THE CHANDRA DEEP FIELD NORTH SURVEY. XIV. X-RAY–DETECTED OBSCURED AGNs AND STARBURST GALAXIES IN THE BRIGHT SUBMILLIMETER SOURCE POPULATION

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ABSTRACT

We provide X-ray constraints and perform the first X-ray spectral analyses for bright SCUBA sources ($f_{500\mu m} \geq 5$ mJy; signal-to-noise ratio $\geq 4$) in an $8.4' \times 8.4'$ area of the 2 Ms Chandra Deep Field North survey containing the Hubble Deep Field North. X-ray emission is detected from seven of the 10 bright submillimeter sources in this region down to 0.5–8.0 keV fluxes of $\approx 1 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$, corresponding to an X-ray–detected submillimeter source density of $360^{+190}_{-130}$ deg$^{-2}$; our analyses suggest that this equates to an X-ray–detected fraction of the bright submillimeter source population of $\geq 36\%$, although systematic effects may be present. Two of the X-ray–detected sources have nearby (within $3''$) X-ray companions, suggesting merging/interacting sources or gravitational lensing effects, and three of the X-ray–detected sources lie within the approximate extent of the protocluster candidate CXO HDFN J123620.0+621554. Five of the X-ray–detected sources have flat effective X-ray spectral slopes ($\Gamma < 1.0$), suggesting obscured AGN activity. X-ray spectral analyses suggest that one of these AGNs may be a Compton-thick source; of the other four AGNs, three appear to be Compton-thin sources and one has poor constraints. The rest-frame unabsorbed X-ray luminosities of these AGNs are more consistent with those of Seyfert galaxies than QSOs (i.e., $L_X \approx 10^{43}$–$10^{44}$ ergs s$^{-1}$). Thus, the low X-ray detection rate of bright submillimeter sources by moderately deep X-ray surveys appears to be due to the relatively low luminosities of the AGNs in these sources rather than Compton-thick absorption. A comparison of these sources with the well-studied, heavily obscured AGN NGC 6240 shows that the average AGN contribution is negligible at submillimeter wavelengths. The X-ray properties of the other two X-ray–detected sources are consistent with those expected from luminous star formation; however, we cannot rule out the possibility that low-luminosity AGNs are present. The three X-ray–undetected sources appear to lie at high redshift ($z > 4$) and could be either AGNs or starburst galaxies.

Key words: cosmology: observations — galaxies: active — submillimeter radiation — surveys — X-rays

1. INTRODUCTION

Due to the strong negative $K$-correction for galaxies at submillimeter ($\lambda = 300$–1000 $\mu m$) wavelengths, submillimeter surveys facilitate observations of the high-redshift universe (e.g., Blain & Longair 1993). For typical starburst galaxies and active galactic nuclei (AGNs), the expected submillimeter flux density is approximately insensitive to redshift for $z \approx 1$–10. Indeed, the majority of the submillimeter-detected sources in SCUBA (Holland et al. 1999) surveys appear to be extremely luminous infrared galaxies at $z \approx 1$–6 (e.g., Smail, Ivison, & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Ivison et al. 1998; Smail et al. 2000, 2002; Dunlop 2001; Blain et al. 2002).

It is generally believed that these submillimeter-detected sources are protogalaxies undergoing intense dust-enshrouded star formation (e.g., Blain et al. 1999; Lilly et al. 1999). However, evidence for AGNs has also been found using a variety of techniques. For example, optical spectroscopic observations have revealed AGNs in a number of optically bright submillimeter sources (e.g., Ivison et al. 1998; Barger et al. 1999a; Soucail et al. 1999), and SCUBA observations of known optically bright quasi-stellar objects (QSOs; i.e., luminous type 1 AGNs) have shown that luminous AGNs constitute a fraction of the submillimeter source population (e.g., McMahon et al. 1999; Page et al. 2001; Isaak et al. 2002; Willott et al. 2002). Although clearly some SCUBA sources host AGNs, the ubiquity of AGNs in the submillimeter source population and their contribution to the submillimeter emission are poorly constrained.

Arguably the best discriminator of AGN activity is the detection of hard X-ray emission ($> 2$ keV). Hard X-ray observations are particularly useful in identifying AGNs in sources where the optical signatures are weak (e.g., optically faint AGNs or AGNs without strong emission lines; Vignati et al. 1999; Mushotzky et al. 2000; Alexander et al. 2001; Hornschemeier et al. 2001). Because of their high-energy X-ray coverage, high X-ray sensitivity, and excellent positional accuracy, the Chandra (Weisskopf et al. 2000) and XMM-Newton (Jansen et al. 2001) observatories offer the best opportunities for the X-ray investigation of SCUBA sources. Although sensitive enough to detect luminous AGNs out to high redshift, the cross-correlation of moderately deep X-ray surveys with SCUBA surveys has yielded little overlap between the X-ray and submillimeter detected source populations (Fabian et al. 2000; Hornschemeier et

1 The exact fraction of optically bright QSOs in the submillimeter source population is poorly known. Since only one of the 15 sources in the SCUBA lens survey (Smail et al. 2002) is a QSO (SMJ 102399–0136 is a broad absorption line QSO [BALQSO]; see Vernet & Cimatti 2001), it is probably on the order of $\approx 5\%$–$10\%$. 

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Targeting X-ray sources detected in the 1 Ms Chandra Deep Field North (CDF-N; Brandt et al. 2001) survey with SCUBA jiggle-map observations, Barger et al. (2001b) showed that submillimeter counterparts can be found for faint X-ray sources. Five of the six X-ray detected submillimeter sources with good X-ray constraints had flat ($\Gamma < 1.0$) effective X-ray spectral slopes, an indicator of obscured AGN activity. However, while clearly showing that many of the AGNs found in submillimeter sources are obscured, Barger et al. (2001b) did not investigate the possibility that the absorption toward the AGNs is Compton thick. Thus strong constraints on the origin of the submillimeter emission were not placed.

The primary aim of this paper is to place strong constraints on the origin of the submillimeter emission from AGN-classified submillimeter sources by determining if their AGNs are obscured by Compton-thin or Compton-thick material. In this study we focus on an 8.4$\times$8.4 region within the 2 Ms CDF-N survey with excellent multi-wavelength data, including deep radio (Richards et al. 1998; Richards 2000a, 2000b) and optical/near-infrared (near-IR) observations (Barger et al. 1999b). Due to the extremely high sensitivity of the 2 Ms CDF-N survey, we have the potential to detect X-ray emission from high-luminosity starburst galaxies (i.e., $L_X$$\approx$10$^{45}$ ergs s$^{-1}$) to $z \approx 2.5$. In this study we place the tightest constraints to date on the X-ray emission from star formation in submillimeter-detected galaxies. The Galactic column density along this line of sight is (1.6$\pm$0.4) $\times$10$^{20}$ cm$^{-2}$ (Stark et al. 1992), and $H_0$ = 65 km s$^{-1}$Mpc$^{-1}$, $\Omega_M = \frac{1}{3}$, and $\Omega_{\Lambda} = \frac{2}{3}$ are adopted throughout.

2. OBSERVATIONS AND SOURCE SAMPLES

2.1. X-Ray Observations

The X-ray results reported in this paper were obtained with ACIS-I (the imaging array of the Advanced CCD Imaging Spectrometer; Garmire et al. 2002) on board Chandra. The 2 Ms CDF-N observations were centered on the Hubble Deep Field North (HDF-N; Williams et al. 1996) and cover $\approx$460 arcmin$^2$. The region investigated in this study extends over an 8.4$\times$8.4 area that has its center near to the aim point of the CDF-N observations. This 70.3 arcmin$^2$ region is defined by the optical and near-IR observations of Barger et al. (1999b) and is referred to here as the reduced Hawaii flanking-field area (see Alexander et al. 2001). The X-ray data processing of these observations was similar to that described in Brandt et al. (2001) for the 1 Ms Chandra exposure. The full 2 Ms source catalog is presented in Alexander et al. (2003).

