THE STAR FORMATION AND NUCLEAR ACCRETION HISTORIES OF NORMAL GALAXIES IN THE AGES SURVEY

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ABSTRACT

We combine IR, optical, and X-ray data from the overlapping, 9.3 deg² NOAO Deep Wide-Field Survey, AGN and Galaxy Evolution Survey (AGES), and XBootes Survey to measure the X-ray evolution of 6146 normal galaxies as a function of absolute optical luminosity, redshift, and spectral type over the largely unexplored redshift range 0.1 ≲ z ≲ 0.5. Because only the closest or brightest of the galaxies are individually detected in X-rays, we use a stacking analysis to determine the mean properties of the sample. Our results suggest that X-ray emission from spectroscopically late-type galaxies is dominated by star formation, while that from early-type galaxies is dominated by a combination of hot gas and active galactic nucleus (AGN) emission. We find that the mean star formation and supermassive black hole accretion rate densities evolve like ∼ (1 + z)³±¹, in agreement with the trends found for samples of bright, individually detectable starburst galaxies and AGN. Our work also corroborates the results of many previous stacking analyses of faint source populations, with improved statistics.

Key words: cosmology: observations – Galaxy: evolution

1. INTRODUCTION

There are three primary sources of galactic X-ray emission: diffuse, hot gas, accreting stellar remnants, such as X-ray binaries, and accreting supermassive black holes (SMBHs), i.e., active galactic nuclei (AGNs). Apart from nearby ellipticals, which tend to be dominated by hot gas emission (e.g., Forman et al. 1994), local surveys indicate that X-ray binaries dominate the flux from “normal” galaxies with quiescent nuclei (e.g., Fabbiano & White 2003; Smith & Wilson 2003; Muno et al. 2004). There are two distinct populations of X-ray binaries: the short-lived (≲ 10⁶ yr), high-mass X-ray binaries (HMXBs) and the long-lived (≳ 10⁹ yr), low-mass X-ray binaries (LMXBs). Because of their short lifetimes, one expects the X-ray emission from HMXBs to track the current star formation rate (SFR). In contrast, the X-ray emission from longer lived LMXBs should track the integrated stellar mass. Kim & Fabbiano (2004) find that

\[ L_{\chi,\text{HMXB}}^{\text{LMAXX}} \simeq 0.67 \times 10^{40}\left(\frac{\text{SFR}}{M_{\odot} \text{yr}^{-1}}\right) \text{ergs s}^{-1}. \]  

In contrast, the (total band: 0.5–8 keV) X-ray emission from LMXBs is well correlated with the K-band flux of galaxies, which in turn is a good tracer of stellar mass. Kim & Fabbiano (2004) find that

\[ L_{\text{X,LMXB}} \simeq 10^{40}\left(\frac{L_K}{L_{K,\star}}\right) \text{ergs s}^{-1}, \]  

where \( L_{K,\star} = \nu_{K} L_{\nu,\star} = 2.6 \times 10^{43} \text{erg s}^{-1} \) corresponds to \( M_{K,\star} = -23.4 \text{mag} \) (Kochanek et al. 2001).

Because the stellar mass density evolves slowly between \( z = 0 \) and \( z \approx 0.5 \) (e.g., Bell 2004 and references therein), we expect little change in the number of LMXBs and assume that Equation (2) holds out to \( z \approx 0.5 \). On the other hand, the SFR density rises rapidly with look-back time, (e.g., \( \propto (1+z)^{7.7\pm0.7} \)) Hogg 2001), so we should see a correspondingly rapid evolution in the X-ray flux of star-forming galaxies due to the increasing number of HMXBs.

The accretion luminosity density of AGNs also rises rapidly with redshift (e.g., \( \propto (1+z)^{2.4\pm0.8} \)) Barger et al. 2005 with higher densities of more luminous sources at higher redshifts (e.g., Barger et al. 2001; Cowie et al. 2003; Ueda et al. 2003; Miyaji 2004; Hasinger 2004; Hasinger et al. 2005). The observed trends suggest that faint AGNs with characteristic X-ray luminosities.
approaching those of bright starbursts, $L_{\text{x}} \lesssim 10^{41}$ erg s$^{-1}$, may be most abundant at $z \lesssim 1$ and, if so, they could produce a substantial fraction of the “normal” galaxy X-ray flux at these redshifts.

Given their similar evolution, spectral shapes (e.g., Ptak et al. 1999), and potentially similar luminosities, it may be difficult to disentangle the X-ray emission from AGNs and star formation at $z \lesssim 1$. Probing the X-ray evolution of normal galaxies between $z \approx 0.1$ and $z \approx 1$ is also difficult, because it requires relatively deep observations over relatively wide areas. In fact, most of our knowledge about the X-ray properties of galaxies still comes from either large-area, local surveys (e.g., Fabbiano 1989; David et al. 1992) or high-redshift, small-volume deep fields (e.g., Georgakakis et al. 2007; Ptak et al. 2007; Tzanavaris & Georgantopoulos 2008).

This is the second in a series of papers in which we attempt to bridge this gap by examining the X-ray evolution of galaxies within the 9.3 deg$^2$ Boötes field of the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999; B. T. Jannuzi et al. 2009, in preparation, A. Dey et al. 2009, in preparation). The XBOötes survey (Murray et al. 2005) obtained a 5 ks Chandra mosaic of the entire 9.3 deg$^2$ field based on 126 ACIS-I pointings. These data are too shallow, however, to detect typical galaxies even at modest redshifts. Fortunately, the wide area of the survey allows us to measure the mean properties of a large, representative population of galaxies by “stacking” (averaging) their X-ray emission (Brandt et al. 2001; Nandra et al. 2002; Hornschemeier et al. 2002; Georgakakis et al. 2003; Lehmer et al. 2005, 2007, 2008; Laird et al. 2005, 2006).

In the first paper in the series, Brand et al. (2005; hereafter B05) employed the stacking technique to examine the X-ray luminosity evolution of $\sim 3300$ optically luminous ($\sim L_*$), red galaxies with photometric redshifts $0.3 < z < 0.9$. By constraining the sample to have the same evolution-corrected, absolute $R$-band magnitude distribution at all redshifts ($M_R < -21.3$, $\langle M_R \rangle \simeq -22.0$), it was possible to follow the nuclear accretion histories of a consistent population of galaxies throughout this epoch. Because these massive, early-type galaxies are the typical hosts of powerful quasars at higher redshifts (McLeod & McLeod 2001; Dunlop et al. 2003), tracking the decay of their nuclear activity to lower redshifts is essential to our understanding of the decline in SMBH accretion from its peak during the quasar phase ($z \gtrsim 2$) to the present. The observed variation in the nuclear accretion rate of the $> L_*$, red galaxies, $L_{\text{x}} \propto (1 + z)^{4.4 \pm 0.4}$, is broadly consistent with the behavior of a bright, individually detected AGNs studied by Barger et al. (2001, hereafter Ba01) and Barger et al. (2005, hereafter Ba05).

In the present paper, we combine the NDWFS and XBOötes surveys with redshifts from the AGN and Galaxy Evolution Survey (AGES, C. S. Kochanek et al. 2009, in preparation) to study the X-ray properties of a complete, flux-limited sample of galaxies as a function of absolute optical luminosity, redshift, stellar mass, and spectral type. While our general procedures are similar to those of other recent stacking analyses (e.g., Brandt et al. 2001; Nandra et al. 2002; Hornschemeier et al. 2002; Georgakakis et al. 2003; Laird et al. 2005, 2006; Lehmer et al. 2007), the number of objects we consider ($\approx 6500$) is 10–100 times larger. The size of our sample allows us to correct the mean exposure time of the XBOötes survey (5 ks) into stacked, effective exposure times that are large enough to detect galaxies at intermediate redshift (Msec).

In Section 2, we describe the data and illustrate our ability to detect X-ray emission from the AGES galaxies through the stacking approach. In Section 3, we provide further details of our stacking analysis and use Monte Carlo simulations to test it and to refine our choices of signal and background apertures. In Section 4, we present measurements of the mean evolution of all the AGES galaxies. We then consider the radial emission profiles of a nearby ($z \lesssim 0.1$) subsample in order to test for weak/obscured AGNs. We also examine the hardness and X-ray to optical luminosity ratios as a function of redshift, stellar mass, and spectroscopic type (late-type, early-type, or AGN). Based on these tests, we evaluate the relative contributions of hot gas, LMXBs, HMXBs, and AGNs emission to the observed signal. We then discuss our results and compare them to previous studies. Lastly, we determine the evolution of the SFR per unit galactic stellar mass and the SFR density based on emission from the late-type galaxy sample and trace the evolution of the nuclear accretion rate and accretion rate density of AGNs in the early-type galaxy sample. We summarize our findings in Section 5. Throughout the paper, we assume a flat $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda,0} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. THE X-RAY DATA, THE GALAXY SAMPLE AND METHODS

The NDWFS obtained $B$, $I$, $R$, and (partial) $K$-band observations of two roughly 9.3 deg$^2$ regions. The Northern Boötes field has also been surveyed at radio (VLA FIRST, Becker et al. 1995; WSRT, de Vries et al. 2002), far-IR (Spitzer/MIPS, Soifer 2004), mid-IR (Spitzer/IRAC, The IRAC Shallow Survey, Eisenhardt et al. 2004), near-IR (NDWFS and the Flamingos Extragalactic Survey; Elston et al. 2006), UV (GALEX; Hoopes 2004), and X-ray (XBOötes, Murray et al. 2005) wavelengths. In particular, the XBOötes survey covered the entire Northern Boötes field with 126 $17' \times 17'$ ACIS-I images of mean exposure time 5 ks using the Chandra X-ray Observatory (Murray et al. 2005). The survey detected approximately 3300 point sources and 43 extended sources in the field with $\geq 4$ counts (4767 sources with $\geq 2$ counts; Kenter et al. 2005).

