ fields \covering \approx 0.3 \ \text{deg}^2\text{ region}, \text{which flanks the} \approx 1 \ \text{Ms} \ CDF-S\. A large fraction of the E-CDF-S \(\approx 80\%\) has been observed with HST in two ACS filters, \(V_{606}\) and \(z_{850}\), through the Galaxy Evolution from Morphology and SEDs (GEMS; Rix et al. 2004) survey. The E-CDF-S *Chandra* observations can detect \(z = 0.1\) off-nuclear sources with projected physical offsets of \(\gtrsim 2 \ \text{kpc}\) and \(0.5-2.0 \ \text{keV luminosities} \ \gtrsim 3 \times 10^{30} \ \text{erg s}^{-1}\) in the most sensitive regions. Furthermore, \(z = 0.1\) sources with physical offsets of \(\gtrsim 3 \ \text{kpc}\) and \(0.5-2.0 \ \text{keV luminosities} \ \gtrsim 3 \times 10^{40} \ \text{erg s}^{-1}\) can be detected over the entire \(\approx 0.3 \ \text{deg}^2\) E-CDF-S field.

The Galactic column densities are \(\approx 1.3 \times 10^{20} \ \text{cm}^{-2}\) for the CDF-N (Lockman 2003) and \(\approx 8.8 \times 10^{19} \ \text{cm}^{-2}\) for the CDF-S and E-CDF-S (Stark et al. 1992). All of the X-ray fluxes and luminosities quoted throughout this paper have been corrected for Galactic absorption using these column densities. Often we quote Poisson errors with values indicating 1\sigma significance levels; these are computed following Gehrels (1986). \(H_0 = 70 \ \text{km s}^{-1} \ \text{Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\) are adopted throughout this paper (Spergel et al. 2003), and the coordinates are J2000.0.

### 4.2 Off-Nuclear Source Sample Construction

#### 4.2.1 Sample Selection

As discussed above, the combination of the high spatial resolution of HST imaging and sensitive X-ray observations with *Chandra* is effective in detecting and classifying off-nuclear
Fig. 4.1: Logarithm of the X-ray-to-optical flux ratio vs. offset in units of positional error for 0.5–2.0 keV detected sources matched to optical sources with $V_{506} < 24$. Large filled squares indicate sources with $V_{506} < 21$, and the circled sources are our off-nuclear source candidates. Flux ratios were computed using point-source X-ray fluxes and integrated host-galaxy optical fluxes. The vertical dotted line indicates the location of $1.5 \times \text{Chandra}$ positional error, which was used to distinguish sources as off-nuclear (see § 4.2.1). Sources with larger $\log[f_X/f_V]$ that lie outside $1.5 \times \text{Chandra}$ positional error are generally low-significance matches and lie outside the optical extent of the matched source. The solid curve indicates the running median offset for sources within a region of size $\Delta \log[f_X/f_V] = 1.5$. The general trend of improved median positional accuracy with increasing $\log[f_X/f_V]$ is expected as the number of “point-like” AGNs contributing to the statistics continually increases.

X-ray sources out to $z \approx 0.3$. The $\approx2$ Ms CDF-N, $\approx1$ Ms CDF-S, and $\approx250$ ks E-CDF-S (hereafter CDFs) are currently the deepest extragalactic X-ray surveys conducted with Chandra (see, e.g., Brandt & Hasinger 2005 for a review), and all of these surveys have good HST coverage. These observations reach 0.5–2.0 keV sensitivity limits ranging from $1.8 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the CDF-N to $1.1 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the E-CDF-S. However, as demonstrated in § 3.4.2 of Alexander et al. (2003) and § 3.3.2 of Lehmer et al. (2005a), legitimate lower-significance X-ray sources below these quoted sensitivity limits can be identified by matching such sources to associated optically bright galaxies. We therefore searched for off-nuclear sources using both the published main Chandra catalogs of Alexander et al. (2003; CDF-N and CDF-S) and Lehmer et al. (2005a; E-CDF-S) as well as additional lower-significance X-ray sources detected in these fields by running the CIAO source-searching algorithm wavdetect (Freeman et al. 2002) at a false-positive probability threshold of $1 \times 10^{-5}$. A total of 933, 689, and 1085 X-ray sources in the CDF-N, CDF-S, and E-CDF-S, respectively, were thus used in our searching; these numbers do not take into account the overlapping regions of the CDF-S and E-CDF-S.

We searched for and classified off-nuclear X-ray source candidates in the CDFs using the following criteria:
1. An X-ray source is considered to be an off-nuclear candidate if its position is offset from the optical nucleus of an optically-bright galaxy (ACS magnitudes of $V_{606} < 21$; see below for a description of how this limit was selected) by $\geq 1.5 \times$ the radius of the Chandra positional error circle (see equations 2 and 3 of Alexander et al. 2003 and Lehmer et al. 2005a, respectively) but is still observed to lie within the optical extent of the candidate host galaxy. The radius of the positional error circle (80–90% confidence) for Chandra sources detected in the CDFs ranges from $\approx 0\,\prime\prime3–1\,\prime\prime5$ and is dependent on the Chandra point-spread function (PSF) size and the number of observed counts. Our required minimum offset of $1.5 \times$ the radius of the Chandra positional error circle was chosen empirically based on histograms showing the number of sources with X-ray-to-optical flux ratios similar to those of active galactic nuclei (AGNs) (i.e., sources with $\log[f_X/f_V] > -0.5$) versus their X-ray-to-optical positional offsets; we found that $\approx 98\%$ of AGN-like sources with $V_{606} < 24$ were matched to within $1.5 \times$ the radius of the Chandra positional error circle. For illustrative purposes, we provide Figure 4.1, which shows the logarithm of the X-ray-to-optical flux ratio ($\log[f_X/f_V]$) versus positional offset in units of the Chandra positional error for 0.5–2.0 keV detected sources with optical counterparts having $V_{606} < 24$. On the basis of our analysis, the number of $V_{606} < 21$ nuclear sources in our sample expected to have offsets larger than $1.5 \times$ the radius of the Chandra positional error circle is calculated to be $\approx 0.91^{+2.11}_{-0.75}$.

2. We required that candidate host galaxies have redshifts in the range of $0 < z \leq 0.3$. We used spectroscopic redshifts for $\approx 98\%$ of the field galaxies in the CDF-N (e.g., Barger et al. 2003; Wirth et al. 2004) and $\approx 6\%$ of the field galaxies in the CDF-S and E-CDF-S (e.g., Szokoly et al. 2004). For the remaining field galaxies in the CDF-N ($\approx 2\%$) and CDF-S and E-CDF-S ($\approx 94\%$), we used high-quality photometric redshifts from GOODS (Mobasher et al. 2004) and COMBO-17 (Wolf et al. 2004), respectively. We note that in the CDF-S and E-CDF-S, where the majority of the field galaxies have only photometric redshifts via the 17-filter photometry from COMBO-17, the redshift uncertainties are small (i.e., $\delta z/(1+z) \approx 0.01$). The selected redshift range was chosen empirically by considering the observed number of off-nuclear sources detected as a function of redshift. Furthermore, for redshifts larger than 0.3, the projected linear distance corresponding to the typical Chandra positional error ($\approx 7$ kpc) becomes unreasonably large for detecting many off-nuclear sources.

3. In an effort to minimize confusion with unrelated background X-ray sources, we further required that each off-nuclear source candidate is detected in either the 0.5–2.0 keV or 0.5–8.0 keV bands and has a 0.5–2.0 keV luminosity $\leq 10^{41}$ erg s$^{-1}$. These restrictions are based on the observed spectral and luminosity properties of local IXOs. X-ray luminosities were computed using the equation

$$ L_X = 4\pi d_L^2 f_X (1+z)^{\Gamma-2} $$

(4.1)

where $d_L$ is the luminosity distance, $f_X$ is the X-ray flux of each source, and $\Gamma$ is the X-ray photon index assuming a power-law Spectral Energy Distribution (SED). We adopt a photon index of $\Gamma = 1.8$ throughout this paper (see § 4.2.2 for justification).
The sky density of optically-bright galaxies is relatively low, and thus the probability of finding an unrelated background X-ray source within the optical extent of these galaxies is also low. In order to estimate the total number of background sources that may be contaminating our sample and to determine the optimal optical-magnitude limit down to which we search for off-nuclear sources, we followed a similar methodology to that outlined in §2 of PC04. We first chose a tentative optical magnitude limit down to which we search for off-nuclear sources. For each candidate host galaxy, we then visually estimated the galactic area within which we would consider an X-ray source to be off-nuclear. This area was approximated by defining an ellipse with a semimajor and semiminor axis and position angle for each galaxy with a circle of radius 1.5 × the radius of the Chandra positional error circle removed. Next, we calculated the average 0.5–2.0 keV sensitivity limit over the relevant area of each galaxy using empirically calculated sensitivity maps that were calibrated appropriately for sources detected by wavdetect using a false-positive probability threshold of $1 \times 10^{-5}$. We chose to use the 0.5–2.0 keV band because of its low background and correspondingly high sensitivity. The number of expected background 0.5–2.0 keV sources per galaxy was estimated using the galactic area, galaxy sensitivity limit, and best-fit number-counts relation presented in §4 of Bauer et al. (2004). Finally, the total number of expected contaminating background sources was computed by summing the contributions from each galaxy. We found that when restricting our search to galaxies with $V_{606} < 21$, the number of expected contaminating background sources in the entire survey is reasonably low (≈2.22), so we chose $V_{606} = 21$ as our optical magnitude limit. For galaxies brighter than this limit, the median (mean) number of expected background X-ray sources was $\approx 0.0029 (0.0064)$ galaxy$^{-1}$. We appropriately correct for contaminating background sources in our analyses below.

### 4.2.2 X-ray and Optical Properties of Off-Nuclear Sources and Host Galaxies

Using the criteria presented above, we identified a total of 24 off-nuclear source candidates (see Fig. 4.2); nine of these were previously detected by H04. The additional source presented in H04 that is not included here (CXOCDFS J033220.35–274555.3) was within 1.5 × the Chandra positional error and was only detected in the 0.5–1.0 keV band. All of the off-nuclear source candidates are coincident with late-type galaxies (i.e., spirals and irregulars); this is generally consistent with studies of IXOs in the local universe (see §4.1). We also note that two of the off-nuclear sources (CXOHDFN J123701.99+621122.1 and CXOHDFDN J123706.12+621711.9) are located in galaxies having discernable bars of optical emission. The X-ray properties of the off-nuclear sources are summarized in Table 4.1 and additional properties, including those of the host-galaxies, are summarized in Table 4.2; median properties of are listed in the last rows of these Tables. The median off-nuclear source is offset by $\approx 2.1 \times$ the Chandra positional error, and only two sources (CXOCDFS J033230.01–274404.0 and CXOECDFFS J033322.97–273430.7) have offsets near our required minimum offset of 1.5 × the Chandra positional error (see Fig. 4.1). CXOCDFS J033230.01–274404.0 was detected and classified as being off-nuclear in both the CDF-S and E-CDF-S data sets independently, lending additional support to its off-nuclear classification.

The off-nuclear X-ray sources span a 0.5–2.0 keV luminosity range of $8 \times 10^{38}$ erg s$^{-1}$ to $6 \times 10^{40}$ erg s$^{-1}$ and have a median luminosity of $\approx 8 \times 10^{39}$ erg s$^{-1}$. The host galaxies have a median redshift of $z \approx 0.14$, which corresponds to a lookback time of $\approx 1.8$ Gyr, and a median $V_{606}$ magnitude of 19.1. In Figure 4.3a, we show the X-ray luminosities of these 24 off-nuclear...
Table 4.1. Off-Nuclear Sources: X-ray Properties

<table>
<thead>
<tr>
<th>Source Name</th>
<th>X-ray Counts</th>
<th>0.5–2.0 keV</th>
<th>0.5–8.0 keV</th>
<th>(\Gamma)</th>
<th>(f_{0.5-2.0\text{ keV}}) (\times 10^{-16}) [cgs]</th>
<th>(f_{0.5-8.0\text{ keV}}) (\times 10^{-16}) [cgs]</th>
<th>(L_{0.5-2.0\text{ keV}}) (\text{log cgs})</th>
<th>(L_{0.5-8.0\text{ keV}}) (\text{log cgs})</th>
<th>Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXOECDFS J033122.00–273620.1</td>
<td>&lt;11.5</td>
<td>17.0(^{+5.8}_{-5.8})</td>
<td>1.8(^a)</td>
<td>&lt;3.36</td>
<td>8.37</td>
<td>&lt;40.2</td>
<td>40.6</td>
<td>E-CDF-S 02</td>
<td></td>
</tr>
<tr>
<td>CXOECDFS J033128.84–275904.8</td>
<td>10.9(^a)</td>
<td>&lt;13.4</td>
<td>1.8(^a)</td>
<td>2.78</td>
<td>&lt;5.71</td>
<td>40.8</td>
<td>&lt;41.1</td>
<td>E-CDF-S 03</td>
<td></td>
</tr>
<tr>
<td>CXOECDFS J033139.05–280221.1</td>
<td>1.5(^{+1.4}_{-1.4})</td>
<td>&lt;14.6</td>
<td>1.8(^a)</td>
<td>0.43</td>
<td>&lt;7.03</td>
<td>39.9</td>
<td>&lt;41.1</td>
<td>E-CDF-S 03</td>
<td></td>
</tr>
<tr>
<td>CXOECDFS J033143.46–275527.8</td>
<td>&lt;4.7</td>
<td>5.4(^{+2.5}_{-2.5})</td>
<td>1.8(^a)</td>
<td>&lt;1.18</td>
<td>2.26</td>
<td>&lt;39.6</td>
<td>39.9</td>
<td>E-CDF-S 03</td>
<td></td>
</tr>
<tr>
<td>CXOECDFS J033143.48–275103.0</td>
<td>10.2(^a)</td>
<td>&lt;16.3</td>
<td>1.8(^a)</td>
<td>2.76</td>
<td>&lt;7.41</td>
<td>40.8</td>
<td>&lt;41.2</td>
<td>E-CDF-S 03</td>
<td></td>
</tr>
<tr>
<td>CXOCDFS J033219.10–274445.6</td>
<td>5.0(^{+2.8}_{-2.4})</td>
<td>&lt;15.6</td>
<td>1.8(^a)</td>
<td>0.33</td>
<td>&lt;1.74</td>
<td>39.6</td>
<td>&lt;40.3</td>
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<tr>
<td>CXOCDFS J033221.91–275427.2</td>
<td>6.9(^{+3.2}_{-1.2})</td>
<td>&lt;21.5</td>
<td>1.8(^a)</td>
<td>0.46</td>
<td>&lt;2.43</td>
<td>39.6</td>
<td>&lt;40.3</td>
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<tr>
<td>CXOECDFS J033230.01–274404.0</td>
<td>87.6(^{+3.2}_{-10.1})</td>
<td>104.0(^{+12.8}_{-11.8})</td>
<td>1.9</td>
<td>6.39</td>
<td>12.28</td>
<td>40.0</td>
<td>40.2</td>
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<td></td>
</tr>
<tr>
<td>CXOECDFS J033234.73–275533.8</td>
<td>&lt;20.6</td>
<td>58.6(^{+12.9}_{-11.8})</td>
<td>1.8(^a)</td>
<td>&lt;1.48</td>
<td>7.05</td>
<td>&lt;38.7</td>
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<td></td>
</tr>
<tr>
<td>CXOECDFS J033249.26–273610.6</td>
<td>38.6(^{+7.8}_{-1.6})</td>
<td>56.7(^{+3.4}_{-1.8})</td>
<td>1.6</td>
<td>9.78</td>
<td>27.46</td>
<td>40.5</td>
<td>40.9</td>
<td>E-CDF-S 01</td>
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</tr>
<tr>
<td>CXOECDFS J033316.29–275040.7</td>
<td>22.1(^{+8.9}_{-2.1})</td>
<td>&lt;22.1</td>
<td>1.8(^a)</td>
<td>5.90</td>
<td>&lt;9.95</td>
<td>40.1</td>
<td>&lt;40.3</td>
<td>E-CDF-S 04</td>
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<tr>
<td>CXOECDFS J033322.97–273430.7</td>
<td>5.3(^{+2.8}_{-2.5})</td>
<td>&lt;15.1</td>
<td>1.8(^a)</td>
<td>1.71</td>
<td>&lt;8.17</td>
<td>39.6</td>
<td>&lt;40.3</td>
<td>E-CDF-S 01</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Indicates this \(\Gamma\) value was assigned; see § 2.2 for details.

\(^b\)Quoted median values were computed using only the sources which were detected in a given band (i.e., limits were not included).

\(^c\)Indicates mean value determined from stacking analyses (see § 2.2 for details).

Note. — All fluxes and luminosities have been corrected for Galactic absorption as discussed at the end of § 1. Col.(1) Off-nuclear X-ray source name. Col.(2) 0.5–2.0 keV source counts. Col.(3) 0.5–8.0 keV source counts. Col.(4) Effective photon index \(\Gamma\). When the number of counts is low (i.e., <30 counts in the 0.5–2.0 keV band), we set \(\Gamma = 1.8\) as per the discussion in § 2.2. Other values of \(\Gamma\) are as reported by Alexander et al. (2003; CDF-N and CDF-S) or Lehmer et al. (2005; E-CDF-S). Col.(5) 0.5–2.0 keV flux in units of \(10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\). Col.(6) 0.5–8.0 keV flux in units of \(10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\). Col.(7) Logarithm of the 0.5–2.0 keV luminosity in units of erg s\(^{-1}\). Col.(8) Logarithm of the 0.5–8.0 keV luminosity in units of erg s\(^{-1}\). Col.(9) Survey field in which each source was identified. For E-CDF-S identifications, the associated field number (i.e., 01–04) indicates the \textit{Chandra} pointing within which the source was detected (see Lehmer et al. 2005 for details). [Please see Lehmer et al. (2006) for all 24 rows of this table.]
Table 4.2. Off-Nuclear Sources: Additional Properties

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Positional Offset In Units Of</th>
<th>$V_{606}$ (mag)</th>
<th>$M_{606}$ (mag)</th>
<th>$\nu L_{\nu}$ (6000 Å) (log cgs)</th>
<th>H04 Detection?</th>
<th>Optical Knot?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXOECDFS J033122.00−273620.1</td>
<td>3.60</td>
<td>2.11</td>
<td>8.88</td>
<td>18.80</td>
<td>0.140</td>
<td>43.4</td>
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<tr>
<td>CXOECDFS J033128.84−275904.8</td>
<td>1.70</td>
<td>2.00</td>
<td>6.97</td>
<td>19.22</td>
<td>0.266</td>
<td>-21.4</td>
</tr>
<tr>
<td>CXOECDFS J033139.05−280221.1</td>
<td>2.28</td>
<td>2.25</td>
<td>8.96</td>
<td>18.24</td>
<td>0.251</td>
<td>-22.2</td>
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<td>CXOECDFS J033143.46−275527.8</td>
<td>1.71</td>
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<td>3.49</td>
<td>17.94</td>
<td>0.112</td>
<td>-20.4</td>
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<tr>
<td>CXOECDFS J033143.48−275103.0</td>
<td>2.28</td>
<td>1.91</td>
<td>9.28</td>
<td>19.57</td>
<td>0.265</td>
<td>-21.1</td>
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<tr>
<td>CXOCDFS J033219.10−274445.6</td>
<td>1.21</td>
<td>2.02</td>
<td>4.01</td>
<td>20.84</td>
<td>0.201</td>
<td>-19.0</td>
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<td>CXOCDFS J033221.91−275427.2</td>
<td>1.81</td>
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<td>5.58</td>
<td>19.82</td>
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<tr>
<td>CXOCDFS J033230.01−274404.0</td>
<td>0.91</td>
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<td>17.53</td>
<td>0.076</td>
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<td>4.71</td>
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<td>3.55</td>
<td>16.78</td>
<td>0.038</td>
<td>-19.4</td>
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<tr>
<td>CXOECDFS J033249.26−273601.0</td>
<td>3.30</td>
<td>5.03</td>
<td>6.72</td>
<td>17.90</td>
<td>0.112</td>
<td>-18.9</td>
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<tr>
<td>CXOECDFS J033316.29−275040.7</td>
<td>3.24</td>
<td>2.31</td>
<td>5.47</td>
<td>17.84</td>
<td>0.090</td>
<td>-20.4</td>
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<td>2.30</td>
<td>1.51</td>
<td>4.08</td>
<td>19.20</td>
<td>0.096</td>
<td>-18.9</td>
</tr>
</tbody>
</table>

Note. — Col.(1) Off-nuclear X-ray source name. Col.(2) X-ray positional offset from the associated optical-source nucleus in units of arcseconds. Col.(3) Same offset in previous column in units of the Chandra positional error. Col.(4) Physical offset in units of kpc. Col.(5) ACS $V_{606}$ observed magnitude of host galaxy. Col.(6) Redshift estimate of the host galaxy for each off-nuclear X-ray source. Superscripts “s” and “p” indicate spectroscopic and photometric redshifts, respectively (see § 2 for details). Col.(7) Absolute magnitude of the host galaxy ($M_{606}$) at $\lambda = 6000$ Å. Col.(8) Logarithm of the host-galaxy, rest-frame 6000 Å luminosity in units of erg s$^{-1}$. Col.(9) Indicates whether each source was previously detected by H04. Col.(10) Indicates whether an optical knot is observed to be coincident with the X-ray source position. [Please see Lehmer et al. (2006) for all 24 rows of this table.]
sources as a function of redshift. The fifteen new objects (filled symbols) presented here significantly improve the source statistics at $L_{0.5-2.0\text{ keV}} \gtrsim 10^{39.5}$ erg s$^{-1}$ and $z = 0.15-0.3$; many of these sources are from the relatively wide solid-angle E-CDF-S survey. All sources with 0.5–2.0 keV upper limits are detected in the 0.5–8.0 keV band.

We constrained the average X-ray spectral shape of our off-nuclear sources by stacking the 0.5–2.0 keV and 2–8 keV source counts and exposures. We then computed a vignetting-corrected band ratio by taking the ratio $\Phi_{2–8\text{ keV}}/\Phi_{0.5-2.0\text{ keV}}$, where $\Phi$ is defined to be the X-ray count rate in units of counts s$^{-1}$. The band ratio was converted into a mean effective photon index $\Gamma_{\text{eff}}$ using the Chandra X-ray Center’s Portable, Interactive, Multi-Mission Simulator (PIMMS). For the 24 off-nuclear X-ray sources, the mean effective photon index is $\Gamma_{\text{eff}} = 1.82^{+0.21}_{-0.17}$, a value consistent with that for IXOs observed in the local universe (e.g., Liu & Mirabel 2005 and references therein). We therefore adopted $\Gamma = 1.8$ when computing X-ray luminosities for our off-nuclear sources using equation 4.1.

Since all of our off-nuclear sources are coincident with late-type galaxies (see Fig. 4.2), we chose to restrict further comparative analyses to galaxies with late-type morphologies. We selected galaxies in the ACS-covered regions of the CDFs and required $V_{606} < 21$ in the redshift range $0 < z \leq 0.3$. At the quoted optical-magnitude limit, roughly half of the objects detected are Galactic stars; these were characterized visually as point-like sources with diffraction spikes and removed from our list of candidate field galaxies. In total, 385 objects were selected as being non-stellar extragalactic sources with $V_{606} < 21$ and $0 < z \leq 0.3$. We visually classified each galaxy as being either an elliptical (48 galaxies) or a spiral or irregular (337 galaxies). Figure 4.3b shows the estimated rest-frame 6000 Å luminosities ($\nu L_\nu [6000\text{ Å}]$) for all of the 337 spiral and irregular galaxies in our sample (small filled circles). Galaxies hosting off-nuclear sources are plotted with larger open and filled symbols (for H04 and new sources, respectively); most of these occupy the high-luminosity end of the distribution. Optical luminosities were estimated using the $V_{606}$ magnitude and applying a $K$-correction assuming an Scd spiral-galaxy optical SED (Coleman et al. 1980); this SED was chosen since it is commonly observed for star-forming galaxies. We chose to use the $V_{606}$ band to compute the 6000 Å luminosities because (1) it is available over all of the CDFs and (2) the 6000 Å continuum traces the emission from relatively old stellar populations. The $K$-corrections for the galaxies are small ($\lesssim 0.4$ mag) and have little dependence on galaxy SED choice. The median 6000 Å luminosities (6000 Å absolute magnitudes, $M_{606}$) of the intermediate-redshift field galaxies and the host galaxies of off-nuclear X-ray sources are $\nu L_\nu (6000\text{ Å}) \approx 1.9 \times 10^{43}$ erg s$^{-1}$ (−19.8) and $\approx 2.7 \times 10^{43}$ erg s$^{-1}$ (−20.2), respectively.