One hundred and ninety-three (193) X-ray sources are detected in the reduced Hawaii flanking-field area with a WAVDETECT (Freeman et al. 2002) false-positive probability threshold of 10$^{-7}$ down to on-axis 0.5$-$2.0 keV (soft-band) and 2$-$8 keV (hard-band) flux limits of $\approx$2.3 $\times$ 10$^{-17}$ ergs cm$^{-2}$ s$^{-1}$ and $\approx$1.4 $\times$ 10$^{-16}$ ergs cm$^{-2}$ s$^{-1}$, respectively. The X-ray coverage in this region is fairly uniform, with 0.5$-$8.0 keV (full-band) effective exposure times of the 193 X-ray detected sources covering 1.28$-$1.94 Ms (with a median time of 1.82 Ms). The adaptively smoothed full-band 2 Ms Chandra image is shown in Figure 1. The positional uncertainties of the X-ray sources are $\approx$1$^{\prime\prime}$, depending on off-axis angle (see Alexander et al. 2003), and the median positional uncertainty is 0$^{\prime\prime}$.3 These small positional uncertainties allow for accurate cross-correlation with multiwavelength counterparts.

2.2. Bright Submillimeter Sources

In this study we focus on bright submillimeter ($f_{850\mu m} > 5$ mJy) sources detected with a signal-to-noise ratio (S/N) $\geq$ 4. This threshold was chosen to guard against possible spurious SCUBA sources (e.g., see the estimated number of spurious sources at different significance thresholds for the SCUBA observations of the ELAIS-N2 and Lockman Hole East regions; Scott et al. 2002). Bright submillimeter sources account for $\approx$20$\%$–30$\%$ of the submillimeter background (Barger, Cowie, Sanders 1999; Smail et al. 2002) and are likely to represent the luminous end of the submillimeter galaxy population.

The submillimeter data used here were taken from a number of different studies (Hughes et al. 1998; Barger, Cowie, & Richards 2000, Barger et al. 2002; Borys et al. 2002). Ten bright submillimeter sources are detected with S/N $\geq$ 4; see Table 1 and Figure 1. If we relaxed the detection threshold to S/N $\geq$ 3.5 another five sources would be added to our sample; however, $\approx$20$\%$ of the sources in the total sample could be spurious (e.g., Scott et al. 2002). Although we have utilized all of the published SCUBA data currently available, this region only has complete SCUBA coverage down to $f_{850 \mu m} = 12$ mJy ($\approx$75$\%$ of the region has SCUBA coverage down to $f_{850 \mu m} = 5$ mJy; e.g., see Fig. 1 of Barger et al. 2002). Therefore, there are likely to be further bright submillimeter sources in this region that have not yet been detected by SCUBA.

Two main observing techniques were employed in these studies: Hughes et al. (1998) and Borys et al. (2002) performed SCUBA scan-map observations, while Barger et al. (2000, 2002) performed SCUBA jiggle-map observations of radio and X-ray sources. The positional uncertainty of a SCUBA source is dependent on the signal-to-noise ratio and is typically $\approx2^{''}$–4$^{''}$ (e.g., Serjeant et al. 2002; Smail et al. 2002; although see Hogg 2001). However, in the cases where radio and X-ray sources have been targeted with SCUBA jiggle-map observations, less than 1$^{''}$ positions can be inferred from the radio and X-ray data.

Seven of the 10 submillimeter sources were detected in SCUBA jiggle-map observations of radio and X-ray sources and have positional uncertainties of less than 1$^{''}$. For these sources we identified optical and near-IR counterparts in the photometric source catalogs produced by Alexander et al. (2001) using a 1$^{''}$ matching radius (see Table 1); these source catalogs were produced from the Barger et al. (1999b) I-band and HK$^\ast$-band images, which reach $\approx2\sigma$ magnitude limits of $I = 25.3$ and HK$^\ast$ = 21.4, respectively.3

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2 We also included the studies of Chapman et al. (2001) and Serjeant et al. (2002) but no further SCUBA sources met our criteria.

3 These images are publicly available at http://www.ifa.hawaii.edu/~cowie/hdflank/hdflank.html. The relationship between the K band and HK$^\ast$ band is HK$^\ast$ – K = 0.13 + 0.05(I–K) (Barger et al. 1999b).
Three of the 10 submillimeter sources were detected in SCUBA scan maps and have positional uncertainties of $\approx 2''$–$4''$. However, in the case of one source (123652.0+621225, which is often referred to as HDF 850.1, the brightest submillimeter source in the HDF-N; Hughes et al. 1998) we can adopt the subarcsecond 1.3 mm source position obtained with the IRAM interferometer on the Plateau de Bure (IRAM PdBI) telescope (i.e., Downes et al. 1999). Dunlop et al. (2002) used these data in combination with extremely sensitive MERLIN+VLA 1.4 GHz radio observations to identify accurately the optical and near-IR counterpart for 123652.0+621225. Since this source is located in the HDF-N, the optical and near-IR constraints are more sensitive than for the other submillimeter sources investigated here (123652.0+621225 has $T > 28.6$ and $K = 23.4$; Dunlop et al. 2002). We must rely on the SCUBA positions for the other two sources since neither source has a radio or X-ray counterpart within 4''. The $\approx 2''$–$4''$ positional uncertainties for these sources are too large to be able to identify optical and near-IR counterparts reliably.

2.3. Source Redshifts

Only one of the submillimeter sources has an optical spectroscopic redshift (123629.1+621045 has $z = 1.013$; Cohen et al. 2000; Hornschemeier et al. 2001) and another source has a redshift estimate based on its multiwavelength spectral energy distribution (SED; 123652.0+621225 has $z = 4.1^{+0.2}_{-0.1}$; Dunlop et al. 2002). However, on the assumption that the other sources obey the radio–to–far-infrared (far-IR; $\lambda = 40–120$ $\mu$m) correlation found for local star-forming galaxies (e.g., Helou, Soifer, & Rowan-Robinson 1985), we can estimate redshifts for all of the radio-detected sources and place redshift lower limits on the radio-undetected sources, using the millimetric redshift technique (e.g., Carilli & Yun 1999). Since the submillimeter emission...
# Table 1

## Basic Properties of the Bright Submillimeter Sources

| Radio ID | I$_{1.4\text{GHz}}$ | $\alpha$ | Radio ID | $\ell$ | $I-K$ | S$_{850\mu\text{m}}$ | Submillimeter Ref | $z$ | $L_{1.4\text{GHz}}$ |
|----------|------------------|---------|----------|-------|-------|-----------------|------------------|----|------------------|
| 12 36 16.15      | +62 15 13.7      | Y       | Y        | 54 ± 8 | ...   | S               | 24.3 < 3.2       | 5.7 ± 1.1 | B02 | 2.4$^{+0.8}_{-0.5}$ |
| 12 36 18.33      | +62 15 50.5      | Y       | Y        | 151 ± 11 | >0.63 | U               | >25.3 ...         | 7.8 ± 1.6 | B00 | 1.7$^{+0.6}_{-0.4}$ |
| 12 36 20.3       | +62 17 01        | N       | N        | <40    | ...   | ...             | ...             | 13.2 ± 2.9 | BY  | >4.8 ...         |
| 12 36 21.1       | +62 12 50        | N       | N        | <40    | ...   | ...             | ...             | 11.4 ± 2.8 | BY  | >4.3 ...         |
| 12 36 22.65      | +62 16 29.7      | Y       | Y        | 71 ± 9 | ...   | S               | 23.4 < 2.5       | 7.1 ± 1.7 | B00 | 2.4$^{+0.8}_{-0.5}$ |
| 12 36 29.13      | +62 10 45.8      | Y       | Y        | 81 ± 9 | >0.80 | U               | 22.2 3.8         | 5.0 ± 1.2 | B02 | 1.01 ± 0.4       |
| 12 36 46.05      | +62 14 48.7      | Y       | Y        | 124 ± 10 | 0.84 ± 0.12 | U | 24.9 < 3.8   | 10.7 ± 2.1         | B02 | 2.3$^{+0.6}_{-0.5}$ |
| 12 36 52.06      | +62 12 25.7      | Y       | N        | 16 ± 4 | 0.42$^{+0.32}_{-0.20}$ | ...   | >28.6 > 5.2 | 7.0 ± 0.5 | HU  | 4.1$^{+0.5}_{-0.6}$ |
| 12 37 07.21      | +62 14 08.1      | Y       | Y        | 45 ± 8 | 0.29 ± 0.16 | U | 25.0 5.0      | 6.2 ± 1.3         | B02 | 2.9$^{+0.6}_{-0.5}$ |
| 12 37 12.09      | +62 12 11.3      | N       | <40      | ...   | ...   | ...             | ...             | 8.0 ± 1.8 | B02 | >3.6 ...         |

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**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

**a** Source coordinates. Taken from, in order of preference, the radio position (if radio detected), the X-ray position (if X-ray detected), or the submillimeter source position.

