X-RAY PROPERTIES OF LYMAN BREAK GALAXIES IN THE HUBBLE DEEP FIELD–NORTH REGION

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ABSTRACT

We describe the X-ray properties of a large sample of z ~ 3 Lyman break galaxies (LBGs) in the region of the Hubble Deep Field–North, derived from the 1 Ms public Chandra observation. Of our sample of 148 LBGs, four are detected individually. This immediately gives a measure of the bright AGN fraction in these galaxies of ~3%, which is in agreement with that derived from the UV spectra. The X-ray color of the detected sources indicates that they are probably moderately obscured. Stacking of the remainder shows a significant detection (6σ) with an average luminosity of 3.4 × 1041 erg s−1 per galaxy in the rest-frame 2–10 keV band. We have also studied a comparison sample of 95 z ~ 1 “Balmer break” galaxies. Eight of these are detected directly, with at least two clear AGNs based on their high X-ray luminosity and very hard X-ray spectra. The remainder are of relatively low luminosity (<1042 erg s−1), and the X-rays could arise from either AGNs or rapid star formation. The X-ray colors and evidence from other wave bands favor the latter interpretation. Excluding the clear AGNs, we deduce a mean X-ray luminosity of 6.6 × 1040 ergs s−1, a factor of ~5 lower than the LBGs. The average ratio of the UV and X-ray luminosities of these star-forming galaxies LUV/LX, however, is approximately the same at z = 1 as it is at z = 3. This scaling implies that the X-ray emission follows the current star formation rate, as measured by the UV luminosity. We use our results to constrain the star formation rate at z ~ 3 from an X-ray perspective. Assuming the locally established correlation between X-ray and far-IR luminosity, the average inferred star formation rate in each LBG is found to be approximately 60 M⊙ yr−1, in excellent agreement with the extinction-corrected UV estimates. This provides an external check on the UV estimates of the star formation rates and on the use of X-ray luminosities to infer these rates in rapidly star-forming galaxies at high redshift.

Subject headings: galaxies: active — galaxies: evolution — galaxies: high-redshift — galaxies: nuclei — X-rays: galaxies

1. INTRODUCTION

ROSAT deep surveys showed that the majority of the soft (0.5–2 keV) X-ray background (XRB) consists of X-rays from broad-line AGNs (Shanks et al. 1991; Hasinger et al. 1998; Lehmann et al. 2001). New data from the Chandra X-Ray Observatory have added considerably to this by resolving the majority of the hard X-ray (2–10 keV) background (Mushotzky et al. 2000; Giacconi et al. 2001, 2002; Brandt et al. 2001b, hereafter B01b; Tozzi et al. 2001; Campana et al. 2001; Cowie et al. 2002). Most of the objects responsible for the hard XRB are also probably AGNs, but they have properties very different from standard broad-line QSOs and are apparently much more numerous (Mushotzky et al. 2000; Barger et al. 2001a; Hornschemeier et al. 2001, hereafter H01; Alexander et al. 2001; Rosati et al. 2002).

Galaxies without a dominant AGN can also produce X-rays, from their X-ray binary populations, supernova remnants, and diffuse hot gas (see, e.g., Fabian 1989). Emission is expected from the evolved stellar populations, primarily from low-mass X-ray binaries (LMXBs; Fabian & Trinchieri 1985), but star formation should enhance this emission, via high-mass X-ray binaries (HMXBs) and Type II supernovae (e.g., Griffiths & Padovani 1990; David, Jones, & Forman 1992). X-rays are therefore a natural consequence of star formation and evolution. In local star-forming galaxies, the prompt emission associated with the starburst apparently dominates (e.g., Moran, Lehnert, & Helfand 1999).

The deepest X-ray surveys have shown the emergence of a population of X-ray sources at faint fluxes, with low LX/Lopt ratio, identified with relatively normal galaxies, without substantial nuclear accretion (Giacconi et al. 2001; H01). They represent only the tip of the iceberg of the non-AGN galaxy populations in the universe, however, with the X-ray...
properties of the majority of galaxies—particularly those at high redshift—remaining undetermined. Indeed, the deep X-ray surveys show source densities much lower than the deepest optical surveys. For example, in the Chandra survey of the Hubble Deep Field–North (HDF-N), B01b find \(\sim 7000\) sources deg\(^{-2}\) at the faintest direct limits ever probed in the X-ray, whereas the WFPC2 and Space Telescope Imaging Spectrograph (STIS) observations of the Hubble Deep Fields show source densities at least 2 orders of magnitude higher (e.g., Williams et al. 1996; Casertano et al. 2000; Gardner, Brown, & Ferguson 2000). Most of these objects are star-forming galaxies distributed over a wide range of redshifts (e.g., Lanzetta, Yahil, & Fernandez-Soto 1996; Mobasher et al. 1996; Connoly et al. 1997; Lowenthal et al. 1997) and should be X-ray sources at some level (e.g., Griffiths & Padovani 1990). Therefore, while the Chandra surveys have resolved the sources that make up the bulk of the luminosity density of the XRB, they have not yet detected the majority of the X-ray sources in the universe.

Promising progress in this regard has been made using stacking analysis. Brandt et al. (2001a, hereafter B01a), using a 500 ks Chandra exposure of the HDF-N region, stacked the X-ray flux from a sample of 17 \(z \sim 0.5\) galaxies with \(M_B \leq -18\). They found a significant detection when adding the signal from the galaxies together, despite the fact that none was detected individually. The mean X-ray luminosity was found to be \(1.3 \times 10^{41}\) ergs s\(^{-1}\), somewhat higher than that typical for galaxies in the local universe, which is typically roughly a few times \(10^{39}\) ergs s\(^{-1}\) (e.g., Fabbiano, Trinchieri, & McDonald 1984; Fabbiano & Trinchieri 1985). One motivation of the B01a investigation was to test the model of White & Ghosh (1998), who suggested that the X-ray luminosity of normal galaxies at \(z = 0.5\)–1 might be elevated compared to those in the local universe, as a result of evolution of LMXBs produced during the peak of the global star formation rate (SFR) at \(z = 1–3\) (Lilly et al. 1996; Madau et al. 1996; Madau, Pozzeti, & Dickinson 1998). Although they did find a fairly high X-ray luminosity for their galaxies, B01a concluded that the White-Ghosh effect was not particularly large, especially considering that their stacked galaxies were the most luminous optically and therefore perhaps the most massive. Most recently, Hornschemeier et al. (2002, hereafter H02) have extended this study to a much larger sample of spiral galaxies in the redshift range \(z = 0.4–1.5\), confirming a modest increase in the ratio of X-ray to B-band luminosity with increasing redshift.

Further development of the White-Ghosh LMXB evolution model (Ghosh & White 2001) has shown consistency with the observations, but it should be borne in mind that the delayed onset of X-rays due to LMXB evolution is a secondary effect. Prompt X-ray emission is expected in star-forming galaxies as a result of the production of HMXBs, in which the formation of X-rays should proceed shortly after formation (e.g., Fabbiano & Trinchieri 1985; David et al. 1992). Therefore, the X-ray emission of non-AGN galaxies should follow the global SFR and can in principle be used to trace it. Furthermore, as X-ray binaries in general have relatively hard X-ray spectra, their X-rays can penetrate the large columns of gas and dust in these starburst galaxies, which can cause considerable uncertainty in the derived SFRs (Steidel et al. 1999, hereafter S99; Blain et al. 1999; Adelberger & Steidel 2000). Regardless of the effects of obscuration, the observation of X-rays offers a different perspective on the star formation process in galaxies, which can then be compared and combined with indicators from other wavelengths (e.g., Cavaliere, Giacconi, & Menci 2000; Menci & Cavaliere 2000).

To make a meaningful contribution to the global star formation debate, it is necessary to determine the X-ray properties of galaxies at high redshift \((z > 1)\), where the global SFR peaks. The first attempt at this has been made by Brandt et al. (2001c, hereafter B01c), who stacked the emission of 24 Lyman break galaxies (LBGs; e.g., Steidel, Pettini, & Hamilton 1995; Steidel et al. 1996) around \(z \sim 3\) from the redshift catalogs of Cohen et al. (2000) and Cohen (2001). They found a \(\sim 3\) \(\sigma\) detection in the soft Chandra band \((0.5–2\) keV), corresponding to a rest-frame luminosity in the \(2–8\) keV band of \(3 \times 10^{41}\) ergs s\(^{-1}\). This is much higher than normal galaxies locally, and B01c concluded that this was due to the elevated SFRs in these galaxies (Steidel et al. 1996). This tentatively verifies that X-ray emission can be used as a probe of the global SFR. Here we improve and expand on the B01c results by considering the X-ray properties of a sample of 148 LBGs in the HDF-N region (this is a factor of 6 larger than the B01c sample), selected from a \(\sim 9\) \(\times\) \(9\) optical photometric survey. To this we add 95 Balmer break galaxies (BBGs) at \(z \sim 1\) to provide an X-ray perspective on star formation in the high-redshift universe.