2.1. X-ray Data

For our current analysis, we use the positions of the 420,000 photons detected in the XBOötes observations, with weights correcting for off-axis vignetting and variations in exposure time, their estimated energies $\epsilon \pm \delta \epsilon$, and their positions relative to the pointing center of the observations. We limited the analysis to photons with $0.5 < \epsilon < 7$ keV, dividing them into total (0.5–7 keV), soft (0.5–2 keV), and hard (2–7 keV) energy bands. The mean total, hard, and soft backgrounds measured during these observations were approximately 2.8, 1.9, and $0.96 \times 10^{-3}$ counts arcsec$^{-2}$, respectively.

For the normal galaxies, the average ratio between the hard and soft X-ray counts is 0.73. To fit this count ratio, we assume an absorbed power-law $dN(E)/dE \propto E^{-\Gamma}$ (counts s$^{-1}$ keV$^{-1}$) for the intrinsic X-ray spectrum. We then use portable, interactive multi-mission simulator (PIMMS v3.9d)$^{10}$ to find the best-fit photon index, $\Gamma = 1.29$, assuming a fairly low absorption column density ($N(H) = 4 \times 10^{20}$ cm$^{-2}$), half of which is the Galactic absorption for the Boötes field from Stark et al. (1992). Factor of 2 changes in the assumed column densities change $\Gamma$ by only a few percent. The spectrum of the “normal” galaxies is very similar to that of the Cosmic X-ray Background (CXB),

$^{10}$ http://heasarc.nasa.gov/Tools/w3pimms.html
\( \Gamma_{\text{CXB}} \simeq 1.4 \) (e.g., Tozzi et al. 2001; Nandra et al. 2004) and of resolved populations in the Chandra Deep Fields (e.g., Civano et al. 2005). Photon indices in this range are also typical for both X-ray binaries and obscured AGNs \( (1 \lesssim \Gamma \lesssim 2 \), e.g., Ptak et al. 1999; Muno et al. 2004). Based on our model of the composite AGES galaxy X-ray spectrum, we estimate that one soft, hard or total band count corresponds to \( 1.05 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \), \( 3.65 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \), and \( 2.14 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively, for an on-axis source with a 5 ks exposure time.

### 2.2. The Galaxy Sample

For our stacking analysis, we cross referenced the XBoötes catalog of X-ray photon positions (i.e., the event list) with those of the galaxies observed by the AGES (C. S. Kochanek et al. 2009, in preparation). We focus on the approximately 6500 galaxies in the 2004 AGES main galaxy sample. This sample consists of all galaxies with \( R < 19.2 \text{ mag} \) and a randomly selected 20\% of galaxies with \( 19.2 < R < 20 \text{ mag} \). We use Vega magnitudes throughout the paper. The spectroscopic redshifts of the galaxies were measured using Hectospec, a robotic 300 fiber spectrograph for the MMT (Fabricant et al. 1998; Roll et al. 1998; Fabricant et al. 2005) and are 95\% complete for \( R < 19.2 \); our analysis is not significantly affected by the modest level of incompleteness. Although we have redshifts for roughly half of the remaining 80\% of galaxies with \( 19.2 < R < 20 \text{ mag} \), we do not include them in this analysis because they were not targeted based on a simple \( R \)-band flux-limited criterion.

Redshifts were measured using two independent data reduction pipelines (the Hectospec pipeline at the CfA and a modified SDSS pipeline at Steward Observatory), and the results were verified by visually inspecting the spectra for features consistent with the pipeline redshift. Both the pipelines and the visual inspection flagged galaxies with spectroscopic signatures of AGNs, both obvious broad-lined systems and those with emission-line ratios characteristic of Type II optical AGNs. We also determined the rest-frame \( K \)-band luminosities, both obvious broadlined systems and those with emission-line ratios characteristic of Type II optical AGNs. We also carried out a principal component analysis of the optical spectra (e.g., Formigginini & Brosch 2004; Ferreras et al. 2006). In our analysis, the level of star formation was largely characterized by the ratio of the second component relative to the first, so we divided the sample into early and late-type galaxies at the median of the distribution of that ratio for the full AGES galaxy sample.

Rest-frame absolute \( R \)-band magnitudes, \( M_R \), were determined by combining the redshift measurements with the standard \( \Lambda \)CDM cosmology and the \texttt{correct} algorithm (Blanton et al. 2003) adapted to the AGES data and the NDWFS \( B_W, I \), and \( R \) photometric filters. Figure 1 shows the distribution of the galaxies as a function of redshift and absolute magnitude. The median redshift of the galaxies is \( \langle z \rangle \simeq 0.25 \) with an appreciable tail extending to \( z \approx 0.6 \). The change in the density of points at fainter magnitudes is due to the random 20\% sampling of the fainter galaxies. To compensate for this effect, we weight the emission from these galaxies by a factor of 5.

We also determined the rest-frame \( K \)-band luminosities, \( L_K \), with \texttt{correct}. We use the \( K \)-band luminosities to estimate the contribution of LMXBs to the observed X-ray emission (Equation (2)), and to estimate the stellar mass

\[
M_* \simeq (8.0 \pm 2.0) \times 10^{10} \left( \frac{L_K}{L_K^*} \right) \, \, M_\odot, \tag{3}
\]

based on the results of Colbert et al. (2004, also see Gilfanov 2004). To explore how late-type galaxies of different masses contribute to star formation, we then combine our estimates of the stellar mass and the SFR (determined using Equation (1)) to compute the specific star formation rate \( \text{SSFR} = \text{SFR}/M_* \) (e.g., Cowie et al. 1996; Guzman et al. 1997; Brinchmann & Ellis 2000; Juneau et al. 2005; Feulner et al. 2004; Pérez-González et al. 2005).

Figure 1. Absolute \( R \)-band magnitudes of the AGES main sample of galaxies as a function of redshift. The transition from higher to lower density background points reflects differences in sampling: all \( R < 19.2 \) galaxies are present but only a random 20\% of galaxies with \( 19.2 < R < 20 \) have been sampled. Four of the eight absolute magnitude strips of galaxies we analyze are outlined.

If, instead of star formation, the X-ray emission is primarily due to accretion onto AGNs, then we can estimate the SMBH growth rates, \( \dot{M}_{\text{BH}} \), using the scaling of Ba01,

\[
\dot{M}_{\text{BH}} = 1.76 \times 10^{-6} \left( \frac{\epsilon}{0.1} \right)^{-1} L_{K>40}^{\text{AGN}} \, M_\odot \text{ yr}^{-1}, \tag{4}
\]

where \( L_{K>40}^{\text{AGN}} \) is the AGN luminosity in units of \( 10^{40} \text{ erg s}^{-1} \), and \( \epsilon \) is the efficiency of energy conversion in AGNs. Cowie et al. (2003) and Ba05 showed that the X-ray luminosities of both obscured and unobscured AGNs (with \( 10^{42} \text{ erg s}^{-1} < L_x < 10^{44} \text{ erg s}^{-1} \)) are consistent with a radiative efficiency of \( \epsilon \approx 0.1 \) all the way to \( z = 0 \). Moreover, the results of AGN models do not agree with observations if one assumes that lower radiative efficiency AGNs dominate black hole growth (e.g., Shankar et al. 2004; Hopkins et al. 2007). We will therefore adopt \( \epsilon = 0.1 \) throughout the paper.

To fit the X-ray luminosities of the AGES galaxies as a function of \( K \)-band luminosity and redshift, we assume

\[
L_x \propto L_K^a (1+z)^b. \tag{5}
\]

In order to estimate the mean star formation density \( \rho_\star \) and nuclear accretion rate density \( \rho_{\text{BH}} \), we must extrapolate our results from the magnitude-limited AGES galaxy samples to fainter fluxes. By assuming our power-law model (Equation (5)) holds for fainter sources and combining the \( K \)-band luminosity functions for late- and early-type galaxies measured by Kochanek et al. (2001), with a change of variables from \( L_K \) to \( L_x \), we compute the X-ray luminosity density as a function of redshift. The X-ray luminosity density can then be converted to star formation or nuclear accretion rate densities using Equations (1) or (4), respectively.