**b** Radio flux density at 1.4 GHz in units of microjanskys and radio spectral index ($\alpha$). The radio flux density upper limits correspond to the 5σ survey limit given in Richards 2000a. The radio spectral index is defined from the 8.5 GHz and 1.4 GHz flux densities as $F_\nu \propto \nu^{-\alpha}$. Taken from Richards 2000a and Dunlop et al. 2002.

**c** Source classification based on radio properties for sources detected in Richards 1999. “S” indicates star-forming galaxy, and “U” indicates that good constraints could not be placed.

**d** I-band Vega-based magnitude and I–K color. The calculated I–K color is determined from I–(H$-K$) = 0.3 following Barger et al. 1999b for all sources except 123652.0+621225. The $I$-band magnitude and $I-K$ color for 123652.0+621225 are taken from Dunlop et al. 2002.

**e** Submillimeter flux density at 850 μm in units of millijanskys.

**f** Reference for submillimeter data (HU = Hughes et al. 1998; B00 = Barger et al. 2000; B02 = Barger et al. 2002; BY = Borys et al. 2002).

**g** Source redshift, either spectroscopic (Cohen et al. 2000; Hornschemeier et al. 2001), based on the source multiwavelength SED (Dunlop et al. 2002), or millimetric (Carilli & Yun 2000); only 123629.1+621045 has a spectroscopic redshift ($z = 1.013$) and only 123652.0+621225 has a SED-based redshift ($z = 4.1^{+0.5}_{-0.6}$). We note that the source redshift of 123629.6+621629 may be $z = 0.46$, based on X-ray spectral analysis (see § 3.3.1).

**h** Rest-frame 1.4 GHz radio luminosity density in units of $10^{38} \text{ W Hz}^{-1}$ determined following eq. (2). The uncertainties on the calculated luminosity densities are determined using the upper and lower redshift bounds. We are unable to place luminosity constraints for the three radio-undetected sources as they all have redshift lower limits.

**i** This source may have been detected at low-significance in the 1 Ms CDF-N study of VROs (Alexander et al. 2002b); see § 2.4.
corresponds to the longer wavelength Rayleigh-Jeans tail of the thermal dust emission detected at far-IR wavelengths, redshifts are directly determined (albeit with considerable uncertainty) on the basis of the radio-to-submillimeter spectral slope. As noted by Smail et al. (2000), this technique should give a lower limit on the source redshift when a component of the radio emission is produced by an AGN.

We determined millimetric redshifts using the redshift estimators of Carilli & Yun (2000), Eales et al. (2000), and Rengarajan & Takeuchi (2001). We found that the Eales et al. (2000) estimator gave the lowest redshift determinations (a minimum redshift of $z = 1.3$ and a maximum redshift of $z > 3.2$), while the Rengarajan & Takeuchi (2001) estimator gave the highest redshift determinations (a minimum redshift of $z = 2.0$ and a maximum redshift of $z > 4.8$). The differences in the redshift determinations are due to the assumed SED and the temperature of the dust that produces the far-IR–to–submillimeter emission. The millimetric redshifts of the source with an optical spectroscopic redshift $(123629.1+621045; z = 1.013)$ cover $z = 1.4–2.3$ ($z = 1.0–3.0$ when the 1σ millimetric redshift uncertainties are taken into account). Clearly, the optical spectroscopic redshift of 123629.1+621045 is marginally in agreement with the millimetric redshift estimates (we note that larger studies find a $\gtrsim 50\%$ agreement between the optical spectroscopic redshifts and millimetric redshifts of submillimeter sources; e.g., Smail et al. 2000, 2002). However, in the absence of better redshift estimations we must determine the redshifts for the majority of these sources using the millimetric redshift technique.

The adopted millimetric redshifts for our sources are determined using the Carilli & Yun (2000) redshift estimator, which provides a good compromise between the Eales et al. (2000) and Rengarajan & Takeuchi (2001) millimetric redshift estimates (see Table 1). We note that, since the typical 1σ millimetric redshift uncertainty for a source is $\Delta z = 0.8$ (the range of redshift uncertainties is $\Delta z = 0.3–1.1$), the differences in these redshift determinations are not critical. However, even given these uncertainties, all sources have $z > 1$ with all millimetric redshift estimators.

2.4. X-Ray–Detected Submillimeter Sources

Five of the 10 submillimeter sources were detected by Barger et al. (2002) in SCUBA jiggle-map observations of X-ray sources and are thus X-ray detected submillimeter sources (see Table 2). We searched for X-ray counterparts for the other five submillimeter sources using a $1^\circ$ matching radius for the three sources with radio counterparts and a $4^\circ$ matching radius for the two sources without radio counterparts. One further X-ray counterpart was found for one of the radio-detected submillimeter sources (123622.6+621629; see Table 2).

Given the low surface density of the submillimeter sources, we can also search for lower significance X-ray sources associated with submillimeter sources without introducing a significant number of spurious X-ray sources. We ran WAVDETECT with a false-positive probability threshold of $10^{-5}$ and found one further match to a radio-detected submillimeter source (123618.3+621551; see Table 2); the probability of this X-ray–submillimeter match being spurious is less than 1%. This source was also detected in the 1 Ms Chandra exposure at a $10^{-5}$ false-positive probability threshold (Alexander et al. 2001) and is probably not detected here at a higher probability threshold since it lies within the bright extended X-ray source CXOHDYN J123620.0+621554 (e.g., Bauer et al. 2002a). Thus, seven (70–30%) of the 10 submillimeter sources have X-ray counterparts.

Three submillimeter sources are X-ray undetected. There is no evidence for excess X-ray emission in the Chandra images for two of these sources (123620.3+621701 and 123621.1+621250); however, there is a suggestion of soft-band emission at the location of 123652.0+621225 (i.e., HDF 850.1). Indeed, 123652.0+621225 lies within 0.5 of the position of an X-ray source detected by WAVDETECT at a $10^{-4}$ false-positive probability threshold in the 1 Ms CDF-N study of very red objects (VROs, $I–K \geq 4$; Alexander et al. 2002b). Since 123652.0+621225 lies closer to the X-ray source than the VRO reported in Alexander et al. (2002b), it may actually be the correct counterpart to this extremely faint, low-significance X-ray source. However, since the X-ray source is not detected at a higher significance level in the 2 Ms Chandra exposure, we consider 123652.0+621225 undetected here.

Examining the association between Chandra and SCUBA sources, Almaini et al. (2003) found little overlap between the source populations but detected a strong clustering signal. They suggested that Chandra and SCUBA sources are generally unrelated (at least down to the depths of their 75 ks Chandra survey) but trace the same large-scale structure. Although there may be some large-scale structure effects present in our sample, the cross-correlation distances between our Chandra and SCUBA sources are much smaller than the up to 100 clustering distances found by Almaini et al. (2003). Thus, we expect all of our X-ray-submillimeter matches to be legitimate.

2.4.1. X-Ray–Detected Submillimeter Source Density

The derived density of X-ray–detected submillimeter sources in this region with $f_{850} \geq 5$ mJy is $360^{+190}_{-130}$ deg$^{-2}$. This source density should be considered a lower limit, since there may be further bright submillimeter sources with X-ray counterparts in this region that have not yet been detected by SCUBA (see §2.2).

We can compare our source density with that found in other studies. The SCUBA survey of the ELAIS-N2 and Lockman Hole East regions (i.e., Scott et al. 2002) contains sensitive Chandra and XMM-Newton observations (down to 0.5–8.0 keV flux limits of $\approx 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$; i.e., Manners et al. 2002; Hasinge et al. 2001). One Chandra counterpart was matched to a submillimeter source in the ELAIS-N2 region (Almaini et al. 2003), corresponding to an X-ray–detected submillimeter source density of $35^{+80}_{-30}$ deg$^{-2}$. Four XMM-Newton counterparts were found for submillimeter sources in the Lockman Hole East region (Ivison et al. 2002), corresponding to a higher X-ray-detected submillimeter source density of $120^{+50}_{-30}$ deg$^{-2}$. The X-ray detected submillimeter source densities found in our study are $\approx 3$–10 times higher than those found by Almaini et al. (2003) and Ivison et al. (2002) because of the greater sensitivity of the 2 Ms Chandra observations.