2. Analysis

2.1. X-Ray Data

Chandra has observed the HDF-N region several times since launch. Details of some of these observations can be found in Hornschemeier et al. (2000), H01, and B01a. The analysis of the full 1 Ms Chandra observation is presented in B01b. For our own analysis, we took the X-ray data from the Chandra public archive. The data have been processed through the standard Chandra analysis software “CIAO” (v2.2). The data from the various HDF-N pointings have been combined, and standard screening criteria have been applied to the event files, including removal of flaring pixels. The nominal exposure time was 977.514 s, with the mean pointing position \(\alpha = 12^h36^m50^s, \delta = 62\degr13'45''12\) (J2000.0). This is close to the central HDF pointing position and the center of the LBG survey field. Our analysis is restricted to an approximately \(10.3\times10.3\) region centered on the mean Chandra pointing (see Fig. 1), which encompasses the optical LBG survey region \((8.7\times8.7)\). We have performed our analysis in two energy bands, 0.5–2 and 2–8 keV, which henceforth we refer to as the soft and hard bands. We also quote some results in the full (0.5–8 keV) band.

The HDF-N data were accumulated in a number of different pointings with different roll angles. This leads to a very inhomogeneous exposure map for the whole ACIS field of view. We have calculated the exposure and instrument maps using the standard CIAO prescription for each pointing separately and combined them to produce effective exposures for each pixel. As the mirror vignetting is energy dependent, we calculated the exposure map at a single energy representative of the mean energy of the photons in each band: 1 keV for the soft image and 5 keV for the hard image. We found a variation in effective exposure in the LBG field from \(\sim 236\) to \(\sim 972\) ks for the soft band and \(231–961\) ks for the
hard band. This effective exposure must be accounted for when converting the observed counts to flux: division of the number of counts by the effective exposure gives a count rate corrected for the exposure, mirror vignetting, and detector efficiency, equivalent to an on-axis count rate. The other important instrumental effect that must be considered is the variation in the point-spread function (PSF) with off-axis angle. The PSF variation is important for two reasons: (1) in the choice of extraction radius when determining source counts and (2) because of the position-dependent correction for counts falling outside the cell. We take an empirical approach to determining the extraction radius, which is discussed below. For the PSF correction of the counts, we used the encircled energy fractions given for the High Resolution Mirror Assembly in the Chandra Proposers' Observatory Guide, Version 3.0.

In converting the on-axis, PSF-corrected count rates to fluxes we have assumed a power-law source spectrum with Galactic $N_H$ of $1.6 \times 10^{20}$ cm$^{-2}$ (Stark et al. 1992). We adopt $\Gamma = 1.4$ for luminous hard X-ray sources that we believe are dominated by an AGN and $\Gamma = 2.0$ for the remainder. The latter is crudely appropriate for the integrated X-ray spectrum of star-forming galaxies. To calculate the luminosity, we adopt a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$. Where available, we adopt the spectroscopic redshift to calculate the luminosity. For LBGs where no spectroscopic redshift is available we adopt the median redshift implied by the selection function of $\langle z \rangle = 3$.

2.2. Optical Data

The LBG candidates were selected using photometric criteria as described in, e.g., S99. The interloper fraction in the LBG surveys as a whole is very small, approximately 4%, all of which are stars. In addition, there are no known interlopers fainter than $R > 24$. A total of 61 of the LBG candidates

Fig. 1.—Chandra soft-band image of the LBG survey region. Crosses show the location of the 148 LBGs, and circles show those directly detected in the X-ray band (Table 1). The properties of the remainder have been determined by stacking (see text).
have been spectroscopically confirmed as galaxies at $z \sim 3$, and only one of the color-selected LBG candidates for which a spectrum has been obtained is not a high-redshift galaxy. Accordingly, we proceed under the assumption that all 148 LBG candidates (excluding the known star) are high-redshift galaxies, whether or not they are spectroscopically confirmed. The Balmer break galaxy candidates are also color selected, based on the existence of that feature in the stellar SED. The selection function is therefore dependent on off-axis angle. These elliptical regions can be excluded from the background analysis. Because of degradation of the PSF, including galaxies at large off-axis angles may have a deleterious effect on the signal-to-noise ratio, if the PSF becomes so wide that we add primarily background counts. In practice we have found that while there is no improvement in signal-to-noise ratio beyond an off-axis angle of $\sim 5'$ radius (Fig. 2), neither does the detection probability threshold was set at $10^{-6}$, such that approximately one spurious source is expected for each run. The wavdetect algorithm defines an elliptical source region with a size and orientation depending on the instrumental PSF, and which is therefore dependent on off-axis angle. These elliptical regions can be excluded from the background analysis.

2.3. Source Detection

Our intent is to characterize the X-ray properties of high-redshift galaxies, rather than necessarily associated detected X-ray sources with optical ones. As our object class is well defined, this allows us to characterize the mean properties of the objects without the bias of X-ray selection. Nonetheless, it is useful to test whether any of the optical galaxies are individually detected in the Chandra image, which might give clues to the origin of the X-rays in both the brightest X-ray sources and the population as a whole. Furthermore, we need to know where the brightest X-ray sources are, whether or not they are associated with our target galaxies, so they can be excluded from the background determination and stacking. We performed source detection in the full, soft and hard bands using the Chandra “wavdetect” algorithm, following B01b. The detection probability threshold was set at $10^{-6}$, such that approximately one spurious source is expected for each run. The wavdetect algorithm defines an elliptical source region with a size and orientation depending on the instrumental PSF, and which is therefore dependent on off-axis angle. These elliptical regions can be excluded from the background analysis.

2.4. Stacking Procedure

The use of stacking to determine mean properties of objects has been applied widely in X-ray astronomy (e.g., Green et al. 1995; della Ceca et al. 1999). By adding together X-ray photons from well-defined classes of object, we can determine their mean X-ray properties. Furthermore, we can remove known, bright X-ray sources from the sample to determine the mean properties of sources too weak to be individually detected. The stacking technique has recently been applied with these Chandra observations of the HDF-N area (B01b; B01c; H02), to determine the properties of high-redshift galaxies including, as mentioned in § 1, a small sample of LBGs. We describe our own procedure in detail here.

The basic technique we have employed is similar to that described in B01a and B01c. First, we add together source counts from a large number of known optical galaxies, excluding known X-ray sources. If we can then estimate the expected background, we can assign a significance to the signal and determine the average flux and luminosity of the typical galaxy. Estimating the source-plus-background signal is simple, with the only complication being the size of the region used to extract the source counts. We do not expect these high-redshift galaxies, which have half-light radii less than 1$''$ (e.g., Giavalisco, Steidel, & Macchetto 1996), to be extended at the resolution of Chandra, so ideally the extraction radius should be comparable to the core of the PSF. In practice we used an entirely empirical approach to determining the optimal extraction radius, by testing several fixed values of that radius and taking the one that gave the maximum source signal. Another approach is to take a variable extraction region whose radius depends on the off-axis angle, i.e., a fixed fraction of the PSF width. In practice stacking experiments using such a detection cell gave lower significances than a fixed cell. This is due to the fact that the extraction cells at large off-axis angles become large and incorporate a large fraction of background. A further problem with using these large detection cells is that it greatly increases the probability of including a galaxy other than the target in the extraction region and invalidating the stacking results.

We found a constant-size 2$''$ radius circular region to give an optimal signal (Fig. 2) and have adopted this value for all subsequent analysis. We note that even at the maximum resolution of the Chandra images (0$''$5 pixels, which we adopt), the extraction cell is relatively small compared to the pixel size and therefore for an arbitrary position our region definition does not always result in a constant number of pixels for each extraction cell. Thus, the definition of whether a pixel is or is not inside the extraction cell becomes important. We define a pixel to be within the extraction radius if the center of that pixel falls within the circle. For the chosen 2$''$ radius the typical number of source pixels in each cell is 20.