We restrict our analysis to a sample of 6146 “normal” galaxies with no optical or X-ray evidence of AGN activity. When
stacked, these galaxies produce a total of 486/669 hard/soft counts above the background level. In Table 1, we compare the emission from the normal galaxies to two classes of sources we exclude from the analysis. We eliminated 47 spectroscopically identified AGN (3 broad line and 44 narrow line) that were not identified in the XBöotes Survey (Kenter et al. 2005), but these produced a stacked flux of only 32/27 hard/soft counts. Much more importantly, we excluded 58 galaxies that were identified both by XBöotes as X-ray sources and by AGES as spectroscopic broad line (24) or narrow line (34) AGN. Although these 58 AGNs represent less than 1% of our sample by number, they generate 787/1196 hard/soft counts – nearly twice the X-ray flux of the normal galaxies – and would therefore dominate our results if they were not eliminated from the analysis (see Figure 5). Note, however, how similar the composite X-ray spectrum of the remaining ”normal” galaxies (Γ_{Normal} ≈ 1.3) is to that of these AGNs (Γ_{AGN} ≈ 1.3) and to that of typical AGNs, which account for the bulk of Cosmic X-ray Background (CXB; Γ_{CXB} ≈ 1.4, e.g., Tozzi et al. 2001; Nandra et al. 2004). The remaining ”normal” galaxies therefore provide a representative sampling of the CXB source population, and, in fact, comprise ≈ 8.8% of the total CXB emission, based on the soft and hard band CXB flux estimates of De Luca & Molendi (2004).

3. METHOD, MONTE CARLO SIMULATIONS, AND TESTS

The basic principle of a stacking analysis is simple. The X-ray images of a large number of sources are stacked to determine the mean properties of a group of objects that are individually undetectable (Brandt et al. 2001; Nandra et al. 2002; Hornschemeier et al. 2002; Georgakakis et al. 2003; Lehmer et al. 2005, 2007; Laird et al. 2005, 2006). Quantitatively, if stacking a sample of n objects yields N_s counts in a signal aperture of area A_s and N_b counts in a background annulus of area A_b, then the mean number of source counts per object in the signal region is

\[ \langle N \rangle_s = \frac{1}{n} \left[ N_s - \frac{A_s}{A_b} N_b \right] . \]

The uncertainties in \( \langle N \rangle_s \) can be computed either by assuming a Poisson distribution of X-ray counts per object,

\[ \sigma = \frac{1}{n} \left[ N_s + A_s^2 / A_b \right]^{1/2} , \]

or by bootstrap resampling of both the galaxy and X-ray photon catalogs (event lists). Adopting the latter method, we generate 100 bootstrap samples by randomly drawing new lists of galaxies and X-ray photons (with replacement) from the input catalogs until each bootstrap sample contains the same number of galaxies and X-ray photons as the real catalogs. Each mock data set is then subjected to the same analysis as the real data. Our error estimates are defined by the range encompassing 68% of the bootstrap results about the true mean. This approach will produce more realistic error bars than the Poisson statistics of the stacked image, particularly if the net flux is dominated by a small fraction of the objects included in the analysis.

As a general proof of principle for the subsequent analyses, Figure 2 shows images of the stacked early-type, late-type, and combined samples of galaxies in three redshift bins, excluding direct X-ray detections and galaxies with optical signatures of AGN activity. Based on the Monte Carlo simulations we discuss in the following section, we adopt a 30 kpc signal aperture and a 30–60 kpc background annulus about the center of each galaxy. Each panel shows this signal aperture and the field-averaged point-spread function (PSF), i.e., the 50% enclosed energy radius averaged over the field and converted to a physical scale based on the mean redshift of each bin. We clearly detect a signal from these ”normal” galaxies.

To understand the X-ray evolution of the galaxies quantitatively, we bin them by absolute magnitude, spectroscopic type and redshift. We analyze the galaxies in staggered, 1 mag wide absolute magnitude strips (see Figure 1), beginning at integer and half-integer absolute magnitudes (i.e., \(-17.5 > M_R > -18.5, -18 > M_R > -19, -18.5 > M_R > -19.5, \ldots, -20 > M_R > -21\)). We divide each strip into two redshift bins that contain roughly equal numbers of galaxies after correcting for the sparse sampling. We also analyze the combined, late-type, and early-type galaxy samples separately. For each bin, we then determine the mean X-ray and rest-frame K-band luminosities of the member galaxies. Because the X-ray and optical luminosities of galaxies are approximately linearly correlated (e.g.,

| Class          | Source            | Number of Objects | Net Hard Counts | Net Soft Counts |
|----------------|-------------------|-------------------|-----------------|-----------------|
| Normal Galaxies| Late-Type Galaxies| 3178              | 240             | 327             |
|                | Early-Type Galaxies| 2968              | 246             | 342             |
| Spectroscopic AGN| Broad Line AGN    | 27                | 319             | 872             |
|                | Narrow Line AGN   | 78                | 496             | 404             |
| X-ray Sources  | Broad Line AGN    | 24                | 319             | 872             |
|                | Narrow Line AGN   | 34                | 468             | 367             |
of exposure time for individual sources. Over the range of redshifts \( \gtrsim 0.4 \) the galaxies in our luminosity and redshift bins generally square root of the number of galaxies in a typical bin. Stacking David et al. 1992; Shapley et al. 2001), the X-ray to optical luminosity ratio should provide a measure of the redshift evolution of normal galaxy X-ray emission that is essentially independent of galaxy (optical) luminosity and stellar mass (Equation (3)).

In addition to spectroscopically identified AGNs, we excluded directly detected X-ray sources that did not satisfy

\[
L_x \lesssim 6.6 \times 10^{42} \text{ erg s}^{-1} \quad \text{(luminosity limit),}
\]

which corresponds to two total band counts observed at the upper redshift limit for the normal galaxies: \( z = 0.6 \). The most luminous detected sources at lower redshifts, with \( 10^{41} \text{ erg s}^{-1} < L_x < 10^{42} \text{ erg s}^{-1} \), are within the range possible for star forming galaxies, (e.g., Norman et al. 2004). Moreover, our bootstrap uncertainty estimates are close to the Poisson limits, which means that the X-ray flux cannot be dominated by a small number of luminous sources.

As an additional check on our ability to detect galaxies and to diagnose problems with background subtraction or contamination, we constructed a null sample to compare with the fluxes of the real sources. To create the null sample we kept the redshifts and (optical) luminosities of the galaxies fixed but assigned them random positions in the field, excluding locations closer than 60 kpc to an AGES galaxy. We then analyzed the random catalog in the same manner as the actual data. In Figure 3, we compare the luminosities of the real galaxies and the “empty” regions. While the real galaxies generate a significant signal in all but the faintest \( M_R \gtrsim -18 \) bins, the mean luminosities of the random fields are always consistent with zero. The uncertainties in the random signal closely follow the expected trend of \( \Phi_{\text{min}} \times 4\pi d_L^2(z) \), where \( \Phi_{\text{min}} \approx 4 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \) is the sensitivity of the observations divided by the square root of the number of galaxies in a typical bin. Stacking the galaxies in our luminosity and redshift bins generally provides \( \gtrsim 25 \times 25 \) times the sensitivity associated with the 5 ks exposure time for individual sources. Over the range of redshifts we probe, this flux limit corresponds to threshold luminosities of \( \approx 10^{48} \text{ erg s}^{-1} \) to \( 10^{40} \text{ erg s}^{-1} \).

The X-ray properties of our stacked galaxy samples are summarized in Tables 2 and 3. Table 2 provides upper limits on the hard and soft band X-ray luminosities of the optically faintest AGES galaxies that were either not detected in X-rays or had net stacked emission with signal-to-noise ratio \((S/N) < 1\) in all X-ray bands. Table 3 provides the data for the detected \((S/N > 1)\) galaxies.

### 3.1. Monte Carlo Simulations

We used Monte Carlo simulations to test our analysis methods and to refine our choices of parameters. We started by generating a mock galaxy catalog using the Brown et al. (2001) R-band luminosity function, a simple model for galaxy evolution, and the AGES main galaxy sample selection criteria including the sparse sampling. The general properties of the resulting synthetic catalog are quite similar to those of the real one. The absolute magnitude strips are a case in point. From faint to bright magnitudes, the real strips with integral, absolute magnitude boundaries in Figure 1 contain 471, 1621, 2526 and 1496 galaxies including the corrections for sparse sampling, while the corresponding strips in the synthetic catalog contain 614, 1630, 2218, and 1527 galaxies.