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4 X-ray sources detected in the soft band (0.5–2.0 keV), hard band (2–8 keV), or full band (0.5–8.0 keV) were matched to submillimeter counterparts.

5 All errors are taken from Tables 1 and 2 of Gehrels (1986) and correspond to the 1σ level; these were calculated assuming Poisson statistics.
| Coordinates | X-Ray Counts | Band Ratio | Effective Flux | Derived Properties | X-Ray Properties of the Bright Submillimeter Sources |
|------------|--------------|------------|----------------|-------------------|---------------------------------------------------|
| $\alpha_{2000}$ | $\delta_{2000}$ | FB$^b$ | SB$^b$ | HB$^b$ | FB$^b$ | SB$^b$ | HF$^f$ | $a_{3X}^f$ | $L_X^g$ | ID$^h$ |
| 12 36 16.15 | +62 15 13.7 | 130.4$^{+14.3}_{-9.0}$ | 68.8$^{+10.2}_{-9.0}$ | 57.4$^{+10.8}_{-9.3}$ | 0.85$^{+0.19}_{-0.19}$ | 0.9$^{+0.2}_{-0.2}$ | 1.01 | 0.16 | 0.80 | 1.30$^{+0.02}_{-0.03}$ | 8.3$^{+2.3}_{-1.2}$ | AGN |
| 12 36 18.33 | +62 15 50.5 | 29.4$^{+3.3}_{-2.7}$ | <17.5 | <17.2 | ... | 1.4 | 0.17 | <0.04 | <0.19 | >1.49 | ... | U |
| 12 36 20.3 | +62 17 01 | <1.55 | <10.4 | <14.1 | <0.10 | <0.03 | <0.19 | >1.49 | ... | U |
| 12 36 21.1 | +62 12 50 | <11.1 | <5.3 | <10.3 | <0.07 | <0.01 | <0.14 | >1.50 | ... | U |
| 12 36 22.65 | +62 16 29.7 | 63.4$^{+1.1}_{-0.7}$ | <13.2 | 56.9$^{+0.7}_{-0.4}$ | >4.39 | <0.6 | 1.03 | <0.03 | 1.15 | 1.41$^{+0.03}_{-0.03}$ | 13.2$^{+19.3}_{-8.3}$ | AGN |
| 12 36 29.13 | +62 10 45.8 | 198.4$^{+1.6}_{-0.3}$ | 66$^{+3.0}_{-0.9}$ | 134$^{+7.2}_{-4.1}$ | 2.05$^{+0.34}_{-0.08}$ | 0.1$^{+0.2}_{-0.1}$ | 2.32 | 0.16 | 2.26 | 1.28$^{+0.03}_{-0.03}$ | 3.1 | AGN |
| 12 36 46.05 | +62 14 48.7 | 13$^{+0.4}_{-0.3}$ | 126$^{+3.0}_{-0.9}$ | <7.5 | <0.6 | 1.4 | 0.08 | 0.03 | <0.09 | 1.49$^{+0.06}_{-0.06}$ | 0.4$^{+0.06}_{-0.02}$ | U |
| 12 36 52.06 | +62 12 25.7 | <9.8 | <10.8 | <4.0 | <0.06 | <0.03 | <0.05 | >1.48 | <1.1 | U |
| 12 37 07.21 | +62 14 08.1 | 84.4$^{+14.4}_{-10.2}$ | 32.6$^{+7.4}_{-6.2}$ | 52.3$^{+9.4}_{-6.2}$ | 3.42 | 0.98 | 0.09 | 0.92 | 1.34$^{+0.03}_{-0.03}$ | 15.9$^{+2.4}_{-0.2}$ | AGN |
| 12 37 12.09 | +62 12 11.3 | 30.7$^{+3.2}_{-2.7}$ | 10.5$^{+5.3}_{-4.1}$ | 20.9$^{+7.2}_{-6.0}$ | 2.00$^{+0.34}_{-0.14}$ | 0.1$^{+0.2}_{-0.1}$ | 0.39 | 0.03 | 0.38 | 1.44$^{+0.02}_{-0.02}$ | >11.3 | AGN |

$^a$ Source coordinates. Taken from Table 1.

$^b$ Source counts and errors or upper limits. Determined following the procedure given in Brandt et al. 2001 for sources detected with WAVDETECT false-positive probability threshold of 10$^{-3}$ and from WAVDETECT for sources detected with WAVDETECT false-positive probability threshold of 10$^{-5}$, “FB” indicates full band, “SB” indicates soft band, and “HB” indicates hard band. Upper limits are calculated following § 3.2.1 of Brandt et al. 2001.

$^c$ Ratio of the count rates in the 2.0–8.0 keV and 0.5–2.0 keV bands. The errors were calculated following the “numerical method” described in § 1.7.3 of Lyons 1991.

$^d$ Effective photon index for the 0.5–8.0 keV band, calculated from the band ratio. The photon indices for the X-ray sources detected with a threshold of 10$^{-5}$ and those with a low number of counts have been set to $\Gamma = 1.4$, a value representative of the X-ray background spectral slope; see Brandt et al. 2001. The photon index is related to the energy index by $\alpha = \Gamma - 1$ where $F_\nu \propto \nu^{-\alpha}$.

$^e$ Fluxes are in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ s$^{-1}$. These fluxes have been calculated following the method described in Brandt et al. 2001. They have not been corrected for Galactic absorption. “FB” indicates full band, “SB” indicates soft band, and “HB” indicates hard band.

$^f$ Submillimeter–to–X-ray spectral index ($a_{3X}$) calculated following eq. (3).

$^g$ Rest-frame full-band luminosity in units of 10$^{43}$ erg s$^{-1}$ calculated following eq. (1). The uncertainties in the calculated luminosities are determined using the upper and lower redshift bounds. For the AGNs the unabsorbed luminosity is given (corrected assuming the absorption is Compton thin and the underlying unabsorbed emission is a $\Gamma = 2.0$ power law), while for the other sources $\Gamma = 2.0$ is assumed. We are unable to place luminosity constraints for the two X-ray–undetected sources with redshift lower limits.

$^h$ Source classification based on X-ray properties; see § 3.2. “AGN” indicates an AGN and “U” indicates that good X-ray spectral constraints could not be placed.

$^i$ X-ray counterpart detected with WAVDETECT with false-positive probability threshold of 10$^{-5}$. 
Three X-ray detected submillimeter sources lie within 1' of the X-ray source CXO HDFN J123620.0+621554; see Figure 1. This extended X-ray source could be a high-redshift ($z \approx 1–2$) cluster or protocluster (Bauer et al. 2002a; Chapman et al. 2003), and the similar millimetric redshifts of the three nearby X-ray detected submillimeter sources suggest that they may be directly associated with CXO HDFN J123620.0+621554. The statistics are extremely poor on how common such sources are. However, if they are rare, then our X-ray–detected submillimeter source density is likely to be higher than average at this X-ray depth; thus our sample may be affected by “cosmic variance.”

2.4.2. Fraction of Submillimeter Sources with X-Ray Counterparts

The reduced Hawaii flanking-field area does not have complete SCUBA coverage down to $f_{850\mu m} = 5$ mJy (see § 2.2), and hence we cannot directly place constraints on the fraction of the bright submillimeter source population with X-ray counterparts. However, based on the submillimeter source density results of Eales et al. (2000) and the compilations of Blain et al. (2002), Cowie, Barger, & Kneib (2002), and Smail et al. (2002), we would expect 300–1000 submillimeter sources deg$^{-2}$ with $f_{850\mu m} \geq 5$ mJy. This suggests that the fraction of bright submillimeter sources in this region with X-ray counterparts is likely to be $\gtrsim 36\%$. Note that this source fraction was not directly measured in our field and systematic effects could be present.

2.4.3. Nearby X-Ray Companions

Two of the X-ray–detected submillimeter sources (123616.1+621513 and 123646.0+621448) have X-ray counterparts within 3'' (see Fig. 2; Alexander et al. 2003). In both cases, one X-ray source has a radio counterpart and one does not. In addition, the radio-detected sources have $I \approx 24–25$, while the radio-undetected sources are optically blank. Given the density of X-ray sources in this region, the probability of two X-ray sources lying within 3'' of each other is $\lesssim 1\%$, and therefore these associations appear to be significant.