Ten of our 24 (41$^{+18}_{-13}$%) off-nuclear X-ray sources appear to be coincident with optical knots of emission (see column 8 of Table 4.2 and the images in Fig. 4.2). In the local universe, IXOs often appear to be located within or near star-forming regions, ranging from small (< 100 pc diameter) diffuse Hα emission complexes to giant ($\gtrsim 500$ pc diameter) H II regions (e.g., Pakull & Mirioni 2002; Liu & Bregman 2005; Ramsey et al. 2006). The optical knots in our sample have apparent diameters of $\approx 500–1000$ pc and optical luminosities of $\nu L_\nu (6000\text{ Å}) \approx 10^{40–41}$ erg s$^{-1}$. These optical properties are broadly consistent with those of giant H II regions in the local universe (e.g., Kennicutt 1984), suggesting these off-nuclear sources trace distant star-formation regions. In the GOODS fields, high-resolution ACS imaging is available over four optical bands ($B_{435}, V_{606}, i_{775},$ and $z_{850}$); for the eight off-nuclear sources with optical knots located in these ACS regions, we analyzed the colors in the immediate vicinity
Fig. 4.2: Advanced Camera for Surveys (ACS) V_606-band postage-stamp images of each off-nuclear source host galaxy. In each image, we show the off-nuclear source name (top), the survey field in which the source is detected (lower right), and the logarithm of the 0.5–2.0 keV luminosity in erg s^{-1} (lower left); a "K" is displayed above the survey field if the off-nuclear source is visually coincident with an optical knot. All sources are detected in either the 0.5–2.0 keV or 0.5–8.0 keV bands; the upper limits shown here are for sources not detected in the 0.5–2.0 keV band. For illustrative purposes, the images are not all the same size; the scale of each image can be deduced from the vertical 3″ bar located in the lower-left corner of each frame. Each off-nuclear source is marked with a circle having a radius equal to the Chandra 80–90% positional error.
Fig. 4.3: (a) X-ray luminosity and redshift of each off-nuclear source. Symbols correspond to objects detected in the CDF-N (circles), CDF-S (triangles), and E-CDF-S (squares) surveys. Filled symbols correspond to off-nuclear sources unique to this study (i.e., not previously discovered by Hornschemeier et al. 2004). Upper limits correspond to sources detected in the 0.5–8.0 keV band but not in the 0.5–2.0 keV band. (b) Rest-frame 6000 Å optical luminosity for spiral and irregular galaxies with \( V_{606} < 21 \) as a function of redshift (small filled circles). Galaxies hosting an off-nuclear source have been outlined with symbols following the convention of Figure 4.3a.
Fig. 4.4: Relative color difference between optical knot and host galaxy ($\Delta(B_{435} - V_{606})$ vs. $\Delta(V_{606} - i_{775})$; see § 4.2.2) for the eight optical knots coincident with off-nuclear X-ray sources in the GOODS regions (filled circles). The plotted error bar in the upper-left corner shows the typical errors of these measurements; the dotted lines show the expected values for the case of the optical knots having the same colors as their host galaxies. The relatively blue optical-knot colors show that these off-nuclear regions are likely populated by a younger stellar population; the source names for the two most extreme cases have been noted.

of the knots. Figure 4.4 shows the relative color difference between the optical knots and their host galaxies. These relative colors are defined as follows:

\[
\begin{align*}
\Delta(B_{435} - V_{606}) &\equiv (B_{435} - V_{606})_{\text{knot}} - (B_{435} - V_{606})_{\text{galaxy}} \\
\Delta(V_{606} - i_{775}) &\equiv (V_{606} - i_{775})_{\text{knot}} - (V_{606} - i_{775})_{\text{galaxy}}.
\end{align*}
\]

(4.2)

We find that the optical knots are relatively blue compared to their host galaxies (i.e., mean values of $\Delta(B_{435} - V_{606}) = -0.22 \pm 0.14$ and $\Delta(V_{606} - i_{775}) = -0.13 \pm 0.18$ are observed). We stacked the 0.5–2.0 keV and 2–8 keV counts from our off-nuclear sources with and without optical knots to see if we could distinguish between the mean effective photon indices ($\Gamma_{\text{eff}}$; see text above) of these two populations. We found that the average spectral shapes of these two populations are statistically consistent (i.e., $\Gamma_{\text{eff}} = 1.90^{+0.26}_{-0.21}$ and $1.70^{+0.41}_{-0.28}$, for sources with and without optical knots, respectively).

We also investigated the optical colors of the host galaxies to see if the off-nuclear sources are found in more actively star-forming galaxies. We utilized $B$- and $V$-band magnitudes from ground-based observations of the CDF-N with the Subaru 8.2 m telescope (Capak et al. 2004), and of the CDF-S and E-CDF-S with the Wide Field Imager of the MPG/ESO telescope at La Silla (see § 2 of Giavalisco et al. 2004); small corrections for the differing bandpasses were applied to the CDF-S and E-CDF-S magnitudes to match those in the CDF-N. Optical emission lines produced by star-forming galaxies can influence the observed broad-band fluxes. At the
Fig. 4.5: Optical $B-V$ color vs. $V_{606}$ magnitude for $V_{606} < 21$, $z < 0.3$ field galaxies in the CDFs (small filled circles). Open symbols indicate galaxies hosting off-nuclear X-ray sources with (squares) and without (circles) optical knots. The horizontal lines indicate mean $B-V$ values for field galaxies (solid line), galaxies hosting off-nuclear sources (dot-dashed line), and galaxies hosting off-nuclear sources with (dashed line) and without (dotted line) optical knots. The inset plot shows the optical colors (i.e., Johnson $U-B$ vs. $V$) for local galaxies from the RC3 catalog (gray filled circles). The six sources highlighted by open triangles are galaxies hosting IXOs coincident with luminous optical knots, and the horizontal lines represent the mean $U-B$ values for RC3 galaxies (solid line) and the subset of RC3 IXO-hosting galaxies with optical knots (dashed line). Note that for both samples, the optical knots are preferentially located in relatively blue, star-forming galaxies.
median redshift of our off-nuclear source sample ($z = 0.14$), the strong nebular emission line due to [O II] $\lambda 3727$ is located in the $B$-band and the redder emission lines from the [O III] $\lambda\lambda 4959, 5007$ doublet and H$\beta$ $\lambda 4861$ are located in the $V$-band. In Figure 4.5, we show the $B-V$ colors vs. $V_{606}$-band magnitudes for our 337 spiral and irregular galaxies in the CDFs. Field galaxies hosting off-nuclear sources have been outlined with open squares and circles, which distinguish between sources with and without optical knots, respectively. The mean $B-V$ optical colors have been plotted for the galaxies (solid line), galaxies hosting off-nuclear sources (dot-dashed line), and galaxies hosting off-nuclear sources with (dashed line) and without (dotted line) optical knots. The typical galaxy hosting an off-nuclear X-ray source shows somewhat bluer optical colors than typical galaxies in the field. We utilized the two-sample Kolmogorov-Smirnov (K-S) test on the unbinned $B-V$ samples of field galaxies and galaxies hosting off-nuclear sources, and repeated the test to compare the $B-V$ sample of field galaxies with off-nuclear sources with and without optical-knot counterparts. We found that, at the $\approx 89\%$ confidence level (i.e., K-S probability $\approx 0.11$), the $B-V$ colors of galaxies hosting off-nuclear sources are statistically different from typical field galaxies in the CDFs. Furthermore, the colors of galaxies hosting off-nuclear sources with optical knots are statistically different from those of typical field galaxies at the $\approx 96\%$ confidence level, but galaxies hosting off-nuclear sources without optical knots have colors statistically consistent with those of typical field galaxies. These tests suggest that off-nuclear sources are indeed preferentially located in galaxies undergoing intense star formation; the optical knots directly trace star-forming complexes in such galaxies. For comparison, we plotted the distribution of Johnson $U-B$ colors versus $V$-band magnitude for RC3 galaxies (inset to Fig. 4.5) and highlighted six local galaxies (NGC 1566, NGC 1672, NGC 3623, NGC 4088, NGC 4303, and NGC 4490) observed to host IXOs coincident with distinct, luminous optical knots from Liu & Bregman (2005). These galaxies appear to be notably bluer than typical RC3 galaxies, and using the K-S test, we find that the colors of these galaxy samples are statistically different at the $\approx 96\%$ confidence level. Locally, the $U$- and $B$-band magnitudes sample the strong emission features expected in the $B$- and $V$-bands, respectively, at $z = 0.14$.

4.3 Analysis and Results

A primary goal of this investigation is to determine whether the “true” luminosity-dependent fraction of galaxies containing off-nuclear X-ray sources ($f_T$) evolves with cosmic time (see § 4.1). Below, we describe our procedure for computing this fraction for our intermediate-redshift galaxy sample and a matched comparison sample of local galaxies from PC04. We assess observational constraints on the X-ray luminosity detection limit and angular resolution for both our sample and that of PC04. To this end, we first describe the computation of the luminosity-dependent “observed” fraction of galaxies hosting off-nuclear sources ($f_O$); this takes into account the spatially varying sensitivity of the Chandra observations. We then estimate the true fraction ($f_T$) by calculating correction factors to $f_O$, which account for (1) the number of off-nuclear sources we expect to miss due to angular-resolution limitations (i.e., the number of off-nuclear sources with offsets smaller than the resolution limit) and (2) the multiplicity of these sources within host galaxies (i.e., the expected number of off-nuclear sources within a galaxy having at least one off-nuclear source).
4.3.1 The Observed Fraction ($f_O$)

To compute the observed fraction of intermediate-redshift galaxies hosting off-nuclear X-ray sources, we followed a procedure similar to that outlined in § 2 of PC04. For each of our 337 spiral and irregular galaxies, we used the 0.5–2.0 keV sensitivity maps described in § 4.2.1 and corresponding redshift information to compute an X-ray luminosity limit above which we could detect an off-nuclear source. All luminosities were calculated using equation 4.1, adopting $\Gamma = 1.8$. In Figure 4.6a, we show the number of galaxies with X-ray coverage sensitive enough to detect an off-nuclear source with $L_X \approx 10^{38.9}$ erg s$^{-1}$ (i.e., the leftmost bin of Fig. 4.6a), and there are 337 galaxies with coverage sensitive enough to detect an off-nuclear source with $L_X \approx 10^{41}$ erg s$^{-1}$ (i.e., the rightmost bin of Fig. 4.6a). Figure 4.6b shows the number of galaxies in each $L_X$ bin of Figure 4.6a observed to host an off-nuclear source of $L_X$ or greater. In Figure 4.6b, the number of galaxies included in a given $L_X$ bin versus its neighboring lower-luminosity $L_X$ bin is affected by both the addition of galaxies hosting off-nuclear sources with less sensitive X-ray coverage and the subtraction of galaxies hosting off-nuclear sources that fall below $L_X$. In order to aid in the understanding of this progression, we have created Figures 4.6c and 4.6d, which show the number of added and subtracted galaxies (in ascending order from $L_X \approx 10^{38.9}$ erg s$^{-1}$ to $L_X \approx 10^{41}$ erg s$^{-1}$), respectively. For example, six galaxies in the first $L_X$ bin of Figure 4.6a that host off-nuclear sources with $L_X \gtrsim 10^{38.9}$ erg s$^{-1}$ are added to the first $L_X \approx 10^{38.9}$ erg s$^{-1}$ bin of Figure 4.6b. In the next higher $L_X$ bin (i.e., $L_X \approx 10^{39.3}$ erg s$^{-1}$), two new galaxies hosting off-nuclear sources with $L_X \gtrsim 10^{39.3}$ erg s$^{-1}$ are added to the appropriate $L_X$ bin of Figure 4.6b, and two galaxies with off-nuclear source luminosities $< 10^{39.3}$ erg s$^{-1}$ are subtracted from the same bin. Thus the total number of galaxies with off-nuclear sources of $L_X \gtrsim 10^{39.3}$ erg s$^{-1}$ remains at six.

In order to calculate the observed fraction of intermediate-redshift galaxies hosting off-nuclear sources ($f_O$), we divide the histogram entries of Figure 4.6b, with the estimated number of background sources subtracted (see § 4.2.1), by those of Figure 4.6a; the observed fraction is presented in Figure 4.7 as a dashed line with shaded 1σ error envelope (computed following Gehrels 1986). The dashed line terminates for $L_X \gtrsim 10^{40.7}$ erg s$^{-1}$ due to the fact that there are no off-nuclear sources in our sample with luminosities exceeding $10^{40.7}$ erg s$^{-1}$; the shaded region therefore represents the 3σ upper limit to $f_O$ for $L_X \gtrsim 10^{40.7}$ erg s$^{-1}$. To make comparisons between the observed fraction of our intermediate-redshift sample and that of the local sample of PC04, we matched the optical-luminosity distribution of the PC04 spiral and irregular galaxies (i.e., Hubble type $\geq 0$) to that of our 337 spiral and irregular galaxies. At the median redshift ($z = 0.14$) of our off-nuclear X-ray source sample, the $V_{606} < 21$ requirement on the inclusion of galaxies in our analyses equates to requiring the rest-frame optical luminosity of a particular galaxy to be $\nu L_{\nu}(6000 \, \text{Å}) \gtrsim 10^{42.6}$ erg s$^{-1}$ ($M_{606} \lesssim -18.1$; see Fig. 4.3b). We created a matched PC04 subsample by applying the same optical luminosity cut to the original PC04 spiral and irregular sample. In total, 329 spiral and irregular galaxies were selected for comparison from the original PC04 sample of 766 galaxies. Figure 4.8 shows the $\nu L_{\nu}(6000 \, \text{Å})$ luminosity distributions of galaxies for both our sample (solid histogram) and the matched subsample of PC04 (dotted histogram). The two luminosity distributions span roughly the same $\nu L_{\nu}(6000 \, \text{Å})$ range and have similar overall shapes; a K-S test indicates that these two distributions are statistically consistent for $\nu L_{\nu}(6000 \, \text{Å}) \gtrsim 10^{42.6}$ erg s$^{-1}$ (i.e., K-S probability $\approx 0.6$).
Fig. 4.6: (a) Number of galaxies in the Chandra deep fields in which we could detect an off-nuclear source of 0.5–2.0 keV luminosity $L_X$. The highest $L_X$ bin contains all 337 spiral and irregular galaxies in our sample. (b) Number of galaxies in each $L_X$ bin of panel (a) containing an off-nuclear source with an X-ray luminosity of $L_X$ or greater. (c) Number of galaxies gained in each $L_X$ bin of panel (b) progressing from the lowest $L_X$ bin to the highest. (d) Number of galaxies dropping out of each $L_X$ bin of panel (b) progressing from the lowest $L_X$ bin to the highest.
Fig. 4.7: Observed fraction of galaxies in the Chandra deep fields hosting an off-nuclear source with a 0.5–2.0 keV luminosity of $L_X$ or greater (dashed line). The shaded area shows the 1σ confidence region, computed using the methods outlined in Gehrels (1986). The dashed line terminates for $L_X \gtrsim 10^{40.7}$ erg s$^{-1}$ due to the lack of off-nuclear sources with luminosities in this regime; the shaded region here represents the 3σ upper limit. The solid points with 1σ error bars and 3σ upper limits represent the observed fraction for the matched PC04 subsample of local galaxies.

PC04 subsample and the procedure described above, we recomputed the relevant observed fraction of local galaxies hosting IXOs ($f_{O,PC04}$); this is shown in Figure 4.7 as filled circles with 1σ error bars and 3σ upper limits.

4.3.2 The True Fraction ($f_T$)

As noted above, the angular resolution of Chandra, while superb, is limited to the classification of off-nuclear sources at intermediate-redshifts that are offset by more than $1.5 \times$ the Chandra positional error from the optical position of the galactic nucleus. Furthermore, the classification of IXOs in the PC04 sample is also limited to X-ray sources offset by $\gtrsim 10''$ (Colbert & Ptak 2002). Therefore, the observed fractions for both our sample and the matched PC04 subsample can only be considered to be lower limits on the true fractions of galaxies hosting off-nuclear sources, and therefore direct comparison between these two samples is not meaningful. To address this problem, we have computed the relevant scaling between the observed and true fractions (for both our sample and the matched PC04 subsample) through simulations using a sample of local IXO-hosting galaxies observed with Chandra; we describe these simulations below.

We calculated the distribution of projected physical offsets of 65 IXOs from 29 Chandra-observed local ($D \lesssim 50$ Mpc) galaxies (compiled by Liu & Mirabel 2005; see references therein). Observations of IXOs in local galaxies with Chandra should be statistically complete for sources with offsets $\gtrsim 0.1$ kpc, assuming a positional accuracy of $\approx 0''.5$ and a maximal galactic distance
Fig. 4.8: Normalized optical-luminosity distributions for field galaxies in this survey (solid histogram) and a matched sample of galaxies in the local universe adapted from the PC04 sample (dotted histogram). To construct the matched sample, we adjusted the original PC04 galaxy sample to include only galaxies with luminosities $\nu L_\nu(6000 \text{ Å}) > 10^{42.6}$ erg s$^{-1}$; this is equivalent to requiring $V_{606} < 21$ for these galaxies if they were placed at $z = 0.14$.

of $\approx 50$ Mpc. The normalized distribution of offsets for the 65 IXOs used here is shown in Figure 4.9 (solid histogram). Similar distributions were calculated using subsets of these IXOs with 0.5–2.0 keV luminosities $> 10^{39.5}$ erg s$^{-1}$; no strong luminosity dependence was observed in the shape of these curves. The overall offset distribution shown in Figure 4.9 indicates that IXOs are often located relatively close to their host-galaxy nucleus, which is considerably different from the scenario where IXOs are distributed throughout galaxies with constant density (dotted curve). This observed distribution is likely due to the high circumnuclear star-formation activity commonly found in normal and starburst galaxies (e.g., Kennicutt 1998) and is consistent with the IXO offset distribution noted by Swartz et al. (2004). The median physical offset for the 65 Chandra-observed local IXOs is $\approx 3$ kpc (vertical dashed line) and the expected resolution for CDF sources at the median redshift ($z = 0.14$) of our off-nuclear source sample is $\approx 2.6$ kpc (vertical dot-dashed line); to first order, this suggests that our observed off-nuclear sources only make up $\sim 50\%$ of the physical offset distribution, and we are plausibly missing about half of the off-nuclear sources.

Next, we computed the fraction of galaxies in which an X-ray source of a given linear offset would be classified as "off-nuclear" for galaxies in both our intermediate-redshift galaxy sample and the matched PC04 subsample. The relevant fractions for each sample are shown as solid curves in the top panels of Figure 4.10; dotted curves show the case where there is no resolution limitation. These offset-dependent fractions are constrained by both the projected physical resolution (the observed rise in the fraction near small offsets) and the projected optical size of the galaxies (the observed decline in the fraction at larger offsets). The angular resolution was taken to be $1.5 \times$ the Chandra positional error for our galaxy sample and was fixed at
Fig. 4.9: Projected physical offset distribution function of Chandra-observed local IXOs (solid histogram). The dashed vertical line represents the median offset for the IXOs used to create the offset distribution function. The dot-dashed vertical line indicates the approximate resolution of Chandra at $z=0.14$, the median redshift of our intermediate-redshift, off-nuclear X-ray source sample. The dotted curve shows the expected distribution of offsets for a constant-density galactic distribution of off-nuclear X-ray sources.

$10''$ for the matched PC04 subsample. The angular size of each galaxy was assumed to be the apparent optical semimajor axis (see § 4.2.1) and $0.5 \times$ the RC3 major-axis diameter ($D_{25}$) for our sample and the matched PC04 subsample, respectively. The solid curves presented in the top panels of Figure 4.10 for each sample are significantly different in the small-offset regime, showing that our sample is more heavily affected by angular-resolution limitations than the matched PC04 subsample. We simulated the expected observable offset distribution of each galaxy sample by convolving the local offset distribution presented in Figure 4.9 (solid histogram) with the detectable fraction curves (top panels of Fig. 4.10; solid curves); these are displayed as solid histograms in the bottom panels of Figure 4.10. For comparison, we have shown the actual observed offset distributions of off-nuclear sources in our sample and the matched PC04 subsample (dashed histograms in the bottom panels of Fig. 4.10, respectively). By inspection, we find that the observed and simulated distributions are consistent.

In order to estimate the number of off-nuclear sources that were missed due to instrumental-resolution limitations, we simulated the expected distributions of offsets for off-nuclear sources in each galaxy sample for the case where there is no resolution limitation. This was done by convolving the local offset distribution function (solid histogram in Fig. 4.9) with the dotted curves in the top panels of Figure 4.10. These resulting distribution functions, normalized by the simulated observed distribution functions (solid histograms in the bottom panels of Fig. 4.10), are presented as dotted histograms in the bottom panels of Figure 4.10. These calculations suggest that 62.1% and 35.0% of the off-nuclear sources would remain unclassified as “off-nuclear” for our intermediate-redshift sample and the matched PC04 subsample, respectively.
Fig. 4.10: (top panels) Fraction of galaxies in which an off-nuclear source could have been detected at a given offset for our data (top-left panel) and for IXOs in the PC04 sample assuming a galaxy size of $0.5 \times$ the RC3 major-axis diameter, $D_{25}$ (top-right panel). Solid lines correspond to the actual resolution of the observations, and dotted lines correspond to the case where there is no resolution limit. (bottom panels) The solid and dotted histograms show the expected distributions of off-nuclear sources given the respective resolution constraints in the top panels and the local Chandra-observed IXO distribution (i.e., Fig. 4.9); the left and right panels correspond to our data and the PC04 data, respectively. For comparison, the actual measured distributions have been plotted (dashed histograms).
In the simple case where we would expect $\approx 1$ off-nuclear source per galaxy, we could simply rescale the observed fractions by a constant scaling factor to obtain the true fractions; we define this scaling factor as $\alpha_s$, which is 2.64 and 1.54 for our off-nuclear source sample and the matched PC04 subsample, respectively. However, observations of IXOs in the local universe, show that, on average, there is more than one IXO per IXO-hosting galaxy (e.g., Colbert & Ptak 2002). Since we observe only one IXO per IXO-hosting galaxy for our intermediate-redshift sample, a simple constant scaling of the observed fraction to obtain the true fraction is not appropriate. Hereafter, we refer to the mean number of observed IXOs per IXO-hosting galaxy as the “multiplicity” factor ($m$), which varies with IXO luminosity; using the Liu & Mirabel (2005) sample of IXOs, we have estimated the “true” luminosity-dependent multiplicity factor ($m_T$). We find that $m_T$ has a value of $\approx 2.1$ and $\approx 1.0$ IXOs per IXO-hosting galaxy for 0.5–2.0 keV luminosities of $L_X \gtrsim 10^{38.9} \text{ erg s}^{-1}$ and $L_X \gtrsim 10^{40} \text{ erg s}^{-1}$, respectively; for comparison, the corresponding observed PC04 multiplicity factor ($m_O, PC04$) has a value of $\approx 1.5$ and $\approx 1.0$ IXOs per IXO-hosting galaxy, respectively. Using the scaling factor $\alpha_s$, the observed multiplicity factor $m_O$, and the true multiplicity factor $m_T$, we converted the observed fraction $f_O$ to the true fraction $f_T$ following

$$f_T = \alpha_s \frac{m_O}{m_T} f_O. \quad (4.3)$$

The luminosity-dependent scaling factors (for our intermediate-redshift sample and the matched PC04 subsample), $\alpha_s m_O/m_T$, which scale $f_O$ to obtain $f_T$, are shown in Figure 4.11a; the resulting true fractions with $1\sigma$ errors (computed following Gehrels 1986) are shown in Figure 4.11b. Fractions measured for our sample ($f_{T, \text{int-z}}$) are shown as the dashed line surrounded by the shaded error envelope, and the matched PC04 fractions ($f_{T, \text{PC04}}$) are plotted as filled black circles with $1\sigma$ error bars and $3\sigma$ upper limits. The dotted curve shows the fraction of our galaxies with an X-ray source of 0.5–2.0 keV luminosity $L_X$ or greater (including both nuclear and off-nuclear sources). This curve was obtained by matching galaxies in our sample to X-ray sources from the main and supplementary Chandra catalogs of the CDFs using a matching criterion of less than one semimajor axis length. Matched sources may include a variety of X-ray sources such as AGNs, luminous nuclear starbursts, and off-nuclear X-ray sources with both small and large offsets (i.e., offsets both less than and greater than $1.5 \times$ the radius of the Chandra positional error circle). This curve represents an upper limit to the true fraction of galaxies hosting off-nuclear sources, and we note that our calculated true fraction is below this limit. Furthermore, based on this curve, we calculate that off-nuclear sources are found in $\approx 75\%$ and $\approx 40\%$ of the $z \leq 0.3$ galaxies detected in the 0.5–2.0 keV bandpass with coverage sensitive enough to detect sources of $L_X > 10^{39} \text{ erg s}^{-1}$ and $L_X > 10^{40.7} \text{ erg s}^{-1}$, respectively. For further comparison, we have plotted the fraction of galaxies with an X-ray source of 0.5–2.0 keV luminosity $L_X$ or greater but with a luminosity upper bound of $10^{41.5} \text{ erg s}^{-1}$ (dot-dashed curve); this upper limit was adopted to include mostly galaxies powered by star-forming processes. Again, our estimate of $f_{T, \text{int-z}}$ appears to be reasonable in comparison to this detection fraction.

Figure 4.11b shows suggestively that the off-nuclear source frequency for field galaxies rises with redshift. We estimate that $\approx 31^{+20}_{-16}\%$ of intermediate-redshift spiral and irregular galaxies with $\nu L_{\nu} (6000 \text{ Å}) \gtrsim 10^{42.6} \text{ erg s}^{-1}$ host off-nuclear sources with $L_X \gtrsim 10^{39} \text{ erg s}^{-1}$ versus $\approx 16^{+5}_{-4}\%$ in the local universe (errors are $1\sigma$). As mentioned in § 4.1, one may plausibly expect that the frequency of off-nuclear sources would rise as a function of redshift due to
Fig. 4.11: (a) Scaling factor \( (\alpha m_\odot/m_T) \) applied to the observed fraction \( (f_0; \text{Fig. 4.7}) \) to obtain the true fraction \( (f_T; \text{Fig. 4.11b}) \) for our sample (dashed line) and the matched PC04 subsample (filled circles). These factors were obtained using the methods discussed in §4.3. (b) True fraction \( (f_T) \) of galaxies in the Chandra deep fields hosting an off-nuclear source with a 0.5–2.0 keV luminosity of \( L_X \) or greater (dashed line with shaded 1σ confidence region). The filled circles with error bars represent the equivalent true fraction for the matched PC04 subsample of local galaxies. In the region where \( L_X \gtrsim 10^{40.7} \) erg s\(^{-1}\), there are no off-nuclear sources in either sample (i.e., the intermediate-redshift or PC04 subsample), and therefore we have plotted 3σ upper limits. The dotted line shows the total X-ray detection fraction for the 337 spiral and irregular galaxies in our sample, which provides an upper limit to the true fraction of galaxies hosting off-nuclear sources. Similarly, the dot-dashed line shows the total X-ray detection fraction for galaxies in our sample but with a luminosity upper-bound of \( 10^{41.5} \) erg s\(^{-1}\).
Fig. 4.12: Ratios of off-nuclear source incidence fractions of our intermediate-redshift galaxy sample and the matched local PC04 subsample \((f_{\text{int}}/f_{\text{PC04}}; \text{filled circles with } 1\sigma \text{ error bars})\); the median ratio is shown as a horizontal dashed line. The shaded region shows the expected increase in the fraction at \(z \approx 0.05 - 0.3\) due to the global increase in star-formation density at these redshifts and the dotted horizontal line shows the expected ratio for the case of no evolution.

the observed global increase in star-formation density, which is measured to be \(\approx 1.2 - 3.0\) times higher at \(z \approx 0.05 - 0.3\) than it is in the local universe (e.g., Pérez-González et al. 2005; Schiminovich et al. 2005). Furthermore, since the number of IXOs in spiral and irregular galaxies is observed to increase linearly with star-formation rate (e.g., Swartz et al. 2004), it is reasonable to expect that the frequency of off-nuclear source incidence for field galaxies would roughly scale linearly with the star-formation density. In Figure 4.12 we show the ratio of off-nuclear source incidence fraction for our intermediate-redshift sample and the matched PC04 subsample (i.e., \(f_{\text{int}}/f_{\text{PC04}}\)) as filled circles with 1\(\sigma\) error bars. Errors on this quantity were computed using the error propagation methodology outlined in § 1.7.3 of Lyons (1991). The fraction ratio for off-nuclear sources with \(L_X \gtrsim 10^{39}\) erg s\(^{-1}\) is \(\approx 1.9^{+1.4}_{-1.1}\), this is elevated from unity at the \(\approx 80\%\) confidence level. The dashed horizontal line shows the median fraction ratio. The shaded region shows the expected ratios for the case where the off-nuclear source incidence fraction scales with star-formation density; the dotted horizontal line shows the case where there is no evolution. We note that these computed ratios appear to be broadly consistent with the expected scaling of off-nuclear source incidence with redshift due to the increased global star-formation density.