To simulate the X-ray data, we began by distributing \( \approx 350,000 \) background photons at random positions in the field with surface densities of \( 1.9 \times 10^{-3} \) hard \((2–7 \text{ keV})\) and \( 0.9 \times 10^{-3} \) soft \((0.5–2 \text{ keV})\) photons arcsec\(^{-2}\), based on the background estimates for the XBoötes survey (Kenter et al. 2005). We then assigned each galaxy an extended X-ray component and a pointlike nucleus. For simplicity, the extended emission consists solely of soft photons and the AGN component consists solely of hard photons. These components have mean luminosities

\[
\begin{align*}
L_{x,40,\text{soft}} &= 5 (L/L_\star)(1+z)^3 \\
L_{x,40,\text{hard}} &= 5 (L/L_\star)(1+z)^4,
\end{align*}
\]

respectively, in units of \( 10^{40} \text{ erg s}^{-1} \), where \( L/L_\star \) is the rest-frame (R-band) optical luminosity in units of the characteristic
Table 3

Summary of Results

| (M_R)/(M_K) | ⟨z⟩ | N_galaxies | Net Counts (h/s) | SN | L_x40 (h/s) | ⟨L_x40⟩/(L_K/L_K+) (h/s) |
|-------------|-----|------------|------------------|----|-------------|---------------------------|
|             |     |            |                  |    |             |                           |
| −19.98/−21.31 | 0.1159 | 375 | 17/34/51 | 0.8/2.0/1.8 | 0.7/0.4/1.1 | 4.3/2.5/6.8 |
| −19.02/−21.33 | 0.1614 | 376 | −1/17/16 | −1/3.0/7 | <1.4/0.4/0.3 | <9.2/2.5/1.8 |
| −19.42/−21.75 | 0.1434 | 580 | −4/7/67 | −3/9.2/3 | <0.8/0.7/0.6 | <3.9/3.2/4.8 |
| −19.47/−21.80 | 0.1979 | 576 | 27/52/79 | 1.5/3.6/3.4 | 2.1/1.1/3.2 | 9.4/5/1.4 |
| −19.93/−22.25 | 0.1709 | 667 | 55/61/116 | 2.4/3.4/0 | 2.6/0.8/3.5 | 7.7/2.4/1.0 |
| −19.94/−22.26 | 0.2464 | 667 | −23/45/22 | −3/4.1/0 | <2.6/1.4< 3.0 | <7.5/4.0/ < 9.0 |
| −20.36/−22.68 | 0.2032 | 555 | 39/59/98 | 2.1/4.2/4.2 | 3.4/1.4/4.8 | 6.3/2.6/8.9 |
| −20.44/−22.75 | 0.3011 | 556 | 3/30/33 | 0.2/1.2/1.9 | 0.6/1.8/2.4 | 1.1/3.4/4.4 |
| −20.85/−23.16 | 0.2465 | 403 | 46/50/96 | 3.1/3.5/1 | 8.5/2.5/11.0 | 10.2/3.1/13.2 |
| −20.90/−23.20 | 0.3774 | 403 | 36/34/70 | 3.6/3.7/5.1 | 17.5/6.6/22.2 | 21.5/6.6/26.6 |
| −21.27/−23.57 | 0.2878 | 195 | 25/39/64 | 2.4/4.4/4.7 | 13.2/5.9/19.1 | 10.2/4.5/14.8 |

Notes. The mean R-band and K-band absolute magnitudes of the galaxies in a bin are (M_R) and (M_K) and the mean redshift is ⟨z⟩. N_galaxies is the effective number of galaxies in the bin, including the correction for sparse sampling. The Net Counts column gives the number of photons observed above background in the hard (h; 2−7 keV), soft (s; 0.5−2 keV) and total (t; 0.5−7 keV) bands; the corresponding signal-to-noise ratio (SN) of the measurements appears in the adjacent column. (Our detection criterion is S/N > 1). L_x40 is the mean X-ray luminosity in the hard, soft and total bands in units of 10^{40} erg s^{-1}, and the final column is the specific X-ray luminosity, (L_x40/(h/s)), for each band. In the cases of negative net counts, 1σ upper limits have been provided. Only bins that contain > 100 galaxies and have net stacked emission with S/N > 1 in at least one X-ray band have been included in the table.

The redshift scaling and the correlation between the X-ray and optical luminosities are motivated both by previous studies (e.g., David et al. 1992; Shapley et al. 2001; Brand et al. 2005) and by our own results (see Section 4).

Luminosity, L, at the knee of the Schecter luminosity function.

Based on the X-ray spectrum of the AGES galaxies, we converted the X-ray fluxes to counts using soft and hard band flux limits of 1.05 × 10^{−15} erg cm^{-2} s^{-1} and 3.65 × 10^{−15} erg cm^{-2} s^{-1}, respectively and K-corrections of (1 + z)^{0.7}, with Γ = 1.29 (see Section 2.1). The hard emission was distributed about the galactic centers using a Gaussian model of the Chandra X-ray Observatory PSF with a 50% enclosed energy radius of

\[ r_{PSF} = 0.5 + 6.0 \left( \frac{D}{10'} \right)^2, \]

where D is the randomly assigned distance of the galaxy from the Chandra X-ray Observatory pointing center in arcminutes (see the Chandra X-ray Observatory Proposers’ Guide). We modeled the extended emission as a Gaussian of dispersion \( r_L = 10(L/L_x40)^{1/2} \) kpc convolved with the PSF to get an overall radial profile of

\[ P_{extended}(R) \propto \exp \left(-\frac{R^2}{2(r_L^2 + r_{PSF}^2)}\right). \]

In this model, the X-ray surface brightness of the galaxies is independent of optical luminosity.

---

Figure 4. Monte Carlo test of the stacking procedure. The solid curve shows the input total band emission profile in our Monte Carlo simulation, and the open circles show the profile extracted by the stacking analysis. The extracted profile agrees with the input profile in all radial bins.

3.2. Radial Emission Profiles

We first verified that our analysis correctly extracts the X-ray emission profiles by analyzing the data for the roughly 800 galaxies in the mock catalog with z ≤ 0.1 (mean redshift \( z \simeq 0.07 \)) and within 10' of the pointing center. We consider only these lower redshift sources because, in spite of the Chandra X-ray Observatory’s high, on-axis resolution, the field-averaged PSF still approaches 2 kpc at \( z \simeq 0.07 \). Figure 4 shows
the extracted profile for the total band. Using a 30 kpc signal aperture and a 30–60 kpc background subtraction annulus, we recover the input profile (and background level) to within the 1σ bootstrap uncertainties. We carry out a similar analysis on the real data in Section 4.1.

At higher redshifts, where we cannot spatially resolve the emission, we concentrate on extracting the redshift evolution of the X-ray luminosity. This involves a trade-off between the signal-to-noise ratio (S/N) and the need for aperture corrections. Larger apertures capture more signal but introduce extra noise from the background, while small apertures lose some of the signal and require more substantial aperture corrections. Redshift-dependent biases will be minimized by using a fixed angular aperture for point sources and a (sufficiently large) fixed physical aperture for extended sources. Since we expect a significant contribution from extended emission in the real data (e.g., Figure 2), we focused on fixed physical apertures with proper radii of $R_{\text{ap}} = 10, 20, 30, 40,$ and $50$ kpc and background annuli extending over the larger of $30–60$ kpc or $R_{\text{ap}} - 2 R_{\text{ap}}$. Adopting a signal aperture of $R_{\text{ap}} = 30$ kpc (at the mean redshift of each bin) led to the most accurate reproduction of the input profiles with the highest S/N; our detection criterion is S/N $> 1$. This fixed physical aperture corresponds to angular apertures of $\sim 15'-5'$ over the range of mean redshifts we analyze ($0.1 < z < 0.5$, see Table 2 and Figure 2). The size of the field-averaged PSF begins to exceed that of significantly smaller apertures, particularly in the higher redshift bins (see Figure 2). For point sources we could apply a redshift-dependent aperture correction to remedy this problem, but it is impossible to do so for extended sources when we are uncertain of their intrinsic profiles. For larger apertures, our signal-to-noise ratio begins to drop due to the increasing fraction of background photons included in the signal region. In the Monte Carlo simulations, small deviations (\lesssim 10 kpc) from $R_{\text{ap}} = 30$ kpc have little effect on the results or the signal-to-noise ratio but larger (factor of 2) changes in the aperture lead to serious problems.