There are two obvious scenarios that can explain the close proximity of the sources in these two pairs: (1) these sources are merging or interacting, or (2) these sources are gravitationally lensed. Unfortunately, since these sources are optically faint, we cannot search for the features of merging, interacting, or gravitational lensing in the current optical images. However, in the gravitational lensing scenario, each member of each pair would generally have similar fluxes at all wavelengths (e.g., see review by Blandford & Narayan 1992). Therefore, the fact that one member of each pair is detected at both optical and radio wavelengths, while the other is not, provides some evidence against gravitational lensing.\footnote{The deep and high-spatial resolution Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) observations to be taken in this field as part of the Great Observatories Origins Deep Survey (GOODS) project should provide a direct test of these two scenarios. See http://www.stsci.edu/science/goods for details of the GOODS project.}

In both cases we have identified the radio-detected X-ray source as the counterpart to the submillimeter source, since the radio and submillimeter emission are more closely matched in frequency space than the X-ray and submillimeter emission. However, it is possible that the radio-undetected X-ray sources could contribute to a fraction of the submillimeter emission.

---

Fig. 2.—$I$-band images of the X-ray detected submillimeter sources with nearby X-ray companions. The contours indicate the extent and intensity of the X-ray emission; the lowest contour corresponds to 2 counts pixel$^{-1}$ and each successive contour represents a factor of 2 increase in the number of counts per pixel. The large crosses mark the locations of the 1.4 GHz radio counterparts and the assumed submillimeter counterparts. Each image is 9''43 on a side.
3. X-RAY PROPERTIES OF SUBMILLIMETER-DETECTED SOURCES

3.1. Basic Source Properties

We show the submillimeter flux density versus full-band X-ray flux of all the sources in Figure 3. As a comparison we also show the submillimeter-detected ROSAT-selected optically bright QSOs (i.e., luminous type 1 AGNs) of Page et al. (2001). There is a clear distinction in X-ray flux between the QSOs and our X-ray–detected submillimeter sources. The former would be detectable in \( \lesssim 10 \) ks Chandra exposures, while the majority of the latter are only detectable in \( \gtrsim 100 \) ks Chandra exposures. Since optical spectroscopic observations of submillimeter sources have shown that optically bright QSOs probably comprise only a small fraction of the submillimeter source population (i.e., \( \approx 5\%-10\% \); see footnote 1; e.g., Barger et al. 1999a; Ivison et al. 2000; Smail et al. 2002), \( \gtrsim 100 \) ks Chandra exposures are clearly required to detect X-ray counterparts for typical bright submillimeter sources.

Figure 3 shows evidence for an anticorrelation between the full-band flux and the submillimeter flux density for our sources. While this anticorrelation could be real, we caution that it may be an artifact caused by small number statistics and sample incompleteness.

![Figure 3](image-url)

Fig. 3.—Submillimeter flux density vs. full-band X-ray flux. The filled circles are the X-ray detected submillimeter sources, and the open circles are the X-ray undetected submillimeter sources (see § 2.4); crosses indicate sources classified as AGNs, and “N” indicates sources that do not have good X-ray spectral constraints (see § 3.2 and Table 2). The filled triangles are the submillimeter-detected QSOs of Page et al. (2001); see § 3.1. The upper limit arrows in the y-axis direction show the approximate full-band flux limits for Chandra ACIS-I surveys of different exposure times. While submillimeter-detected QSOs are detectable in \( \lesssim 10 \) ks Chandra exposures, \( \gtrsim 100 \) ks Chandra exposures are required to detect typical submillimeter sources.

3.2. X-Ray Source Classification

3.2.1. X-Ray Spectral Slopes and Luminosities

The effective X-ray photon index (\( \Gamma \)) of a source can provide a simple constraint on its nature.\(^7\) Within the context of AGN-classified sources, obscured AGNs have considerably flatter effective X-ray spectral slopes than the canonical \( \Gamma \gtrsim 2.0 \) photon index of unobscured AGNs (e.g., George et al. 2000), as a result of the energy-dependent photoelectric absorption of the X-ray emission (e.g., Risaliti, Maiolino, & Salvati 1999). Star-forming galaxies are also distinguishable from obscured AGNs, since their rest-frame \( \approx 2-8 \) keV emission is often consistent with that of a \( \Gamma \approx 2.0 \) power law (e.g., Kim, Fabbiano, & Trinchieri 1992a, 1992b; Ptak et al. 1999).\(^8\)

The X-ray luminosity of a source can provide a further check on the nature of the X-ray emission, since very few starburst galaxies have full-band luminosities in excess of \( L_X \approx 10^{42} \) ergs s\(^{-1} \), even when including luminous sources at moderate redshifts (e.g., Moran, Lehnert, & Helfand 1999; Zezas, Alonso-Herrero, & Ward 2001; Alexander et al. 2002a). While this would usually be a reasonable upper limit to the expected X-ray luminosity from star formation activity, given the extreme infrared luminosities of submillimeter sources (\( L_{IR} = 10^{42}-10^{43} \) L\(_{\odot} \); e.g., Ivison et al. 1998; Smail et al. 2002), we might expect full-band luminosities up to an order of magnitude larger (i.e., up to \( L_X \approx 10^{43} \) ergs s\(^{-1} \)) for this source class.\(^9\)

The X-ray–band ratio versus redshift for the six sources with band ratio constraints is shown in Figure 4. Five of the X-ray–detected submillimeter sources have effective photon indices of \( \Gamma < 1.0 \). Such flat X-ray spectral slopes are only likely to be produced by obscured AGN activity, and, under the assumption that the underlying continuum follows a \( \Gamma = 2.0 \) power law, these sources have intrinsic column densities of \( N_H \gtrsim 10^{23} \) cm\(^{-2} \).

The rest-frame X-ray luminosities of these sources are calculated as

\[
L_X = 4\pi d_L^2 f_X (1 + z)^{-2} \text{ergs s}^{-1},
\]

where \( d_L \) is the luminosity distance (cm), \( f_X \) is the X-ray flux (ergs cm\(^{-2}\) s\(^{-1}\)), and \( \Gamma = 2.0 \) is the assumed photon index.

Assuming the underlying continuum follows a \( \Gamma = 2.0 \) power law, the unabsorbed rest-frame full-band luminosities (\( L_X \approx 10^{43}-10^{44} \) ergs s\(^{-1} \)) of the five sources with flat X-ray spectral slopes are also consistent with obscured AGN activity (the intrinsic absorption is calculated from the band ratios; i.e., see Fig. 4). These sources are classified hereafter as AGNs (see Table 2).

The X-ray spectral constraints are weak for the other five submillimeter sources. The rest-frame full-band luminosities or upper limits (\( L_X \approx 10^{42}-10^{43} \) ergs s\(^{-1} \)) for the three sources with luminosity constraints (see Table 2) suggest that their X-ray emission could be produced by luminous starburst galaxies, none having been found to date.
star formation activity. However, since we cannot rule out AGNs in any of these five sources (e.g., they could be extremely highly obscured or of low luminosity), they are classified here as unknown (see Table 2).

3.2.2. X-Ray Emission from Star Formation

From a comparison of the X-ray and radio luminosities of starburst galaxies detected in the 1 Ms Chandra exposure of the CDF-N, Bauer et al. (2002b) showed that the radio emission can be used to predict the X-ray emission from star formation (see also Ranalli, Comastri, & Setti 2002). The main assumption in this prediction is that the radio emission is dominated by star formation; the presence of an AGN component to the radio emission will lead to an over-prediction of the contribution from star formation at X-ray energies.

None of the radio-detected submillimeter sources is classified by Richards (1999) as an AGN on the basis of its radio emission, although four sources are classified as unknown (see Table 1). Since only two of these four sources are classified as AGNs at X-ray energies and all but one have steep radio spectral slopes, the radio emission is likely to be dominated by star formation activity in most cases (e.g., Condon 1992; Richards 2000a). The rest-frame radio luminosity densities of these sources are calculated as

$$L_{1.4\text{GHz}} = 4\pi d_L^2 f_{1.4\text{GHz}} 10^{-36}(1 + z)^{\alpha - 1} \text{ W Hz}^{-1}, \quad (2)$$

where $d_L$ is the luminosity distance (cm), $f_{1.4\text{GHz}}$ is the 1.4 GHz flux density (microjanskys), and $\alpha$ corresponds to the radio spectral index. In determining the radio luminosity density we have assumed $\alpha = 0.8$, the average spectral index for star-forming galaxies (e.g., Yun, Reddy, & Condon 2001).