4.3.3 Consistency Check

We have performed consistency checks on the results above by degrading the resolution of the PC04 subsample to match that of our intermediate-redshift sample and doing similar analyses to those above. This was achieved by calculating the median physical resolution of
our intermediate-redshift galaxy sample (i.e., the median physical offset corresponding to 1.5 \times the \textit{Chandra} positional error) and generating a subsample of PC04 IXOs with offsets greater than this median offset. Using this subset of IXOs, we calculated the resolution-normalized observed fraction \( f_{\text{O,PC04}}^{\text{norm}} \). In comparison to the intermediate-redshift observed fraction \( f_{\text{O,int-z}} \), we find results consistent with those presented above. For example, we find that for sources with \( L_X \gtrsim 10^{39} \text{ erg s}^{-1} \), the resolution-normalized fraction ratio \( f_{\text{O,int-z}}/f_{\text{O,PC04}}^{\text{norm}} \approx 2.7^{+2.0}_{-1.3} \).

4.4 Summary and Future Work

We have presented the largest sample to date of intermediate-redshift (\( z \lesssim 0.3; \ z_{\text{median}} = 0.14 \)), off-nuclear X-ray sources hosted in optically-bright (\( V_{606} < 21 \)) field galaxies in the \textit{Chandra} deep fields. These off-nuclear X-ray sources were found to have similar X-ray spectral shapes and optical environments to IXOs in the local universe and are exclusively found to be coincident with late-type spiral and irregular galaxies. Using this sample, we found that the fraction of spiral and irregular galaxies hosting an off-nuclear X-ray source as a function of X-ray luminosity is suggestively higher at intermediate-redshifts; for off-nuclear sources with 0.5–2.0 keV luminosities \( \gtrsim 10^{39} \text{ erg s}^{-1} \), this fraction is measured to be \( \approx 31^{+20}_{-16}\% \) for intermediate-redshift field galaxies versus \( \approx 16^{+5}_{-4}\% \) for local galaxies (see Fig. 4.11). In computing this fraction, we have accounted for the facts that (1) the X-ray sensitivity limit varies spatially over these fields and (2) the angular resolution of \textit{Chandra} limits the classification of off-nuclear sources.

Although the angular-resolution limitations of \textit{Chandra} would remain, the current situation could still be improved by future \textit{Chandra} observations over these fields. We note that only \( \approx 20 \) of the spiral and irregular galaxies (\( \approx 6\% \)) in our sample have X-ray coverage sensitive enough to detect off-nuclear sources of 0.5–2.0 keV luminosity \( L_X \approx 10^{39} \text{ erg s}^{-1} \) (see Fig. 4.6a), a regime where \( \approx 31\% \) of the galaxies are expected to host off-nuclear X-ray sources; these sources are dispersed over all of the CDFs. Deeper \textit{Chandra} observations over the CDFs would not only improve the source statistics in this regime but would also improve the positional accuracies of brighter sources too. In the \( \approx 2 \text{ Ms CDF-N} \), sources near the aim point that have sufficient photon counts have positional accuracies of \( \approx 0''3 \). At this resolution, field galaxies at \( z = 0.1 \) and \( z = 0.3 \) with off-nuclear sources offset by \( \gtrsim 0.8 \text{ kpc} \) and \( \gtrsim 2.0 \text{ kpc} \), respectively, could be identified, and more stringent constraints could be placed on the statistical properties of these sources. Such observations covering the presently-classified off-nuclear sources would improve our knowledge of their spectral and variability properties. Furthermore, we note that other programs that utilize deep \textit{Chandra} exposures in combination with \textit{HST} observations (e.g., the Extended Groth Strip; Nandra et al. 2005) could build upon the present intermediate-redshift, off-nuclear source sample and improve the statistical constraints on their frequency in field galaxies.

Presently, \textit{Chandra} is the only observatory capable of classifying and characterizing intermediate-redshift, off-nuclear X-ray sources. X-ray missions of the relatively near future (e.g., \textit{Constellation-X} and \textit{XEUS})\(^1\) will be capable of placing tighter constraints on the spectral and temporal properties of these sources. However, our understanding of the statistical properties of this population and its evolution with cosmic time can only be substantially improved.

\(^1\)For further information regarding \textit{Constellation-X} and \textit{XEUS}, visit http://constellation.gsfc.nasa.gov/ and http://www.rssd.esa.int/XEUS/, respectively.
by future X-ray missions with subarcsecond imaging capabilities such as *Generation-X*,\(^2\) which is planned to have imaging (≈0′′1 resolution) and sensitivity capabilities which greatly supersede those already available through *Chandra*. At \(z \approx 2\), an off-nuclear source with an X-ray luminosity of \(\approx 10^{39}\) erg s\(^{-1}\) and a physical offset of \(\gtrsim 0.8\) kpc could be detected and classified in a moderate-length *Generation-X* exposure. Somewhat more luminous off-nuclear sources (\(L_X \gtrsim 10^{39.5}\) erg s\(^{-1}\)) with offsets as small as \(\approx 0.6\) kpc could be isolated using *Generation-X* at \(z \approx 4\).

Our results suggest that the majority of the X-ray activity from normal and starburst galaxies can be explained by the presence of luminous (\(L_X \gtrsim 10^{39}\) erg s\(^{-1}\)) off-nuclear X-ray sources (see, e.g., Fig. 4.11b); this is consistent with studies of X-ray point-source populations in local galaxies (e.g., Colbert et al. 2004). As discussed in § 4.1, the global star formation rate increases with redshift, and the mean X-ray luminosity for field galaxies also rises as a function of redshift. If this increase in the X-ray emission is indeed mainly due to the presence of many luminous off-nuclear sources associated with star formation, then we would expect that for distant, energetic star-forming galaxies such as Lyman break galaxies (LBGs), there may be significant crowding of luminous off-nuclear sources. The mean 0.5–2.0 keV luminosity for LBGs at \(z \approx 3\) is \(\approx 10^{41}\) erg s\(^{-1}\) (e.g., Lehmer et al. 2005b). If we assume that the majority of this emission is coming from luminous off-nuclear sources, then we may expect that the average LBG would have \(\approx 5–10\) off-nuclear sources each with \(L_X \approx 10^{39.9}\) erg s\(^{-1}\). When adopting an angular radius of \(\approx 0.3\) for a typical \(z \approx 3\) LBG (e.g., Ferguson et al. 2004), we find that the corresponding off-nuclear source density and mean angular separation would be \(\approx 20–40\) arcsec\(^{-2}\) and \(\approx 0.′′16–0.′′22\), respectively. Future missions such as *Generation-X* would suffer from non-negligible source confusion from the multiple off-nuclear sources within these distant LBGs.

Chapter 5

The X-ray Evolution of Late-Type Galaxies in the

Chandra Deep Fields

5.1 Introduction

Investigations focusing on global changes in star-formation activity and stellar-mass build-up in field galaxies have provided significant insight into the physical evolution of galaxies and their constituent stellar populations. It has now been well-established that the global star-formation rate density has declined by roughly an order of magnitude since \( z \approx 1–1.5 \) (e.g., Lilly et al. 1996; Madau et al. 1996; Steidel et al. 1999; Hopkins et al. 2004; Pérez-González et al. 2005; Schiminovich et al. 2005; Colbert et al. 2006). Recent investigations into the details of this evolution have shown that the star-formation history of a given galaxy depends strongly on its stellar mass (e.g., Cowie et al. 1996; Juneau et al. 2005; Bundy et al. 2006; Noeske et al. 2007a,b; Zheng et al. 2007); the peak star-formation epoch for the most massive galaxies occurred earlier in cosmic history than it did for galaxies with lower masses.

X-ray studies of normal late-type galaxies (i.e., those that are not dominated by luminous active galactic nuclei [AGNs]) have shown that X-ray emission provides a useful, relatively-unobscured measure of star-formation activity (e.g., Bauer et al. 2002a; Cohen 2003; Ranalli et al. 2003; Colbert et al. 2004; Grimm et al. 2003; Gilfanov et al. 2004a; Persic et al. 2004; Persic & Rephaeli 2007; however, see Barger et al. 2007). In normal galaxies, X-ray emission originates from X-ray binaries, supernovae, supernova remnants, hot (\( \approx 0.2–1 \) keV) interstellar gas, and O-stars (see, e.g., Fabbiano 1989, 2006 for reviews). Sensitive Chandra and XMM-Newton studies of local late-type galaxies have shown that high-mass X-ray binaries (HMXBs) and low-mass X-ray binaries (LMXBs) typically dominate the total non-nuclear X-ray power output (e.g., Zezas et al. 2002; Bauer et al. 2003; Soria & Wu 2003; Swartz et al. 2003; Jenkins et al. 2005; Kilgard et al. 2005; however, see, e.g., Doane et al. 2004). Observations indicate that the integrated X-ray emission from HMXB and LMXB populations trace galaxy star-formation rate (SFR) and stellar mass (\( M_\star \)), respectively. For example, using Chandra observations of 32 local galaxies, Colbert et al. (2004) found that the summed 0.3–8 keV non-nuclear point-source emission from a given galaxy (\( L_{\text{XP}} \)) can be approximated as \( L_{\text{XP}} \approx \alpha M_\star + \beta \text{SFR} \), where \( \alpha \) and \( \beta \) are constants. Therefore, galaxies having relatively high star-formation rates per unit mass (specific star-formation rates, SSFRs) generally have dominant X-ray point-source contributions from HMXBs (e.g., late-type star-forming galaxies), while those with relatively low SSFRs have point-source emission primarily from LMXBs (e.g., massive early-type galaxies).

If the X-ray binary populations are similarly dominating the normal-galaxy X-ray power output over a significant fraction of cosmic time, then there should be a rapid increase in the globally-averaged X-ray luminosity of normal star-forming galaxies with cosmic look-back time in response to the increasing global star-formation rate density (e.g., Ghosh & White 2001). In this scenario, HMXBs trace the immediate star-formation rate of a galaxy and LMXBs trace its...
star-formation history with a lag of a few Gyr. With the advent of deep Chandra and XMM-Newton surveys (see, e.g., Brandt & Hasinger 2005 for a review), it has become possible to study the X-ray properties of normal galaxies out to $z \geq 1$ and $z \approx 0.3$, respectively (see, e.g., Hornschemeier et al. 2000, 2002, 2003; Brandt et al. 2001; Alexander et al. 2002b; Nandra et al. 2002; Georgakakis et al. 2003, 2007; Norman et al. 2004; Georgantopoulos et al. 2005; Laird et al. 2005, 2006; Lehmer et al. 2005a, 2006, 2007; Kim et al. 2006; Tzanavaris et al. 2006; Rosa-Gonzalez et al. 2007). Initial studies have shown suggestive evidence for a global increase in the X-ray activity from normal galaxies with redshift. For example, using a $\approx 1$ Ms exposure of a subregion within the Chandra Deep Field-North, Hornschemeier et al. (2002) tentatively observed a factor of $\approx 2–3$ increase in $L_X/L_B$ from $z = 0$ to 1.4 for $L_B^*$ galaxies. However, the details of this evolution, including dependences on the physical properties of galaxies (e.g., optical morphology, optical luminosity, stellar mass, environment, and star-formation rate), remained unexplored.

In this paper, we study how the X-ray properties of late-type field galaxies evolve as a function of optical luminosity, stellar mass, and star-formation rate over the redshift range of $z = 0–1.4$. We construct late-type galaxy samples located in two of the most well-studied extragalactic X-ray survey fields, the $\approx 2$ Ms Chandra Deep Field-North (CDF-N; Alexander et al. 2003) and the Extended Chandra Deep Field-South (E-CDF-S), which is composed of the central $\approx 1$ Ms Chandra Deep Field-South (CDF-S; Giacconi et al. 2002) and four flanking $\approx 250$ ks Chandra observations (Lehmer et al. 2005b). These Chandra Deep Fields (hereafter CDFs) reach 0.5–2 keV detection limits of $\approx 2.5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ in the most sensitive regions and $\approx 3 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ over the majority of the CDFs; these levels are sufficient to detect moderately-powerful X-ray sources ($L_{0.5-2\text{ keV}} \approx 10^{41.5}$ erg s$^{-1}$) at $z = 1.4$ and $z = 0.6$, respectively. Therefore, the CDFs comprise an unprecedented data set for effectively studying the X-ray emission and evolution of cosmologically distant normal galaxies with minimal contamination from powerful AGNs.

The Galactic column densities are $1.3 \times 10^{20}$ cm$^{-2}$ for the CDF-N (Lockman 2004) and $8.8 \times 10^{19}$ cm$^{-2}$ for the E-CDF-S (Stark et al. 1992). All of the X-ray fluxes and luminosities quoted throughout this paper have been corrected for Galactic absorption. Unless stated otherwise, we quote optical magnitudes based upon the Vega magnitude system. In the X-ray band, we make use three standard bandpasses: 0.5–2 keV (soft band [SB]), 2–8 keV (hard band [HB]), 0.5–8 keV (full band [FB]). Throughout this paper, we make estimates of stellar mass and star-formation rates using a Kroupa (2001) initial mass function (IMF); when making comparisons between these estimates and those quoted in other studies, we have adjusted all values to correspond to our adopted IMF. $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ are adopted throughout this paper (e.g., Spergel et al. 2003), which imply a look-back time of 7.7 Gyr at $z = 1$.

5.2 Late-Type Galaxy Sample Selection

We constructed an optically selected sample of late-type galaxies within the CDFs to use for our subsequent analyses. We restricted our galaxy selection to regions of the CDFs where Hubble Space Telescope (HST) observations were available to allow the best possible morphological classifications. The HST observations in the CDFs have been carried out via the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004a) and Galaxy Evolution from
Morphology and SEDs (GEMS; Rix et al. 2004; Caldwell et al. 2005) programs; these surveys cover \( \approx 90\% \) of the Chandra-observed regions of the CDFs with the Advanced Camera for Surveys (ACS). In the GOODS and GEMS regions, photometry was available in four \( (B_{435}, V_{606}, i_{775}, \text{and} \ z_{850}) \) and two \( (V_{606} \text{and} \ z_{850}) \) ACS passbands, respectively.

5.2.1 Galaxy Selection Footprint

We began building our sample by selecting all galaxies having \( z_{850} < 23 \). This initial selection criterion was motivated by (1) the availability of deep \( z_{850} \) band imaging over all of the CDFs, (2) the fact that the \( z_{850} \) emission probes rest-frame optical light redward of the 4000 Å break for galaxies at \( z \lesssim 1 \), which constitutes a large majority of the galaxies with \( z_{850} < 23 \), and (3) the availability of reliable redshifts (both spectroscopic and photometric) for CDF galaxies with \( z_{850} < 23 \) (see details below). In order to isolate most effectively distant X-ray–detected AGNs, we further restricted our sample to include only galaxies that were located in the most sensitive areas of the CDFs where the Chandra point-spread function (PSF) was small. We therefore chose to include sources having optical positions that were within \( 6.0 \) of at least one of the six Chandra aimpoints in the CDFs\(^1\); the corresponding total areal footprint is \( \approx 0.18 \) deg\(^2\). Furthermore, we removed obvious Galactic stars that were identified via optical spectral properties or the presence of obvious diffraction spikes in the \( z_{850} \) band images. Under these restrictions, we found 6809 galaxies.

5.2.2 Redshifts

We cross-correlated our initial sample of 6809 galaxies with the available spectroscopic and photometric redshift catalogs (e.g., Barger et al. 2003a; Le Fèvre et al. 2004; Szokoly et al. 2004; Wirth et al. 2004; Wolf et al. 2004; Mobasher et al. 2004; Mignoli et al. 2005; Vanzella et al. 2005, 2006; Silverman et al. 2007a). All galaxies that did not have spectroscopic redshifts were located in the E-CDF-S where highly-accurate (median \( \delta z/1+z \approx 0.02 \) for galaxies with \( z_{850} < 23 \)) photometric redshifts were available via COMBO-17 (Classifying Objects by Medium-Band Observations in 17 Filters; Wolf et al. 2004). In total, 6575 (\( \approx 97\% \)) of our sources had either spectroscopic or photometric redshifts. Visual inspection of the 234 galaxies in the E-CDF-S without redshifts indicated that these sources were mainly faint galaxies near bright stars, as well as a handful of sources that were subgalactic features within relatively nearby galaxies. Whenever possible, we adopted spectroscopic redshifts as the most accurate redshifts for our galaxies. Using the redshift information, we filtered our sample to include only sources with \( z < 1.4 \) in the \( \approx 2 \) Ms CDF-N, \( z < 1 \) in the \( \approx 1 \) Ms CDF-S, and \( z < 0.6 \) in the \( \approx 250 \) ks regions of the E-CDF-S; these redshift limits represent the largest distances at which we would expect to identify moderately luminous \( (L_{0.5-2 \ \text{keV}} \gtrsim 10^{41.5} \ \text{erg} \ \text{s}^{-1}) \) AGNs effectively in each respective field. In total, 3271 galaxies remained after filtering our sample based on redshift properties. We used spectroscopic redshifts for 1231 (\( \approx 38\% \)) galaxies and photometric redshifts for the remaining 2043 (\( \approx 62\% \)) galaxies.

\(^1\)For the CDF aimpoints, see Tables 1 and A1 of Alexander et al. (2003) for the \( \approx 2 \) Ms CDF-N and \( \approx 1 \) Ms CDF-S, respectively, as well as Table 1 of Lehmer et al. (2005b) for the \( \approx 250 \) ks E-CDF-S.
Fig. 5.1: Rest-frame $U-V$ color versus $M_V$ (color-magnitude diagrams) for the 3271 $z \approx 0$–1.4 galaxies with $z_{5850} < 23$ that were within 6.0 of at least one CDF aimpoint. Each panel shows the color-magnitude relation for a given redshift bin (annotated in the upper left-hand corners). The dashed line in each panel represents the estimated division between red (large $U-V$ values) and blue (small $U-V$ values) galaxy populations, which was estimated using equation 5.1 and the median redshift of the galaxies in each bin. The inset histogram in each panel shows the distribution of rest-frame $U-V$. The vertical dotted line in each inset plot indicates the estimated division between red and blue galaxy populations, which was calculated using equation 5.1 and the median redshift and $M_V$ for galaxies in each redshift bin (see § 5.2.3).
5.2.3 Rest-Frame Color and Morphological Selection

The optical-color distribution for field galaxies has been shown to be bimodal, separating “red” and “blue” galaxy populations (e.g., Strateva et al. 2001; Hogg et al. 2002a; Blanton et al. 2003; Baldry et al. 2004). Studies of the color-magnitude relation for distant galaxy populations have shown that this color bimodality is observed to persist out to at least $z \approx 1–1.5$ (see, e.g., Bell et al. 2004a; Faber et al. 2005; Labbe et al. 2007). We therefore filtered our galaxy sample to include only sources that had blue rest-frame optical colors, as expected for late-type galaxies with young stellar populations. We utilized the $U, B, V, R, I, z'$, and $HK'$ photometric catalogs of Capak et al. (2004) in the CDF-N and the 17-bandpass photometry available through COMBO-17 in the E-CDF-S to estimate rest-frame $U - V$ colors and absolute $U, B, and V$ band magnitudes ($M_U, M_B,$ and $M_V$, respectively) for each of the 3271 galaxies in our sample. For each galaxy, we constructed a rest-frame spectral energy distribution (SED) using our photometric data. For these SEDs, the rest-frame $U, B,$ and $V$ filters are well-sampled at all relevant redshifts, with the exception of sources at $z \gtrsim 0.7$ where the wavelength range of the available data lies blueward of the rest-frame V band. For sources at $z \gtrsim 0.7$, we linearly extrapolated our SED to cover the V filter. We convolved these SEDs with Johnson $U, B,$ and $V$ filter curves and computed rest-frame absolute magnitudes for each respective filter following equation 5 of Hogg et al. (2002b). For sources in the E-CDF-S, these computed absolute magnitudes are consistent with those presented by Wolf et al. (2004).

In Figure 5.1 (small filled circles), we present rest-frame $U - V$ colors versus $M_V$ for our galaxies in six redshift ranges. For clarity, we also show inset histograms giving the distribution of rest-frame $U - V$ colors for each redshift interval. We utilized the rest-frame $U - V$ color to divide roughly populations of red and blue galaxies. Use of the rest-frame $U - V$ color was motivated by Bell et al. (2004a), who note that the $U$ and $V$ bandpass pair straddles the 4000 Å break, which is particularly sensitive to age and metallicity variations of galactic stellar populations. The dashed lines in Figure 5.1 show the empirically-determined redshift-dependent color divisions that separate blue and red galaxy populations; we calculated these divisions following § 5 of Bell et al. (2004a):

$$(U - V)_{\text{rest}} = 1.15 - 0.31z - 0.08(M_V + 20.7).$$  (5.1)

Galaxies having rest-frame $U - V$ less than the values provided by equation 5.1 are often referred to as “blue-cloud” galaxies, while those with rest-frame $U - V$ greater than the division are called “red-sequence” galaxies. The redshift-dependence of the blue-cloud/red-sequence galaxy division is thought to be largely due to the evolution of the mean age and dust content of the blue-cloud population, with a smaller contribution from changes in metallicity. In total, we found 2475 blue-cloud galaxies and 796 red-sequence galaxies.

Generally, the blue-cloud and red-sequence populations are composed of late-type and early-type galaxies, respectively (see, e.g., Bell et al. 2004b, 2005; McIntosh et al. 2005). In support of this point, we have created Figure 5.2, which shows the fraction of E-CDF-S galaxies in our sample having blue-cloud (dashed histogram) and red-sequence (dotted histogram) colors as a function of galaxy Sérsic index $n$. We utilized the Häussler et al. (2007) Sérsic indices, which were computed using the GEMS $z_{850}$ images and the GALFIT (Peng et al. 2002) two-dimensional light-profile fitting program. Light-profile studies of large galaxy samples have found empirically that a Sérsic cutoff of $n = 2.5$ can roughly discriminate between late-type and
Fig. 5.2: Fraction of our initial sample of \( z = 0-1.4 \) galaxies in the E-CDF-S having blue-cloud (dashed histogram) and red-sequence (dotted histogram) colors as a function of the Sérsic index \( (n) \). The solid vertical line indicates \( n = 2.5 \), the empirical cutoff between late-type \( (n \leq 2.5) \) and early-type galaxies \( (n > 2.5) \).

early-type galaxies (e.g., Blanton et al. 2003; Shen et al. 2003; Hogg et al. 2004). Galaxies with \( n \leq 2.5 \) are generally late-type galaxies, while the majority of galaxies with \( n > 2.5 \) are early-types (vertical line in Fig. 5.2). Figure 5.2 shows that there is reasonable agreement between late-type and early-type galaxy populations selected using rest-frame optical colors and Sérsic indices.

We refined further our division between late-type and early-type morphologies by visually inspecting the \( z_{850} \)-band images of our entire sample of 3271 galaxies to see if there were obvious cases where the rest-frame optical colors provided an inaccurate morphological classification. For example, late-type galaxies that are highly inclined to our line of sight may experience significant reddening of the young (and blue) disk population and will have red-sequence colors. Also, due to variations of the stellar populations in galaxies of a given morphological class, there will be some scatter in rest-frame \( U-V \) color near the division of the red-sequence and blue-cloud regimes. This will lead to a number of “green” galaxies that are misclassified morphologically when the classification is based solely on rest-frame color. Based on our visual inspection, we found 71 obvious early-type galaxies with blue-cloud colors, and 140 obvious late-type galaxies with red-sequence colors; we reclassified these sources as late-type and early-type galaxies, respectively. In Figure 5.3, we show \( z_{850} \)-band postage-stamp images of ten obvious early-type galaxies with blue-cloud colors (top panels), as well as ten obvious late-type galaxies with red-sequence colors (bottom panels). After reclassifying these objects, we were
left with 2544 late-type galaxies and 727 early-type galaxies with $z = 0–1.4$. Since we were interested in studying the properties of the late-type galaxy populations, we hereafter refer to our sample of 2544 late-type galaxies as our main sample, which we use in subsequent analyses.