Because of degradation of the PSF, including galaxies at large off-axis angles may have a deleterious effect on the signal-to-noise ratio, if the PSF becomes so wide that we add primarily background counts. In practice we have found that while there is no improvement in signal-to-noise ratio beyond an off-axis angle of $\sim 5'$ radius (Fig. 2), neither does the signal significantly degrade. In other words, the loss of source counts out of the fixed extraction cell is almost exactly balanced by the increase due to the larger number of galaxies considered. Despite these “diminishing returns,” we prefer to analyze the entire sample of LBGs and BBGs as the larger number of galaxies makes our conclusions regarding their mean properties more statistically robust.

To estimate if the summed counts constitute a significant signal, we estimated the background in several ways (see also B01b). First, we randomly shuffled the galaxy positions by $3'' - 10''$ and extracted the counts from these regions. Second, we chose random positions within the region of interest. We repeated these shuffled and random experiments...
typically 1000 times, which is sufficient to give an accurate estimate of the background counts and the dispersion, for comparison with Poisson statistics. For significantly larger numbers of trials and particularly for the shuffled positions, the estimates lose independence. Finally, we estimated the background from a background map produced by the wavdetect software, which is effectively a heavily smoothed version of the image with known sources removed. As shown in Figure 2, our results are not sensitive to the background estimation method, and generally we have adopted the shuffle method when quoting the results.

The instrumental effects discussed above may cause our estimates to be unrepresentative of the background at the tested source positions. In particular, for the shuffled and randomized estimates, the total exposure time at the tested background positions, instrumental efficiency, vignetting, and source-cell definitions are different for the background positions than they are for the source positions. However, as typically a large number of galaxy positions are tested, on average the shuffled or randomized positions should represent similar instrumental characteristics to the source positions. Thus, it should be valid to perform the stacking without applying these corrections, which depend on our uncertain knowledge of the instruments. In addition, in this very deep image most of the diffuse XRB is resolved and the particle background will dominate. Unlike source photons, the expected distribution of these particle events is unlikely to be well represented by the combined instrument/exposure map. Nonuniformities in the particle background may be present, but they are difficult to quantify and are probably best accounted for at the current time by taking a large number of random realizations, as we have done here. Therefore, the only correction we have applied to the background estimates is the simple one of the total number of pixels in each background realization relative to the total pixels in the source regions. This can be nonnegligible, if a significantly different number of background test positions fall in “masked” regions (i.e., where sources are directly detected) when compared to the galaxy cells.

3. RESULTS

3.1. Direct Detections

We detected 125 and 107 sources in the soft and hard bands. Four of the LBGs were found to be coincident with directly detected Chandra sources in the 0.5–2 keV band (2–8 keV at \( z = 3 \)). The detected sources are listed in Table 1. All four sources are also identified by a simple extraction of counts in the 2.5 detection cell we used for stacking, and we have used this extraction to calculate the source fluxes. The weakest had 20 counts in this cell, with only 1.14 expected from background. All four are therefore extremely secure X-ray sources. In contrast, the fifth brightest LBG has only 6 counts, which, although individually significant at \( \sim 99.8\% \) confidence, is not significant considering the number of trials.

The optical positions of the detected LBGs were within less than 0.5 of the Chandra centroid determined by wavdetect, consistent with the positional error (B01c). There is some possibility that the detected X-ray sources are not associated with the LBGs, but we believe these are secure. Given the number of test positions and detected sources, we estimate the chance probability that one of the associations is spurious to be less than 5\%, and that they all are to be less than \( 10^{-6} \). All four of the directly detected sources have already been reported by B01b, but only one has been identified (CXOHDFN J123633.4+621418 by H01), with a \( z = 3.4 \) broad-line AGN (Cohen et al. 2000). The other spectroscopically identified LBG in our sample is CXOHDFN J123719.9+620955 (=MMD 12) at \( z = 2.643 \) (Steidel et al. 2002). It shows strong C iv, C iii, and He ii emission in addition to Ly\( \alpha \) and is almost certainly also an AGN. While neither of the other two detected X-ray sources have been attempted spectroscopically, as discussed above the interloper fraction using the Lyman break technique is extremely small, and it is highly likely that these are also galaxies at \( z \sim 3 \). The X-ray luminosities of all of these galaxies in the 2–10 keV band are therefore greater than \( 10^{43} \) ergs s\(^{-1} \) (Table 1), and as discussed below all the directly detected

![Figure 2](image-url)
galaxies almost certainly host bright AGNs. This conclusion is further supported in three of the four cases by their detection in the hard band (2–8 keV observed frame or $\approx$8–30 keV rest frame). The hardness ratio (HS) of the detected sources, calculated by summing the counts in the 2–8 and 0.5–2 keV bands and dividing them, is $HS = 0.44 \pm 0.04$. This corresponds to an unabsorbed spectral index of $\Gamma = 1.5^{+0.05}_{-0.10}$. Assuming an intrinsic spectrum of $\Gamma = 2.0$, more typical of local Seyfert galaxies and soft X-ray-selected quasars (e.g., Nandra & Pounds 1994; Georgantopoulos et al. 1996), the color implies a large absorbing column of $N_H = 1.2^{+0.3}_{-0.1} \times 10^{23}$ cm$^{-2}$, if the material is intrinsic to the source at $z = 3$. The latter is much higher than is typically observed in low-redshift Seyfert 1 galaxies (e.g., Turner & Pounds 1989; Nandra & Pounds 1994), but at the low end of that seen in type 2 Seyfert galaxies (Awaki et al. 1991; Risaliti, Maiolino, & Salvati 1999).

The wavdetect direct detection threshold is $3 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ in the soft band for the maximum exposure in the image (see also B01b). This corresponds to a luminosity of $\sim 2 \times 10^{42}$ ergs s$^{-1}$ at the median redshift of $(z) = 3$. In the hard band the corresponding limit is $1.5 \times 10^{46}$ erg s$^{-1}$. These limits are a factor of $\sim 4$ worse than the minimum exposure point.

Turning to the BBG sample, we found seven significant soft-band detections, which are also given in Table 1. Of these, two have previously been reported by H01, with one being identified with a broad-line AGN at $z = 0.962$ (Cohen et al. 2000). This source—in the HDF proper—is CXOHDFN J123646.3+621405 (MFFN 252) and is very bright, with 554 counts (Table 1) and an even stronger detection in the hard band with 658 total counts. This source has an implied luminosity of $L_X > 10^{43}$ ergs s$^{-1}$, making its properties rather similar to the directly detected LBGs. The hardness ratio is larger ($HS = 1.18$), implying an extremely flat spectrum of $\Gamma = 0.6$, but also consistent with a $\Gamma = 2.0$ spectrum and a column of $N_H = 7 \times 10^{23}$ cm$^{-2}$ at the source redshift of $z = 0.962$. This is in fact similar to the spectrum inferred for the detected LBGs. If the sources are absorbed, the lower hardness ratio for the LBGs may simply be due to a negative $K$-correction, with the absorption being redshifted out of the bandpass.

B01a have performed a direct spectral fit for this object based on the 500 ks observation and found that the source is indeed absorbed, with $\Gamma = 1.6$ and $N_H = 4 \times 10^{22}$ cm$^{-2}$, although both parameters have fairly large errors. The other H01 detection was CXOHDFN J123657.4+621026 (=FFN 71). The soft-band flux of this source ($14$ counts) is similar to the remaining five sources, which range from 8 to 27 counts. The brightest one has an implied luminosity of $10^{42}$ ergs s$^{-1}$.