A comparison of the rest-frame full-band X-ray and radio luminosities of the radio-detected submillimeter sources is shown in Figure 5. The predicted X-ray luminosity from star formation activity for all of the radio-detected submillimeter sources is $L_X \approx 10^{42} - 10^{43} \text{ ergs s}^{-1}$. The AGN-classified sources are on average $\approx 10$ times more luminous at X-ray energies than predicted by star formation. However, the X-ray emission from the other three radio-detected submillimeter sources could be completely dominated by star formation activity.

3.3. X-Ray Spectral Analysis

Our interpretation of the X-ray spectral slopes and luminosities for the five AGN-classified sources (see § 3.2.1) was based on the assumption that the obscuration to the X-ray-emitting source is not optically thick to Compton scattering. However, in some cases, the obscuration may be Compton thick (i.e., $N_H > 1.5 \times 10^{24} \text{ cm}^{-2}$) and the observed X-ray emission will be predominantly produced by reflection and scattering processes (e.g., Matt et al. 1997; Turner et al. 1997a; Matt et al. 2000). The most direct discrimination between Compton-thin and Compton-thick absorption is made with X-ray spectral analysis. The X-ray spectrum of a
Compton-thick AGN is generally characterized by a large equivalent width iron Kα emission line (EW ≥ 0.5 keV; e.g., Matt, Brandt, & Fabian 1996; Maiolino et al. 1998; Bassani et al. 1999; Matt et al. 2000) and a flat or inverted (Γ < 0.0) X-ray spectral slope as a result of pure reflection. By contrast, the X-ray spectrum of a Compton-thin AGN is usually well fitted by an absorbed power-law model and a smaller equivalent width iron Kα emission line (generally EW ≈ 0.1–0.5 keV; Nandra et al. 1997; Turner et al. 1997b; Bassani et al. 1999).

To account for the range of roll angles and aim points in the 20 separate observations that comprise the 2 Ms CDF-N, we used the ACIS source extraction code (ACIS Extract) described in Broos et al. (2002). Briefly, for each source this code extracts the counts from each of the observations, taking into account the changing shape and size of the PSF with off-axis angle as given in the Chandra X-ray Center (CXC) PSF library. A local background is extracted after background subtraction method to verify that no spurious residual features were present in the background-subtracted data. We carried out several checks of the background-subtraction method to verify that no spurious residual features were present in the background-subtracted data.

We only considered two simple models for the X-ray spectral fitting: (1) a power-law model with Galactic absorption and (2) a power-law with both Galactic and additional absorption. The results are given in Table 3. As expected, the photon indices derived using the Galactic absorbed power-law emission model are in good agreement (within ±0.2) with those calculated from the band ratio. When fitted with an absorbed power-law model, the best-fitting photon indices and observed absorption for three of the sources are in broad agreement with those expected for Compton-thin AGNs (e.g., Turner et al. 1997b; Bassani et al. 1999), while two sources have particularly flat photon indices (123622.6+612629 and 123712.0+621211), possibly indicative of reflection and Compton-thick absorption. However, with only ≈30 full-band counts, 123712.0+621211 is probably too faint to provide reliable constraints.

To investigate whether any of these sources could be Compton-thick AGNs we searched for emission-line features in the 2 σ binned X-ray spectra. The only source that showed evidence for an emission-line feature was 123622.6+612629 (see Fig. 6); this was also one of the sources with a flat photon index. To assess whether this ≈4.4 keV emission-line feature was real, we simulated 10,000 low-count (≈90 full-band counts) X-ray spectra using the FAKEIT routine within XSPEC; the input model was a Galactic absorbed Γ = −0.7 power law. Thirty-four (0.34%) of the simulations produced a feature with an equivalent width as large as or larger than that measured in the data, corresponding to a significance level of 2.9 σ. While this provides an estimation of the significance of this feature if we were expecting it to appear at ≈4.4 keV, it does not take into account of the fact that we simply identified the most significant feature among a total of 150 eV) we would expect ≈30 distinguishable features. However, by adding unresolved Gaussian lines, we estimate that we would only be able to distinguish six features in the

### Table 3

| Object Name | PL \( \Gamma^a \) | PL+ABS \( \Gamma^b \) | \( \tilde{N}_H \) (cm\(^{-2}\)) \( ^c \) |
|-------------|-----------------|-----------------|-----------------|
| 123616.1+612513       | 1.0±0.3         | 2.2±0.8         | 0.8±0.4         |
| 123622.6+612629       | 0.7±0.4         | 0.1±0.3         | 1.4±1.3         |
| 123629.1+621045       | 0.3±0.2         | 1.3±0.6         | 1.0±0.3         |
| 123702.7+621408       | 0.5±0.4         | 1.6±0.7         | 1.1±0.7         |
| 123712.0+621211       | 0.0±0.3         | 0.5±0.5         | <0.8            |

Note.—The uncertainties refer to the 90% confidence level (for one interesting parameter).

\( ^a \) Best-fit photon index for Galactic absorption model.

\( ^b \) Best-fit photon index for absorbed power-law model.

\( ^c \) Best-fit column density in units of \( 10^{22} \) cm\(^{-2}\) at \( z = 0 \); the column density at the source redshift \( (\tilde{N}_H)_S \) is related to the best-fit column density at \( z = 0 \) by \( \tilde{N}_H_S \approx (1+z)^{2.6} \tilde{N}_H \).

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10 ACIS Extract is a part of the TARA software package and can be accessed from http://www.astro.psu.edu/xray/docs/TARA/ae_users_guide.html.

11 See http://asc.harvard.edu/ciao2.2/documents_dictionary.html#psf.
X-ray spectrum of 123622.6+621629; this demonstrates that photon statistics are more important than spectral resolution in low-count sources. Thus, the adjusted significance level for this feature is \( \approx 2.3 \sigma \) (i.e., \( 6 \times 0.34\% \)).

3.3.1. 123622.6+621629: A Compton-thick AGN?

Assuming that this \( \approx 2.3 \sigma \) emission feature is a redshifted, unresolved 6.4 keV iron K\( \alpha \) emission line, the observed energy (4.4 \( \pm \) 0.1 keV) implies \( z = 0.46^{+0.03}_{-0.02} \) and a rest-frame equivalent width of \( 0.7^{+0.4}_{-0.8} \) keV. The moderately large equivalent width of this possible 6.4 keV iron K\( \alpha \) emission line, and the inverted X-ray spectral slope (\( \Gamma = -0.7 \); see Table 3), provide evidence that 123622.6+621629 may be a Compton-thick AGN. Under the assumption that the underlying AGN model is the same as that fitted to the Compton-thick AGN NGC 6240 (Vignati et al. 1999), the unabsorbed rest-frame full-band luminosity at \( z \approx 0.46 \) is \( L_X \approx 10^{43} \) ergs s\(^{-1}\).

The inferred redshift (\( z = 0.46^{+0.03}_{-0.02} \)) is in considerable disagreement with the millidemic redshift (\( z = 2.4^{+1.1}_{-0.8} \)). However, we note that, since 123622.6+621629 is detected in both the U band (Barger et al. 2000) and the U\(_r\) band (Hogg et al. 2000), it is actually likely to lie at \( z < 2 \) (to avoid the Lyman break). With a faint optical counterpart (\( I = 23.4 \)), the absolute optical magnitude of 123622.6+621629 at \( z \approx 0.46 \) would correspond to that expected from a dwarf galaxy (i.e., \( \approx 3-4 \) mags below \( L_\odot \)). There are no known examples of luminous AGNs in dwarf galaxies in the local universe (e.g., McLeod & Rieke 1995), although it is possible that 123622.6+621629 is an \( L_\star \) galaxy with \( \approx 3-4 \) mags of dust extinction.

If 123622.6+621629 lies at redshift of \( z \approx 0.46 \), then its properties are atypical for a submillimeter source (e.g., Ivison et al. 2000; Smail et al. 2002). However, we note that 123622.6+621629 shares many similar characteristics with FN1-40, a \( z = 0.45 \) submillimeter source with an \( I = 24 \) optical counterpart (Chapman et al. 2002). Although good X-ray constraints do not exist for FN1-40, the lack of broad optical emission lines led Chapman et al. (2002) to claim no evidence for AGN activity. While FN1-40 is clearly not a broad-line AGN, we note that with an [O \( \mathit{iii} \)] \( \lambda 5007/H\beta \) emission line ratio of \( \gtrsim 3 \) (see Fig. 2 of Chapman et al. 2002), it could be a narrow-line AGN (e.g., Baldwin, Phillips, & Terlevich 1981; Veilleux & Osterbrock 1987). Hence, FN1-40 and 123622.6+621629 may be similar objects. Optical spectroscopy is clearly required to determine the redshift of 123622.6+621629 and help shed light on the origin of its \( \approx 2.3 \sigma \) emission feature.