Using $R_{\text{ap}} = 30$ kpc and 30–60 kpc background annuli, which we adopt throughout the remainder of the paper, we successfully recover the input luminosity evolution (Equation (9)); i.e., when we fit our results with a double power law model (Equation (5)), we find scalings for the soft and hard band X-ray luminosities that are statistically consistent with the input evolution rates and normalization:

$$L_{x40,\text{soft}} = (4.7 \pm 1.7) \left( \frac{L_{K}}{L_{K*}} \right)^{0.1 \pm 0.2} (1 + z)^{2.7 \pm 0.8}.$$

$$L_{x40,\text{hard}} = (4.0 \pm 2.4) \left( \frac{L_{K}}{L_{K*}} \right)^{0.9 \pm 0.3} (1 + z)^{3.4 \pm 1.1}.$$

4. RESULTS

We now turn to the real sources, starting with a comparison of the X-ray emission from normal galaxies and from spectroscopic AGNs. Figure 5 shows the specific X-ray luminosity, $(L_{x40})/(L_{K}/L_{K*})$, as a function of $(L_{K}/L_{K*})$ for both the normal galaxies and the full sample including the X-ray and spectroscopically flagged AGNs. With the top and right axes, we also show the inferred scaling with stellar mass, based on Equation (3), although this conversion does not apply when the bright AGNs dominate the K-band flux. While the AGNs have significantly larger X-ray luminosities than the “normal” galaxies, the “normal” galaxies are clearly detected. The two points at each $L_{K}$ show the evolution of the normal galaxy X-ray emission from the low to high redshift bin in each absolute magnitude strip (Figure 1). When we fit the normal galaxy data as a double power law in K-band luminosity and redshift (Equation (5)), we find that

$$L_{x40} = (6.0 \pm 1.0) \left( \frac{L_{K}}{L_{K*}} \right)^{1.1 \pm 0.2} (1 + z)^{3.2 \pm 0.8},$$

$$L_{x40,\text{hard}} = (4.6 \pm 0.9) \left( \frac{L_{K}}{L_{K*}} \right)^{1.2 \pm 0.3} (1 + z)^{3.5 \pm 1.0},$$

$$L_{x40,\text{soft}} = (2.0 \pm 0.5) \left( \frac{L_{K}}{L_{K*}} \right)^{1.1 \pm 0.2} (1 + z)^{2.7 \pm 0.7}.$$

for the total, hard, and soft X-ray bands, respectively, in units of $10^{40}$ erg s$^{-1}$. Because our results indicate that $L_{x}$ is roughly proportional to $L_{K}$ in all X-ray bands, the specific X-ray luminosities of the galaxies should evolve similarly regardless of their optical luminosity or mass.

The X-ray luminosities we measure are roughly an order of magnitude brighter than the contribution expected from LMXBs (Equation (2)), so we are left with three major candidates for the origin of the emission—HMXBs associated with recent star formation, accretion onto SMBHs (AGNs), and hot gas. We use three tests to try to determine the dominant source(s). We first use fits to the AGES spectra to divide the normal galaxies into late-type and early-type subsamples. Doing so allows us to compare the X-ray emission from galaxies with and without (optical) spectroscopic signatures of star formation. The resulting subsamples contain 3178 late-type galaxies and 2968 early-type galaxies. Second, we examine the radial emission profiles of the low redshift galaxies, since emission due to star
formation and hot gas will be more spatially extended than emission from AGN. Third, we compare the hardness ratios of the galaxies, in terms of the hard and soft band counts $C_{\text{hard}}$ and $C_{\text{soft}}$, $HR = (C_{\text{hard}} - C_{\text{soft}})/(C_{\text{hard}} + C_{\text{soft}})$, to the typical values expected for X-ray binaries, AGNs, and hot gas.

4.1. Radial Emission Profiles

Figure 6 shows the average, background-subtracted soft, hard, and total band emission profiles of 488 (360 late-type and 128 early-type) low redshift ($z < 0.1$), galaxies within 10' of the Chandra X-ray Observatory optical axis, excluding X-ray sources that violate our luminosity limit (Equation (8)) and AGNs identified through optical spectroscopy. The mean redshift of these galaxies is $z \approx 0.07$. Rather than use a model for the PSF (Equation (10)), we determined it empirically by averaging the emission profiles of $\approx 500$ $z > 1$ X-ray-selected AGNs from the XBoötes survey. As with the galaxies, we used only AGN sources within 10' of the Chandra field centers and stacked the emission based on the optical positions. We then applied the angular corrections needed to put the PSF model on the same physical scale as the galaxies.

![Figure 6.](image)

**Figure 6.** Background-subtracted radial emission profiles of 360 late-type (top) and 128 early-type (bottom) galaxies with $z < 0.1$, a mean redshift of $z \approx 0.07$ and within 10' of Chandra X-ray Observatory field centers. The solid, dashed, and dotted curves represent the total, hard, and soft band profiles, respectively, in each panel. The dot-dashed curve shows an empirical model of the PSF, based on the radial emission of $\approx 500$, $z > 1$ AGN within 10' of a Chandra X-ray Observatory field center. We have shifted the normalization of the PSF model to match the amplitude of the galaxy profile in each panel.

4.2. Hardness Ratios

In Figure 7, we show the HRs based on the hard- and soft-band counts of the two galaxy classes. To improve the statistical significance of our HRs, we combine hard and soft counts from bins of comparable redshifts in adjacent absolute magnitude strips (Figure 1). For reference, we compare these HRs to those observed in these bands for accreting binaries (HR $\gtrsim -1$, e.g., Muno et al. 2004), Type I AGN (HR $\gtrsim -0.5$, e.g., Rosati et al. 2002; Franceschini et al. 2005), Type II AGN ($0 \lesssim HR \lesssim 1$, e.g., Rosati et al. 2002), and hot gas with a temperature of 0.5–1 keV (HR $\simeq -1$).

![Figure 7.](image)

**Figure 7.** Redshift evolution of the hardness ratio (HR) for the late-type (squares) and early-type (circles) samples of galaxies. The late-type galaxies exhibit slightly harder spectra than the early-type galaxies, which is most likely due to the early-types' characteristically larger halos of soft X-ray emitting gas. Typical HRs of HMXBs and LMXBs (dashed line) as well as Type I (dotted line) and Type II AGNs (typically above the dashed line) have been included for reference.

We find that the emission profiles of the late-type galaxies are clearly extended while those of the early-type galaxies have a more pronounced nuclear component. We use the Kolmogorov–Smirnov (K–S) test to compare the radial distribution of (total band) photons from the late-type galaxies, early-type galaxies, and high redshift AGNs. Within 5 kpc of the stacking centers, we find that the early-type galaxy distribution ($\propto r^{-1.1}$) is consistent with the AGN distribution (K–S likelihood 97%), while the late-type galaxy distribution ($\propto r^{-0.2}$) is not (K–S likelihood 3%). However, if we analyze the full extraction region, neither galaxy profile is consistent with the AGN model (K–S likelihood < 1%). Between 10 and 30 kpc, both galaxy types show significant ($\gtrsim 2.5\sigma$) emission, which we attribute primarily to diffuse gas and LMXBs. Soft X-ray emitting gas has been observed out to $\gtrsim 20$ kpc around late-type (e.g., Strickland et al. 2004) and early-type (e.g., Mathews & Brighenti 2003) galaxies, as have LMXBs (late-type; e.g., Wang et al. 1999; early-type: e.g., Kim et al. 2006), leading to extended profiles like those in Figure 6. Our results imply that the emission from the low-redshift early-type galaxies comes from a combination of AGN, hot gas, and LMXBs. In contrast, because the emission from the late-type galaxies is significantly less centrally concentrated than the emission of AGNs—even within a radius of 5 kpc—the dominant source of the late-type galaxy flux is most likely a radially extended distribution of HMXBs and LMXBs.
of both galaxy types become somewhat harder with increasing redshift. This is most likely a consequence of the larger amount of soft X-ray emitting gas in earlier type galaxies and the steadily increasing contributions of HMXBs and AGN, respectively, to the late-type and early-type galaxy spectra at higher redshifts.

4.3. Luminosity Evolution

To isolate the dependence of \( L_x \) on \( L_K \), we examined the evolution of the X-ray luminosity of the early and late-type galaxies in three narrow redshift slices: \( (z) = 0.20 \pm 0.02 \) (three-pointed stars), \( (z) = 0.25 \pm 0.02 \) (five-pointed stars), and \( (z) = 0.35 \pm 0.03 \) (seven-pointed stars). In all redshift slices, the specific X-ray luminosities are relatively flat in \( L_K \) (roughly, \( L_{x, \text{late}} \propto L_K^{1.2 \pm 0.3} \propto L_{x, \text{early}} \); see Section 4.3), indicating an approximately linear correlation between \( L_x \) and \( L_K \) as found previously (e.g., David et al. 1992; Shapley et al. 2001).

The reduced \( \chi^2 \) (per degree of freedom) for these fits are 0.78 and 0.81 for the hard and soft bands, respectively. If we fit the early-type galaxies, we find that

\[
L_{x40, \text{hard}}^{\text{LATE}} = (3.0 \pm 0.6) \left( \frac{L_K}{L_{K*}} \right)^{1.0 \pm 0.3} (1 + z)^{3.9 \pm 0.8},
\]

\[
L_{x40, \text{soft}}^{\text{LATE}} = (1.8 \pm 0.4) \left( \frac{L_K}{L_{K*}} \right)^{1.1 \pm 0.2} (1 + z)^{3.1 \pm 0.8}.
\]
2. the X-ray luminosity is significantly higher than what would be expected from LMXBs on the basis of the K-band luminosities, Equation (2), assuming a hardness ratio of HR = 0 (e.g., Munoz et al. 2004).