| Name                  | Offsets (arcsec) | $R$  | $\gamma$ | Counts | $L_{2-10}$ (10^{16} ergs cm^{-2} s^{-1}) | $F_{0.2-0.5}$ (10^{16} ergs cm^{-2} s^{-1}) | $F_{0.5-2}$ (10^{16} ergs cm^{-2} s^{-1}) | $L_X$ (10^{42} ergs s^{-1}) |
|-----------------------|------------------|------|----------|--------|----------------------------------------|---------------------------------------------|------------------------------------------|---------------------------------|
| J123633.4+621418       | oC 34            | 0.49 | 24.15    | 3.406  | 72                                     | 1.20                                        | 5.6 \pm 1.1                             | 5.9 \pm 0.7                     |
| J123655.8+621200       | CC 10            | 0.20 | 24.36    | ...    | 22                                     | 1.20                                        | 3.2 \pm 0.8                             | 1.2 \pm 0.3                     |
| J123702.6+621244       | MMD 34           | 0.13 | 25.32    | ...    | 20                                     | 1.14                                        | \leq 2.1                                | 1.4 \pm 0.3                     |
| J123719.9+620955       | MMD 12           | 0.29 | 24.84    | 2.643  | 78                                     | 1.20                                        | 18.3 \pm 2.6                            | 4.2 \pm 0.5                     |
| J123627.3+621258       | MFFN 205         | 0.63 | 22.57    | 1.221  | 9                                      | 1.27                                        | 0.43 \pm 0.14                           | <2.2                           |
| J123633.7+621006       | FFN 64           | 0.54 | 22.55    | 1.016  | 27                                     | 1.33                                        | 1.49 \pm 0.29                           | 2.8 \pm 0.8                    |
| J123634.5+621241       | FFN 228          | 0.44 | 23.46    | 1.225  | 18                                     | 1.27                                        | 0.89 \pm 0.21                           | <2.2                           |
| J123646.3+621405       | MFFN 252         | 0.22 | 22.04    | 0.962  | 554                                    | 1.27                                        | 27.9 \pm 1.2                            | 171.2 \pm 6.7                  |
| J123646.3+621529       | MFFN 317         | 0.84 | 22.12    | 0.853  | 12                                     | 1.33                                        | 0.57 \pm 0.16                           | <2.2                           |
| J123653.6+621115       | AFFN 83          | 0.37 | 23.34    | 0.890  | 8                                      | 1.33                                        | 0.36 \pm 0.13                           | <2.2                           |
| J123657.4+621025       | MFFN 71          | 0.47 | 23.55    | 0.847  | 14                                     | 1.14                                        | 0.72 \pm 0.19                           | <2.2                           |
| J123707.9+621606b       | FFN 379          | 0.11 | 22.17    | 0.936  | 23                                     | 2.81                                        | <0.45                                   | 6.2 \pm 1.3                    |

Note—Col. (1): *Chandra* designation based on the wavelet-detected position in the full band. Col. (2): LBG/BBG survey name. Col. (3): Offset between *Chandra* and optical position in arcseconds. Col. (4): R magnitude. Col. (5): Spectroscopic redshift. Col. (6): Photons in the 2–5 keV detection cell (soft band). Col. (7): Expected background counts in the cell. Col. (8): Soft-band flux. Col. (9): Hard-band flux. Col. (10): Rest-frame 2–10 keV luminosity assuming an unabsorbed $\Gamma = 2$ power law and converted from the soft-band flux.

a Also hard-band detection.

b Luminosity converted from hard-band flux.

c This source has no significant detection in the soft band (6 counts). Counts and background refer to hard-band counts.
We do not detect the stacked LBGs in the hard band, with a 3σ upper limit of ∼60 counts, corresponding to a rest-frame (8–32 keV) luminosity of 1.2 × 10^{42} ergs s^{-1}. Assuming that the stacked LBGs have the same X-ray spectrum as the detected ones (i.e., with HS = 0.44), we predict 33 counts in the hard band from the stacked images, consistent with the observed limit. Thus, we cannot state definitively whether the stacked LBGs have a spectrum significantly different from the directly detected ones.

Stacking the 87 nondetected BBGs in the soft band, we again find a highly significant signal, this time at ~8–9σ (Table 2; Fig. 3), with a total of ~90 counts attributable to the galaxies—about 1 per source. Here the mean flux per galaxy of 6.4 × 10^{-18} ergs cm^{-2} s^{-1} corresponds to much lower luminosity of 3.3 × 10^{40} ergs s^{-1} in the 2–10 keV band, a factor of ~10 lower than the LBGs. On the other hand, many of the BBGs detected directly have luminosities below the detection threshold if they were at z = 3. We would therefore have included them in the “stack” of LBGs, meaning that this is not necessarily a fair comparison. Indeed, only the bright AGN CXOHDFN J123646.3+621405 (MFFN 252) has a luminosity large enough to have been detectable at z = 3. Adding back in the other sources results in an inferred mean luminosity of 6.6 × 10^{40} ergs s^{-1}, still a factor of ~5 lower than the LBGs. We note that the one very secure AGN in the BBG sample MFFN 252 is more luminous individually than the sum of the entire remainder of the sample. Furthermore, the six additional BBGs individually detected in the soft band contribute approximately half of the X-ray luminosity of the sample (excluding MFFN 252).

The stack of BBGs is not detected in the hard band either, with a 3σ upper limit of ~44 counts. The implied hardness ratio is incompatible with the detected AGN MFFN 252 in the BBG sample at high confidence: the stacked sources are much softer than this. They are also different at 2.6σ from the colors of the directly detected LBGs of HS = 0.44. As neither the LBG nor the BBG stack is detected in the hard band, their colors are of course consistent with each other.

Table 2

| Sample (1) | Band (2) | S (3) | B (4) | B^{1/2} (5) | σ_B (6) | S/N (7) | F_X (×10^{-18} ergs cm^{-2} s^{-1}) | L_X (×10^{44} ergs s^{-1}) |
|------------|---------|------|------|-----------|-------|-------|-----------------------------|---------------------|
| LBG....... | Soft    | 252  | 176.4| 13.3      | 13.5  | 5.7   | 3.3 ± 0.7                   | 3.4 ± 0.7           |
| BBG....... | Soft    | 206  | 118.0| 10.9      | 10.9  | 8.1   | 6.4 ± 1.0                   | 0.33 ± 0.05         |
| LBG....... | Hard    | 404  | 385.9| 19.6      | 18.6  | 0.9   | <11.7                      | <12.0               |
| BBG....... | Hard    | 252  | 228.8| 15.1      | 14.8  | 1.7   | <14.1                      | <0.87               |

| Sample (1) | Band (2) | S (3) | B (4) | B^{1/2} (5) | σ_B (6) | S/N (7) | F_X (×10^{-18} ergs cm^{-2} s^{-1}) | L_X (×10^{44} ergs s^{-1}) |
|------------|---------|------|------|-----------|-------|-------|-----------------------------|---------------------|
| LBG....... | Soft    | 252  | 175.2| 13.2      | 14.2  | 5.6   | 3.4 ± 0.7                   | 3.5 ± 0.6           |
| BBG....... | Soft    | 206  | 113.4| 10.6      | 11.1  | 8.3   | 7.2 ± 1.0                   | 0.37 ± 0.05         |
| LBG....... | Hard    | 404  | 377.5| 19.4      | 19.8  | 1.3   | <11.7                      | <12.0               |
| BBG....... | Hard    | 252  | 232.8| 15.2      | 15.7  | 1.2   | <14.1                      | <0.87               |

Note.—Col. (1): Galaxy sample. Col. (2): Observed frame energy band; soft is 0.5–2 keV and hard 2–8 keV. Col. (3): Source counts. Col. (4): Background counts. Col. (5): Poisson error on background counts. Col. (6): Dispersion of background counts. Col. (7): Signal-to-noise ratio [(S - B)/N], where the noise N is the larger of B^{1/2} and σ_B. Col. (8): X-ray flux per galaxy in the given band; upper limits are 3σ. Col. (9): X-ray luminosity in the 2–10 keV band, derived from the soft-band flux assuming Γ = 2.0 and Galactic N_H, or in the 10–50 keV band derived from the hard counts.

Stacking the BBGs in exactly the same rest-frame band as the LBGs (2–8 keV, i.e., observed 1–4 keV band) gives a consistent 2–10 keV luminosity.

3.2. Stacking

The results of the stacking are summarized in Table 2. As can be seen from this, and Figures 2 and 3, stacking the 144 undetected LBGs gives a strong signal of 6σ above the expected background level. An excess of 75 counts is obtained. Our detection is considerably more significant than the ∼3σ detection obtained by B01c, as a result of the much larger number of galaxies we have available for stacking. Indeed, for an inclusion radius 1.5–2′ (16–30 galaxies), which is similar to the central HDF used by B01 with 24 galaxies, we obtain a very similar significance (Fig. 2). The mean count rate corresponds to a flux of 3.3 × 10^{-18} ergs cm^{-2} s^{-1} per galaxy, with a luminosity of 3.4 × 10^{41} ergs cm^{-2} s^{-1}. Approximately 0.5 count is detected from each of these LBGs on average. It is also interesting to consider the properties of the nondetected sources using the stacking technique.
These star-forming galaxies evidently have hard spectra if they have high X-ray luminosity \( L_X > 10^{43} \text{ ergs s}^{-1} \), which fits in with our suggestion that they are AGNs. The lower luminosity stacked sources have softer X-ray colors, which may be indicative of star formation.