4. THE ORIGIN OF THE SUBMILLIMETER EMISSION

It is often assumed that the submillimeter emission from sources detected in SCUBA surveys can provide an obscured indicator of the star formation rate (e.g., Blain et al. 1999). However, five of the 10 submillimeter sources investigated here clearly host obscured AGNs. While the AGNs obviously dominate the X-ray emission in these sources, this does not necessarily imply that the submillimeter emission is also powered by the AGNs. Unfortunately, the broadband submillimeter emission itself cannot provide an unambiguous diagnostic of the nature of the dominant physical mechanism, since it is likely to be reprocessed thermal emission produced via the absorption of the primary emission by dust grains.\(^{12}\)

CO observations can provide some insight into the origin of the submillimeter emission by measuring the molecular gas mass and hence constraining the expected dust mass and emission from star formation (e.g., Young & Scoville 1991). For instance, CO observations have been used to show that star formation activity may account for \( \approx 50\% \) of the submillimeter emission from the \( z = 2.80 \) BALQSO SMM J02399–0136 (e.g., Frayer et al. 1998) and perhaps all of the submillimeter emission from the \( z = 2.56 \) galaxy SMM J14011+0252 (e.g., Frayer et al. 1999; Ivison et al. 2001). However, in the absence of CO observations we must adopt an indirect strategy in estimating the origin of the submillimeter emission from our submillimeter sources.

4.1. Constraints from the Submillimeter–to–X-Ray Spectral Slopes

The relative importance of AGN and star formation activity in our submillimeter sources can be estimated by comparing their submillimeter–to–X-ray spectral slopes (\( \alpha_{\text{SX}} \)) to those of well-studied nearby galaxies. We calculate \( \alpha_{\text{SX}} \) as

\[
\alpha_{\text{SX}} = - \left( \log \left( \frac{f_{2\text{keV}}}{f_{850\mu\text{m}}} \right) - 0.18 \right) \times 0.163 ,
\]

where \( f_{2\text{keV}} \) is the observed flux density at 2 keV (keV cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\)), calculated from the full-band flux using the estimated photon index, and \( f_{850\mu\text{m}} \) is the observed flux density at 850 \( \mu\text{m} \) (millijanskys). Larger values of \( \alpha_{\text{SX}} \) indicate stronger submillimeter emission relative to the X-ray emission.

Following Fabian et al. (2000) we have compared our sources with the QSO 3C273, the Compton-thick AGN NGC 6240, and the archetypal ultraluminous starburst galaxy Arp 220. While 3C273 is clearly a powerful unobscured QSO, NGC 6240 contains components of obscured AGN and star formation activity. By contrast, the emission from Arp 220 appears to be entirely dominated by star formation. If an AGN is present in Arp 220, then to remain undetected at X-ray energies it must be either of low luminosity or have extreme absorption (i.e., \( N_H \approx 10^{25} - 10^{26} \) cm\(^{-2}\)) and a small component of scattered emission (e.g., Iwasawa et al. 2001, 2003; Clements et al. 2002). Since NGC 6240 has a considerably flatter X-ray spectral slope than 3C273 and Arp 220, the analysis of the submillimeter–to–X-ray spectral slopes requires knowledge of the X-ray photon index for each source. For instance, at a given submillimeter luminosity, the 2 keV flux density of a \( \Gamma = 0.0 \) source will be \( \approx 5 \) times lower than that of a \( \Gamma = 2.0 \) source. Therefore, when interpreting the data for an unobscured QSO, the comparison should be made with 3C273, while, when interpreting the data for an obscured AGN, the comparison should be made with NGC 6240.

\(^{12}\) Further insight into the origin of the submillimeter emission may come from determining its spatial distribution (i.e., AGN emission is typically confined to the central galactic regions, while star formation can be more widespread). Such observations should be possible with the advent of the Atacama Large Millimeter Array (ALMA; see http://www.alma.nrao.edu) in Chile and the Submillimeter Array (SMA; see http://sma-www.harvard.edu) in Hawaii.
The submillimeter–to–X-ray spectral slope versus redshift of all the sources is shown in Figure 7. The AGN-classified sources have larger \( \alpha_{\text{SX}} \) values than NGC 6240, suggesting that their AGNs are comparatively weaker at X-ray energies (with respect to their submillimeter emission). Under the assumption that the obscuration in these sources is Compton thin (as expected for the majority of AGN-classified sources), they are on average \( \approx 15-150 \) times less luminous at X-ray energies (for a given submillimeter luminosity) than NGC 6240 (assuming a column density of \( N_{\text{H}} = 5 \times 10^{23} \text{ cm}^{-2} \); i.e., top dotted line, Fig. 7). Taking all of the AGN-classified sources together, they are on average \( \approx 70 \) times less luminous at X-ray energies (for a given submillimeter luminosity) than NGC 6240. As can be seen from Figure 7, these results are relatively insensitive to redshift, so long as the AGN-classified sources lie at \( z > 1 \). The only source where we have evidence that this may not be the case is the possible Compton-thick AGN 123622.6+621629 (see § 3.3.1 and Fig. 6). Under the assumption that the obscuration to this source is the same as that found for NGC 6240 (i.e., Compton-thick absorption with a 5% scattering fraction; Vignati et al. 1999), at \( z \approx 0.46 \) it would be \( \approx 80 \) times less luminous at X-ray energies (for a given submillimeter luminosity) than NGC 6240 (see Fig. 7).

We suggested in § 3 that the X-ray emission from the submillimeter sources without good X-ray constraints may be produced by star-formation activity in some cases. This hypothesis is further supported for the two sources with millimeter redshifts of \( z < 4 \), since their submillimeter–to–X-ray spectral slopes are comparable to that expected from Arp 220 at \( z > 1 \) (see Fig. 7). However, we cannot distinguish between star formation and AGN scenarios for the three \( z > 4 \) sources.

4.2. Constraints from NGC 6240

Although the individual constraints on the origin of the submillimeter emission from the AGN-classified sources are weak, they all clearly have larger submillimeter–to–X-ray spectral slopes than NGC 6240. Even though NGC 6240 is a nearby source (\( \approx 115 \) Mpc in our chosen cosmology), the origin of its submillimeter emission is poorly known. For instance, the application of radiative transfer models shows that the far-IR to submillimeter emission can be almost completely explained by starburst activity (Rowan-Robinson & Crawford 1989), and the infrared (imaging and spectroscopy) characteristics of NGC 6240 suggest that star formation dominates the bolometric luminosity (Genzel et al. 1998). Furthermore, its nuclear optical spectrum shows the characteristics of a LINER (e.g., Veilleux et al. 1995). Conversely, consideration of the energetics of the AGN derived from X-ray observations suggests that it may contribute \( \approx 50\% \) of the far-IR–to–submillimeter luminosity (e.g., Iwasawa & Comastri 1998; Vignati et al. 1999; Lira et al. 2002).

Assuming that the AGN completely dominates the submillimeter emission in NGC 6240 (an extreme hypothesis) and the X-ray emission from the AGN scales linearly with submillimeter luminosity, the contribution to the submillimeter emission from AGN activity in the AGN-classified sources would be 0.6%–6.6% (as determined from the \( \approx 15–150 \) times difference in X-ray luminosity for a given submillimeter luminosity; see § 4.1). Following the same assumptions, the average contribution to the submillimeter emission from AGN activity would be \( \approx 1.4\% \). Hence, although there is considerable uncertainty in the AGN contribution at submillimeter wavelengths, these analyses strongly suggest that the submillimeter emission is dominated by star formation activity. This conclusion is likely to be valid even if the \( z > 4 \) sources are also found to contain AGNs (see Fig. 7).