These similarities are not surprising, as we expect the X-ray emission of LMXBs and hot gas to be nearly time-independent for \( z \lesssim 0.5 \), while the HMXB and AGN emission should be evolving rapidly and at approximately the same rate (\( \propto (1 + z)^{2.5} \); e.g., David et al. 1992; Shapley et al. 2001; Hogg 2001; Norman et al. 2004; and Schiminovich et al. 2005 and Ba01 and Ba05, respectively).

4.4. Comparisons to Previous Work

In general, we find excellent agreement between our results and those of earlier studies of normal galaxy X-ray evolution, but our uncertainties are smaller. There are three general categories of earlier results: surveys of nearby, individual galaxies, stacking analyses of low to intermediate-redshift galaxies and stacking analyses of intermediate to high-redshift galaxies in small-area, deep fields (CDF-N and CDF-S). Taking the late-type and early-type galaxies in turn, we first consider the Shapley et al. (2001, S01) and O’Sullivan et al. (2001, OS01) analyses of galaxies in the HDF-N/CDF-N, finding 29, \( \equiv 29 \), that 29, \( \equiv 29 \), are consistent with the values we find for massive early-type galaxies at 0. These results are consistent with those of G03 and with our earlier work (B05), where we incorporate the soft-band panel; upper limit in the hard-band panel and Brand et al. (2005, B05; six-pointed star in both panels at \( z = 0.4 \pm 0.1 \)). The best-fit curve for soft- and hard-band emission from the AGES galaxies is also shown. The shaded region in the lower right panel shows the local O’Sullivan et al. (2001, OS01) \( L_\text{soft} \) trend, roughly \( \log(L_{\text{soft}}) = (0.3 \pm 0.3) + (1.7 \pm 0.2) \log(L_x / L_K), \) which encompasses both the scatter in and error bars on the OS01 data points.

Figure 10. Same as Figure 9 for the early-type sample of galaxies. For comparison, we have plotted the specific X-ray luminosities of \( z \approx 0.1 \) L, galaxies found by Georgakakis et al. (2003, G03; four-pointed star in the soft-band panel) and Brand et al. (2005, B05; six-pointed star in both panels at \( z = 0.4 \pm 0.1 \)). The best-fit curve for soft- and hard-band emission from the AGES galaxies is also shown. The shaded region in the lower right panel shows the local O’Sullivan et al. (2001, OS01) \( L_\text{soft} \equiv L_K \) trend, roughly \( \log(L_{\text{soft}}) = (0.3 \pm 0.3) + (1.7 \pm 0.2) \log(L_x / L_K), \) which encompasses both the scatter in and error bars on the OS01 data points.

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Our results for the ROSAT PSPC (0.1–2.5 keV) X-ray survey of 401 local early-type galaxies discussed in O’Sullivan et al. (2001). Because the hot gas emission from the early-type galaxies is primarily a function of galaxy mass rather than epoch, there should be little difference between the soft band flux of the local and AGES galaxies (at \( 0.15 \lesssim z \lesssim 0.45 \)), provided that the soft band AGN contamination in the AGES sample is small. Figure 10 shows that the soft band luminosity from the AGES early-type galaxies is, in fact, comparable to that of the local sample even at high optical luminosities (which tend to be associated with higher redshifts in the AGES sample). In contrast, the total luminosity of the AGES early-type galaxies is consistently higher than that of the local sample. Figure 10 also demonstrates that the hard X-ray component of the early-type galaxies is well in excess of the estimated LMXB emission and undergoes rapid, positive redshift evolution. These findings reinforce our conclusions in Section 4.2, that the soft band flux of the AGES early-type galaxies comes primarily from hot gas, while the more rapidly evolving hard component comes primarily from AGN.

Our results for the massive (\( \sim L_\odot \)) early-type galaxies agree with those of G03 and with our earlier work (B05), where we found that bright red (\( M_B < -21.3 \)) galaxies at \( z \approx 0.4 \) had total X-ray luminosities of \( L_x \approx 10^{41} \) ergs s\(^{-1}\). By incorporating the results of G03 and B05 with ours, we gain more leverage on the behavior of \( L_x \) early-type galaxies at lower \( (z \approx 0.1) \) and higher \( (0.5 \lesssim z \lesssim 0.9) \) redshifts than what we can probe with AGES alone. Using this combined sample, we find that the hard and soft band luminosities of \( L_x \) early-type galaxies follow the trends

\[
L_{\text{early}} (z) = (3.6 \pm 1.5)(1 + z)^{5.5 \pm 1.7}
\]

assuming \( H = K = 0.27 \) mag and a 50\% uncertainty in the normalization of the correlation. It is clear that Equation (16) agrees very well with Equation (14) at \( z = 0 \), and, as shown in Figure 9, the agreement extends to all redshifts if we allow for evolution (see Figure 9). Similar trends have been found in other local surveys (e.g., David et al. 1992).

Georgakakis et al. (2003, G03) considered 200 galaxies in the 2dF redshift survey with \( (L_B) \sim L_\ast \) at a mean redshift \( (z) \approx 0.1 \). They measured mean soft band luminosities of \( \log(L_x / \text{ergs s}^{-1}) \sim 40 \pm 0.2, 39.7 \pm 0.4, 40.5 \pm 0.2 \) for the combined, late-type and early-type samples. They also estimated an upper limit of \( \log(L_x / \text{ergs s}^{-1}) \sim 40.5 \) on the hard band luminosities of the samples. These results are consistent with ours, particularly if we allow for positive redshift evolution of the X-ray luminosity between \( (z) \approx 0.1 \) for G03 and our points for galaxies of similar optical luminosities at \( z \approx 0.25 \) and 0.45.

Hornschemeier et al. (2002, H02) conducted a stacking analysis of late-type galaxies in the HDF-N/CDF-N, finding that 29, \( \equiv 29 \), in the redshift range 0.4–0.75 have mean total (0.5–8 keV) and soft band (0.5–2 keV) luminosities of \( L_x = 2.9 \pm 0.4 \) and 1.3 \pm 0.2, respectively. These too are consistent with the values we find for \( 0.7L_\ast \) galaxies at \( 0.2 \lesssim z \lesssim 0.3 \) (3.6 \pm 0.8 and 1.6 \pm 0.3, respectively).

Turning to the early-type galaxies, we first checked the relative contributions of hot gas and AGN emission by comparing

\[
L_{\text{early}} (z) = (3.6 \pm 1.5)(1 + z)^{5.5 \pm 1.7}
\]
Figure 11. Mean hard (top) and soft (bottom) specific X-ray luminosities of \( \approx L_\text{e} \) early-type galaxies from G03 (2dF, \( z = 0.1 \)), this work (AGES: filled points), and B05 (NDWFS: open points at \( z \gtrsim 0.4 \)). The solid lines are global fits to the combined samples (see Section 4.4).

and

\[
I_{\text{x,soft}} = (2.0 \pm 0.8)(1 + z)^{2.8 \pm 1.1}
\]  

out to \( z \approx 1 \). These global fits, which are shown in Figure 11, are consistent with those found for the AGES \( L_\text{e} \) early-type galaxies alone (Equation (15) at \( L_K = L_{K_\star} \)).

Lehmer et al. (2007) conducted a stacking analysis of 222 optically bright (\( \approx L_{B_\star} \)) early-type galaxies in the E-CDF-S with photometric redshifts ranging from 0 to 0.7. The mean hard X-ray luminosity trend inferred for AGN in the Lehmer et al. galaxy sample is in excellent agreement with the hard band trend found in B05 (see Lehmer et al. 2007, Figure 13) and in the present paper (Figure 11).

5. INTERPRETATION AS STAR FORMATION AND NUCLEAR ACCRETION

In this section, we interpret the trends in X-ray luminosity in terms of star formation (HMXBs) and nuclear accretion (AGN) after estimating and subtracting the additional contributions of LMXBs and hot gas. Under the assumption, discussed in the introduction, that Equation (2) holds out to \( z \approx 0.5 \), LMXBs represent a modest contribution to the emission from the late-type (\( \lesssim 15\% \)) and early-type (\( \lesssim 20\% \)) galaxies. The comparison of the (primarily) hot gas emission from local early-type galaxies (O’Sullivan et al. 2001) shown in Figure 10 suggests that, at all redshifts, \( \approx 50\% \) of the soft band (and \( \lesssim 20\% \) of the total) emission of the AGES early-type galaxies is produced by hot gas. Based on these arguments, we conclude that \( \lesssim 85\% \) of the X-ray flux of the late-type galaxies is produced by HMXBs and \( \gtrsim 60\% \) of the total (and \( \gtrsim 80\% \) of the hard) X-ray flux of the early-type galaxies is produced by low luminosity AGN. In the analysis that follows, we use the hard and soft band luminosities of the late-type galaxies to estimate the evolution of star formation rates in normal galaxies and the hard band luminosity of the early-type galaxies to estimate the growth rates of supermassive black holes in normal galaxies.