3.3. Statistical Considerations

The designation of some sources as “detections” and others not is an arbitrary distinction, which is normally applied in a conservative manner to avoid a high probability of false detections (e.g., Miller et al. 2001). This distinction is particularly striking in the case of Chandra surveys for weak sources as the background is so very low. For example, in our optimal extraction radius of 2′.5, we predict typically 1.25 background counts in the soft band, and thus observing only five photons in a single cell is significant at greater than 99% confidence. In practice many cells are tested, but given that we are strictly in the Poisson regime, the number of sources considered to be “real” depends on an arbitrary threshold. Where this is set (whether at, say, 8 or 9 photons, for example) can dramatically change the number of sources considered to be significant. This also makes the source detection process severely susceptible to “Eddington bias”: only randomly positive fluctuations are treated as detections.

Stacking of objects not selected in the X-ray band is actually advantageous in this regard, since if all objects are included, there is no such bias. The disadvantage is that the stacked objects, while having well-defined selection criteria in some other band (in our case the optical/UV), may have heterogeneous properties in the X-rays. A particular consideration in our case, for example, is whether the X-rays from these high-redshift galaxies arise from nuclear accreting black holes (i.e., AGNs) or from processes related to star formation (X-ray binaries, supernova remnants, winds, etc.). Stacking all of the objects together gives us an estimate of the mean luminosity of the sources, but not much more.

In practice we have not stacked all of the objects but have designated some of them direct detections and excluded them from the stacking procedure. This allows us to examine the properties of those sources individually, compare them with other properties, and search for correlations. It also gives more meaning to the stacked signal for the weaker sources, which would otherwise be swamped by inclusion of the direct detections. Nonetheless, the application of a detection threshold makes us potentially susceptible to the Eddington bias. Examining the distribution of counts obtained for each galaxy may allow quantification of this bias and furthermore should let us examine the (related) issue of whether the stacked signal is dominated by just a few subthreshold objects and therefore not representative of the mean of the population.

Figure 4 shows the distribution of counts obtained in the detection cell for both the LBGs and BBGs. In both cases, we have calculated an arbitrary detection threshold (similar to that of the wavdetect algorithm) corresponding to a number of counts for which there is 99% confidence that the source has more counts than expected from the background level, after accounting for the number of trials. In both cases this threshold is 8 counts.

Looking at the LBGs first, there is a very clear distinction between those sources we consider detections, which are all well above the threshold level, and those we have included in the stacking, which form a continuous distribution. Even for the weakest detected source with 20 counts, the probability that we obtain such a large number based on the background level (vertical dotted line) is vanishingly small. This probability remains negligible when we calculate it based on the mean counts per cell derived from the stacked galaxies (i.e., source plus background per cell for all sources with less than 8 counts). Thus, the detected sources are not consistent with simply being Eddington-biased examples of the stacked population and must have significantly higher fluxes. This justifies our exclusion of them from the stacking process, particularly because, as we shall discuss below, the
luminosity corresponding to these fluxes places them at a level at or above which an AGN origin is almost certain. The X-rays from the remainder of the objects may or may not arise from AGNs, but including the X-rays from the brightest objects would clearly swamp the stacked emission.

We have also investigated whether the stacked signal could be due to just a few “bright” sources just below the detection threshold. This is particularly relevant to our discussion as it is possible that a few subthreshold AGNs might contribute the entire stacked signal, invalidating our conclusions about the mean emission of the typical galaxy. Four sources in the LBG stack have as many as 6 counts. The probability of individually obtaining such a large amount of counts given the background level is approximately $9 \times 10^{-3}$. Accounting for the number of trials, however, we find that the probability of one or more sources being observed with such a high number of counts is 0.73. To calculate the probability that four (or more) such bright cells would be detected, it is easiest to use simulations. We find this probability to be about 4%, offering some (weak) evidence that the distribution is “top heavy.” A highly conservative way of determining the minimum number of galaxies that must contribute to the stacked signal is to remove the galaxies with the most counts systematically until the signal becomes insignificant. For the LBGs we can remove all four sources with 6 counts and still obtain a significant signal at the 3.9 $\sigma$ level. If we further remove all seven cells with 5 counts, the signal drops to below 2 $\sigma$. Thus, in principle the detected signal could be reproduced even if 90% of the LBGs emitted no X-rays at all. In practice the count distribution is a random realization of the Poisson fluctuations in each cell, and it is highly unlikely that—even if the above null hypothesis is true—the X-ray “active” cells would happen to produce the highest number of counts. In addition, the mean counts per cell for these 11 bright cells is 5.36, yet we observe no cells with greater than 7 counts. The probability that this would happen in 11 trials with the given mean is less than 3%. It is therefore much more likely that a large number of the LBGs contribute to the signal. Having said that, given the wide range of optical magnitudes, extinctions, SFRs, and nuclear AGN contributions in the LBGs, it is highly likely that the sources in the stack exhibit a range of X-ray luminosities. This will only be quantifiable with improved X-ray data.

For the BBGs there appears to be a more continuous distribution around the threshold level and a less clear distinction between detected and nondetected sources. Here the mean source-plus-background signal per cell for the stacked sources is 2.37, and both the probability calculations and simulations show that obtaining 12 counts is very unlikely by chance if this is the mean of the distribution ($p < 10^{-5}$). We (and wavdetect) have also designated the two sources with 8 and 9 counts as significant, and the simulations confirm that indeed the probability of obtaining them is less than 1% based on the background level. It is not especially unlikely, however, that these sources have a significantly different flux from the remainder of the stack. The simulations give 9 counts or more given a mean of 2.37 about 7% of the time and 8 counts or more for more than 20% of the time. The 8 and 9 count cells are therefore consistent with simply being sources that are part of the stack, which are undergoing random positive fluctuations. Nonetheless, there is a clear range in luminosities in the BBG sample, which is again expected on other grounds. The results from the BBGs circumstantially support our conclusion that the LBG signal is not dominated by a few objects: when the X-ray–bright end of the BBG distribution is removed (by the sources being detected), a highly significant signal remains from the weaker objects. This is also likely the case for the LBGs. The fact that we do directly detect the bright end of the BBG population and can therefore identify the brightest sources means that we can examine whether or not they stand out in any other way. We now discuss the non–X-ray properties of these galaxies.

4. MULTI-WAVE BAND PROPERTIES OF THE SOURCES

A crucial question that we discuss in detail below is that of whether the X-rays we have detected from these high-red-
shift galaxies are due to accreting nuclear black holes (AGNs) or processes associated with star formation such as X-ray binaries, supernova, diffuse emission, etc. The non–X-ray properties of our sample of high-redshift galaxies offer some clues to this. As we have already mentioned, there are two LBGs detected directly in the X-rays and for which spectroscopy is available. Both show evidence for AGN activity in their UV spectra. It is very likely that the X-rays from these arise from the active nucleus. The other two LBGs that are bright X-ray sources have not been attempted spectroscopically, and it will be interesting to see if future observations reveal AGN signatures in their UV spectra. At least one additional LBG, oMD 49 at if, is a possible candidate for AGN activity in their UV spectra. It is very likely that the X-rays from these arise from the active nucleus. The other two LBGs that are bright X-ray sources have not been attempted spectroscopically, and it will be interesting to see if future observations reveal AGN signatures in their UV spectra. At least one additional LBG, oMD 49 at if, is a possible candidate for AGN activity in their UV spectra.

In passing we note that a similar debate between AGNs and starbursts exists. As we have already mentioned, a critical issue is whether the X-rays we detect from the LBGs and BBGs arise from AGNs or star-forming processes. B01b made no clear distinction between the two, noting that low-luminosity AGNs are very common in nearby galaxies (Ho, Filippenko, & Sargent 1997), and therefore at least some contribution from a nuclear accreting black hole may be considered “normal.” While this may be so, discriminating between starbursts and accretion is extremely important if the X-ray observations are to be interpreted in detail and astrophysical conclusions drawn. For example, the stacking shows that the LBGs have X-ray luminosities approximately 2 orders of magnitude greater than spiral galaxies in the nearby universe. If these additional X-rays are from AGNs, it implies that the LBGs are typically going through a fairly vigorous phase of black hole growth, accompanying their copious star formation. Such a conclusion would have strong implications for ideas connecting galaxy and black hole formation (e.g., Silk & Rees 1998; Haehnelt & Kauffmann 2000). On the other hand, the enhanced X-ray emission may simply reflect the intense star formation in these objects. If this is the case, it may be possible to use the X-ray emission as a tracer of the SFR, and as we are able to observe the hard X-ray emission, the estimates should suffer relatively little bias due to absorption (cf. the UV; S99; Adelberger & Steidel 2000). X-ray observations of high-redshift, non-AGN galaxies are therefore potentially an important tracer of the cosmic star formation history (e.g., Lilly et al. 1996; Madau et al. 1996, 1998; S99; Blain et al. 1999; Cowie, Songaila, & Barger 1999; Barger, Cowie, & Richards 2000). Clearly there are important conclusions to be drawn whether or not the X-rays from these high-redshift galaxies are from AGNs or star formation, but the conclusions are quite different depending on which mechanism dominates. In passing we note that a similar debate between AGNs and star formation exists in the discussion of luminous infrared/submillimeter galaxies (e.g., Sanders et al. 1988; Sanders & Mirabel 1996; Genzel et al. 1998), which is still not resolved. Both processes are likely to contribute to some extent. We
now discuss in detail the likely origin of the X-rays we have observed.