5. DISCUSSION

It has been known for some time that AGNs comprise a fraction of the submillimeter source population. Indeed, the first identified source in a SCUBA blank-field survey was found to be an AGN (SMM J02399–0136; Ivison et al. 1998), and at least three of the 15 submillimeter-detected sources in the SCUBA-lens survey are AGNs (Smail et al. 2002). In all these cases the evidence for AGN activity was found via optical spectroscopy of optically bright sources. The advantage of searching for AGNs with X-ray observations is that the limitations of optical spectroscopy are removed, allowing optically faint AGNs and AGNs without strong emission lines to be identified (e.g., Vignati et al. 1999; Mushotzky et al. 2000; Alexander et al. 2001; Hornschemeier et al. 2001). However, obviously the lack of...
optical spectroscopy for the majority of our sources leads to considerable uncertainties in their source redshifts. In this final section, we discuss the dependence of our results on the assumed source redshifts, the fraction and properties of AGNs in the submillimeter source population, and the AGN contribution to the submillimeter emission in SCUBA sources.

5.1. Dependence of the Results on Source Redshifts

The redshifts for the majority of the submillimeter sources are derived from the radio-to-submillimeter spectral slope and are uncertain. As mentioned in § 4.1, these uncertainties should not change our main result (i.e., that the average AGN contribution to the submillimeter emission is of the order of \(\approx 1.4\%\)) so long as the sources lie at \(z > 1\). However, we note here that, since the redshift tracks for the template galaxies rise to lower values of \(\alpha_{\text{SX}}\) at \(z < 1\) (see Fig. 7), the case for star formation dominating the submillimeter emission is even stronger for sources at lower redshifts (as may be the case for 123622.6+621629; see § 3.3.1). Finally, we also note that, although the implied column densities and X-ray luminosities of the AGN-classified sources will be lower if they lie at \(z < 1\), since \(\Gamma < 1\) power-law emission is only likely to be produced by obscured AGN activity, their classification as AGNs is insensitive to redshift.

5.2. AGNs in the Bright Submillimeter Source Population

In this study we have shown that five of the seven X-ray–detected submillimeter sources appear to be obscured AGNs, placing a lower limit on the source density of obscured AGNs with \(f_{850\mu m} \geq 5\) mJy of \(260^{+170}_{-110}\) deg\(^{-2}\). Under the same assumptions as those used in determining the fraction of the bright submillimeter source population with X-ray counterparts (see § 2.4.2), this suggests that \(\geq 26\%\) of the bright submillimeter source population host AGNs (in reasonable agreement with model predictions; e.g., Almaini, Lawrence, & Boyle 1999; Fabian & Iwasawa 1999).

Ivison et al. (2002) found a similar AGN fraction to that derived here using the moderately deep XMM-Newton observations of the Lockman Hole East region (e.g., Hasinger et al. 2001). However, their submillimeter-detected AGN source density is \(\approx 2\) times smaller (i.e., \(120^{+30}_{-20}\) deg\(^{-2}\) vs. \(260^{+130}_{-110}\) deg\(^{-2}\)). The difference in the submillimeter-detected AGN source densities is mostly due to the higher sensitivity of our X-ray observations. Hence the similarity between the AGN fraction found by Ivison et al. (2002) and our lower limit may indicate that our estimated AGN fraction is conservative.

The unabsorbed rest-frame full-band luminosities of the AGN-classified sources are \(L_X \approx 10^{43} – 10^{44}\) ergs s\(^{-1}\). This range of X-ray luminosity is typical of luminous Seyfert galaxies. Therefore, although the majority of the submillimeter sources is likely to consist of extremely luminous infrared galaxies (e.g., Ivison et al. 1998; Smail et al. 2002), their AGNs are comparatively weak. For example, typical QSOs of similar infrared luminosity (e.g., Isaak et al. 2002; Page et al. 2001) are \(\approx 10 – 100\) times more luminous at X-ray energies (e.g., Page et al. 2001; Vignali et al. 2001, 2003). Under the assumption that bright submillimeter sources are massive protogalaxies (e.g., Blain et al. 1999; Lilly et al. 1999), the luminosities of these AGNs are consistent with those expected for growing supermassive black holes (e.g., Archibald et al. 2002).

5.3. AGN Contribution to the Submillimeter Emission

The current constraints suggest that the total contribution to the submillimeter emission from AGN activity is unlikely to be more than \(\approx 1.4\%\) (at least for \(f_{850\mu m} \geq 5\) mJy) however, as noted in § 2.2, there is likely to be further bright submillimeter sources in our region that have not yet been detected by SCUBA. In addition, we have not considered the possible contribution from optically bright submillimeter-detected QSOs. Although optically bright submillimeter-detected QSOs may comprise only \(\approx 5\% – 10\%\) of the bright submillimeter source population (see footnote 1), their submillimeter emission could have a large AGN component (perhaps of the order of \(\approx 50\%\); Frayer et al. 1998; Bautz et al. 2000). Hence, although optically bright submillimeter-detected QSOs may not be numerically significant, they may provide the bulk of the AGN emission at submillimeter wavelengths (i.e., \(\approx 2.5\% – 5.5\%\)).

6. CONCLUSIONS

We have used the 2 Ms Chandra exposure of the CDF-N to constrain the X-ray properties of bright SCUBA sources (\(f_{850\mu m} \geq 5\) mJy; S/N \(\geq 4\)). In this study we have focused on the X-ray spectral properties of the X-ray–detected submillimeter sources to determine whether the AGN-classified sources are Compton thick or Compton thin. We have used these results to constrain the contribution to the submillimeter emission from AGN activity. Our main results are the following:

1. Seven of the 10 bright submillimeter sources are detected with X-ray emission. The corresponding source density of bright submillimeter sources with X-ray counterparts (\(360^{+190}_{-130}\) deg\(^{-2}\)) suggests that \(\geq 36\%\) of bright submillimeter sources have X-ray counterparts at this X-ray depth; however, we note that this fraction is somewhat uncertain, since this region does not have complete SCUBA coverage down to \(f_{850\mu m} = 5\) mJy. See § 2.

2. Five of the X-ray–detected submillimeter sources have flat X-ray spectral slopes (\(\Gamma < 1\)) and luminous X-ray emission (\(L_X \approx 10^{43} – 10^{44}\) ergs s\(^{-1}\)), suggesting obscured AGN activity with \(N_H \approx 10^{23}\) cm\(^{-2}\). One source is possibly a Compton-thick AGN, since it has an extremely flat X-ray spectral slope (\(\Gamma \approx -0.7\)) and shows possible evidence (\(\approx 2.3\) \(\sigma\)) for a redshifted 6.4 keV iron K\(_\alpha\) emission line; however, the inferred redshift (\(z = 0.46^{+0.03}_{-0.02}\)) is in considerable disagreement with the millimetric redshift (\(z = 2.4^{+1.1}_{-0.8}\)). See § 3.

3. A comparison of the five AGN-classified sources to the well-studied, heavily obscured AGN NGC 6240 suggests that the AGNs in these sources contribute, on average, a negligible fraction (i.e., \(\approx 1.4\%\)) of the submillimeter emission. Hence, the submillimeter emission from these sources appears to be dominated by star formation. This result is relatively insensitive to redshift. See § 4.
4. The X-ray constraints are weak for the other five submillimeter sources. We find that the X-ray properties for the two sources with millimetric redshifts of $z < 4$ are consistent with those expected from luminous star formation activity ($L_X \approx 10^{42} - 10^{43}$ ergs s$^{-1}$). The submillimeter–to–X-ray spectral slopes of these sources are also similar to those expected from Arp 220 (the archetypal ultraluminous dusty starburst galaxy) at $z > 1$; however, we cannot rule out the possibility that low-luminosity AGNs are present in these sources. The three $z > 4$ sources could be either AGNs or starburst galaxies. See §§ 3 and 4.

5. The fraction of the bright submillimeter source population with AGN activity (i.e., $\gtrsim 26\%$) is in reasonable agreement with model predictions. The comparatively low X-ray luminosities of the AGN-classified sources are more consistent with Seyfert galaxies than QSOs. We suggest that optically bright submillimeter-detected QSOs (i.e., luminous type 1 AGNs), although possibly not numerically significant, may provide the bulk of the AGN emission at submillimeter wavelengths. See § 5.

These results show that the low X-ray detection rate of bright submillimeter sources by moderately deep X-ray surveys is probably due to the relatively low luminosities of the AGNs in these sources rather than Compton-thick absorption. The current constraints therefore suggest that the total contribution from AGNs to the submillimeter emission in the bright submillimeter source population is negligible. Hence, the submillimeter emission of bright submillimeter sources appears to be predominantly powered by star formation activity and therefore can be used to determine star formation rates.

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