5.3 Physical Properties and Redshift Evolution of Late-Type Galaxies

The primary goal of this study is to investigate the X-ray evolution of normal (i.e., non-AGN) late-type galaxies and to determine how this evolution depends upon three intrinsic physical properties: optical luminosity, stellar mass, and star-formation rate. Below, we describe how we
estimated each of these physical properties for the galaxies in our main sample. We note that the populations of late-type galaxies that we are investigating here have been selected via their intrinsic physical properties, which may have changed significantly from the observed epoch to the present day. For example, it is expected that a significant fraction of the late-type galaxies in our main sample will evolve into early-type galaxies via mergers or passive stellar evolution (e.g., Bell et al. 2007). Ideally, we would like to study the evolution of the X-ray properties of late-type galaxies while controlling for such changes in the physical nature of each galaxy. However, since the details of this evolution are highly complex and not well understood for a given galaxy, such a task is beyond the scope of this paper. We therefore investigate the X-ray evolution of normal late-type galaxy populations in relation to their observed physical properties.

5.3.1 Optical Luminosity

In order to study late-type galaxy samples selected using an observable quantity, we made use of the $B$-band luminosity ($L_B$). In § 5.2.3, we computed absolute $B$-band magnitudes $M_B$ for galaxies in our main sample using photometrically-derived SEDs. The $B$-band emission from a given late-type galaxy will be significantly influenced by large populations of old ($\gtrsim 100$ Myr) stars (measured by the stellar mass) as well as the younger and less-numerous massive stars that reside in star-forming regions (measured by the star-formation rate). In Figure 5.4a, we show $L_B$ (expressed in solar units; $L_{B,\odot} = 5.2 \times 10^{32} \text{ erg s}^{-1}$) versus redshift for galaxies in our main sample. The redshift-dependent selection limit of $L_B$ for our sample is set by our $z_{850} < 23$ criterion, and at $z = 0.5$ ($z = 1.4$) this limit corresponds to roughly $L_B \approx 3 \times 10^9 L_{B,\odot}$ ($L_B \approx 4 \times 10^{10} L_{B,\odot}$).

5.3.2 Stellar Mass

As discussed in § 5.1, the X-ray emission from LMXB populations is proportional to galaxy stellar mass. It is therefore useful to select late-type galaxies via their stellar masses as a means for estimating the LMXB contribution to their X-ray emission. To estimate the stellar mass ($M_*$) of each of our galaxies, we exploited the tight correlation between rest-frame optical color and stellar mass-to-light ratio (e.g., Bell & de Jong 2001; Bell et al. 2003; Kauffmann et al. 2003a; see also, Borch et al. 2006). For this calculation, we used a combination of rest-frame $B-V$ colors and rest-frame $K$-band luminosities. $K$-band luminosities were computed by fitting all available optical/near-IR photometric data to a grid of 69 synthetic spectra generated by the PÉGASE stellar population synthesis code (Fioc & Rocca-Volmerange 1997). These templates assume a single formation epoch with an exponentially decaying star-formation history (time constant $\tau = 1$ Gyr) and a Kroupa et al. (1993) IMF; the template grid spans ages of 1 Myr to 15 Gyr. When performing spectral fits, we supplemented the optical/near-IR photometry used in § 5.2.3, which was available for all sources in our main sample, with additional near-IR photometry from (1) $J$ and $K_s$ imaging through the ESO Imaging Survey (Olsen et al. 2006) and (2) Spitzer IRAC imaging (3.6, 4.5, 5.8, and 8.0$\mu$m; Fazio et al. 2004) through the GOODS (Dickinson et al., in preparation) and SWIRE (Lonsdale et al. 2003) surveys. Using a matching radius of 2$''$, we found 2206 ($\approx 87\%$) of our 2544 late-type galaxies had at least one near-IR match. For each galaxy in our main sample, we convolved the best-fit SED with the $K$-band filter function to approximate the rest-frame $K$-band luminosity, $L_K$. We adopted the prescription
Fig. 5.4: Rest-frame $B$-band luminosity $L_B$ (a), stellar mass $M_*$ (b), and star-formation rate SFR (c) versus redshift for sources in our main sample. In Figure 5.4c, we have included only SFRs for the 880 late-type galaxies in our main sample that have 24$\mu$m counterparts (see § 5.3.3 for details); the dashed curve indicates roughly the SFR detection limit for sources without 24$\mu$m counterparts. X-ray–detected normal galaxies and AGNs have been indicated with open circles and diamonds, respectively. The thick gray rectangles indicate regions where galaxy populations were selected for X-ray stacking (see §§ 5.4.2 and 5.5.1). For each galaxy, $M_*$ and SFR were computed following equations 5.2 and 5.3, respectively.
outlined in Appendix 2 of Bell et al. (2003) to estimate $M_\star$ using rest-frame $B-V$ color and $K$-band luminosity:

$$\log M_\star / M_\odot = \log L_K / L_{K,\odot} + 0.135 (B-V) - 0.306. \tag{5.2}$$

The numerical constants in equation 5.2 were supplied by Table 7 of Bell et al. (2003) and are appropriate for our choice of $B-V$ color and $L_K$; the normalization has been adjusted by $-0.1$ dex to account for our adopted Kroupa (2001) IMF (see § 5.1). We compared our stellar-mass estimates with those computed by Borch et al. (2006) for 1766 ($\approx 69\%$ of our main sample) galaxies in the COMBO-17 survey and find excellent agreement between methods, with an overall scatter of $\approx 0.2$ dex.

In Figure 5.4b, we show $M_\star$ versus redshift for our sample of late-type galaxies. We note that our stellar-mass estimates are broadly limited by the $z_{850} < 23$ criterion used in our sample selection. At $z = 0.5$ ($z = 1.4$) our samples are representative for late-type galaxies with $M_\star \gtrsim 10^9 M_\odot$ ($M_\star \gtrsim 10^{10} M_\odot$).

### 5.3.3 Star-Formation Rates

Since the X-ray emission from normal late-type galaxies is known to be strongly correlated with SFR, it is of particular interest to understand how changes in SFR have contributed to the X-ray evolution of the normal late-type galaxy population. To calculate SFRs for the galaxies in our main sample, we utilized estimates of both the ultraviolet luminosities ($L_{UV}$) originating from young stars and the infrared luminosities (8–1000 µm; $L_{IR}$) from dust that obscures UV light in star-forming regions (see, e.g., Kennicutt 1998 for a review). The former quantity was computed following $L_{UV} = 3.3 \nu l_\nu(2800 \text{ Å})$, where $l_\nu(2800 \text{ Å})$ is the rest-frame 2800 Å monochromatic luminosity (see § 3.2 of Bell et al. 2005). $l_\nu(2800 \text{ Å})$ was approximated using the optical SEDs discussed in § 5.2.3. The latter quantity ($L_{IR}$) was computed using observed-frame 24 µm flux densities (i.e., 24 µm/$1+z$) from observations with the MIPS (Rieke et al. 2004) camera onboard the Spitzer Space Telescope.

Over the CDFs, deep 24 µm observations were available for the GOODS fields ($f_{24\mu m, \text{lim}} \approx 30 \mu$Jy, 6σ).\(^2\) For the remaining area (covering the outer regions of the E-CDF-S), shallower 24 µm observations ($f_{24\mu m, \text{lim}} \approx 120 \mu$Jy) were available through SWIRE. We matched the positions of the 2544 late-type galaxies in our main sample with those from the available 24 µm source catalogs, requiring that the HST and Spitzer centroids be offset by no more than 1″. We found successful matches for 880 ($\approx 35\%$) of our late-type galaxies. For these sources, we converted 24 µm flux densities to $L_{IR}$ following the methods outlined in Papovich & Bell (2002). Briefly, we utilized the entire grid of 64 infrared SEDs provided by Dale et al. (2001) to estimate the mean conversion factor $\eta(z)$, which transforms observed-frame 24 µm luminosity $\nu l_\nu(24\mu m/1+z)$ to $L_{IR}$ as a function of redshift [i.e., $L_{IR} = \eta(z) \nu l_\nu(24\mu m/1+z)$]. The mean conversion factor spans the tight range of $\eta = 8.6–11.6$ over the redshift range $z = 0–1$, and it covers a larger range $\eta = 5–24$ at $z = 1–1.4$. We note that different choices of infrared SEDs yield similar results at $z \lesssim 1$, but become significantly discrepant at $z \gtrsim 1$ (see, e.g., Fig. 2 of Papovich & Bell 2002).

\(^2\)Available at http://ssc.spitzer.caltech.edu/legacy/goodshistory.html.
Using our estimates of $L_{\text{UV}}$ and $L_{\text{IR}}$, we calculated star-formation rates for galaxies in our sample using the following equation:

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 9.8 \times 10^{-11}(L_{\text{IR}} + L_{\text{UV}}),$$

where $L_{\text{IR}}$ and $L_{\text{UV}}$ are expressed in units of the solar bolometric luminosity ($L_\odot = 3.9 \times 10^{33}$ erg s$^{-1}$). Equation 5.3 was adopted from § 3.2 of Bell et al. (2005) and was derived using PÉGASE stellar-population models, which assumed a 100 Myr old population with constant SFR and a Kroupa (2001) IMF (see Bell 2003 for further details). In Figure 5.4c, we show the distribution of SFRs for the 880 galaxies in our main sample that had 24μm counterparts. We note that for sources in our main sample that were within the GOODS regions, the infrared detection fraction drops from $\approx 100\%$ for galaxies with $z_{850} = 20 \pm 0.2$ to $\approx 20\%$ for galaxies with $z_{850} = 22.8 \pm 0.2$. This demonstrates that our SFR completeness is limited primarily by the 24μm sensitivity limit and that our sample of $z_{850} < 23$ late-type galaxies is highly representative of galaxy populations above the apparent redshift-dependent SFR limit shown in Figure 5.4c (dashed curve). At $z = 0.5$ ($z = 1.4$), this limit corresponds to SFR $\approx 1 M_\odot \text{ yr}^{-1}$ (SFR $\approx 30 M_\odot \text{ yr}^{-1}$).

As a consistency check on our UV-plus-infrared SFR estimates SFR(UV+IR), we calculated radio-derived SFRs using 1.4 GHz observations, SFR(1.4 GHz), following equation 7 of Schmitt et al. (2006), which we adjusted to be consistent with our adopted Kroupa (2001) IMF. We matched sources in our main sample to 1.4 GHz catalogs, which were derived from observations using the VLA in the CDF-N ($\approx 30 \mu$Jy; Richards et al. 1998) and the ATCA in the E-CDF-S ($\approx 60 \mu$Jy; Afonso et al. 2006; Rovilos et al. 2007). Using a matching radius of 1″5, we found a total of 42 radio sources coincident with our late-type galaxies. We found that 37 ($\approx 88\%$) of the radio-detected sources had 24μm counterparts, allowing for reasonable comparison between derived SFRs. For these sources we found reasonable agreement between SFRs derived from UV-plus-infrared and radio measurements [SFR(1.4 GHz)/SFR(UV+IR) = 1.3 ± 0.9]. A large number of late-type galaxies (760 sources) in our main sample were detected in the 24μm observations that were not detected at 1.4 GHz. These sources had SFR(1.4 GHz) upper limits that were consistent with that expected from estimates of SFR(UV+IR).

5.4 Analysis

5.4.1 X-ray–Detected Late-Type Galaxies

We utilized the multiwavelength observations in the CDFs to obtain a census of the active galaxies in our main sample. We began by matching the optical positions of our galaxies to the X-ray positions of point sources in the CDF catalogs of Alexander et al. (2003)$^3$ for the $\approx 2$ Ms CDF-N and $\approx 1$ Ms CDF-S and Lehmer et al. (2005b)$^4$ for the $\approx 250$ ks E-CDF-S. For a successful match, we required that the optical and X-ray centroids be displaced by no more than 1.5 times the radius of the Chandra positional error circles (80%–90% confidence), which

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3 See http://www.astro.psu.edu/users/niel/hdf/hdf-chandra.html for the relevant source catalogs and data products for the $\approx 2$ Ms CDF-N and $\approx 1$ Ms CDF-S.

4 See http://www.astro.psu.edu/users/niel/ecdfs/ecdfs-chandra.html for the relevant source catalogs and data products for the $\approx 250$ ks E-CDF-S.
are provided in each respective catalog. We note that for a small number of the galaxies in our sample at $z \lesssim 0.3$, moderately luminous off-nuclear X-ray sources (e.g., ultraluminous X-ray sources [ULXs]) that are intrinsically related to the galaxies may lie outside of our adopted matching radius; we utilized the off-nuclear X-ray source catalog of Lehmer et al. (2006) to identify such galaxies and assign X-ray properties (see details below).

The Chandra source catalogs were generated using wavdetect (Freeman et al. 2002) with false-positive probability thresholds of $1 \times 10^{-7}$ and $1 \times 10^{-6}$ for the Alexander et al. (2003) and Lehmer et al. (2005b) point-source catalogs, respectively. However, as demonstrated in § 3.4.2 of Alexander et al. (2003) and § 3.3.2 of Lehmer et al. (2005b), legitimate lower significance X-ray sources, detected by running wavdetect at a false-positive probability threshold of $1 \times 10^{-5}$, can be isolated by matching with relatively bright optical sources; therefore, when matching our late-type galaxies to X-ray-detected sources, we utilized this technique. The sky surface density for all 2544 late-type galaxies in our main sample ranges from $\approx 23000 \text{ deg}^{-2}$ in the CDF-N to $\approx 8800 \text{ deg}^{-2}$ in the $\approx 250 \text{ ks E-CDF-S}$. The large difference between these source densities is primarily due to differences in applied redshift cuts (see § 5.2.2). Given the fact that the positional uncertainties are generally small ($\lesssim 1''5$) for sources within $6'0$ of the Chandra aim points, as is the case for sources in our main sample, the corresponding estimated number of spurious matches is small. We estimate that when using wavdetect with a false-positive probability threshold of $1 \times 10^{-5}$, we expect $\approx 1.8$ spurious matches. When including the off-nuclear sources from Lehmer et al. (2006), we expect an additional $\approx 0.5$ false sources; this brings our total spurious matching estimate to $\approx 2.3$ sources for our main sample.

Using the matching criteria above, we find that 216 late-type galaxies are detected in at least one of the 0.5–2 keV, 2–8 keV, or 0.5–8 keV bandpasses. Out of these 216 galaxies, 12 are known off-nuclear X-ray sources from Lehmer et al. (2006). Since only one off-nuclear source is detected for each host galaxy, we assume that the off-nuclear point-source dominates the total X-ray emission from each host galaxy. We therefore adopted the X-ray properties presented in Table 1 of Lehmer et al. (2006) for each off-nuclear host galaxy.

The unprecedented depths of the CDFs allow for the individual X-ray detection of luminous normal galaxies over the entire redshift range of our main sample ($z = 0–1.4$); however, the majority of the X-ray–detected sources in even the most-sensitive regions of the CDFs will be distant ($z \gtrsim 0.5$) AGNs (e.g., Bauer et al. 2004), which we want to separate from our normal late-type galaxy sample. We identified AGN candidates using three primary criteria, which utilize (1) X-ray hardness to identify luminous obscured sources, (2) X-ray–to–optical flux ratios to identify additional relatively-unobscured AGNs, and (3) the X-ray–SFR correlation to identify additional lower-luminosity AGNs that are significantly influencing the total X-ray emission. As a final check on our AGN identifications we utilized optical spectroscopic information to identify sources with obvious AGN signatures (see criterion 4 below). In the sections below we provide details of each criteria.

1. X-ray Hardness.—One unique signature of obscured ($N_{\text{HI}} \gtrsim 10^{22} \text{ cm}^{-2}$) AGN activity is a hard X-ray spectrum. For normal galaxies, the collective emission from X-ray binaries dominates the total 0.5–8 keV power output. On average, these sources have observed power-law X-ray SEDs with spectral slopes of $\Gamma \approx 1.5–1.7$ for LMXBs (e.g., Church & Balucinska-Church 2001; Irwin et al. 2003) and $\Gamma \approx 1–2$ for HMXBs and ULXs (e.g., Sasaki et al. 2003; Liu & Mirabel 2005; Liu et al. 2006). To identify obscured AGNs in our sample effectively, we flagged
Fig. 5.5: Count-rate ratio in the 2–8 keV to 0.5–2 keV bandpasses ($\Phi_{2-8\text{ keV}}/\Phi_{0.5-2\text{ keV}}$) versus the logarithm of the 0.5–8 keV flux ($\log f_{0.5-8\text{ keV}}$) for X-ray–detected sources in our main sample. Off-nuclear X-ray sources catalogued by Lehmer et al. (2006) have been highlighted with open squares. The shaded region represents sources with effective photon indices $\Gamma_{\text{eff}} < \sim 1$; we classified these sources as AGN candidates (see § 5.4, criterion 1). For reference, we have plotted lines corresponding to $\Gamma_{\text{eff}} = 0.5$, 1, and 2 (dashed lines).

Sources having effective photon indices of $\Gamma_{\text{eff}} < \sim 1$ as AGN candidates. We determined $\Gamma_{\text{eff}}$ using the 2–8 keV to 0.5–2 keV hardness ratio $\Phi_{2-8\text{ keV}}/\Phi_{0.5-2\text{ keV}}$, where $\Phi$ is the count rate for each bandpass. A few sources have only 0.5–8 keV detections. Since these sources were not detected in the 0.5–2 keV bandpass, our most sensitive bandpass, there must be a significant contribution from the 2–8 keV bandpass such that $\Phi_{2-8\text{ keV}}/\Phi_{0.5-2\text{ keV}} > \sim 1$ ($\Gamma_{\text{eff}} > \sim 0.9$). We therefore classified these sources as AGN candidates. In Figure 5.5, we show the $\Phi_{2-8\text{ keV}}/\Phi_{0.5-2\text{ keV}}$ hardness ratio versus the logarithm of the 0.5–8 keV flux $\log f_{0.5-8\text{ keV}}$ for the X-ray–detected sources in our main sample. The shaded area highlights the region corresponding to $\Gamma_{\text{eff}} < \sim 1$. We note that one of our off-nuclear X-ray source candidates (open squares) would satisfy this criterion; however, due to its off-nuclear classification, we do not classify it as an AGN candidate. Using criterion 1, we identified a total of 70 obscured AGN candidates.

2. X-ray–to–Optical Flux Ratio.—Detailed analyses of the X-ray spectra of luminous AGNs in the $\approx 1$ Ms CDF-S show that the intrinsic AGN photon index is relatively steep, $\langle \Gamma \rangle = 1.75 \pm 0.02$ (e.g., Tozzi et al. 2006). Therefore, luminous AGNs having column densities of $N_H \lesssim 10^{22}$ cm$^{-2}$ will often have effective photon indices of $\Gamma_{\text{eff}} > 1$ and would not have been classified as potential AGNs by criterion 1. In order to identify luminous AGNs with $N_H \lesssim 10^{22}$ cm$^{-2}$, we utilized the X-ray–to–optical flux ratio ($f_{0.5-8\text{ keV}}/f_R$) as a discriminator of AGN activity (e.g., Maccacaro et al. 1988; Hornschemeier et al. 2000; Bauer et al. 2004). We identified sources with $\log (f_{0.5-8\text{ keV}}/f_R) > -1$ (see § 4.1.1 of Bauer et al. 2004 for justification) as unobscured AGN candidates. In Figure 5.6, we show the $R$-band magnitude versus $\log f_{0.5-8\text{ keV}}$ for sources in our main sample; the shaded area shows the region where
Fig. 5.6: R-band magnitude versus $\log f_{0.5-8\text{ keV}}$ for X-ray–detected sources in our main sample. Open circles represent sources that were classified as AGN candidates by criterion 1 (see § 5.4.1 and Fig. 5.5), and filled circles represent all other sources; open squares have the same meaning as in Figure 5.5. The shaded area represents the region where $\log(f_{0.5-8\text{ keV}}/f_R) > -1$; we classified sources in this region as AGN candidates (see § 5.4.1, criterion 2). For reference, the dashed lines represent $\log(f_{0.5-8\text{ keV}}/f_R) = -2$, $-1$, and 1.

Sources that were classified as AGN candidates via criterion 1 are denoted with open symbols. In total, 40 X-ray–detected sources satisfied criterion 2, and 15 of these sources were uniquely identified using this criterion (i.e., not identified by criterion 1).

3. X-ray–to–SFR Correlation.—Taken together, criteria 1 and 2 provide an effective means for identifying AGNs that are affected by large absorption column densities (criterion 1) and those that are notably X-ray overluminous for a given optical luminosity (criterion 2). However, these criteria will still miss moderately luminous unobscured AGNs that have $\log(f_{0.5-8\text{ keV}}/f_R) < -1$ (see, e.g., Peterson et al. 2006). Although an accurate classification for all such sources is currently not possible, the situation can be mitigated using the available multiwavelength data.

We therefore exploited the correlation between X-ray luminosity $L_X$ and SFR (see § 5.1) to identify additional AGN candidates in our main sample that have significant X-ray excesses over what is expected based on the $L_X$-SFR correlation. In order to calculate the rest-frame luminosity ($L_{E_1-E_2}$; where $E_1$ and $E_2$ are the photon-energy lower and upper bounds, respectively) of a source having a power-law SED, we used the following equation:

$$L_{E_1-E_2} = 4\pi d_L^2 f_{E_1-E_2}(1+z)^{\Gamma-2},$$

(5.4)

where $f_{E_1-E_2}$ is the observed-frame emission in the $E_1-E_2$ bandpass and $d_L$ is the luminosity distance. Using equation 5.4 and an adopted photon index of $\Gamma = 2$, we calculated 0.5–8 keV luminosities for X-ray–detected sources in our sample. In Figure 5.7, we show the logarithm of the 0.5–8 keV luminosity $\log L_{0.5-8\text{ keV}}$ versus SFR (computed following equation 5.3) for galaxies in our main sample that had 24μm counterparts (see § 5.3.3). Several estimates of the $L_X$-SFR correlation have been shown for reference (Bauer et al. 2002a; Ranalli et al. 2003;
Fig. 5.7: Logarithm of the 0.5–8 keV luminosity $L_{0.5-8\text{ keV}}$ versus SFR for X-ray–detected sources in our sample that have 24$\mu$m counterparts. Open circles represent sources that were classified as AGN candidates via criteria 1 and 2 (see § 5.4.1 and Figs. 5.5 and 5.6), and filled circles represent all other sources; open squares have the same meaning as in Figure 5.5. We have shown the X-ray-SFR relations calibrated by Bauer et al. (2002), Ranalli et al. (2003), Gilfanov et al. (2004a), and Persic & Rephaeli (2007); each respective curve has been annotated in the figure. The shaded area above the thick dashed line represents the region where $L_{0.5-8\text{ keV}}$ is three times larger than its value predicted by Persic & Rephaeli (2007); we classified 0.5–8 keV detections that lie in this region as AGN candidates (see § 5.4.1, criterion 3).

Gilfanov et al. 2004a; Persic & Rephaeli 2007, hereafter PR07); these correlations have been corrected for differences in X-ray bandpass and SED as well as adopted IMFs. Hereafter, we adopt the $L_X$-SFR correlation from PR07 for comparisons; however, the use of other $L_X$-SFR correlations would yield similar results and conclusions. Open squares show the locations of the galaxies hosting off-nuclear sources, which appear to be preferentially located near the $L_X$-SFR correlation. Open circles indicate sources that were identified as AGN candidates via criteria 1 and 2. Generally, these AGNs have $L_{0.5-8\text{ keV}}$/SFR $\gtrsim 3$ times that predicted by the PR07 $L_X$-SFR correlation (thick dashed line). We therefore classified all sources in this regime (shaded region) as AGN candidates. We note that sources having only 0.5–8 keV upper limits were not classified as AGNs. However, sources that were detected in the 0.5–8 keV bandpass that had only upper limits on the SFR were classified as AGN candidates if they were within the shaded region of Figure 5.7. Using this criterion, we identified 97 potential AGN candidates, of which 32 were unique to criterion 3.

4. Optical Spectroscopy.—As a final check on our AGN classifications, we searched the optical spectroscopic catalogs available for CDF sources (e.g., Barger et al. 2003a; Le Fevre et al. 2004; Szokoly et al. 2004; Wirth et al. 2004; Vanzella et al. 2005, 2006) to isolate additional luminous AGNs in our sample. In total, we found 13 galaxies in our main sample that were classified as AGNs via optical spectroscopy and all of these sources had been identified as AGN candidates by the previous criteria. We note that the majority of the X-ray–detected AGNs have moderate luminosities (intrinsic $L_X \approx 10^{41}–10^{43}$ erg s$^{-1}$) and therefore often have high-excitation
Fig. 5.8: Logarithm of the 0.5–8 keV luminosity $L_{0.5-8\text{ keV}}$ versus redshift for the 216 X-ray–detected sources in our main sample. Open circles indicate all of the AGN candidates that were isolated using the four criteria outlined in § 5.4.1, and filled circles represent potential normal galaxies; open squares have the same meaning as in Figure 5.5. The estimated 0.5–8 keV detection limits for the $\approx2$ Ms CDF-N, the $\approx1$ Ms CDF-S, and the $\approx250$ ks E-CDF-S have been indicated with dotted, dashed, and dot-dashed curves, respectively.

AGN emission lines that are too faint with respect to stellar emission to be identified via optical spectroscopy (e.g., Moran et al. 2002). Therefore, it is not surprising that we do not find any additional AGNs using this criterion.

To summarize, in the X-ray band we have detected a total of 216 ($\approx9\%$) late-type galaxies out of the 2544 sources in our main sample. Using the criteria presented above, we classified 117 X-ray–detected sources as AGN candidates. The remaining 99 sources that we do not classify as AGN candidates are considered to be normal late-type galaxies, and we include these galaxies in subsequent X-ray stacking analyses (see details in § 5.5 below). Thus we use 2427 late-type galaxies in our stacking analyses. In Figure 5.8 we show $\log L_{0.5-8\text{ keV}}$ versus redshift for X-ray–detected sources in our main sample, and in Table 5.1 we summarize their properties. AGN candidates are denoted with open circles and normal galaxies are plotted with filled circles. We note that the above criteria are not completely sufficient to classify all X-ray–detected sources that are truly AGNs as AGN candidates (see, e.g., Peterson et al. 2006). Such a misclassification is possible for low-luminosity AGNs that are only detected in the more sensitive 0.5–2 keV bandpass, which have 2–8 keV emission too weak for an accurate classification.