The X-rays from the four directly detected LBGs and the one very bright BBG are almost certainly from nuclear, accreting supermassive black holes (i.e., AGNs), based on their X-ray luminosity alone. In the extreme, local starburst luminosities never exceed $L_X = 10^{42}$ ergs s$^{-1}$ (Zezas, Georgantopoulos, & Ward 1998; Moran et al. 1999). The SFRs may be even higher in these high-redshift galaxies, but the observation of X-ray luminosities greater than $10^{43}$ ergs s$^{-1}$ is a good indicator that an AGN is the dominant X-ray emission mechanism. The detection of these sources in the hard band (above 8 keV rest frame for the LBGs) and their hard X-ray color is another strong indication that these are AGNs: star-forming processes tend to present softer spectra. Where optical/UV spectra are available, they also exhibit high-ionization (and sometimes broad) emission lines confirming their AGN nature. The other source that is very likely to be AGN dominated is the BBG detected in the hard band only: galaxies with such hard X-ray spectra are very likely to house obscured AGNs.

For the remainder of the sources, X-ray luminosity cannot be used to discriminate, as they have $L_X < 10^{42}$ ergs s$^{-1}$. This could be accounted for by either AGNs or star-forming processes. The colors are unremarkable for unobscured AGNs, but it is noteworthy that at least the stacked BBGs have X-ray colors significantly softer than the directly detected, secure AGNs in both the BBG and LBG samples. This is consistent with the idea that the X-rays come from star formation, rather than AGNs. The only unambiguous way to determine the origin of the emission in these sources is by high-quality X-ray imaging at $\sim 0.1$ resolution. Such data are unlikely to be available for some time. Time variability in the X-rays would be another clear indication that an AGN dominates, but once again such diagnostics are not currently available and will not be unless we can detect the galaxies directly, rather than by stacking. There are further clues, however, from the multi–wave band data, and these tend to favor star formation over accretion as the likely source of the X-rays.

First, we note that only one LBG not directly detected in the X-ray band shows prominent high excitation or broadband emission in its UV spectrum. None of the BBGs save for the single, bright X-ray source shows clear AGN signatures in the optical spectrum. This in itself is not a certain indicator that an AGN is not present, as deep Chandra surveys clearly show that there is a large population of high-luminosity X-ray sources that exhibit no optical signature of AGN activity (Mushotzky et al. 2000; H01). Unless the reddening is large, however, low-level AGN activity may be easier to pick up in the rest-frame UV than in the optical because so many of the high-excitation AGN signatures are UV lines. We observe this band in the LBGs and find no such evidence, but UV spectroscopy is lacking for the BBGs. It would clearly be interesting to see if any AGN spectral lines are revealed at 1000–2000 Å rest frame in the X-ray–bright BBGs.

Another fairly robust discriminator between AGN and starburst activity is the radio emission. The 1.4 GHz source counts show an upturn below a few millijanskys, above which AGNs dominate and below which starburst galaxies dominate the counts (e.g., Windhorst et al. 1985, 1993). Submilljanskys sources may therefore have contributions from both, but extended radio emission is expected from starburst activity, and core-dominated emission from AGNs. The radio morphology can therefore in principle be used to discriminate and quantify the AGN and starburst contributions. As mentioned above, none of the BBGs has been detected at 1.4 GHz, and therefore no strong inferences can be made, only the relatively weak statement that there appear to be no radio-quiet AGNs in the sample. For the BBGs, one object is strong and clearly core dominated at 20 mas resolution (Garrett et al. 2001). This is CXOHDFN J123646.3+621405 (=MFFN 252), which we have already noted as the brightest X-ray source and a known AGN. Of the other two strong radio detections, one is marginally resolved and the other unresolved at 2" resolution. The other important inference from the radio is that the brightest BBGs in the X-ray are also the brightest in the radio, with the detections contributing similar percentages of the total flux in each band. If the bulk of the X-rays come from star formation, this is expected, as roughly speaking both fluxes should scale with the SFR of the galaxy (e.g., Condon 1992). In the AGN case this is not expected: the radio fluxes of standard QSOs have a bimodal distribution that is dominated by radio-quiet AGNs, so we do not expect bright X-ray sources necessarily also to be bright radio sources. The implication would be that the new population of obscured AGNs revealed by Chandra have different radio properties to normal QSOs. The key test in the radio is to perform higher resolution radio imaging at submilliojansky levels. If the galaxies are typically resolved in the radio, they are almost certain to be starbursts.

As discussed in § 4, in addition to being strong radio sources, the X-ray–bright objects in the LBG population stands out in other ways. For example, they tend to be ISO sources. This is again expected for starbursts, with the mid-IR following the SFR (e.g., Rowan-Robinson et al. 1997). This may also be expected for AGNs, however, as the mid-IR is thought to be emitted by dust heated by the active nucleus (e.g., Alonso-Herrero et al. 2001). They also have rather red near-UV colors and are among the brightest BBGs in the optical. All these properties point suggestively, if not conclusively, toward star formation: the brightest X-ray objects in the BBG sample also have the strongest star formation indicators.

The final and arguably most compelling argument for star formation comes from comparing the LBG and BBG samples. The mean UV luminosity of the LBGs in our sample ($\nu L_{\nu}$ at 1700 Å rest frame) is $3.6 \times 10^{10}$ L$_{\odot}$. The mean UV luminosity of the BBGs ($\nu L_{\nu}$ at 2000 Å rest frame) for our adopted cosmology is $7.8 \times 10^{10}$ L$_{\odot}$. Thus, the BBGs are on average 4.6 times more luminous in the UV than the BBGs, reflecting the fact that they have SFRs higher by roughly the same factor. When we subject the BBG sample to the same X-ray luminosity threshold as the stacked LBGs, the ratio of the X-ray luminosities of 5.3 $\pm$ 1.3 is remarkably similar to and entirely consistent with the ratio of the UV luminosities. In other words, the ratio of the X-ray to UV luminosity, $L_X/L_{UV}$, is the same at $z = 1$ as at $z = 3$. This very strongly implies that the X-ray emission follows the current SFR, as measured by the UV.

Although we cannot at this point be completely certain about the origin of the X-rays in the low-$L_X$ galaxies, the evidence favors an origin in star formation processes, rather than a dominant AGN contribution. We will therefore make this assumption for the purposes of discussing our results further.
5.2. Bright AGNs in Star-forming Galaxies

The Lyman break technique should select all objects that are bright enough in the UV to show the spectral break due to intergalactic medium absorption, regardless of whether the UV emission is from hot stars or, say, an AGN accretion disk. Selection of AGNs from the LBG sample can therefore be based on the existence of high-excitation lines in the UV spectra or by the detection of strong X-ray emission. We find four clear AGNs in our sample of 148 LBGs—about 3%. Although the numbers are clearly very small at this point, this agrees rather well with the proportion of LBGs that show high-excitation UV emission lines (2.6%; Steidel et al. 2002). This, and the fact that we detect no strong X-ray sources in LBGs that have no UV AGN signatures, suggests that there are no powerful AGNs in the LBGs that are completely hidden in the UV. At first glance this is surprising, as Chandra observations have shown a large population of X-ray sources in galaxies with no obvious optical or UV AGN signatures (Mushotzky et al. 2000; Barger et al. 2001a; H01). It should be noted, however, that these “X-ray only” AGNs tend to lie in galaxies that are either very faint in the optical (Mushotzky et al. 2000; Alexander et al. 2001) or evolved bulge galaxies (e.g., Mushotzky et al. 2000; Cowie et al. 2001). The very faint optical sources would not have been picked up in the LBG survey, and there may not have been enough time for massive bulge galaxies to evolve by $z = 3$. Alternatively or additionally, these AGNs may simply be too heavily obscured to be detected in the rest-frame UV in the LBG surveys. Therefore, the AGN number counts derived from this work represent a lower limit, as there may be bright accreting black holes in galaxies that are too red or faint to be selected by the Lyman break technique. Strenuous follow-up of detected X-ray sources in the HDF-N and other deep fields will show whether there is such a population. Indeed it has been suggested that X-ray emission may be used as a “signpost” to find relatively evolved galaxies at high redshift (Cowie et al. 2001).