Before we implement these assumptions, we must also consider the possibility that the flux from the high redshift late-type galaxies is being contaminated by AGN. Since we cannot resolve their radial emission profiles as we did for the nearby subsamples (Section 4.1) and their luminosity evolution is fairly similar to that of the early-type galaxies, which we largely attribute to AGN, we must find other ways to address this possibility. Fortunately, there are three key properties of the late-type galaxy emission that suggest the level of AGN contamination is small. First, the star formation signatures in the late-type galaxy optical spectra are necessarily correlated with a significant flux from HMXBs (Equation (1)), suggesting that only a small fraction of the late-type galaxy emission could come from AGN. Second, the X-ray emission from late-type galaxies is extended at low redshifts (Figure 6), directly demonstrating the absence of AGN among the nearby members of the sample. Third, the Poisson and bootstrap error estimates are similar at all redshifts, which they would not be if a small number of individual, high-count sources (AGN) were hidden within the sample. This disfavors small to moderate AGN contamination. Significant AGN contamination is also disfavored by our analysis and comparisons to previous work in Section 5.1.

5.1. Star Formation Rates in the Late-type Galaxies

Studies of star formation over the redshift range \( 0 \leq z \leq 3 \) have demonstrated that the relationship between X-ray luminosity and SFRs is reasonably universal (e.g., Brandt et al. 2001; Seibert et al. 2002; Nandra et al. 2002; Cohen 2003; Grimm et al. 2003; Persic et al. 2004; Reddy & Steidel 2004; Lehmer et al. 2005). We use Equation (1) to estimate the hard band SFR from \( L_{\text{x,hard}} = L_{\text{x,hard}}^{\text{HMXB}} - L_{\text{x,hard}}^{\text{LMXB}} \), where \( L_{\text{x,hard}}^{\text{LMXB}} \) is based on Equation (2) and a typical LMXB spectrum with \( H/R = 0 \) (e.g., Munu et al. 2004) and \( L_{\text{x,hard}}^{\text{HMXB}} \) is given in Equation (15). The result is

\[
\text{SFRhard} = (6.4 \pm 1.8)(L_E / L_{K_\star})^{1.2 \pm 0.4} \times (1 + z)^{3.4 \pm 1.2} \times M_\odot \text{yr}^{-1}.
\]  

Using Equation (3) to estimate the stellar mass \( M_\star \) of the galaxies, we find that SFR\text{hard} corresponds to a specific star formation rate (SSFR = SFR/\( M_\star \)) of

\[
\text{SSFRhard} = (8.4 \pm 2.4) \times 10^{-2}(1 + z)^{3.4 \pm 1.2} \times (M_\star / 10^{11} M_\odot)^{0.2 \pm 0.4} \text{Gyr}^{-1}.
\]  

Based on the work of Ranalli et al. (2003, as modified by Gilfanov et al. 2004) we also use Equation (1) to estimate the soft band SFR from \( L_{\text{x,soft}}^{\text{HMXB}} = L_{\text{x,soft}}^{\text{LATE}} - L_{\text{x,soft}}^{\text{LMXB}} \).

\[
\text{SFRsoft} = (3.4 \pm 0.7)(L_E / L_{K_\star})^{1.1 \pm 0.2} \times (1 + z)^{2.4 \pm 1.0} \times M_\odot \text{yr}^{-1}.
\]
and a corresponding specific star formation rate of

$$\text{SSFR}_{\text{soft}} = (4.3 \pm 0.9) \times 10^{-2}(1 + z)^{2.4 \pm 1.0} \times (M_*/10^{11} M_\odot)^{0.1 \pm 0.2} \text{ Gyr}^{-1}. \quad (22)$$

As shown in Figure 12, the results of earlier SSFR studies by Bauer et al. (2005), Bell et al. (2005), and Feulner et al. (2004) fall within the range encompassed by our hard and soft band SSFR trends (Equations (20) and (22)), but we have smaller uncertainties due to our larger sample size. Our results also agree with those of more recent analyses of comparable large galaxy samples (Noeske et al. 2007 and Zheng et al. 2007) in bins of similar stellar mass ($10.5 \lesssim \log(M_*/M_\odot) \lesssim 11$) and redshift ($0.2 \lesssim z \lesssim 0.45$ and $z \sim 0.3$, respectively).

We compute the star formation rate per comoving volume, $\dot{\rho}_s$, by integrating Equations (19) and (21) over the comoving density of the late-type galaxies (see Section 2.2). These results are shown in Figure 13. We find

$$\dot{\rho}_{s,\text{hard}} = (2.1 \pm 0.4) \times 10^{-2}(1 + z)^{2.9 \pm 0.7} \frac{M_\odot}{\text{yr Mpc}^3} \quad (23)$$

and

$$\dot{\rho}_{s,\text{soft}} = (1.6 \pm 0.3) \times 10^{-2}(1 + z)^{2.5 \pm 0.5} \frac{M_\odot}{\text{yr Mpc}^3} \quad (24)$$

for the hard and soft bands, respectively. As illustrated in Figure 13, our results are broadly consistent with the range of $\dot{\rho}_s$ values inferred from the standard extinction-corrected ultraviolet luminosity measurements of GALEX (Schiminovich et al. 2005).

It is important to note that significantly larger extinction corrections have already been ruled out by neutrino detectors. Values of $\dot{\rho}_s$ more than 50\% larger than $\dot{\rho}_{s,\text{hard}}$ would be in serious conflict with the Super-Kamiokande upper limit (Malek et al. 2003) on the Diffuse Supernova Neutrino Background (DSNB) from $M > 8 M_\odot$ stars (Strigari et al. 2005; Hopkins & Beacom 2006).

Our soft-band estimates of $\dot{\rho}_s$ sit closer to the GALEX minimum extinction correction curve. Nevertheless, the consistency of our hard and soft band results with each other and with the range of GALEX results indicates that we are in general agreement with earlier studies (e.g., based on H\alpha measurements: Tresse & Maddox 1998; Tresse et al. 2002; Pérez-González et al. 2003; and Brinchmann et al. 2004 and the meta-analysis of Hogg 2001) as well as more recent comprehensive studies (e.g., Hopkins & Beacom 2006).

The level of agreement between our hard and soft band results also provides a check on the contamination of our sample by AGN. We first note that the soft band SSFR and $\dot{\rho}_s$ values (Equations (22) and (24)) are systematically lower than the corresponding hard band values (Equations (20) and (23)), but this is not uncommon. Many previous studies have also generally inferred lower SFR and $\dot{\rho}_s$ values based on soft band flux (e.g., G03 and Norman et al. 2004), suggesting that a low-normalization conversion between the soft band X-ray flux and the star formation rate (e.g., Hornschemeier et al. 2005), rather than contamination in the hard band, is to blame for this discrepancy. Furthermore, if sources harder than X-ray binaries, like Type II AGN (see Figure 7), were contributing excess hard band emission to the late-type galaxy flux, $\dot{\rho}_{s,\text{hard}}$ (Equation (23)) would lie above rather than slightly below the GALEX best-fit curve (Figure 13).

### 5.2. Accretion Rates in the Early-type Galaxies

For the early-type galaxies, we use Equation (2) to estimate and subtract the contamination from LMXBs and use the remaining hard X-ray luminosity to determine the average supermassive black hole growth rate via Equation (4). Assuming a constant accretion efficiency of $\epsilon = 0.1$, we find that

$$M_{BH} = (5.8 \pm 1.1) \times 10^{-6}(L_K/L_{K*})^{1.1 \pm 0.4} \times (1 + z)^{3.3 \pm 0.7} \frac{M_\odot}{\text{yr}}. \quad (25)$$

This growth rate (see Figure 14) is roughly an order of magnitude below the estimates of Ba01 ($M_{BH} \gtrsim 10^{-4} M_\odot \text{yr}^{-1}$), because we are considering very different source populations. The Ba01 estimates are based on directly detected X-ray sources with luminosities exceeding $10^{42}$ erg s$^{-1}$, while we have eliminated such bright sources and consider only “normal” galaxies with mean luminosities of order $10^{41}$ erg s$^{-1}$. The rapid redshift
evolution of the accretion rate in normal galaxies is consistent, however, with the redshift evolution of bright AGN found by Ba01 and Ba05.