In addition to the X-ray–detected sources, we also expect there to be additional AGNs that lie below the X-ray detection threshold that are not identified here. For example, moderately luminous (intrinsic $L_X \approx 10^{42}$–$10^{43}$ erg s$^{-1}$) Compton-thick AGNs, which are highly obscured by large intrinsic column densities ($N_H \gtrsim 10^{24}$ cm$^{-2}$), may go undetected in even the most-sensitive regions of the CDFs. However, such Compton-thick AGNs will generally expel their energy through dust-reprocessed infrared emission and in principle can be traceable via their infrared...
Table 5.1. X-ray Detected Late-Type Galaxies: Source Properties

<table>
<thead>
<tr>
<th>Source Name</th>
<th>$z_{850}$</th>
<th>$z$</th>
<th>$L_B$</th>
<th>$M_*$</th>
<th>SFR</th>
<th>Survey</th>
<th>$E_{0.5-8\text{ keV}}$</th>
<th>$f_{0.5-8\text{ keV}}$</th>
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</thead>
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<tr>
<td>J033132.81–280115.9.</td>
<td>17.19</td>
<td>0.15^p</td>
<td>10.39</td>
<td>10.57</td>
<td>&lt;6.53</td>
<td>E-CDF-S 03</td>
<td>217</td>
<td>-15.06</td>
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<tr>
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<td>22.17</td>
<td>0.15^p</td>
<td>8.85</td>
<td>8.59</td>
<td>0.24</td>
<td>E-CDF-S 03</td>
<td>217</td>
<td>-15.45</td>
</tr>
<tr>
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<td>0.51^p</td>
<td>10.84</td>
<td>10.98</td>
<td>&lt;12.62</td>
<td>E-CDF-S 03</td>
<td>239</td>
<td>-15.02</td>
</tr>
<tr>
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<td>17.83</td>
<td>0.11^p</td>
<td>10.20</td>
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<td>&lt;1.19</td>
<td>E-CDF-S 03</td>
<td>236</td>
<td>-15.64</td>
</tr>
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<td>0.56^p</td>
<td>10.60</td>
<td>10.97</td>
<td>5.29</td>
<td>E-CDF-S 02</td>
<td>229</td>
<td>-15.56</td>
</tr>
</tbody>
</table>

Note. — Col.(1): Chandra source name. Col.(2): ACS $z_{850}$-band magnitude. Col.(3): Redshift estimate. Superscripts “s” and “p” indicate spectroscopic and photometric redshifts, respectively (see § 5.2 for details). Col.(4): Logarithm of the rest-frame B-band luminosity in units of $L_{B,\odot}$. Col.(5): Logarithm of the stellar mass in units of $M_\odot$. Col.(6): Star-formation rate in units of $M_\odot \; \text{yr}^{-1}$. Col.(7): Survey field in which each source was identified. For E-CDF-S identifications, the associated field number (i.e., 01–04) indicates the Chandra pointing within which the source was detected (see Lehmer et al. 2005b for details). Col.(8): Effective 0.5–8 keV exposure time (in units of ks). Col.(9)–(11): Logarithm of the 0.5–8 keV, 0.5–2 keV, and 2–8 keV flux in units of erg cm$^{-2}$ s$^{-1}$. Col.(12)–(14): Logarithm of the 0.5–8 keV, 0.5–2 keV, and 2–8 keV rest-frame luminosity in units of erg s$^{-1}$. Col.(15): Effective photon index ($\Gamma_{\text{eff}}$). Col.(16): Logarithm of the 0.5–8.0 keV to R-band flux ratio. Col.(17): AGN candidate (Y/N)? Col.(18): AGN selection criteria used (i.e., 1–4; see § 5.4.1 for details). All 216 entries of Table 1 are available electronically. A portion is shown here for guidance regarding its form and content.
<table>
<thead>
<tr>
<th>Selection Type (1)</th>
<th>$z_{\text{mean}}$ (2)</th>
<th>$N_{\text{gal}}$ (3)</th>
<th>$N_{\text{det}}$ (4)</th>
<th>0.5–8 keV (5)</th>
<th>0.5–2 keV (6)</th>
<th>2–8 keV (7)</th>
<th>0.5–8 keV (8)</th>
<th>0.5–2 keV (9)</th>
<th>2–8 keV (10)</th>
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<td>$\log L_B/L_{B,\odot} = 9.5–10.0.$</td>
<td>0.23 ± 0.07</td>
<td>122</td>
<td>7</td>
<td>207.1</td>
<td>151.1</td>
<td>56.1</td>
<td>8.4</td>
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<td>3.0</td>
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<td>$\log L_B/L_{B,\odot} = 9.5–10.0.$</td>
<td>0.46 ± 0.06</td>
<td>362</td>
<td>1</td>
<td>181.6</td>
<td>149.9</td>
<td>32.7</td>
<td>4.9</td>
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<td>1.1</td>
</tr>
<tr>
<td>$\log L_B/L_{B,\odot} = 10.0–10.5.$</td>
<td>0.24 ± 0.02</td>
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<td>3</td>
<td>85.3</td>
<td>74.2</td>
<td>11.0</td>
<td>6.5</td>
<td>7.4</td>
<td>1.3</td>
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<tr>
<td>$\log L_B/L_{B,\odot} = 10.0–10.5.$</td>
<td>0.33 ± 0.03</td>
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<td>69.7</td>
<td>55.2</td>
<td>14.9</td>
<td>5.0</td>
<td>5.8</td>
<td>1.5</td>
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<td>0.41 ± 0.03</td>
<td>63</td>
<td>7</td>
<td>198.1</td>
<td>142.3</td>
<td>56.1</td>
<td>9.3</td>
<td>9.7</td>
<td>3.6</td>
</tr>
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<td>$\log L_B/L_{B,\odot} = 10.0–10.5.$</td>
<td>0.51 ± 0.02</td>
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<td>7</td>
<td>361.3</td>
<td>253.3</td>
<td>109.3</td>
<td>11.0</td>
<td>11.7</td>
<td>4.4</td>
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<td>0.57 ± 0.02</td>
<td>103</td>
<td>2</td>
<td>103.1</td>
<td>90.4</td>
<td>12.8</td>
<td>4.9</td>
<td>6.6</td>
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<td>0.67 ± 0.02</td>
<td>75</td>
<td>2</td>
<td>160.8</td>
<td>96.4</td>
<td>64.2</td>
<td>6.4</td>
<td>6.2</td>
<td>3.3</td>
</tr>
<tr>
<td>$\log L_B/L_{B,\odot} = 10.0–10.5.$</td>
<td>0.75 ± 0.02</td>
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<td>1</td>
<td>153.8</td>
<td>97.5</td>
<td>56.4</td>
<td>6.5</td>
<td>6.6</td>
<td>3.1</td>
</tr>
<tr>
<td>$\log L_B/L_{B,\odot} = 10.0–10.5.$</td>
<td>0.84 ± 0.02</td>
<td>65</td>
<td>3</td>
<td>118.2</td>
<td>76.4</td>
<td>41.8</td>
<td>4.8</td>
<td>5.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Note. — Col.(1): Physical property (i.e., $L_B$, $M_\star$, and SFR) used to select the stacked sample. Col.(2): Mean redshift ($z_{\text{mean}}$) and 1 σ standard deviation. Col.(3): Number of galaxies stacked ($N_{\text{gal}}$). Col.(4): Number of X-ray–detected normal galaxies stacked. Col.(5)–(7): Net source counts ($S-B$) for the 0.5–8 keV, 0.5–2 keV, and 2–8 keV bandpasses. Col.(8)–(10): Signal-to-noise ratio (S/N) for the 0.5–8 keV, 0.5–2 keV, and 2–8 keV bandpasses. Col.(11)–(13): Logarithm of the mean 0.5–8 keV, 0.5–2 keV, and 2–8 keV flux in units of erg cm$^{-2}$ s$^{-1}$. Col.(14)–(16): Fraction of the mean 0.5–8 keV, 0.5–2 keV, and 2–8 keV flux originating from the X-ray–undetected galaxies. Col.(17)–(19): Logarithm of the mean 0.5–8 keV, 0.5–2 keV, and 2–8 keV rest-frame luminosity. Col.(20): Mean effective photon index ($\Gamma_{\text{eff}}$). Col.(21): Logarithm of the 0.5–8.0 keV to $R$-band flux ratio. Col.(22)–(24): Mean values of $L_B$, $M_\star$, and SFR for samples selected by $L_B$, $M_\star$, and SFR, respectively. Col.(25)–(27): Logarithm of the ratios $L_X/L_B$ (ergs s$^{-1}$ $L_{B,\odot}^{-1}$), $L_X/M_\star$, (ergs s$^{-1}$ $M_\odot$), and $L_X$/SFR (ergs s$^{-1}$ $M_\odot$ yr$^{-1}$) for samples selected by $L_B$, $M_\star$, and SFR, respectively. Col.(28)–(30): Estimated fraction of the mean 0.5–8 keV, 0.5–2 keV, and 2–8 keV stacked emission originating from undetected AGNs. All 44 entries of Table 2 are available electronically. A portion is shown here for guidance regarding its form and content.
properties. In §5.3.3, we noted that the SFRs derived from the UV-plus-infrared emission are consistent with those derived from radio (1.4 GHz) observations. Since the radio emission should not be significantly affected by reprocessed dust, we would have plausibly expected luminous Compton-thick AGNs to have notable infrared excesses over the radio emission (e.g., Daddi et al. 2007a,b). The reasonable agreement between SFR(UV+IR) and SFR(1.4 GHz) suggests that such AGNs are not prevalent in our late-type galaxy sample. As an additional test, we utilized IRAC photometry (see §5.3.2) to search for infrared power-law sources having near-IR spectral properties characteristic of luminous AGNs (e.g., Alonso-Herrero et al. 2006; Donley et al. 2007). When searching for power-law sources, we adopted the criteria discussed in Donley et al. (2007). We found that no sources in our sample satisfied these criteria, which is consistent with the finding that most IRAC power-law sources reside at $z \gtrsim 1$.

In §5.5.2, we use the 2–8 keV AGN fraction as a function of X-ray luminosity to argue quantitatively that we do not expect misclassified AGNs (detected only in the 0.5–2 keV bandpass) and low-luminosity AGNs below the X-ray detection limit to have a serious impact on our results.

5.4.2 X-ray Stacking Analyses of Normal Late-Type Galaxy Populations

The majority of the normal late-type galaxies that make up our main sample ($\approx 96\%$) were not detected individually in the X-ray bandpass. In order to study the mean X-ray properties of these sources, we implemented stacking analyses of galaxy populations selected by their physical properties. We divided our main sample into subsamples (to be used for stacking) of normal late-type galaxies selected by both physical properties (i.e., $B$-band luminosity, stellar mass, and star-formation rate) and redshifts. In Figure 5.4, we have highlighted the divisions of our sample with thick gray rectangles, and for normal late-type galaxies in each region, we used X-ray stacking analyses to constrain average properties.

For each of the subsamples defined above, we performed X-ray stacking in each of the three bandpasses (see §5.1). We expect these bandpasses to sample effectively power-law X-ray emission originating from X-ray binaries (i.e., HMXBs and LMXBs) with a minor contribution from hot interstellar gas in the SB for late-type galaxies at $z \lesssim 0.5$. In our analyses, we used data products presented in Alexander et al. (2003) for the $\approx 2$ Ms CDF-N and $\approx 1$ Ms CDF-S and Lehmer et al. (2005b) for the $\approx 250$ ks E-CDF-S (see footnotes 10 and 11). Our stacking procedure itself was similar to that discussed in §3 of Steffen et al. (2007). This procedure differs from past stacking analyses (e.g., Lehmer et al. 2007) in how the local X-ray background of each stacked sample is determined, and produces results that are in good agreement with the method discussed in §2.2 of Lehmer et al. (2007). For completeness, we have outlined this procedure below.

Using a circular aperture with radius $R_{ap} = 1''5$, we extracted Chandra source-plus-background counts $S_i$ and exposure times $T_i$ (in units of cm$^2$ s) for each galaxy using images and exposure maps, respectively. For a given source, we used only Chandra pointings with aim-points (see footnote 9) that were offset from the source position by less than 6:0; hereafter, we refer to this maximum offset as the inclusion radius, $R_{incl}$. Since the Chandra PSF increases in size with off-axis angle and degrades the sensitivity for sources that are far off-axis, our choices

\footnote{Note that $R_{incl}$ has the same meaning as it did in Lehmer et al. (2007).}
of \(R_{\text{ap}}\) and \(R_{\text{incl}}\) allow for a maximal stacked signal with the majority of the PSF being sampled by our stacking aperture (see § 2.2 and Fig. 3 of Lehmer et al. 2007). For galaxies that were within 6.0 of more than one of the CDF aimpoints, we added source counts and exposure times from all appropriate images and exposure maps, respectively; however, there were very few sources in our main sample that met this criterion.

Using background maps (see § 4.2 of Alexander et al. 2003 for the \(\approx 2\) Ms CDF-N and \(\approx 1\) Ms CDF-S and § 4 of Lehmer et al. 2005b for the \(\approx 250\) ks E-CDF-S) and exposure maps, we measured local backgrounds \(B_{i,\text{local}}\) and exposure times \(T_{i,\text{local}}\) within a 30 pixel \(\times\) 30 pixel \((\approx 15'' \times 15'')\) square, centered on each source with the 1''5 radius circle masked out. Here again, if a source was within 6'' of more than one of the CDF aimpoints, we summed the local backgrounds and exposure times. We estimated the expected number of background counts in each circular aperture \(B_i\) by scaling the background counts within the square by the relative exposure times of the circular aperture and the square (i.e., \(B_i = B_{i,\text{local}} \times T_i/T_{i,\text{local}}\)). This approach is similar to scaling the background counts in the square by the relative areas of the circular aperture and the square; however, by using exposure times, we are able to account more accurately for spatial variations in pixel sensitivity due to chip gaps, bad pixels, and vignetting. Furthermore, comparisons between this method and the Monte Carlo method used in Lehmer et al. (2007) to compute \(B_i\) give excellent agreement and are most convergent for large numbers of Monte Carlo trials.

When stacking galaxy populations, we excluded sources that were (1) classified as AGN candidates (via the criteria outlined in § 5.4.1), (2) within 10'' of an unrelated source detected in the X-ray catalogs, (3) within the extent of extended X-ray sources (see Bauer et al. 2002b, § 3.4 of Giacconi et al. 2002, and § 6 of Lehmer et al. 2005b), and (4) located within 3'' of another late-type galaxy in our main sample. We note that we include X-ray–detected normal galaxies when stacking our samples, since we are interested in the average properties of the normal late-type galaxy population. We tested the effects of including such sources by stacking samples both with and without X-ray–detected sources included, and find similar results for both cases. Typically, the X-ray–detected sources contribute \(\approx 10–40\%\) of the counts in the total stacked signal. For each of the subsamples of normal late-type galaxies outlined in Figure 5.4 (gray rectangles), we determined stacked source-plus-background \((S = \sum_i S_i)\) and background counts \((B = \sum_i B_i)\) to determine net counts \((S-B)\). For each stacked sample, we required that the signal-to-noise ratio \([S/N = (S-B)/\sqrt{B}; \text{where } |S-B| \gg B \text{ and } B \geq 20]\) be greater than or equal to 3 (i.e., \(\gtrsim 99.9\%\) confidence) for a detection. For stacked samples without significant detections, 3\(\sigma\) upper limits were placed on the source counts.

We converted the net counts obtained from each stacked sample to absorption-corrected fluxes and rest-frame luminosities using a power-law SED with \(\Gamma = 2\). Due to the fact that our 1''5 radius stacking aperture encircles only a fraction of the PSF\(^6\) for sources at relatively large off-axis angle, we calculated aperture corrections \(\xi_i\) for each stacked source \(i\). Since we are calculating average X-ray counts from the summed emission of many sources of differing backgrounds and exposure times, we used a single, representative exposure-weighted aperture correction, \(\xi\). This factor, which was determined for each stacked sample, was calculated as

\(^6\)At off-axis angles \(\theta \approx 3'\), our 1''5 radius circular aperture contains an encircled-energy fraction of \(\approx 100\%, 100\%, \text{ and } 80\%\) for the SB, HB, and FB, respectively; however at \(\theta \approx 6'\), this fraction decreases to \(\approx 30\%, 25\%, \text{ and } 25\%\), respectively.
Fig. 5.9: Effective photon index ($\Gamma_{\text{eff}}$) versus the logarithm of the X-ray–to–optical flux ratio ($\log f_{0.5-8 \text{ keV}}/f_R$) for 44 stacked samples selected via observed properties: $L_B$ (filled circles), $M_*$ (filled squares), and SFR (filled triangles). The median logarithm of the X-ray–to–optical flux ratio is indicated with a vertical dotted line ($\log f_{0.5-8 \text{ keV}}/f_R = -2.5$). The median effective photon index for the samples that were detected in both the SB and HB is indicated with a horizontal dotted line ($\Gamma_{\text{median}}^{\text{eff}} = 1.42$). X-ray–detected sources have been shown with open circles and diamonds, which indicate AGN candidates and normal galaxies, respectively. The shaded regions and corresponding boundaries (dashed lines) represent areas where X-ray–detected sources were classified as AGN candidates (for details, see discussion of criteria 1 and 2 in § 5.4.1).

follows:

$$\xi \equiv \sum_i \xi_i \times T_i,$$

(5.5)

where $T = \sum_i T_i$. The average aperture corrections ($\xi$) for sources in our main sample were $\approx 1.6$, $1.8$, and $1.7$ for the SB, HB, and FB, respectively. Using our adopted SED, we estimated observed mean X-ray fluxes using the following equation:

$$f_{E_1-E_2} = A_{E_1-E_2} \xi \left( \frac{S-B}{T} \right),$$

(5.6)

where $A_{E_1-E_2}$ is a bandpass-dependent factor that incorporates both the X-ray SED information as well as Galactic extinction using the column densities listed in § 5.1. These mean X-ray fluxes were then converted to rest-frame luminosities following equation 5.4, assuming a photon index of $\Gamma = 2$. 
5.5 Results

5.5.1 Stacking Results

Using the stacking analysis methods discussed in § 5.4.2, we stacked the late-type galaxy samples presented in Figure 5.4 (stacked samples are denoted with thick gray rectangles). These samples were selected using $L_B$, $M_*$, and SFR, which include 14, 17, and 13 stacked samples (44 total), respectively. In Table 5.2, we tabulate our X-ray stacking results. We found significant (i.e., $S/N \gtrsim 3$) X-ray detections in the 0.5–2 keV and 0.5–8 keV bandpasses for all stacked samples. In the 2–8 keV bandpass, 18 out of the 44 stacked samples were detected, and these samples generally constitute the most optically luminous and massive galaxies, as well as those galaxies that are most actively forming stars.

In Figure 5.9, we show the effective photon index ($\Gamma_{\text{eff}}$) versus the logarithm of the X-ray–to–optical mean flux ratio ($\log f_{0.5-8 \text{ keV}}/f_R$) for our 44 stacked samples (filled symbols) that were selected via their observed properties. Effective photon indices were estimated using HB-to-SB count-rate ratios (i.e., $\Phi_{2-8 \text{ keV}}/\Phi_{0.5-2 \text{ keV}}$). All 44 stacked samples have X-ray–to–optical flux ratios and X-ray spectra consistent with normal galaxies (unshaded region in Fig. 5.9), suggesting that these samples are not heavily contaminated by an underlying population of AGNs. We find a median logarithm of the X-ray–to–optical flux ratio of $\log f_{0.5-8 \text{ keV}}/f_R = -2.5$ (vertical dotted line), and for samples that were detected in both the HB and SB, the median effective photon index is $\Gamma_{\text{median}} = 1.42$ (horizontal dotted line). These values are characteristic of galaxies dominated by X-ray binary populations.

In Figure 5.10, we show the logarithm of the ratio of the 0.5–8 keV luminosity (hereafter, $L_X$) to each physical property (i.e., $\log L_X/L_B$, $\log L_X/M_*$, and $\log L_X/SFR$) versus redshift for our samples. For the purpose of comparing our results to those for nearby late-type galaxy populations, we made use of the Shapley et al. (2001; hereafter S01) sample of 234 normal local ($D < \sim 100$ Mpc) spiral and irregular galaxies. These galaxies were observed in the 0.2–4 keV band using the Einstein IPC and HRI (Fabbiano et al. 1992) and X-ray–luminous AGNs have been excised from the sample. To avoid the inclusion of early-type S0 galaxies, we chose to utilize 169 normal late-type galaxies from the S01 sample with morphological types $T > 2$ (Sa–Irr Hubble types).

The S01 sample covers ranges of $L_B$ and $M_*$ that are well-matched to our main sample and are representative of late-type galaxies in the local universe. In order to compute mean X-ray luminosities for samples that were directly comparable with our results, we divided the S01 sample into the same intervals of $L_B$ and $M_*$ that were used for our main sample (see Figs. 5.4a and 5.4b). Since several of the S01 galaxies had only X-ray upper limits available, we computed mean X-ray luminosities and errors using the Kaplan-Meier estimator available through the Astronomy SURVival Analysis software package (ASURV Rev. 1.2; Isobe & Feigelson 1990; LaValley et al.1992); the Kaplan-Meier estimator handles censored data sets appropriately. When computing these mean X-ray luminosities, we filtered the S01 samples appropriately into distance intervals to avoid the Malmquist bias. In Figures 5.10a and 5.10b, we show the corresponding values of $\log L_X/L_B$ and $\log L_X/M_*$, respectively, for the S01 sample with open symbols. By contrast, the SFRs of the local sample are generally too low ($< \sim 1–10 M_\odot \text{ yr}^{-1}$) to provide a meaningful comparison with our distant 24µm-detected sources. This is due to the strong positive evolution of the star-formation rate density with redshift (see § 5.1), which
Fig. 5.10: Logarithm of (a) the X-ray–to–B-band mean luminosity ratio \(\log L_X / L_B\), (b) the X-ray–to–stellar-mass mean ratio \(\log L_X / M_\star\), and (c) the X-ray–to–star-formation-rate mean ratio \(\log L_X / \text{SFR}\) versus redshift (filled symbols and curves) for stacked normal late-type galaxy samples selected by \(L_B\) (Fig. 5.4a), \(M_\star\) (Fig. 5.4b), and \(\text{SFR}\) (Fig. 5.4c), respectively. Quoted X-ray luminosities correspond to the 0.5–8 keV bandpass and were calculated following the methods described in § 5.4.2, assuming a power-law SED with photon index of \(\Gamma = 2\). Symbols and curves correspond to unique ranges of \(L_B\), \(M_\star\), and \(\text{SFR}\), which are annotated in each respective figure. For reference, in Figures 5.10a and 5.10b we have plotted the corresponding values of \(\log L_X / L_B\) and \(\log L_X / M_\star\), respectively, for normal late-type galaxies in the local universe (open symbols) using the S01 sample. In Figure 5.10b we show the expected LMXB contribution based on Gilfanov et al. (2004b; dashed line). Finally, in Figure 5.10c we show the local \(L_X\)-SFR relation and its \(\approx 20\%\) dispersion (dashed line with shading) derived by PR07.
makes SFRs that are common for galaxies in our sample (≥ 1–10 \( M_\odot \) yr\(^{-1}\)) comparatively rare at \( z = 0 \).

From Figures 5.10a and 5.10b, it is apparent that there is significant positive redshift evolution in \( \log L_X/L_B \) and \( \log L_X/M_\ast \) over the redshift range of \( z \approx 0–1.4 \). For each of the six total selection ranges of \( L_B \) and \( M_\ast \), the redshift progression of X-ray luminosities is inconsistent with a constant at the >99.9% confidence level. For the most optically luminous (\( L_B = 3–20 \times 10^{10} \ L_{B,\odot} \)) and massive (\( M_\ast = 1–20 \times 10^{10} \ M_\odot \)) late-type galaxies at \( z = 1.4 \), \( L_X/L_B \) and \( L_X/M_\ast \) are measured to be larger than their local values by factors of 4.4 ± 1.0 and 8.9 ± 2.5, respectively.

In Figure 5.10b, we show the estimated LMXB contribution to \( \log L_X/M_\ast \) (dashed line) based on Table 5 of Gilfanov et al. (2004b). This value is ≈ 5–10 times lower than all mean values of \( L_X/M_\ast \), suggesting that on average LMXBs play a fairly small role in the X-ray emission from our stacked samples. Furthermore, late-type galaxies in the local universe with similar stellar masses are often found to have HMXB emission that is ≈ 2–10 times more luminous than what is expected from LMXBs (see open symbols in Fig. 5.10b and Fig. 3 of Gilfanov et al. 2004c). For galaxy samples selected via SFR, we find no evidence for significant evolution in \( \log L_X/SFR \) (Fig. 5.10c). For each of the three ranges of SFR, \( \log L_X/SFR \) is consistent with a constant value, and has a best-fit ratio of \( \log L_X/SFR = 39.86 \pm 0.04 \) (\( \chi^2 = 8.5 \) for 12 degrees of freedom). These results suggest that the contribution from LMXBs is small and that the integrated X-ray emission from our late-type galaxies is dominated by HMXBs and that their evolution is likely due to the evolution of star-formation activity.

Since the X-ray emission from our late-type galaxies is dominated by star-formation processes, we note that our \( M_\ast \)-selected stacking results show suggestive evidence for “cosmic downsizing” (see Fig. 5.10b). We find that at \( z \approx 1 \) the X-ray emission per unit stellar mass is a factor of ≈ 2–3 larger for galaxies with \( M_\ast = 3–10 \times 10^9 \ M_\odot \) versus that observed for galaxies with \( M_\ast = 1–20 \times 10^{10} \ M_\odot \). This result is broadly consistent with observed differences in the mean SFR per unit stellar mass found by Zheng et al. (2007) for \( z \approx 1 \) galaxies of comparable stellar masses.