The AGN fraction in the LBGs also agrees roughly with the estimate of Barger et al. (2001b), on the basis of Chandra data, that at any given time 4% of galaxies are going through a luminous (X-ray) AGN phase. Certainly, we do not find any evidence that the LBGs are going through a more active period of radiatively efficient black hole accretion than galaxies at lower redshift, or galaxies that are not going through a period of extreme star formation. The connection between black holes and galaxy formation/evolution appears to be very strong, at least for massive galaxies in the local universe (Ferrarese & Merritt 2000; Gebhardt et al. 2000). One might therefore naively expect that the LBGs, which are the likely progenitors of these local galaxies and are in the process of forming a large fraction of their stars, should also be actively growing black holes (e.g., Page et al. 2001). This appears not to be the case, unless the accretion proceeds in a radiatively inefficient flow (e.g., Narayan & Yi 1994; Blandford & Begelman 1999). On the other hand, Shapley et al. (2001) have shown that the typical stellar mass of $L^*$ LBGs is $\sim (1-2) \times 10^{10} M_\odot$. Assuming that these form a future bulge, and using the local relation between black hole and bulge mass of approximately 0.2% (Merritt & Ferrarese 2001), we therefore expect them to host black holes of mass $(2-4) \times 10^7 M_\odot$. The 2–10 keV luminosity of our detected AGN is $\sim 10^{45}$ erg s$^{-1}$, and the bolometric luminosity of the AGN is therefore likely to be $\sim$ few times $10^{44}$ ergs s$^{-1}$ (Padovani & Rafanelli 1988; Elvis et al. 1994). They are therefore radiating at a relatively high fraction ($>10\%$) of the Eddington limit.

Turning to the BBGs, we find one very clear AGN, MFFN 252, out of a sample of 95. This object is extremely bright in X-rays and shows optical broad lines and extremely compact radio emission. The other likely AGN in the sample is the object detected only in the Chandra hard X-ray band. This implies an AGN fraction similar to the LBGs, but any conclusions about the proportion of AGNs in $z \sim 1$ star-forming galaxies are considerably less robust. As these are selected on the Balmer break, a feature of the stellar SED, one could miss galaxies in which this feature was masked by strong AGN emission. Indeed H01 report as many as nine additional identified X-ray sources (presumably AGNs) in the redshift range $z = 0.7–1.3$ in the HDF-N. However, these objects may simply have been excluded from the BBG sample as a result of the narrowness of the selection function or because no spectroscopic redshift has yet been obtained. We await larger samples to clarify this issue.

There is good evidence that MFFN 252 is absorbed in the X-ray from both the X-ray color and direct fitting (B01a), and this is also indicated by the X-ray color of the detected LBGs. The fact that there is significant obscuration is no great surprise, given the existence of dusty starburst gas in these galaxies. At least in MFFN 252 we clearly see the broad emission lines, however, so it appears that while the nuclear X-rays are obscured, the broad-line region is not. This is therefore more suggestive of obscuration close to the nuclear regions, perhaps which is relatively dust free. The local analog is the “archetypal” Seyfert NGC 4151, which has strong optical and UV broad lines but is heavily absorbed in the X-ray. Presumably the absorbing material in this object either is very close to the nuclear source (i.e., within the broad-line region) or has very little dust, perhaps as a result of the fact that it is above the sublimation temperature. MFFN 252 may therefore contain a “warm absorber” at high redshift.

5.3. Star Formation Rates from the X-Ray Data

While a contribution from an AGN cannot be strongly ruled out, the vast majority of these high-redshift star-forming galaxies appear to have X-ray emission dominated by star formation processes. As mentioned in § 1, X-ray emission in normal galaxies arises from the evolved stars (primarily LMXBs), but in starburst galaxies it is mainly from systems involving massive stars. The LBGs in particular are not thought to contain any evolved stellar populations and are almost certainly too young to have formed a large population of LMXBs, which have formation timescales of order 0.5–1 Gyr (White & Ghosh 1998 and references therein). Therefore, the strong X-ray emission is much more likely to be associated with HMXBs and Type II supernovae, perhaps further enhanced by hot diffuse gas and hot stars, associated with star-forming regions. In addition, many local galaxies are found to contain “superluminous” X-ray sources (e.g., Colbert & Mushotzky 1999; Kaaret et al. 2001; Fabbiano, Zezas, & Murray 2001), which can account in a large fraction of the hard X-ray (2–10 keV) luminosity. There is suggestive evidence that these mysterious sources are located preferentially in starburst galaxies, and if so they
are potentially a major contributor to the luminosity observed in our high-redshift samples.

The typical luminosity of the LBGs of $3.4 \times 10^{41}$ ergs s$^{-1}$ is much larger than that observed in normal galaxies at low redshift, by around 2 orders of magnitude. Furthermore, as we have already stated, the X-ray luminosity seems to scale with the UV luminosity to a high degree of accuracy. This strongly suggests that the hard X-ray luminosity follows the star formation: the LBGs are selected to be UV luminous and have much higher SFRs than normal spiral galaxies in the nearby universe. The fact that we expect and observe more X-ray emission from galaxies exhibiting starburst activity suggests that one may be able to use the X-ray luminosity as a probe of the individual and global SFRs (Cavaliere et al. 2000; Menci & Cavaliere 2000). There is considerable uncertainty, however, about the formation and evolution of the stellar systems that produce X-rays, not least the “superluminous” sources mentioned above, and therefore there is no simple way of, say, turning an initial mass function into an estimate of the instantaneous X-ray luminosity. We await further theoretical work in this area and verification in local starburst galaxies. In the meantime, we adopt an empirical approach to estimating the SFR in the LBGs.

David et al. (1992) have shown that there is a strong correlation between the 0.5–4.5 keV X-ray luminosity ($L_{0.5-4.5}$) and the far-IR (FIR) bolometric luminosity $L_{\text{FIR}}$, in a large sample of IRAS-selected normal and starburst galaxies. As the FIR luminosity is an excellent indicator of the current SFR (e.g., Leitherer & Heckman 1995; Kennicutt 1998), we can use the David et al. (1992) correlation to convert $L_X$ to SFR via the predicted $L_{\text{FIR}}$. We predict an average FIR luminosity for the LBGs of $2.5 \times 10^{41} L_\odot$, similar to that inferred by Adelberger & Steidel (2000). We can then convert $L_{\text{FIR}}$ to SFR using the expressions given in Kennicutt (1988) or the very similar one in Rowan-Robinson (2000). This crude method yields the following conversion:

$$\text{SFR} = 18L_{41} M_\odot \text{yr}^{-1},$$

where $L_{41}$ is the 2–10 keV X-ray luminosity in units of $10^{41}$ ergs s$^{-1}$ for our adopted cosmology. Thus, the X-ray luminosity of the LBGs corresponds to an SFR of $64 \pm 13 M_\odot$ yr$^{-1}$ for each LBG. The corresponding value for the BBGs is $12 \pm 2 M_\odot$ yr$^{-1}$. The errors given are statistical only. In practice systematic errors in the determination of the SFR and uncertainties in the various conversions dominate.

It is not currently possible to make an independent estimate of the global SFR from the X-ray data alone. This would require determining the X-ray contribution from star-forming processes from all detected sources at a given redshift and then correcting for incompleteness. As we cannot even directly detect individual star-forming galaxies at $z \sim 3$, much more sensitive X-ray data are needed. We can, however, use the X-ray data to make an estimate of the contribution of the UV-selected LBGs to the global SFR. The UV survey in itself incomplete, but S99 have calculated the effective cosmological volume corrected for incompleteness in the UV sample. We can then use these estimates to derive the global SFR from the LBGs. The corresponding estimate, along with those from other wave bands, is shown in Figure 5. Note that this plot has been converted into our preferred cosmology ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$) and therefore differs from most global SFR plots.