We estimate the accretion rate density $\dot{\rho}_{BH}$ by integrating the accretion rate per unit (stellar) luminosity over the early-type galaxy luminosity function (see Section 2.2). We find that

$$\dot{\rho}_{BH} = (2.0 \pm 0.4) \times 10^{-8} (1 + z)^{2.9 \pm 0.7} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}. \quad (26)$$

As shown in Figure 15, the evolution rate we determine is consistent with the rates found by Ba01 ($\dot{\rho}_{BH} \propto (1 + z)^{3.4 \pm 1}$) and Ba05 ($\dot{\rho}_{BH} \propto (1 + z)^{3.2 \pm 0.8}$) but we have a systematically lower normalization for $\dot{\rho}_{BH}$ because of the different source populations we have examined. This suggests that even at $z < 0.5$ the aggregate growth rate of black holes in normal galaxies is still a factor of a few less than that occurring in the much smaller number of bright, low-redshift AGN.

6. SUMMARY AND CONCLUSIONS

After eliminating AGN flagged by AGES spectroscopy and X-ray sources brighter than our luminosity limit (Equation (8)), we used a stacking technique to determine the average X-ray properties of a magnitude-limited sample of 6146 ($R < 20$ mag, $z < 0.6$) apparently normal galaxies. The results substantially improve our knowledge of normal galaxy X-ray evolution over the redshift range $0.1 \lesssim z \lesssim 0.5$, which has been difficult to probe based on either local studies of individual objects or small-area deep fields.

We spectroscopically divided the galaxies into late-type and early-type subsamples. The spectroscopic signatures of star formation, spatially extended radial emission profiles, luminosity evolution, and low LMXB emission ($\lesssim 15\%$) of the late-type galaxies suggest that their X-ray emission is dominated by HMXBs and therefore traces the star formation rate.

Conversely, because the early-type galaxies lack spectroscopic evidence for star formation, yet have rapidly evolving hard X-ray luminosities that are well in excess of that expected from LMXBs ($\lesssim 20\%$), we concluded that their emission is increasingly dominated by AGN at higher redshifts.

When we use a double power law ($L_x \propto L_K^p (1 + z)^q$, Equation (5)) to fit the trends in the X-ray emission, we see that the X-ray luminosity increases monotonically from low mass galaxies at low redshift to high mass galaxies at high redshift for both galaxy types. The redshift evolution of the late-type galaxies, $L_x \propto (1 + z)^{3.4 \pm 1}$, is in good agreement with previous estimates (e.g., H02, Ptak et al. 2001) and with theoretical expectations for normal, star-forming galaxies (Ghosh & White 2001). The optical luminosity dependence of the late-type galaxy emission, roughly $L_x \propto L_K^{1.2 \pm 0.3}$, also matches previous results (e.g., S01; David et al. 1992). In addition, the specific star formation rates, SSFR = SFR/$M_\ast$, and star formation rate densities, $\rho_\ast$, we infer from the hard and soft band emission of the late-type galaxies span the range of previously reported values (Figures 12 and 13).

The specific X-ray luminosities we found for the early-type galaxies are in good agreement with the results of past studies (O’Sullivan et al. 2001; G03; B05; and Lehmer et al. 2007). Additionally, our work provides the first X-ray estimates of the SMBH accretion rates, $M_{BH}$, and accretion rate densities, $\dot{\rho}_{BH}$, in normal galaxies at these redshifts. Our findings suggest that the redshift evolution of low luminosity AGN in our early-type galaxy sample is similar to that of higher luminosity AGN (Ba01 and Ba05), which we exclude from our analysis. However, the lower luminosity AGN contribute little to the overall growth of supermassive black holes. In general, our work shows that there is a continuum rather than a sudden break in the star formation and SMBH accretion histories of galaxies from the powerful starbursts and AGN of the past to the fainter, optically-normal galaxies more prevalent today.

Our analysis of the X-ray evolution of galaxies in the NDWFS XBoötes field can be significantly expanded in the future. A second phase of AGES has doubled the size of the spectroscopic sample and extended the redshift range of galaxies. If combined with photometric redshifts based on the very extensive, multiwavelength NDWFS photometry, it will be possible to reach $z \sim 1$ to a uniform luminosity limit and greatly reduce statistical errors.

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REFERENCES

Barger, A. J., et al. 2001, ApJ, 122, 2177 (Ba01)
Barger, A. J., et al. 2005, ApJ, 129, 578 (Ba05)
Bauer, F. E., Alexander, D. M., Brandt, W. N., Hornschemeier, A. E., Vignali, C., Garmire, G. P., & Schneider, D. P. 2002, ApJ, 568, L85
Bauer, A. E., et al. 2005, ApJ, 625, L89
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Brinchmann, J., & Ellis, R. S. 2000, ApJ, 536, L77
Bell, E. F. 2004, in Invited Review in Planets to Cosmology: Essential Science (arXiv:astro-ph/0408023)
Bell, E. F., et al. 2005, ApJ, 625, 23
Blanton, M. J., et al. 2003, AJ, 125, 2348
Brand, K., et al. 2005, ApJ, 626, 723 (B05)
Brandt, W. N., et al. 2001, AJ, 122, 2177
Barger, A. J., et al. 2001, AJ, 122, 2177 (Ba01)
Kim, D.-W., & Fabian, G. 2004, ApJ, 611, 846
Kim, E., et al. 2006, ApJ, 647, 276
Kochanek, C. S., et al. 2001, ApJ, 560, L566
Laird, E. S., et al. 2005, MNRAS, 359, 47
Laird, E. S., et al. 2006, MNRAS, 373, 217
Lehmer, B. D., et al. 2005, AJ, 121, 1
Lehmer, B. D., et al. 2007, ApJ, 657, 681
Lehmer, B. D., et al. 2008, ApJ, 681, 1163
Malek, M., et al. 2003, Phys. Rev. Lett., 90, 061101
Mathews, W. G., & Brighenti, F. 2003, ARA&A, 41, 191
McLeod, K. K., & McLeod, B. A. 2001, ApJ, 546, 782
Miyaji, T., 2004, in Multicolor and Multiband Space Surveys, ed. A. M. Koekemoer (Cambridge: Cambridge Univ. Press), 475
Muno, M. P., et al. 2004, ApJ, 613, 1179
Murray, S., et al. 2005, ApJS, 161, 1
Nandra, K., Mushotzky, R. F., Arnaud, K., Steidel, C. C., Adelberger, K. L., Gardner, J. P., Teplitz, H. I., & Windhorst, R. A. 2002, ApJ, 576, 625
Nandra, K., et al. 2004, MNRAS, 356, 568
Noeske, K. G., et al. 2007, ApJ, 660, 47
Norman, C., et al. 2004, ApJ, 607, 721
O’Sullivan, E., Forbes, D. A., & Ponman, T. J. 2001, MNRAS, 328, 461 (OS01)
Pérez-González, P. G., et al. 2003, ApJ, 591, 827
Pérez-González, P. G., et al. 2005, ApJ, 630, 82
Persic, M., et al. 2004, A&A, 420, 79
Ptak, A., Griffiths, R., White, N., & Ghosh, P. 2001, ApJ, 559, L91
Ptak, A., Mobasher, B., Hornschemeier, A., Bauer, F., & Norman, C. 2007, ApJ, 667, 826
Ptak, A., Serlemitsos, P., Yaqoob, T., & Mushotzky, R. K. 1999, ApJS, 120, 179
Ranalli, P., et al. 2003, A&A, 399, 39
Reddy, N., & Steidel, C. C. 2004, ApJ, 603, L13
Roll, B. J., et al. 1998, Proc. SPIE, 3355, 324
Rosati, P., et al. 2002, ApJ, 566, 667
Schiminovich, D., et al. 2005, ApJ, 619, 47
Seibert, M., Heckman, T. M., & Meurer, G. R. 2002, AJ, 124, 46
Shankar, F., et al. 2004, MNRAS, 354, 1020
Shapley, A., Fabian, G., & Esbrí, P. B. 2001, ApJS, 137, 139 (S01)
Smith, D. A., & Wilson, A. S. 2003, ApJ, 591, 138
Soifer, B. T. (the Spitzer NOAO Team) 2004, American Astronomical Society Meeting, 204
Stark, A. A., et al. 1992, ApJ, 79, 77
Strickland, D. K., et al. 2004, ApJS, 151, 193
Strigari, L. E., Beacom, J. F., Walker, T. P., & Zhang, P. 2005, J. Cosmol. Astropart. Phys., JCAP04(2005)017
Tozzi, P., et al. 2001, ApJ, 562, 42
Tresse, L., & Maddox, S. J. 1998, ApJ, 495, 691
Tresse, L., et al. 2002, MNRAS, 337, 369
Tzanavaris, P., & Georgantopoulos, I. 2008, A&A, 480, 663
Ueda, Y., et al. 2003, ApJ, 598, 886
Wang, Q. D., et al. 1999, ApJ, 523, 121
Zheng, X. Z., et al. 2007, ApJ, 661, 41