In order to quantify the dependences of the X-ray luminosity on redshift and physical properties, we performed multivariate parametric fitting to our stacked data. For each galaxy sample selected via \( L_B, M_\ast, \) and SFR, we investigated the redshift evolution of the X-ray luminosity. For this analysis, we fit our data to a power-law parametric form:

\[
\log L_X(f_{\text{phys}}, z) = A + B \log f_{\text{phys}} + C \log(1 + z),
\]

where \( f_{\text{phys}} \) is a place holder for each of the three physical properties (\( L_B, M_\ast, \) and SFR) used for our sample selections, and A, B, and C are fitting constants. For each sample, we utilized our X-ray stacking results, equation 5.7, and \( \chi^2 \) fitting to estimate the constants A, B, and C. For our adopted three-component model, we constrained A, B, and C using 90% confidence errors (\( \Delta \chi^2 = 2.7 \)). The S01 local data points were not used for these fits due to differences in galaxy selection, instrument calibration, and AGN identification.

In Table 5.3, we tabulate our constraints on \( \chi^2, A, B, \) and C for these fits. We find that this particular choice (i.e., eqn. 7) of parameterization does not provide acceptable fits for galaxy samples selected via \( L_B \) and \( M_\ast \). However, for galaxy samples selected via SFR, we find a good
Table 5.3.  Parametric Fitting Results For Stacked Samples

<table>
<thead>
<tr>
<th>$f_{\text{phys}}$</th>
<th>$\nu$</th>
<th>$\chi^2$</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>$L_B$........</td>
<td>11</td>
<td>38.08</td>
<td>31.20 ± 0.87</td>
<td>0.86 ± 0.09</td>
<td>2.81 ± 0.43</td>
</tr>
<tr>
<td>$M_{\ast}$.....</td>
<td>14</td>
<td>39.70</td>
<td>33.11 ± 0.62</td>
<td>0.67 ± 0.03</td>
<td>3.97 ± 0.33</td>
</tr>
<tr>
<td>SFR.....</td>
<td>10</td>
<td>5.73</td>
<td>39.85 ± 0.02</td>
<td>0.92 ± 0.07</td>
<td>0.40 ± 0.47</td>
</tr>
</tbody>
</table>

Note. — This table contains basic fitting parameters for $\chi^2$ fits to our X-ray stacking results. For each sample, selected by physical property $f_{\text{phys}}$, we performed parametric fits for the mean 0.5–8 keV luminosity $L_X$ following $\log L_X = A + B \log f_{\text{phys}} + C \log (1+z)$. Col.(1): Physical parameter $f_{\text{phys}}$ used in fitting our stacking results. Col.(2): Number of degrees of freedom used in each fit. Col.(3): Minimum $\chi^2$ value for each fit. Col.(4)–(6): Best-fit values of $A$, $B$, and $C$ with errors (90% confidence). For further details, see § 5.1.

fit for this parameterization ($\chi^2 = 5.73$ for ten degrees of freedom). We constrain the evolution of $\log L_X/\text{SFR}$ to be independent of or at most weakly dependent on redshift [$\propto (1+z)^{0.40±0.47}$].

Based on radio observations of distant star-forming galaxies with SFR $\approx 3–300 M_\odot$ yr$^{-1}$ in the CDF-N and CDF-S, Barger et al. (2007) reported that the X-ray upper limits for X-ray–undetected sources were below the level expected from the $L_X$-SFR correlation, thus suggesting that the correlation may not hold in the high-redshift universe. However, our stacking results suggest that the $L_X$-SFR correlation does in fact hold for average galaxies with SFR = 1–5 $M_\odot$ yr$^{-1}$ (SFR = 15–100 $M_\odot$ yr$^{-1}$) out to $z \approx 0.5$ ($z \approx 1.4$).

For illustrative purposes we have created Figure 5.11, which shows log SFR versus log $L_X$ for normal star-forming galaxies selected from several different sources including X-ray–detected galaxies from our main sample (filled gray circles and limits), stacked galaxies from this study (filled black symbols), local galaxies from PR07 (open circles), local ultraluminous infrared galaxies from PR07 (ULIRGs; open squares), and stacked $z \sim 3$ Lyman break galaxies (LBGs; stars; see § 5.6 for details). For all data used in this plot, we have normalized SFRs appropriately to be consistent with our adopted Kroupa (2001) IMF and have adjusted X-ray luminosities to correspond to the 0.5–8 keV band using a $\Gamma = 2$ power-law SED. The best-fit $L_X$-SFR correlations for local galaxies from PR07 (solid curve) and $z = 0–1.4$ late-type galaxies from this study ($\log L_X/\text{SFR} = 39.86$; dotted curve) have been shown for reference. For comparison, we have shown the SFRs for three well-studied star-forming galaxies: M101, M82, and Arp 220.

5.5.2 AGN Contribution to Stacked Signals

In this section we estimate the contribution to our stacked signals from contaminating AGNs that have X-ray luminosities below our X-ray detection limit. This analysis is similar in
Fig. 5.11: Logarithm of the star-formation rate $\log \text{SFR}$ versus the logarithm of the X-ray luminosity $\log L_X$ for normal late-type galaxies. X-ray–detected sources from our main sample are indicated as small gray dots and limits. Results from our X-ray stacking analyses of late-type galaxies selected via observed SFR are shown as large filled circles, squares, and triangles, which have the same meaning as in Figure 5.10; z $\sim$ 3 LBGs that were both uncorrected and corrected for AGN contamination have been shown plotted as a filled star and open star, respectively. For comparison, we show the local galaxy sample from PR07, which include normal late-type galaxies (open circles) and luminous infrared galaxies (LIRGs; open squares); the best-fit PR07 relation is shown as a solid curve. The SFRs for M101, M82, and Arp 220 are indicated (horizontal dashed lines).
nature to that in § § 3.1 and 3.2.2 of Lehmer et al. (2007), which was performed for early-type galaxies. We implement the observed cumulative AGN fraction \( f_C \): the fraction of galaxies harboring an AGN with 2–8 keV luminosity of \( L_{2-8 \, \text{keV}} \) or greater. Hereafter, we compute \( f_C \) by taking the number of candidate AGNs in a particular galaxy sample with a 2–8 keV luminosity of \( L_{2-8 \, \text{keV}} \) or greater and dividing it by the number of galaxies in which we could have detected an AGN with luminosity \( L_{2-8 \, \text{keV}} \). The latter number is computed by considering the redshift of each galaxy and its corresponding sensitivity limit, as obtained from spatially varying sensitivity maps (see § 4.2 of Alexander et al. 2003 and § 4 of Lehmer et al. 2005b); these sensitivity maps were calibrated empirically using sources detected by wavdetect at a false-positive probability threshold of \( 1 \times 10^{-5} \).

The quantity \( f_C \) is not only a function of \( L_{2-8 \, \text{keV}} \), but is also dependent on the properties of the galaxy sample: for example, in our case redshift and the physical property \( f_{\text{phys}} \) (i.e., \( L_B \), \( M_* \), and SFR) of the galaxy population may plausibly play a role in \( f_C \). In our analyses, we assume that each of the respective dependencies (i.e., \( L_{2-8 \, \text{keV}} \), \( z \), and \( f_{\text{phys}} \)) are independent of each other, such that \( f_C \propto g(L_{2-8 \, \text{keV}}) \times g(z) \times g(p_{\text{phys}}) \), where \( g \) represents the functional dependence of the cumulative AGN fraction for each indicated variable (\( L_{2-8 \, \text{keV}} \), \( z \), and \( f_{\text{phys}} \)). We made use of the 2–8 keV bandpass because of its ability to probe relatively unattenuated X-ray emission in a regime of the X-ray spectrum where we expect there to be minimal emission from normal galaxies (see also criterion 1 of § 5.4.1 for further details). In total 59 (≈50\%) of our 117 X-ray–detected AGN candidates had 0.5–8 keV detections; we use these AGNs in our AGN fraction analyses.

We began constructing \( f_C \) by estimating the shape of \( g(L_{2-8 \, \text{keV}}) \) using late-type galaxies with \( z = 0.1–1 \) and \( L_B \gtrsim 2 \times 10^{10} \, L_{\odot} \), an optical luminosity regime where we have a relatively large number of sources and are approximately complete out to \( z = 1 \) (see Fig 5.4a). We split this sample into two subsets about \( z = 0.6 \), to test whether there is substantial evolution in the shape and normalization of \( g(L_{2-8 \, \text{keV}}) \) over this redshift range. In Figure 5.12, we show \( g(L_{2-8 \, \text{keV}}) \) for galaxies in the redshift ranges \( z \lesssim 0.6 \) (\( z_{\text{median}} = 0.51 \); filled circles) and \( z = 0.6–1 \) (\( z_{\text{median}} = 0.84 \); open triangles). From Figure 5.12, we see that the overall shape and normalization of \( g(L_{2-8 \, \text{keV}}) \) for late-type galaxies with \( L_B \gtrsim 2 \times 10^{10} \, L_{\odot} \) is similar for galaxies at \( z_{\text{median}} = 0.51 \) and \( z_{\text{median}} = 0.84 \). We fit the shape of \( g(L_{2-8 \, \text{keV}}) \) using least-squares fitting of the 2–8 keV luminosity dependent cumulative AGN fraction using all galaxies from \( z = 0–1 \) with \( L_B \gtrsim 2 \times 10^{10} \, L_{\odot} \). For these fits, we found that the data was well-fit by an exponential function, which we parameterized as \( \log g(L_{2-8 \, \text{keV}}) \propto a \exp[-b(\log L_{2-8 \, \text{keV}} - 39)^2] \), where \( a \) and \( b \) are fitting constants. By construction, this function is only valid for \( \log L_{2-8 \, \text{keV}} > 39 \), which is \( \approx 1–2 \) orders of magnitude less luminous than a typical stacked X-ray luminosity of our late-type galaxy samples (see Table 5.2 and Fig. 5.10). We find best-fit values of \( a = -0.8 \) and \( b = -0.05 \); in Figure 5.12 (thick black curve), we show our best-fit relation for \( g(L_{2-8 \, \text{keV}}) \).

We constrained further the redshift evolution of \( f_C \) [i.e., the shape of \( g(z) \)] by dividing our main late-type galaxy sample into five nearly independent redshift bins (with \( z = 0.1–0.8 \)) and calculating \( f_C \) for fixed ranges of \( L_{2-8 \, \text{keV}} \) and \( f_{\text{phys}} \). In Figure 5.13, we show \( g(z) \) as a function of redshift for late-type galaxies with \( L_{2-8 \, \text{keV}} \gtrsim 10^{41.5} \, \text{erg s}^{-1} \) and \( L_B \gtrsim 10^{10} \, L_{\odot} \), the approximate completeness limit at \( z \approx 0.8 \) (see Fig. 5.4a). Using these data and \( \chi^2 \) fitting [assuming a \((1+z)^n\) dependence], we constrained the redshift evolution of \( g(z) \) to be proportional to \((1+z)^{0.03\pm0.19}\); similar results were found for different ranges of \( L_{2-8 \, \text{keV}} \) and \( L_B \). This result differs from that
Fig. 5.12: Cumulative X-ray luminosity dependent AGN fraction $g(L_{2-8\text{ keV}})$ versus $L_{2-8\text{ keV}}$ for late-type galaxies with $L_B > 2 \times 10^{10} L_{\odot}$ at $z \approx 0.6$ (filled circles) and $z = 0.6-1$ (open triangles). For reference, we have indicated the corresponding AGN fraction for Lyman break galaxies at $z \sim 3$ (filled stars; see § 5.5 for further details). We have indicated the median X-ray detection limit for galaxies in each redshift range (downward-pointing arrows along the x-axis). The solid curve represents the best-fit relation for $g(L_{2-8\text{ keV}})$, which was fit using all late-type galaxies with $z \approx 0-1$ and $L_B > 2 \times 10^{10} L_{\odot}$ in our main sample. For reference, we have shown the estimated AGN fraction for galaxies with $L_B \approx 5 \times 10^{9}$, $10^{10}$, and $10^{11} L_{\odot}$ (dotted curves; see § 5.4.2 for further details).

Fig. 5.13: Cumulative redshift-dependent AGN fraction $g_z(z)$ versus redshift for late-type galaxy samples with $L_B > 10^{10} L_{\odot}$ and $L_{2-8\text{ keV}} > 10^{41.5}$ erg s$^{-1}$. We find no significant evolution of $g_z(z)$ over the redshift range $z \approx 0.1-0.8$. 

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 broadcasters, media outlets, and other organizations to engage with the public about this exciting new discovery.
Fig. 5.14: Cumulative AGN fraction \( g_p(f_{\text{phys}}) \) versus \( (a) L_B \), \( (b) M_\star \), and \( (c) \) SFR for late-type galaxies with \( L_{2-8\text{ keV}} \geq 10^{41.5} \) erg s\(^{-1}\) at \( z < 0.6 \) (dashed curves) and \( z = 0.6-1 \) (dotted curves). In each plot, we have indicated the best-fit relation (solid line), which is calculated using all galaxies with \( L_{2-8\text{ keV}} \geq 10^{41.5} \) erg s\(^{-1}\) and \( z < 0.6 \). The downward-pointing arrows indicate which values of \( f_{\text{phys}} \) were chosen for computing \( g_0 \) in equation 5.8. For reference, the bin sizes of \( f_{\text{phys}} \) used to compute each value of \( g_p(f_{\text{phys}}) \) and the typical errors of \( g_p(f_{\text{phys}}) \) have been indicated in the lower right-hand corner of each plot.

observed for early-type galaxies, where the AGN fraction and mean AGN emission has been found to evolve as \( \approx (1 + z)^3 \) (e.g., Brand et al. 2005; Lehmer et al. 2007). We note that the lack of evolution of the AGN fraction does not necessarily imply that the optically-luminous (i.e., \( L_B \approx 10^{10} L_{B,\odot} \)) late-type galaxy AGN number density is constant over \( z \approx 0-1 \). For example, \( L_B^* \) has been shown to fade by \( \approx 1 \) mag since \( z \approx 1 \) (e.g., Lilly et al. 1995; Wolf et al. 2003; Faber et al. 2005), suggesting that there are fewer optically luminous late-type galaxies in the local universe than at \( z = 1 \). Based on the above results, we conclude that there is little redshift evolution in the late-type galaxy AGN fraction over the redshift range \( z = 0.1-0.8 \), and hereafter we assume that \( g_p(z) \) remains roughly constant out to \( z = 1.4 \).

To constrain the overall dependence of \( f_C \) on \( f_{\text{phys}} \) [i.e., \( g_p(f_{\text{phys}}) \)], we calculated the cumulative AGN fractions for late-type galaxy samples with \( f_{\text{phys}} \) by holding the ranges of \( L_{2-8\text{ keV}} \) and \( z \) fixed and varying \( f_{\text{phys}} \). In Figure 5.14, we show \( g_p(f_{\text{phys}}) \) versus \( \log L_B \) (Fig. 5.14a), \( \log M_\star \) (Fig. 5.14b), and SFR (Fig. 5.14c) for \( L_{2-8\text{ keV}} \geq 10^{41.5} \) erg s\(^{-1}\) at \( z \approx 0.6 \) (dashed curves) and \( z = 0.6-1 \) (dotted curves). We calculated \( g_p(f_{\text{phys}}) \) for intervals of \( f_{\text{phys}} \) where we are approximately complete at \( z = 0.6 \) (for the \( z \approx 0.6 \) interval) and \( z = 1 \) (for the \( z = 0.6-1 \) interval; see Fig. 5.4). For each sample, we again utilized least-squares fitting to approximate the \( f_{\text{phys}} \) dependence of \( g_p(f_{\text{phys}}) \). These fits were performed using all data over the redshift range \( z = 0-1 \) assuming a functional dependence of \( \log g_p(f_{\text{phys}}) \propto c \log f_{\text{phys}} \). In each panel of Figure 5.14, we show the best-fit solutions for \( g_p(f_{\text{phys}}) \) with the gray curves. We find that the AGN fraction is strongly dependent on \( L_B \) (Fig. 5.14a) and \( M_\star \) (Fig. 5.14b), such that more optically-luminous and massive galaxies have larger AGN fractions; this result is consistent with studies of the AGN host galaxies in the local universe (e.g., Kauffmann et al. 2003b; Nandra et al. 2007; Silverman
et al. 2007b). Also, the AGN fraction seems to be mildly dependent on the galaxy SFR; however, this is likely due to the fact that the SFR is larger on average for more massive galaxies.

Based on the above estimates of the shapes of $g_L(L_{2–8\text{ keV}})$, $g_c(z)$, and $g_p(J_{\text{phys}})$, we approximated empirically $f_C$ for each choice of $f_{\text{phys}}$ following:

$$
\log f_C = \log g_0 + a \exp[-b(\log L_{2–8\text{ keV}} - 39)^2] + c \log f_{\text{phys}},
$$

where $g_0$ represents the normalization of each relation based upon the value of $f_C$ at $L_{2–8\text{ keV}} > 10^{41.5}$ erg s$^{-1}$ and $L_B = 10^{10} L_{B,\odot}$, $M_* = 10^{10} M_{\odot}$, and SFR = 2 $M_{\odot}$ yr$^{-1}$, for galaxy samples selected via $L_B$, $M_*$, and SFR, respectively. We note that only $g_0$ and $c$ are dependent upon our choice of $f_{\text{phys}}$; we find for the set of physical parameters $f_{\text{phys}} = [L_B, M_*, \text{SFR}]$ that $g_0 = [8.9 \times 10^{-15}, 3.4 \times 10^{-12}, 0.21]$ and $c = [1.3, 1.08, 0.6]$. For reference, in Figure 5.12 we have shown curves of $f_C$ for $L_B = 5 \times 10^9$, $10^{10}$, and $10^{11} L_{B,\odot}$ (dotted curves).

To estimate the AGN contamination expected for each of our stacked samples presented in § 5.5.1, we followed closely the procedure in § 3.2.2 of Lehmer et al. (2007). Briefly, we (1) converted the cumulative AGN fractions $f_C$ for each stacked sample (computed via eqn. 8) to their differential forms $f_D$ (i.e., the 2–8 keV luminosity dependent fraction of galaxies harboring AGNs within discrete X-ray luminosity bins of width $\Delta \log L_{2–8\text{ keV}} = 0.5$). (2) estimated for each stacked sample the 2–8 keV luminosity dependent fraction of galaxies that were below our $L_{2–8\text{ keV}}$ detection limit $f_B$. (3) multiplied $f_D$ by $f_B$ to calculate the fraction of sources that harbor an undetected AGN with 2–8 keV luminosity $L_{2–8\text{ keV}}$ (in bins of width $\Delta \log L_{2–8\text{ keV}} = 0.5$), $f_U$, and (4) approximated the total 2–8 keV AGN contamination $L_{0.5–2\text{ keV}}(\text{contam})$ of each stacked sample using the following summation:

$$
L_{2–8\text{ keV}}(\text{contam}) = \sum_i f_{U,i} \times L_{2–8\text{ keV},i},
$$

where the summation is over all bins of $\Delta \log L_{2–8\text{ keV}} = 0.5$ in the range $\log L_{2–8\text{ keV}} = 39–45$. We converted each value of $L_{2–8\text{ keV}}(\text{contam})$ to estimated values of $L_{0.5–2\text{ keV}}(\text{contam})$ and $L_{0.5–2\text{ keV}}(\text{contam})$ by assuming the contaminating AGN emission roughly follows an X-ray SED described by a power-law. In order to constrain the average photon index of the power-law, we stacked all X-ray–detected AGNs in our stacked samples with 0.5–8 keV luminosities below $10^{42}$ erg s$^{-1}$. For these AGNs, we find a stacked effective photon index of $\Gamma_{\text{eff}} = 1.07 \pm 0.04$. If the intrinsic value of the photon index is $\Gamma = 2$, at the median redshift of our main sample ($z_{\text{median}} = 0.5$), $\Gamma_{\text{eff}} = 1.07$ corresponds to an intrinsic X-ray column density of $N_H \approx 1–2 \times 10^{21} \text{ cm}^{-2}$. If we assume $\Gamma_{\text{eff}} = 1$ describes well the effective SED of the X-ray–undetected AGNs in our stacked sample, we find that AGN contamination can account for $\approx 2–25\%$ (median of $\approx 5\%$) of the 0.5–8 keV emission from our stacked samples, suggesting that AGNs are not providing a significant contribution to our stacked results.

In Table 5.2 (cols. 25–27), we have provided the estimated fractional AGN contribution to each stacked sample [i.e., $L_{E_i–E_j}/L_{E_i–E_j}$] for the FB, SB, and HB using the technique described above and an assumed $\Gamma_{\text{eff}} = 1$. We find that the estimated AGN contamination is largest for galaxy samples with large values of $L_B$, $M_*$, and SFR. We note that the X-ray SED used in this calculation has an important effect on the overall estimate of the AGN contamination. Since our estimates for contamination in the 0.5–8 keV and 0.5–2 keV bandpasses decrease as $\Gamma_{\text{eff}}$ decreases, the amount of contamination in our samples may be underestimated if our choice
of $\Gamma_{\text{eff}}$ is too flat; however, we find that for conservative choices of $\Gamma_{\text{eff}}$ (i.e., $\Gamma_{\text{eff}} < 2$) that are representative of even unobscured AGNs (for reference, see open symbols in Fig. 5.9), the AGN contamination remains low ($\approx 40\%$) and has no material effect on our results.

### 5.6 Extension to Distant Lyman Break Galaxies

As noted in § 5.1, the global star-formation rate density has been observed to increase with redshift out to $z \sim 1$–1.5. Investigations of the most distant Lyman break galaxies (LBGs) at $z \sim 2$–10 show that the star-formation density peaks around $z \approx 1$–3 and gradually declines toward higher redshifts (e.g., Steidel et al. 1999; Giavalisco 2002, 2004b; Bouwens et al. 2004, 2005; Dickinson et al. 2004). To investigate whether the mean X-ray activity from normal late-type galaxies follows a similar trend, we studied the X-ray properties of a sample of $z = 3.01 \pm 0.24$ LBGs, which were identified as U-band “dropouts” through the GOODS project (see Lehmer et al. 2005a for details).

We filtered the original Lehmer et al. (2005a) sample to include only LBGs that (1) were within the central $\approx 4.0$ of the $\approx 2$ Ms CDF-N and $\approx 1$ Ms CDF-S, and (2) had rest-frame $B$-band luminosities that were similar to the most optically luminous ($L_B = 3$–20 $\times 10^{10} L_{\odot}$) $z = 0$–1.4 late-type galaxies used in this study. $B$-band luminosities were calculated by applying $k$-corrections to the $z_{850}$-band flux (from GOODS), where $k$-corrections were derived using an SED appropriate for LBGs (see § 2.2 of Lehmer et al. 2005a for details). We found that 85 $z \sim 3$ LBGs from the Lehmer et al. (2005a) sample satisfied these two selection criteria.

After removing three obvious ($L_{2-8 \text{ keV}} \gtrsim 10^{43}$ erg s$^{-1}$) X-ray–detected AGNs from our $z \sim 3$ LBG sample, we performed X-ray stacking analyses as described in § 5.4.2. We found a significant ($3.7\sigma$) detection in the 0.5–2 keV bandpass, which corresponds roughly to rest-frame 2–8 keV emission. Assuming an intrinsic power-law X-ray spectrum with a photon index of $\Gamma = 2$, we found a mean 0.5–8 keV luminosity of $L_X = (4.9 \pm 1.4) \times 10^{41}$ erg s$^{-1}$ for our $z \sim 3$ LBGs.

Since our LBGs reside in the high-redshift universe, AGN contamination is expected to have a more significant effect on these results than it did for our $z = 0$–1.4 late-type galaxies. The median X-ray luminosity detection limit is $\approx 8 \times 10^{41}$ erg s$^{-1}$ and $\approx 10^{43}$ erg s$^{-1}$ for the 0.5–2 keV and 2–8 keV bandpasses, respectively. To estimate the AGN contamination, we followed the approach outlined in § 5.5.2, which made use of the 2–8 keV luminosity dependent AGN fraction ($f_C$). In Figure 5.12 (filled stars), we show the X-ray luminosity dependent AGN fraction $g_{L,\text{LBG}}(L_{2-8 \text{ keV}})$ for $z \sim 3$ LBGs. We note that at $L_{2-8 \text{ keV}} \gtrsim 10^{43}$ erg s$^{-1}$, the cumulative AGN fraction for $z \sim 3$ LBGs is a factor of $\approx 3$–4 times larger than that computed for our $z = 0$–1 late-type galaxy sample with similar optical luminosities. Using the functional form for $f_C$ presented in equation 5.8, but with a $\approx 3$–4 times larger normalization factor for $z \sim 3$ LBGs (i.e., $g_{0,\text{LBG}} \approx 3$–4 $g_0$), we find that AGN emission may plausibly account for $\approx 50$–70% of the observed 0.5–2 keV emission.

In Figure 5.15, we show the X-ray–to–$B$-band mean luminosity ratio for $L_B = 3$–20 $\times 10^{10} L_{\odot}$ star-forming galaxies (i.e., late-type galaxies and LBGs) as a function of the age of the Universe. Together, these data span $\approx 85\%$ of cosmic history (i.e., out to $z \sim 3$). As presented in § 5.5.1, $L_X/L_B$ shows significant evolution over the redshift range $z = 0$–1.4, and after correcting for AGN contamination, we find that $L_X/L_B$ is similar for $z \sim 3$ LBGs and $z = 1.4$ late-type galaxies. This result suggests that the non-AGN X-ray emission for the most luminous star-forming galaxies...
Fig. 5.15: Logarithm of the X-ray–to–B-band mean luminosity ratio \( \log L_X/L_B \) versus the age of the Universe (for our adopted cosmology, the current age of the Universe is 13.47 Gyr) for star-forming galaxies with \( L_B = 3–20 \times 10^{10} L_{B,\odot} \). For reference, redshift has been plotted along the top axis. We have included mean values of \( L_X/L_B \) for the S01 local sample of late-type galaxies (open circles), our stacked samples at \( z \approx 0.5–1.4 \) (large filled circles), and \( z \approx 3 \) LBGs that were both uncorrected (filled star) and corrected (open star) for AGN contamination. At \( z \approx 0.1–0.4 \), we have plotted \( L_X/L_B \) for individual late-type galaxies from our main sample (small filled circles and upper limits); the mean values and errors for these galaxies, computed using ASURV, has been indicated.

may plausibly reach a peak near \( z \approx 1.5–3 \), which has been predicted roughly from simulations of how the normal-galaxy X-ray emission is expected to respond due to global changes in the star-formation rate density (e.g., Ghosh & White 2001).