![Figure 5](image-url)

**Figure 5.** Global SFR ($M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$) as a function of redshift, derived from the UV luminosity density (open symbols). Low-redshift data ($z < 2$) are taken from Lilly et al. (1996), Connolly et al. (1997), and Wilson et al. (2002). The higher redshift points in the two panels are from the $z = 3$ and $z = 4$ LBG samples of S99. The data are shown without (top) and with (bottom) the extinction corrections of S99. Adelberger & Steidel (2000) have carried out these corrections more carefully and derive a similar, although slightly larger, value. The filled symbol shows our X-ray estimate of the contribution to the global SFR from the $z \sim 3$ LBGs. The X-ray estimate is clearly well in excess of the UV estimate when uncorrected for extinction, demonstrating that the hard X-rays we measure are not to be strongly affected by absorption. It agrees remarkably well, however, with the extinction-corrected value, validating those corrections and demonstrating that the X-rays can be used to provide a reasonable estimate of the SFR. We note, however, that contamination of the stacked X-rays by low-level AGNs would reduce our estimate. We also stress that our observations do not give an X-ray estimate of the global SFR, but an estimate from the X-rays of the contribution of UV-selected star-forming galaxies.

It can be seen that the X-ray estimate of the SFR at $z = 3$ is far higher than the UV estimate uncorrected for extinction. It agrees extremely well, however, with the extinction-corrected values of S99. The X-ray estimate is slightly higher, which may reflect larger UV extinction estimates as inferred by Adelberger & Steidel (2000). It should be noted that, of course, the point plotted in Figure 5 does not represent a true X-ray estimate of the global SFR, as we have only considered the X-ray properties of the UV-selected LBGs. In one sense it represents a lower bound, as we cannot exclude the possibility that there are X-ray—emitting, star-forming galaxies that are too heavily obscured to be picked up in the LBG surveys. On the other hand, the X-ray estimate of the SFR does represent a validation of the extinction corrections presented by S99 and Adelberger & Steidel (2000). Alternatively, if we assume that the extinction corrections are accurate, the agreement validates the conversion between X-ray luminosity and SFR and confirms that the contamination of the X-ray emission of the stacked LBGs by AGNs is relatively minor (barring a conspiracy in which they cancel each other out). As already mentioned, this conclusion is strongly supported by the fact that the ratio of the average UV luminosity—a primary SF indicator—to the X-ray luminosity is the same for rapidly star-forming galaxies at $z = 1$ and $z = 3$, despite a large difference in the absolute values.

Our data can also be used to estimate the average X-ray flux at $z \sim 3$ that originates from the LBGs, which may be relevant to, e.g., models of He II reionization, which occurs around this epoch (Kriss et al. 2001). Assuming a
spectrum with $\Gamma = 2.0$ extending from 0.1–100 keV, the total X-ray fluence is found to be $1.6 \times 10^{46}$ ergs cm$^{-2}$ s$^{-1}$ Mpc$^{-1}$, around 75% of which arises from the sources we have designated AGNs, and around 25% of which we have attributed to star-forming processes.

Our observations also indicate that, when considering the X-ray emission of high-redshift star-forming galaxies, the primary factor in determining the X-ray luminosity is the current SFR. As has been pointed out by White & Ghosh (1998) and further explored by Ghosh & White (2001) and Ptak et al. (2001), there is a secondary effect due to the long evolutionary timescale of LMXBs. Their prediction is that galaxies should exhibit enhanced X-ray emission $\sim 0.5–1$ Gyr after their major episode of star formation due to the “turn on” of the LMXB population. Indeed, the original galaxy stacking experiments of B01a and H02 were in part intended to test this hypothesis, and in doing so these authors have explored the “evolution” of the ratio of the X-ray to B-band luminosity of spiral galaxies as a function of redshift. H02 in particular find a modest increase out to $z \sim 1.5$, which is consistent with the revised estimates of this effect given by Ghosh & White (2001). In the context of this model, our LBGs should show lower $L_X/L_B$ ratios than intermediate-redshift galaxies, as there has not been sufficient time for the LMXB populations to evolve to produce X-rays. Performing such a comparison with these heavily star-forming galaxies is rather difficult, however, as their blue light is completely dominated by massive, young stars. This may also be true of some of the higher redshift galaxies considered by H02. When making such comparisons, it is therefore essential to consider the contributions (in all wave bands) of both young and evolved stellar populations. In our case it appears that the former completely dominate the X-ray emission.

Apparently the most extreme examples of the high-redshift starburst phenomenon are the hyperluminous IRAS galaxies and bright submillimeter sources discovered by SCUBA. Estimates of the individual SFRs are even higher than the LBGs, at $\sim 1000 M_\odot$ yr$^{-1}$ or greater (e.g., Rowan-Robinson 2000). Our analysis has shown a fairly strict scaling between the hard X-ray luminosity and SFR, and if this continues to the level of these extreme FIR galaxies, we predict X-ray luminosities of $\sim 10^{44}$ ergs s$^{-1}$. Very few hyperluminous IRAS galaxies have been observed sensitively in the hard X-ray, but several deep Chandra surveys have been undertaken of fields surveyed by SCUBA including the HDF-N. Bautz et al. (2000) have reported the detection of two gravitationally lensed submillimeter sources in the field of the cluster A370. They both have observed fluxes corresponding to luminosities of $\sim$few times $10^{45}$ ergs s$^{-1}$, and Bautz et al. (2000) argue that the intrinsic luminosities are probably much higher if they are absorbed. These objects probably host AGNs responsible for much of the X-ray emission. On the other hand, most SCUBA sources are rather weak X-ray sources (e.g., Fabian et al. 2000; Barger et al. 2001c; Almaini et al. 2002). Very deep X-ray data are required to reveal the X-ray emission from star formation, however, and it remains to be seen whether the correlation between $L_X$ and SFR is extended to these extreme FIR galaxies.

We stress that the above estimates of the SFR rely on the assumption that the stacked X-rays are primarily associated with star-forming processes. Although we have been able to exclude the brightest AGN contributions based on their X-ray luminosity, low-level AGN activity remains a possible contributor, particularly if AGN and starburst activity is coeval (Page et al. 2001; Priddey & McMahon 2001).

### 5.4. Future Prospects

Our work, as well as that of B01c and H02, has demonstrated that star-forming galaxies at $z = 1–3$ are significant X-ray sources. Indeed, it appears that these objects may dominate the X-ray number counts at faint fluxes. Miyaji & Griffiths (2002) have performed a fluctuation analysis of this same field, constraining the number counts, log $N$–log $S$, at very faint fluxes. At the level of detection of the stacked LBGs and BBGs $\sim 5 \times 10^{-18}$ ergs cm$^{-2}$ s$^{-1}$, they find $\sim 30,000$ X-ray sources deg$^{-2}$, albeit with a large uncertainty (range of $\sim 15,000–80,000$). Our stacking analysis indicates that at this flux level the LBGs and BBGs alone contribute 10,000 sources deg$^{-2}$. When we consider that these sources occupy only small slices in redshift space, it seems almost certain that actively star-forming galaxies such as these will dominate the X-ray number counts at faint fluxes (below $\sim 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$). Future high-sensitivity X-ray satellites such as XEUS and Generation-X will therefore detect them in very large numbers and, of course, will be able to define their individual properties, rather than the group properties we have described here. With the development of detailed population synthesis models for the X-ray sources, this will allow independent estimates of both the individual and global SFRs from the X-ray data alone. As shown by Figure 2, in order to avoid excessive contamination by background and galaxies outside the cell, a $\sim 2''$ PSF is necessary to be able to detect these sources without suffering from confusion problems. This sets a minimum requirement for the spatial resolution of these future missions if they are to be able to detect and study high-redshift star-forming galaxies. To provide a clear distinction between AGNs and star-forming processes, which is necessary for a clean estimate of the SFRs from the X-ray data, it is necessary to resolve the X-ray emission from the star-forming regions. Here the requirement is for $\sim 0.1''$ resolution, based on the UV morphologies.

We have found several LBGs and at least one BBG that contain bright, nuclear X-ray sources, which are almost certainly AGNs. If these objects are otherwise typical in terms of their star formation properties, the nuclear AGN X-rays can be used as a diagnostic tool with future high-throughput, high spectral resolution data. Absorption of the X-rays in the starburst gas will present not only a measurement of the total column density (and therefore the gas mass), but absorption-line spectroscopy can be used to determine the elemental abundances, kinematics, etc. This too offers great potential for future X-ray satellites, beginning with Constellation-X.

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