To test whether the \( L_X \)-SFR correlation is similar for \( z \approx 3 \) LBGs as we found for late-type galaxies at \( z = 0–1.4 \), we approximated absorption-corrected SFRs for the \( z \approx 3 \) LBGs using UV band emission. These SFRs were approximated following \( \text{SFR} = 9.8 \times 10^{-11} \gamma L_{UV} \), where \( \gamma \approx 6 \) is the absorption-correction factor (see Giavalisco et al. 2004b). As described in § 5.3.3, we approximated the UV luminosity following \( L_{UV} = 3.3 \nu l_\nu(2800 \text{ Å}) \); however, here \( l_\nu(2800 \text{ Å}) \) was derived using our adopted LBG SED. We find that the mean SFR for optically-luminous \( z \approx 3 \) LBGs is \( \approx 60 \, M_\odot \, \text{yr}^{-1} \). After correcting the mean stacked X-ray luminosity for AGN contamination, we find an X-ray–to–SFR ratio of \( \log L_X/\text{SFR} \approx 39.4–39.6 \), which is suggestively lower than its value for \( z = 0–1.4 \) late-type galaxies (i.e., \( \log L_X/\text{SFR} \approx 39.86 \pm 0.04 \)). For reference, in Figure 5.11 we have plotted \( \log \text{SFR} \) versus \( \log L_X \) for the \( z \approx 3 \) LBGs both uncorrected (filled star) and corrected (open star) for AGN contamination. This shows that these LBGs
have average X-ray and SFR properties comparable (within a factor of ≈2) to some of the most luminous starburst galaxies in the local universe such as Arp 220 (e.g., McDowell et al. 2003).

5.7 Summary

We have investigated the X-ray emission from 2544 normal late-type galaxies over the redshift range $z = 0–1.4$ that lie within the Chandra Deep Fields (CDFs). Our late-type galaxy sample was constructed primarily using color-magnitude diagrams, which incorporated rest-frame $U-V$ color and absolute $V$-band magnitudes, to isolate blue late-type galaxies (see § 5.2 for details). In total, 216 ($≈9\%$) of our late-type galaxies were detected individually in the X-ray band. Based on X-ray and optical spectral properties, X-ray–to–optical flux ratios, and the correlation between X-ray luminosity and star-formation rate, we infer that 116 ($≈54\%$) of the X-ray–detected late-type galaxies are dominated by AGN emission. The remaining 99 X-ray–detected galaxies had X-ray and multiwavelength properties consistent with normal late-type galaxies with X-ray emission dominated by X-ray binaries (HMXBs and LMXBs). To study the X-ray emission and evolution from large representative populations of late-type galaxies (i.e., including the X-ray–undetected sources), we utilized X-ray stacking analyses of galaxy populations with AGN candidates removed. We stacked normal galaxy samples that were selected via their rest-frame $B$-band luminosity ($L_B$), stellar mass ($M_*$), and star-formation rate (SFR) in redshift bins (see § 5.5). Furthermore, we compared these results with those found for a sample of $z \sim 3$ LBGs from Lehmer et al. (2005a). In the points below, we summarize our key findings:

1. We obtained significant detections in the 0.5–8 keV bandpass for all of our stacked samples. We estimated that LMXB and low-level AGNs provide only low-level contributions to the stacked X-ray emission from our samples and that HMXBs constitute the dominate X-ray–emitting component. Normal late-type galaxy samples selected via $L_B$ and $M_*$ show significant (at the >99.9% confidence level) evolution in their average X-ray properties from $z = 0$ to 1.4. For the most optically luminous ($L_B \approx 5 \times 10^{10} L_{B,\odot}$) and massive ($M_* \approx 3 \times 10^{10} M_\odot$) late-type galaxies at $z = 1.4$, $L_X/L_B$ and $L_X/M_*$ are measured to be larger than their local values by factors of $≈3–5$ and $≈6.5–11.5$, respectively. Additionally, we found evidence for “cosmic downsizing” by which galaxies of lower stellar mass generally have larger X-ray–to–stellar-mass mean ratios ($L_X/M_*$) than their higher-mass analogs. By $z \approx 1$, galaxies with $M_* \approx 6 \times 10^9 M_\odot$ are a factor of $≈2–3$ times more X-ray luminous per unit stellar mass than galaxies with $M_* \approx 3 \times 10^{10} M_\odot$.

2. For normal late-type galaxies selected via SFR, we found that the X-ray luminosity is well-predicted by a constant $L_X$–to–SFR ratio, similar to the $L_X$–SFR correlation reported by previous authors (e.g., PR07). This implies that the $L_X$–SFR correlation holds out to at least $z = 0.5$, 1, and 1.4 for galaxies with SFR $≈ 2$, 10, and $50 M_\odot$ yr$^{-1}$, respectively, and supports the idea that the strong X-ray evolution observed for normal late-type galaxies selected via $L_B$ and $M_*$ is likely due to strong changes in SFR.

3. The X-ray properties of our most optically-luminous ($L_B = 3–20 \times 10^{10} L_{B,\odot}$) late-type galaxies at $z = 1.4$ are comparable to those for $z \sim 3$ LBGs with similar optical luminosities, once X-ray–undetected AGN contamination in the LBG population has been accounted
for. This suggests that there may plausibly be a peak in $L_X/L_B$ for optically-luminous star-forming galaxies between $z \sim 1.4$–3. We estimate a mean SFR of $\approx 60 \, M_\odot \, \text{yr}^{-1}$ for these LBGs. We find that the observed mean X-ray luminosity is suggestively underluminous based on the $L_X$-SFR correlation prediction; this result is similar to that found for local ULIRGs with comparable SFRs.
Chapter 6

The X-ray Properties of Distant Lyman Break Galaxies

6.1 Introduction

Determination of the basic X-ray properties of “normal” (i.e., not hosting a luminous AGN) galaxies out to high redshift has been motivated in part by Ghosh & White (2001, hereafter GW01) who developed a model of the evolution of X-ray luminosity with redshift. GW01 predict that, globally, X-ray emission from normal galaxies should peak at $z \approx 1.5–3$ due to a maximum in the global star formation rate (SFR) at $z \approx 2.5–3.5$ (e.g., Blain et al. 1999). Heightened X-ray emission at these redshifts is expected due to an increase in the global population of low mass X-ray binaries (LMXBs). LMXBs evolve on timescales of $\sim 1$ Gyr, and therefore their X-ray signatures should lag behind more immediate tracers of star formation.

Stacking analyses and deep X-ray surveys with the Chandra X-ray Observatory (hereafter Chandra) have enabled testing of these predictions out to cosmologically interesting distances. Stacking techniques generally involve the addition of X-ray counts at known positions of galaxies to yield average X-ray detections where individual sources lie below the detection threshold. For example, Hornschemeier et al. (2002, hereafter H02) used stacking with a $\approx 1$ Ms exposure of the Chandra Deep Field-North (CDF-N) to investigate the evolution of the X-ray luminosities of $z = 0.4–1.5$ spiral galaxies. This analysis shows suggestive evidence for evolution in X-ray luminosity with redshift at a level somewhat lower than that predicted by GW01. H02 also found that the X-ray to $B$-band luminosity ratio, $L_X/L_B$, is elevated for $z \approx 1$ spirals with rest-frame $L_B \approx L^*_B$ as compared with galaxies in the local Universe. $L_X/L_B$ has been shown to be linked to star formation activity. This is supported by the existence of an empirical correlation between $L_X/L_B$ and $L_{60\mu m}/L_{100\mu m}$ (Fabbiano & Shapley 2002). Here, the quantity $L_{60\mu m}/L_{100\mu m}$ is a measure of far infrared color temperature, which has been shown to increase with star formation activity (e.g., Helou et al. 1991). More recent stacking analyses of large samples of galaxies in the $\approx 2$ Ms CDF-N and $\approx 1$ Ms Chandra Deep Field-South (CDF-S) show that the X-ray properties of normal galaxies of all morphological types evolve similarly from $z = 0.4–1.5$ (Wu et al. 2004).

At higher redshifts ($z \approx 2–6$) stacking analyses have been performed using individually undetected normal galaxies (e.g., Brandt et al. 2001, hereafter B01; Nandra et al. 2002, hereafter N02; Malhotra et al. 2003; Bremer et al. 2004; Moustakas & Immler 2004 Reddy & Steidel 2004; Wang et al. 2004a). At $z \sim 3$ these galaxies often have mean X-ray luminosities and $L_X/L_B$ comparable to bright starburst galaxies in the local Universe. The heightened X-ray emission from these galaxies is probably due to newly formed high mass X-ray binaries (HMXBs) and young supernova remnants. HMXBs have much shorter formation timescales than LMXBs and are therefore more immediate tracers of cosmic star formation history.

Recently, large samples of galaxies have been identified at $z \sim 3$, 4, 5, and 6 as part of the Great Observatories Origins Deep Survey (GOODS). These galaxies were isolated via the
Lyman break technique (e.g., Steidel et al. 1995; Madau et al. 1996; Steidel et al. 1999), which estimates the redshift of a galaxy based on its "dropout" bandpass (see § 6.2.1). Lyman break galaxies (LBGs) generally show rest-frame UV/optical characteristics similar to those of local starburst galaxies—weak or absent Lyman $\alpha$ emission, P Cygni features from C IV and other lines, and strong interstellar UV absorption lines such as Si II, O I, C II, Si IV, and Al II (see e.g., Steidel et al. 1996; Shapley et al. 2003). The GOODS covers $\approx316$ arcmin$^2$ of sky in two fields, GOODS-North (GOODS-N) and GOODS-South (GOODS-S; Giavalisco et al. 2004a). Both fields are subregions of the Chandra Deep Fields for which Chandra has acquired an $\approx 2$ Ms observation of the CDF-N (Alexander et al. 2003, hereafter A03) and an $\approx 1$ Ms observation of the Chandra Deep Field-South (CDF-S; Giacconi et al. 2002; A03).

In this paper, we use stacking techniques to constrain the X-ray properties of LBGs in the GOODS fields. We improve on results from B01 and N02 by increasing the number of galaxies at $z \sim 3$ from 24 (B01) and 148 (N02) to 449, and we add to this samples of 1734, 629, and 247 galaxies at $z \sim 4, 5, \text{ and } 6$, respectively.

The Galactic column densities are $1.3 \times 10^{20}$ cm$^{-2}$ (Lockman 2003) and $8.0 \times 10^{19}$ cm$^{-2}$ (Stark et al. 1992) for the CDF-N and CDF-S, respectively. $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ are adopted throughout this paper (Spergel et al. 2003). Coordinates are J2000.0.

6.2 Analysis

6.2.1 Samples

The Lyman break technique has been utilized in the GOODS regions, where deep mosaic images have been taken using the HST Advanced Camera for Surveys (ACS) with bandpasses $B_{435}, V_{606}, i_{775}, \text{ and } z_{850}$ (Giavalisco et al. 2004b, hereafter G04); the full-depth, five-epoch ACS images have been used here. Additional ground-based photometry has been obtained over the GOODS fields in the $U$ band at KPNO (Capak et al. 2004, GOODS-N) and CTIO (GOODS-S). Identification of these LBGs is based on the following color equations:

$U$-dropouts:

$$ (U - B_{450}) \geq 0.75 + 0.5(B_{450} - z_{850}) \land $$

$$ (U - B_{450}) \geq 0.9 \land (B_{450} - z_{850}) \leq 4.0 $$

$B_{435}$-dropouts:

$$ (B_{450} - V_{606}) \geq 1.2 + 1.4 \times (V_{606} - z_{850}) \land $$

$$ (B_{450} - V_{606}) \geq 1.2 \land (V_{606} - z_{850}) \leq 1.2 $$

$V_{606}$-dropouts:

$$ [(V_{606} - i_{775}) > 1.5 + 0.9 \times (i_{775} - z_{850})] \lor $$

$$ [(V_{606} - i_{775}) > 2.0] \land (V_{606} - i_{775}) \geq 1.2 \land $$

$$ (i_{775} - z_{850}) \leq 1.3 \land S/N (B_{450}) < 2.0 $$

$i_{775}$-dropouts:

$$ (i_{775} - z_{850}) \geq 1.3 \land $$

$$ S/N (B_{450}) < 2.0 \land S/N (V_{606}) < 2.0 $$
Fig. 6.1: $z_{850}$ magnitude vs. redshift for X-ray stacking analyses of LBGs. Filled (our LBGs) and open symbols (other investigations) represent the estimated mean $z_{850}$ and redshift with error bars showing the 1σ spread for each quantity. The Brandt et al. (2001) measurements (plus signs) represent the positions of individual LBGs with spectroscopic redshifts.

Here the symbols $\wedge$ and $\vee$ correspond to the logical operators AND and OR, respectively. Monte Carlo simulations of the color-selection procedure (e.g., G04) indicate that these color criteria select galaxies with mean redshifts and 1σ redshift ranges of $z = 3.01 \pm 0.24$, $3.78 \pm 0.34$, $4.92 \pm 0.33$, and $5.74 \pm 0.36$ for $U$-, $B_{435}$-, $V_{606}$-, and $i_{775}$-dropouts, respectively. Dropout lists created in G04 were inspected and filtered to minimize the number of interlopers and contaminants in the samples. The interloper fraction is predicted to be $\approx 10\%$ for $U$-dropouts and $B_{435}$-dropouts. This fraction increases to become significant for $V_{606}$-dropouts and $i_{775}$-dropouts ($\approx 20\%$ and $40\%$, respectively; see Dickinson et al. 2004; G04).

The LBGs used in our stacking analyses have average redshifts and $z_{850}$ magnitudes as shown in Figure 6.1; for comparison the $z_{850}$ magnitudes of several other stacking analyses in this redshift range are also plotted. Galaxies in this survey probe relatively faint optical fluxes over a wider range of redshifts ($z \approx 3−6$) than those used for previous X-ray stacking analyses. The corresponding lookback times for $U$-, $B_{435}$-, $V_{606}$-, and $i_{775}$-dropouts are 11.5, 12.1, 12.5, and 12.7 Gyr, respectively (see, e.g., Hogg 2000).

The stacking procedure used in our analyses was similar to that of B01 and N02; the intent was to obtain average X-ray properties (e.g., luminosities and spectral shapes). At each LBG position, photon counts and effective exposure times (from exposure maps, which include the effects of vignetting) were extracted from circular apertures and summed to give a total number of counts and a total effective exposure time. We excluded LBGs located within 10″ of individually detected X-ray sources in A03; this avoids contamination by unrelated sources. This exclusion process led to the rejection of 99, 267, 127, and 31 $U$-, $B_{435}$-, $V_{606}$-, and $i_{775}$-dropouts, respectively ($\approx 18\%$, $13\%$, $17\%$, and $11\%$ of the respective LBG populations). A
Fig. 6.2: (a) The achieved signal-to-noise ratio (S/N) as a function of inclusion radius for stacking $U$-dropouts. Note that the number of stacked sources rises with increasing inclusion radius and is maximized at $\approx 9.0$. (b) Signal-to-noise ratio (S/N) as a function of extraction radius. Here, the signal is strongest for an aperture radius of $\approx 1.5\arcsec$. This process of optimizing the S/N was achieved iteratively and appears here in convergence.

small number of LBGs (18) were found to be within the positional errors of Chandra sources; their characteristics are given in § 6.3.1 and listed in Table 6.1.

The background was estimated through Monte Carlo analysis using a background map (see § 4.2 of A03). Each LBG position was shifted randomly within $25\arcsec$ of the original position, and background counts were obtained for each new position and summed just as they were for the LBGs themselves. This procedure was repeated 10,000 times to obtain an accurate estimate of the local background and its dispersion. To verify our results were not biased by gradients in the local background, we also tried shifting in regions with radii of $10\arcsec$, $15\arcsec$, $20\arcsec$, $30\arcsec$, and $35\arcsec$ and found no material differences in our results.

Our stacking procedure maximized the signal-to-noise ratio (hereafter, S/N)$^1$ by varying the aperture cell size for extracting X-ray counts and the off-axis angle (angle between a particular source and the average CDF-N or CDF-S aim points) within which sources were included in stacking. This procedure was performed using $U$-dropouts because of their strong X-ray signal. We avoided stacking sources that were outside a certain off-axis angle due to the increased size of the point-spread function (PSF) and confusion with background in this region. In the maximization process we chose a specific aperture cell size and stacked sources within various off-axis angles (hereafter, inclusion radii) until S/N was maximized. Sources within the resulting inclusion radius were then stacked using variable aperture cell sizes. S/N was maximized for a specific aperture cell size, and the process was repeated iteratively until convergence. Figures 6.2a and 6.2b show the result of this process. We found that S/N peaks for an inclusion radius $\approx 9.0$ and an aperture size of $\approx 1.5\arcsec$ (as expected for small off-axis angles); these values are used throughout our analyses.

$^1$Here, S/N $\equiv (S-B)/B^{0.5}$, where $S$ is the source plus background counts and $B$ is the average background counts obtained from the Monte Carlo procedure. This approximation is accurate for $|S-B| \ll B$ and $B \geq 20$, which applies to all cases in our analyses.
Table 6.1. X-ray Properties of Individually Detected LBGs

<table>
<thead>
<tr>
<th>Chandra Name</th>
<th>Dropout Bandpass</th>
<th>Pos. Er. (arcsec)</th>
<th>Offset (arcsec)</th>
<th>Counts SB (10^{-16} cgs)</th>
<th>$f_{0.5-2 \text{ keV}}$ (10^{-16} cgs)</th>
<th>$f_{2-8 \text{ keV}}$ (10^{-16} cgs)</th>
<th>$\Gamma$</th>
<th>$L_{\text{2-8 keV}}$ (10^{43} erg s^{-1})</th>
<th>$z_{850}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J033201.6−274327</td>
<td>$U$</td>
<td>0.4</td>
<td>0.15</td>
<td>2.726'</td>
<td>450.7</td>
<td>27.7</td>
<td>56.2</td>
<td>1.5</td>
<td>14.9</td>
</tr>
<tr>
<td>J033209.4−274807</td>
<td>$U$</td>
<td>0.3</td>
<td>0.10</td>
<td>2.81'</td>
<td>195.6</td>
<td>11.0</td>
<td>59.7</td>
<td>0.8</td>
<td>6.4</td>
</tr>
<tr>
<td>J033218.2−275241</td>
<td>$U$</td>
<td>0.6</td>
<td>0.10</td>
<td>2.80'</td>
<td>55.9</td>
<td>3.6</td>
<td>6.3</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>J033222.2−274937</td>
<td>$B_{335}$</td>
<td>0.6</td>
<td>0.19</td>
<td>—</td>
<td>10.1</td>
<td>0.6</td>
<td>&lt; 3.8</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>J033229.8−275106</td>
<td>$B_{335}$</td>
<td>0.6</td>
<td>0.14</td>
<td>3.70'</td>
<td>53.5</td>
<td>3.1</td>
<td>31.8</td>
<td>0.4</td>
<td>3.4</td>
</tr>
<tr>
<td>J033238.8−275122</td>
<td>$B_{335}$</td>
<td>0.6</td>
<td>0.25</td>
<td>—</td>
<td>16.2</td>
<td>1.1</td>
<td>8.9</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>J033239.1−274439</td>
<td>$B_{335}$</td>
<td>0.6</td>
<td>0.24</td>
<td>—</td>
<td>76.2</td>
<td>4.6</td>
<td>21.0</td>
<td>0.9</td>
<td>5.4</td>
</tr>
<tr>
<td>J033239.7−274851</td>
<td>$B_{335}$</td>
<td>0.3</td>
<td>0.14</td>
<td>3.64'</td>
<td>134.6</td>
<td>7.5</td>
<td>7.1</td>
<td>0.4</td>
<td>5.3</td>
</tr>
<tr>
<td>J033242.8−274702</td>
<td>$B_{335}$</td>
<td>0.6</td>
<td>0.13</td>
<td>3.19'</td>
<td>112.0</td>
<td>6.3</td>
<td>16.4</td>
<td>1.3</td>
<td>5.0</td>
</tr>
<tr>
<td>J033243.2−274914</td>
<td>$U$</td>
<td>0.3</td>
<td>0.02</td>
<td>1.92'</td>
<td>621.4</td>
<td>36.6</td>
<td>61.1</td>
<td>1.7</td>
<td>8.4</td>
</tr>
<tr>
<td>J033244.3−275251</td>
<td>$U$</td>
<td>0.7</td>
<td>0.29</td>
<td>3.47'</td>
<td>85.4</td>
<td>5.4</td>
<td>6.8</td>
<td>1.9</td>
<td>5.2</td>
</tr>
<tr>
<td>J033250.2−275252</td>
<td>$B_{335}$</td>
<td>0.4</td>
<td>0.33</td>
<td>3.6'</td>
<td>404.2</td>
<td>24.0</td>
<td>75.3</td>
<td>1.2</td>
<td>25.1</td>
</tr>
<tr>
<td>J123621.0+621412</td>
<td>$U$</td>
<td>0.6</td>
<td>0.16</td>
<td>1.74'</td>
<td>131.9</td>
<td>3.7</td>
<td>6.0</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>J123642.2+620612</td>
<td>$B_{335}$</td>
<td>0.4</td>
<td>0.39</td>
<td>0.70'</td>
<td>126.4</td>
<td>3.9</td>
<td>12.6</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>J123647.9+621020</td>
<td>$V_{606}$</td>
<td>0.6</td>
<td>0.26</td>
<td>—</td>
<td>28.1</td>
<td>0.8</td>
<td>19.4</td>
<td>&gt; 0.3</td>
<td>1.7</td>
</tr>
<tr>
<td>J123648.0+620941</td>
<td>$V_{606}$</td>
<td>0.6</td>
<td>0.23</td>
<td>5.18'</td>
<td>96.7</td>
<td>2.7</td>
<td>4.9</td>
<td>1.6</td>
<td>6.7</td>
</tr>
<tr>
<td>J123701.6+621146</td>
<td>$I_{775}$</td>
<td>0.6</td>
<td>0.43</td>
<td>1.52'</td>
<td>13.9</td>
<td>0.4</td>
<td>&lt; 1.2</td>
<td>1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>J123714.3+621208</td>
<td>$U$</td>
<td>0.6</td>
<td>0.14</td>
<td>3.14'</td>
<td>74.0</td>
<td>2.2</td>
<td>5.2</td>
<td>1.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Mean count rates $\Phi$ were calculated by subtracting our best estimate of the local background counts $B$ from the background plus source counts $S$ and dividing by the total effective exposure time $T$ [i.e., $\Phi = (S - B)/T$]. To convert count rate to flux we used the Galactic column densities discussed in § 6.1 and adopted a power-law photon index of $\Gamma = 2.0$, appropriate for starburst galaxies (e.g., Kim et al. 1992; Ptak et al. 1999). Sources were stacked in both the GOODS-N and GOODS-S fields, so we used a statistically weighted Galactic column density. X-ray luminosities were calculated following Schmidt & Green (1986):

$$L_X = 4\pi d_L^2 f_X (1+z)^{\Gamma-2} \text{ erg s}^{-1}$$

(6.5)

where $d_L$ is the luminosity distance (cm), and $f_X$ is the X-ray flux (erg cm$^{-2}$ s$^{-1}$).

### 6.2.2 Subsets

The large number of LBGs in our sample enabled investigation of the contribution of specific subsets to the signal. We chose to divide the original dropout lists based on galaxy morphology (U-dropouts only) and rest-frame $B$-band luminosity. We used the CAS morphology system (Conselice 2003, hereafter C03) to divide the U-dropout list according to the observed-frame $z_{850}$-band (rest-frame $\lambda\lambda 2000-2500$) concentration and asymmetry parameters. We note that the CAS parameters have been derived using rest-frame UV light and may have somewhat different physical interpretations than those quoted for the local Universe. Concentration ($C$) is proportional to the logarithm of the ratio of the radii containing 80% and 20% of the source flux:

$$C = 5 \times \log \left( \frac{r_{80\%}}{r_{20\%}} \right)$$

(6.6)

Galaxies with high $C$ values (e.g., bulge dominated systems locally) are generally brightest in their central regions (Conselice et al. 2002). Asymmetry ($A$) is defined for a galaxy by taking the absolute value of the difference in fluxes of the galaxy’s image and its 180 degree rotated analog and dividing by the original image flux (see Conselice, Bershady, & Jangren 2000; C03, for details). Generally disk-dominated systems and galaxy mergers are observed to have high $A$ values in the local Universe. Parameter values of $A = 0.1$ and $C = 2.7$ were chosen to divide the U-dropout list roughly in half, resulting in lists of LBGs with $A < 0.1$, $A > 0.1$, $C < 2.7$, and $C > 2.7$.

We also divided our original dropout lists into subsets based on rest-frame $B$-band luminosity. Rest-frame $B$-band luminosities were calculated using a spectral energy distribution (SED) and applying $K$-corrections to the fluxes (e.g., Schneider, Gunn, & Hoessel 1983; Hogg 2002). $K$-corrected ACS magnitudes were used in these computations, thus the derived rest-frame $B$-band luminosities are strongly dependent on the SED choice. An SED for LBGs was used in calculating $K$-corrections. This SED was derived from the Bruzual & Charlot (2003) solar metallicity models, with a Salpeter initial mass function, and aged by 144 Myr at constant SFR. Optically bright and faint sublists were generated by dividing each dropout list (i.e., $U$-, $B_{435}$-, $V_{606}$-, and $i_{775}$-dropouts) at its mean rest-frame $B$-band luminosity. This corresponding mean rest-frame $B$-band luminosities used in these divisions were $L_B \approx 5.3$, $5.5$, $4.1$, and $5.5 \times 10^{43}$ erg s$^{-1}$ ($M_B \approx -20.6$, $-20.5$, $-20.1$, $-20.6$) for $U$-, $B_{435}$-, $V_{606}$-, and $i_{775}$-dropouts, respectively. Because rest-frame $B$-band luminosity distributions are asymmetric with skew tails toward high luminosity, splitting at the mean leads to two lists with unequal sizes.
6.3 Results

6.3.1 Detected Sources

Over the GOODS fields seven $U$-dropouts, eight $B_{435}$-dropouts, two $V_{606}$-dropouts, and one $i_{775}$-dropout were found to be coincident with Chandra sources within the positional errors (see Table 6.1).\(^2\) Positional errors, photon counts, effective photon indices, and fluxes for these sources were determined in A03. The 2–8 keV X-ray luminosities were computed using eqn. 6.5.\(^3\) We investigated the probability of obtaining a false match by shifting all of our LBG positions and checking to see if the new positions were coincident with Chandra sources. LBG positions were shifted by 10\(''\) in 16 different directions, and an average of \(\approx 2\) detections were obtained for each direction.

Of the 18 detected sources, we find that 14 have corresponding spectroscopic (Barger et al. 2003a; Cristiani et al. 2004; Szokoly et al. 2004) and/or photometric (Barger et al. 2003a; Mobasher et al. 2004; Zheng et al. 2004) redshifts. Of these 14 sources, four (J123621.0+621412, J123642.2+620612, J123701.6+621146, J033243.2–274914) have redshifts inconsistent with those determined by the Lyman break technique. We note that the redshifts derived for three of the four sources (J123621.0+621412, J123642.2+620612, and J123701.6+621146) are photometric redshifts, implying there are still uncertainties in their values. These may perhaps be dismissed as being “inconsistent.” The spectroscopic redshift of \(z = 1.92\) for $U$-dropout J033243.2–274914 would therefore be the only remaining discrepant case. This LBG may be an interloper (see § 6.2.1 for probabilities) or falsely matched. Furthermore, the colors of some AGN may satisfy the color criteria used to select normal galaxies of differing redshifts. This may cause a discrepancy between spectroscopic and color-selected redshifts derived for these AGN.

The detected sources are mostly AGN with moderate luminosities (i.e., \(L_X \approx 10^{43}–10^{44.5}\) erg s\(^{-1}\)), characteristic of luminous Seyfert type galaxies to quasars. Several of these sources have been characterized in previous investigations. J123648.0+620941 is the highest redshift quasar known (\(z = 5.186\)) in the CDF-N and -S fields (e.g., Barger et al. 2003b; Vignali et al. 2002). J033201.6–274327, J033218.2–275241, J033243.2–274914, J033244.3–275251 (Szokoly et al. 2004), and J033209.4–274807 (Schreier et al. 2001) have been spectroscopically classified as broad-line AGN. J123701.6+621146 and J123647.9+620941 are both Very Red Objects (\(I–K \geq 4\), VROs; Alexander et al. 2002a). J033229.8–275105 has been identified as a putative type 2 QSO (Norman et al. 2002). Finally, three additional sources (J033239.7–274851, J033242.8–274702, and J033250.2–275252) have been cataloged as high-redshift QSO candidates (Cristiani et al. 2004).

Following Alexander et al. (2002b) we assume detected sources with 2–8 keV \(L_X > 1.5 \times 10^{42}\) erg s\(^{-1}\) or \(\Gamma < 1.0\) are AGN. Only one source (J123642.2+620612) falls outside these criteria, leaving 17 clear AGN. The derived AGN fractions for our $U$-, $B_{435}$-, $V_{606}$-, and $i_{775}$-dropouts are \(\approx 1.2%\), \(0.4%\), \(0.3%\), and \(0.4%\), respectively; these fractions are lower than others.

\(^2\)Note that the Lyman break technique is a statistical process for isolating galaxies at a given redshift. Due to the statistical nature of this process, we do not expect to recover all objects within the ACS flux limits that may reside at the redshifts under investigation here.

\(^3\)For reference, the on-axis sensitivity limit for the 2 Ms CDF-N is \(\approx 2.5 \times 10^{-17}\) erg cm\(^{-2}\) s\(^{-1}\) in the soft band corresponding to rest-frame 2–8 keV luminosities of 2.0, 4.0, 6.8, and \(10.4 \times 10^{42}\) erg s\(^{-1}\) at \(z = 3\), 4, 5, and 6, respectively (\(\Gamma = 2\)).
found in previous investigations. For comparison, the AGN fraction derived from N02 is \( \approx 2.7\% \). In comparison to our \( B_{435\,\text{-}}, V_{606\,\text{-}}, \) and \( i_{775\,\text{-}} \)-dropouts, our \( U \)-dropouts and the LBGs used by N02 are relatively luminous in the optical. The corresponding AGN fractions therefore suggest X-ray luminous AGN are generally optically luminous as well.

### 6.3.2 Stacked Sources

The results of our stacking analyses of individually undetected sources are found in Table 6.2. Hereafter, unless stated otherwise, we discuss the results in reference to the soft-band stacking analyses where we obtain significant detections; we do not obtain significant detections in the hard- or full-bands (this result is understandable due to the significantly lower background in the soft-band). The stacking procedure was repeated for the GOODS-N and GOODS-S fields individually; results from the two fields were statistically consistent. Generally, we detect the stacked emission from \( U \)-dropouts (\( \sim 7\sigma \)) and all subsets generated therefrom. We do not obtain significant detections (S/N > 3\( \sigma \)) for general samples of \( B_{435\,\text{-}}, V_{606\,\text{-}}, \) and \( i_{775\,\text{-}} \)-dropouts, but we note a suggestive positive fluctuation (\( \sim 2\sigma \)) for our \( B_{435\,\text{-}} \)-dropouts. We do, however, obtain a significant detection for the bright subset of \( B_{435\,\text{-}} \)-dropouts (\( \sim 3\sigma \)). Figure 6.3a shows the distributions of counts obtained for the individual galaxies being stacked for both \( U \)-dropouts and the bright subset of \( B_{435\,\text{-}} \)-dropouts. We obtained an average of 3.1 and 2.3 counts per cell for \( U \)- and bright \( B_{435\,\text{-}} \)-dropouts, respectively. The summed numbers of source plus background counts were 1351 counts for \( U \)-dropouts and 926 for bright \( B_{435\,\text{-}} \)-dropouts. In the 10,000 Monte Carlo trials where we shifted the aperture cells to random positions and summed background counts, we found that no trials produced \( \gtrsim 1351 \) counts for \( U \)-dropouts and only 6 trials produced \( \gtrsim 926 \) counts for \( B_{435\,\text{-}} \)-dropouts. Gaussian statistics predict \( \approx 0 \) and 5 Monte Carlo trials should exceed the total source plus background counts for our analysis of \( U \)-dropouts and bright \( B_{435\,\text{-}} \)-dropouts, respectively. Figure 6.3b shows the Monte Carlo distributions obtained when stacking random positions over 10,000 trials. In both cases the detection confidence levels are greater than 99.9\%.

Stacked and smoothed images are displayed in Figure 6.4. The images have effective exposure times of \( \approx 0.7 \) and 0.5 Gs (22 and 16 yr) for \( U \)- and bright \( B_{435\,\text{-}} \)-dropouts, respectively. Stacked \( V_{606\,\text{-}} \) and \( i_{775\,\text{-}} \)-dropouts and subsets thereof produced no significant detections (i.e, S/N < 3\( \sigma \)). We also attempted to merge the bright subsets of \( V_{606\,\text{-}} \)-dropouts and \( i_{775\,\text{-}} \)-dropouts and failed to obtain detections. X-ray emission constraints for these LBGs are tabulated in Table 6.2.

### 6.4 Discussion

Using the \( \approx 2 \) Ms CDF-N plus \( \approx 1 \) Ms CDF-S we have placed constraints on the X-ray properties of LBGs identified in the 316 arcmin\(^2\) GOODS-N and -S fields. We have used X-ray stacking techniques on samples of 449, 1734, 629, and 247 individually undetected LBGs at \( z \sim 3, 4, 5, \) and 6, respectively (\( U \)-, \( B_{435\,\text{-}}, V_{606\,\text{-}}, \) and \( i_{775\,\text{-}} \)-dropouts, respectively) to obtain their average X-ray properties. X-ray emission from LBGs is expected to be largely due to activity associated with star-forming processes (e.g., HMXBs and young supernova remnants) with a low-level contribution from low-luminosity AGN (LLAGN; e.g., Ho et al. 2001). With the intent to investigate normal/starburst galaxies we have rejected LBGs coincident with known \textit{Chandra} sources from our stacking analyses. Considering \textit{Chandra}'s superb sensitivity for detecting luminous AGN, we are confident that this rejection process has effectively removed strong accretion-dominated
### Table 6.2. Stacking Results For Normal LBGs

<table>
<thead>
<tr>
<th>Data Type (1)</th>
<th>Dropout (2)</th>
<th>(N) (3)</th>
<th>S/N (4)</th>
<th>E(Ms) (5)</th>
<th>(N_{\text{trials}} &gt; S) (6)</th>
<th>(f_X) (10(^{18}) erg cm(^{-2}) s(^{-1})) (7)</th>
<th>(L_X) (10(^{41}) ergs s(^{-1})) (8)</th>
<th>(L_B) (10(^{43}) ergs s(^{-1})) (9)</th>
<th>(\log(L_X/L_B)) (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>(U) 449</td>
<td>7.1</td>
<td>663.9</td>
<td>0</td>
<td>1.9 ± 0.4</td>
<td>1.5 ± 0.3</td>
<td>5.3</td>
<td>-2.6 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Bright</td>
<td>(U) 201</td>
<td>5.9</td>
<td>274.8</td>
<td>0</td>
<td>2.4 ± 0.6</td>
<td>1.9 ± 0.5</td>
<td>10.3</td>
<td>-2.7 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>Dim</td>
<td>(U) 248</td>
<td>4.2</td>
<td>389.2</td>
<td>0</td>
<td>1.5 ± 0.5</td>
<td>1.2 ± 0.4</td>
<td>3.1</td>
<td>-2.4 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>(C &gt; 2.7)</td>
<td>(U) 223</td>
<td>4.8</td>
<td>332.7</td>
<td>0</td>
<td>1.8 ± 0.6</td>
<td>1.4 ± 0.4</td>
<td>4.5</td>
<td>-2.5 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>(C \leq 2.7)</td>
<td>(U) 226</td>
<td>5.2</td>
<td>331.2</td>
<td>0</td>
<td>1.9 ± 0.6</td>
<td>1.5 ± 0.4</td>
<td>6.1</td>
<td>-2.6 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>(A &gt; 0.1)</td>
<td>(U) 213</td>
<td>6.4</td>
<td>312.7</td>
<td>0</td>
<td>2.5 ± 0.6</td>
<td>2.0 ± 0.5</td>
<td>6.7</td>
<td>-2.5 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>(A \leq 0.1)</td>
<td>(U) 236</td>
<td>3.6</td>
<td>351.2</td>
<td>0</td>
<td>1.3 ± 0.5</td>
<td>1.0 ± 0.4</td>
<td>4.3</td>
<td>-2.6 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>(B_{435})1734</td>
<td>2.1</td>
<td>2102.2</td>
<td>197</td>
<td>(\lesssim 0.6)</td>
<td>(\lesssim 0.9)</td>
<td>2.9</td>
<td>(\lesssim -2.4)</td>
<td></td>
</tr>
<tr>
<td>Bright</td>
<td>(B_{435})395</td>
<td>3.2</td>
<td>485.5</td>
<td>6</td>
<td>1.0 ± 0.5</td>
<td>1.4 ± 0.6</td>
<td>9.2</td>
<td>-2.8 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Dim</td>
<td>(B_{435})1339</td>
<td>0.6</td>
<td>1616.8</td>
<td>2783</td>
<td>(\lesssim 0.7)</td>
<td>(\lesssim 1.0)</td>
<td>2.1</td>
<td>(\lesssim -2.7)</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>(V_{606})629</td>
<td>0.2</td>
<td>804.9</td>
<td>4067</td>
<td>(\lesssim 1.0)</td>
<td>(\lesssim 2.8)</td>
<td>2.6</td>
<td>(\lesssim -2.8)</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>(i_{775})247</td>
<td>1.2</td>
<td>296.0</td>
<td>1065</td>
<td>(\lesssim 1.7)</td>
<td>(\lesssim 7.1)</td>
<td>3.7</td>
<td>(\lesssim -1.8)</td>
<td></td>
</tr>
</tbody>
</table>

Note. — The data apply to stacking analyses in the soft band. Col.(1): Description of the LBG sample stacked. “Bright” and “Dim” subsets were created by splitting the “General” lists at rest-frame \(B\)-band luminosities \(\approx 5.3 \times 10^{43}\) erg s\(^{-1}\) (for \(U\)-dropouts and \(B_{435}\)-dropouts, respectively. Col.(2): Photometric dropout bandpass. Col.(3): Number of sources being stacked. Col.(4): Signal-to-noise ratio \((S−B)/B^{1.5}\). Col.(5): Total, stacked effective exposure time. Col.(6): Number of Monte Carlo trials (out of 10,000) that produced a background estimate \(> S\). Col.(7): X-ray (0.5–2 keV) flux. Col.(8): 2–8 keV rest-frame luminosity. Col.(9): Rest-frame \(B\)-band luminosity. Col.(10): Logarithm of X-ray to \(B\)-band luminosity ratio.
Fig. 6.3: (a) Histogram of the count distribution for $U$-dropouts (upper panel) and $B_{435}$-dropouts (lower panel). The vertical dotted lines show the mean source plus background counts per aperture cell, and the vertical dashed lines show the mean background counts per aperture cell. (b) Results from Monte Carlo estimates of the background level for $U$-dropouts (upper panel) and $B_{435}$-dropouts (lower panel). The detection level is represented with downward pointing arrows.

Fig. 6.4: Stacked soft-band images of 449 $U$-dropouts ($\approx 0.7$ Gs exposure) and 395 optically bright $B_{435}$-dropouts ($\approx 0.5$ Gs exposure). Stacked emission from these LBGs is significantly detected in the soft-band with significances of $\sim 7\sigma$ ($U$-dropouts) and $\sim 3\sigma$ (bright $B_{435}$-dropouts). The images are $15'' \times 15''$ ($0''5$ pixel$^{-1}$) and were adaptively smoothed at $2.5\sigma$ using the CIAO tool CSMOOTH. The faint "nebulosity" observed in the optically bright $B_{435}$-dropouts is attributed to smoothing over noise. The black circles are centered on our $1''5$ radius aperture cell that was used in the stacking analyses.
X-ray sources that would heavily contaminate our stacked signal. We have identified 18 LBGs coincident with Chandra sources (see § 6.3.1). With the possible exception of one source we find these objects are moderately luminous AGN comprising ≈0.5% of the LBG population from $z \sim 3$–6.

Using our stacking procedure (see § 6.2) we detect X-ray emission from LBGs at $z \sim 3$ and an optically bright subset of LBGs at $z \sim 4$. X-ray count rates derived from our soft-band detections and hard-band upper limits (3σ) were used to constrain the spectral slopes of these LBGs. The 2–8 keV to 0.5–2 keV band ratio ($\Phi_{2–8 \text{ keV}}/\Phi_{0.5–2 \text{ keV}}$) is calculated to be < 0.9 for $U$-dropouts corresponding to an effective photon index lower limit of $\Gamma > 0.8$; a consistent, less tightly constrained photon index is also derived for our bright $B_{435}$-dropouts. This lower limit is consistent with our assumed $\Gamma = 2$ photon index, which is expected for galaxies with high star formation activity. The derived average 2–8 keV X-ray luminosities for these LBGs are $\approx 1.5$ and $1.4 \times 10^{41}$ erg s$^{-1}$ for $U$-dropouts and bright $B_{435}$-dropouts, respectively, a factor of $\approx 5$–10 times higher than for typical starburst galaxies in the local Universe (e.g., M82; Griffiths et al. 2000). Furthermore, our LBGs are a factor of $\approx 2$ less X-ray luminous than those studied by B01 and N02.

Assuming the X-ray luminosity functions of our individually undetected LBGs at high redshifts have similar functional forms to those of normal/starburst galaxies in the local Universe, we can estimate the expected median X-ray luminosities for these LBGs. This is important because, for a luminosity function with significant skewness, the median will differ from the mean. We have investigated this using the David et al. (1992, hereafter DJF92) sample of 71 normal/starburst galaxies in the local Universe and find the mean to median X-ray luminosity ratio $L_{X}^{\text{mean}}/L_{X}^{\text{median}} \approx 5$. The mean 2–8 keV X-ray luminosity for these 71 galaxies is $\approx 6 \times 10^{40}$ erg s$^{-1}$, a factor of $\approx 2.5$ lower than the mean X-ray luminosities of our $U$-dropouts and optically bright subset of $B_{435}$-dropouts. If we assume the $L_{X}^{\text{mean}}/L_{X}^{\text{median}}$ ratio for our LBGs is similar to that of the DJF92 sample, the corresponding median 2–8 keV X-ray luminosity would be $\approx 3 \times 10^{40}$ erg s$^{-1}$.

The strong $U$-dropout signal allows investigation of the contribution of specific subsets to the photon statistics (see § 6.2.2 for details and Table 6.2 for results). We find that the optically luminous $U$-dropouts contribute most of the X-ray flux ($S/N_{\text{bright}} \approx 1.5 \times S/N_{\text{dim}}$). It is possible that the emission from rest-frame UV may be heavily obscured by dust as would be expected if LBGs were a “scaled-up” population of ultraluminous infrared galaxies (ULIRGs; e.g., Goldader et al. 2002). The X-ray to $B$-band mean luminosity ratios for these LBGs suggests that this is likely not the case, and the intrinsic dust attenuation from LBGs is similar to that expected for star-forming galaxies (see Seibert et al. 2002). We find that relatively asymmetric sources ($A > 0.1$) dominate the photon counts. However, the rest-frame $B$-band luminosities of these LBGs are somewhat elevated as compared with sources of low-asymmetry index (i.e., $A \leq 0.1$), and we therefore offer no further interpretation. Furthermore, stacking of the two LBG subsets split by concentration index ($C > 2.7$ and $C \leq 2.7$) show that these two morphological subsets have similar X-ray properties. No additional information was extracted from our divisions on asymmetry and concentration.

Recent investigations have found that hard X-ray emission largely associated with HMXBs can be used as a direct indicator of SFR (e.g., Bauer et al. 2002; Ranalli et al. 2003; Grimm et al. 2003; Persic et al. 2004). If we assume the majority of the X-ray emission from our stacked detections of $U$-dropouts and bright $B_{435}$-dropouts is unobscured X-ray emission from HMXBs,
we expect the corresponding mean SFRs to be $\approx 85–240 \, M_\odot \, yr^{-1}$. These SFRs were derived using the linear SFR–$L_{2–10 \, keV}$ relation given by equation 2 of Persic et al. (2004) assuming a correlation error of 20%. For comparison, the mean SFRs derived from the rest-frame 1500 Å fluxes are estimated to be $\approx 65$ and $10 M_\odot \, yr^{-1}$ for our $U$-dropouts and bright $B_{435}$-dropouts, respectively, without UV extinction. When a correction is made for dust extinction, the corresponding SFRs are $\approx 400$ and $60 M_\odot \, yr^{-1}$ (see G04). The reasonable agreement between the X-ray and UV extinction-corrected derived SFRs broadly supports our assumption that the X-ray emission is dominated by star-forming processes with little contribution needed from LLAGN.

The X-ray luminosities for star-forming galaxies (such as LBGs) are potential tracers of global star formation history (Lilly et al. 1996; Madau et al. 1996; Blain et al. 1999). A global estimate of the SFR can be implicitly drawn from these LBGs by considering the mean X-ray luminosity per mean B-band luminosity, $L_X/L_B$ (mean quantities). The power-law index ($\alpha$) for this relation has been reported to range from $\approx 1$ (Fabbiano & Trinchieri 1985; DJF92) to as high as $\approx 1.5$ (Shapley et al. 2001) for galaxies in the local Universe. We find that $L_X/L_B$ shows suggestive evidence for evolution with redshift as illustrated in Figure 6.5a. Here our $U$-dropouts and bright $B_{435}$-dropouts are plotted and compared with the results for normal galaxies at $z \approx 0$ (DJF92) and early-type spirals from

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4In our stacking analyses we compute an average $L_X$ for a given stack of source positions. We therefore refer to $L_X/L_B$ as meaning $\langle L_X \rangle / \langle L_B \rangle$, where $\langle L_X \rangle$ and $\langle L_B \rangle$ are mean quantities. When necessary for comparisons, data regarding $L_X/L_B$ have been converted to this form.
\[ z \approx 0.05–1.5 \] (Wu et al. 2004). From these data we infer a peak in \( L_X/L_B \) at \( z \approx 1.5–3.0 \), consistent with predictions of GW01. These results, while based on larger samples of galaxies, are consistent with the near constancy of \( L_X/L_{UV} \) at \( z \sim 1 \) and \( z \sim 3 \) reported by N02 for Balmer break galaxies and LBGs, respectively. In this description the global SFR is expected to peak at \( z \approx 2.5–3.5 \). During this epoch, X-ray emission is observed due to contributions from HMXBs and supernovae. Shortly after the UV luminous population evolves, X-ray emission will continue in the form of LMXBs resulting in an increase in \( L_X/L_B \).

When stacking LBGs at higher redshift, \( z \sim 5 \) and 6 (\( V_{606} \)- and \( i_{775} \)-dropouts, respectively), we do not obtain significant detections. The AGN contribution may be slightly more significant for these LBGs where the Chandra exposures are only capable of detecting individual objects with \( 2–8 \) keV luminosities \( \gtrsim 10^{43} \) erg s\(^{-1} \) (implying many Seyfert type AGN might not be individually detected at these redshifts). In light of these limits we therefore place constraints on the average AGN content of these LBGs. The derived rest-frame 2–8 keV luminosity upper limits (3\( \sigma \)) for the \( V_{606} \)- and \( i_{775} \)-dropouts are 2.8 and \( 7.1 \times 10^{41} \) erg s\(^{-1} \). Such upper limits are characteristic of bright starburst or low-luminosity Seyfert type galaxies and are the tightest constraints yet to be placed on the X-ray properties of LBGs at \( z \gtrsim 5 \). For comparison, X-ray analyses of 44 LBGs at \( z \sim 5 \) (Bremer et al. 2003) and 54 LBGs at \( z \sim 6 \) (Moustakas & Immler 2004) constrain their average 2–8 keV X-ray luminosities to be less than 3 and \( 7 \times 10^{42} \) erg s\(^{-1} \) (3\( \sigma \)), respectively.

Figure 6.5b shows the overall \( L_X/L_B \) vs \( L_X \) results for both individually detected and stacked LBGs. Stacking analyses show that the individually undetected LBGs at \( z \sim 3, 4, 5, \) and 6 have \( L_X/L_B \) ratios characteristic of local starburst galaxies. Our individually detected LBGs have much larger \( L_X/L_B \) ratios, which are expected for X-ray luminous AGN.
Chapter 7

Key Discoveries of this Thesis

The body of work presented in this thesis represents new and exciting contributions to our knowledge of the X-ray properties and evolution of normal (non-AGN) galaxies through deep Chandra observations. This work has been carried out over the years 2004–2007, a time when the Chandra Deep Fields (CDFs) received important new observations from Chandra (e.g., through the Extended Chandra Deep Field-South survey; see Chapter 2) and other multiwavelength (e.g., through HST, Spitzer, ATCA, COMBO-17, etc.) instruments. In the points below, I outline the key discoveries presented in this thesis.

1. For the first time, we investigated the X-ray activity from early-type galaxies in the last half of cosmic time (i.e., since $z \approx 0.7$). We found that for massive early-type galaxies, the soft (0.5–2 keV) X-ray emission is likely dominated by hot interstellar gas and does not seem to undergo significant evolution with redshift. The near constancy of the hot gas X-ray emission suggests that some significant form of heating must occur to keep the gas from cooling. We show that the gas must be poorly heated by radiation from the luminous AGN population, which evolves strongly over the redshift range; however, kinetic feedback from AGNs may provide significant heating of the gas so long as the kinetic power does not evolve strongly (see Chapter 3).

2. Off-nuclear X-ray sources in late-type galaxies at intermediate redshifts ($z \approx 0.05–0.3$) have X-ray luminosities and optical environments similar to intermediate-luminosity X-ray objects and ultraluminous X-ray sources in the local universe, which are commonly found in star-forming regions. We found that the fraction of galaxies hosting these off-nuclear sources has suggestively increased from $z \approx 0–0.15$ in a manner consistent with the increase in global star-formation activity over this redshift range (see Chapter 4).

3. We found that the mean X-ray luminosities of late-type galaxy populations at $z \approx 0–1.4$ are well correlated with their population-averaged star-formation rates (over the range SFR $= 1–100 \, M_\odot \, \text{yr}^{-1}$). For late-type galaxy populations that were selected using equal intervals of luminosity or stellar mass, in several redshift bins, we found that the X-ray activity evolves by a factor of $\approx 4–10$ over the redshift range of $z \approx 0–1.4$. We also found evidence for “cosmic downsizing” such that X-ray activity, which is associated with star-formation activity, peaks at lower redshifts for lower-mass galaxies than it does for more massive galaxies (see Chapter 5).

4. For Lyman break galaxies (LBGs) at redshift near the peak era of star-formation activity in the Universe ($z \sim 3–4$), the X-ray emission and star-formation properties of these galaxies are on average similar to the most active star-forming galaxies in the local universe. When comparing the LBG population to late-type galaxies at $z \approx 0–1.4$, we found suggestive evidence for a peak in the X-ray activity at $z \approx 1.4–3$ (Chapter 6).
Bibliography

Buckley, J., & James, I. 1979, Biometrika, 66, 439
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