DETECTION OF IRON Ka EMISSION FROM A COMPLETE SAMPLE OF SUBMILLIMETER GALAXIES

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ABSTRACT

We present an X-ray stacking analysis of a sample of 38 submillimeter galaxies (SMGs) with (z) = 2.6 discovered at ≥4σ significance in the Lockman Hole North with the MAMBO array. We find a 5σ detection in the stacked soft band (0.5–2.0 keV) image, and no significant detection in the hard band (2.0–8 keV). We also perform rest-frame spectral stacking based on spectroscopic and photometric redshifts and find a 4σ detection of Fe Ka emission with an equivalent width of EW ≥ 1 keV. The centroid of the Fe Ka emission lies near 6.7 keV, indicating a possible contribution from highly ionized Fe xxv or Fe xxvi; there is also a slight indication that the line emission is more spatially extended than the X-ray continuum. This is the first X-ray analysis of a complete, flux-limited sample of SMGs with statistically robust radio counterparts.

Key words: galaxies: active – galaxies: formation – submillimeter: galaxies – X-rays: galaxies

1. INTRODUCTION

Submillimeter galaxies (SMGs) are distant star-forming systems with tremendous infrared luminosities (LIR [8–1000 μm] ≥ 10^{12} L⊙). In the (sub)millimeter waveband, they are observable out to high redshifts due to the strong negative K-correction in the Rayleigh–Jeans regime of their thermal spectrum (see, e.g., Blain et al. 2002). The prevalence of SMGs at z > 1 (Chapman et al. 2005), in combination with their high rates of dust-obscured star formation, imply that they may be responsible for the production of a significant fraction of all the stellar mass in present-day galaxies. X-ray (Alexander et al. 2003, 2005a) and mid-infrared (Valiante et al. 2007; Menéndez-Delmestre et al. 2007, 2009; Pope et al. 2008) spectroscopy shows that SMGs frequently contain active galactic nuclei (AGNs) as well as powerful starbursts. This connection between star formation and accretion at high redshift may help explain the black hole mass–bulge mass relation in present-day galaxies (e.g., Alexander et al. 2005b). However, it remains hard to determine the relative importance of accretion and star formation for the SMG population as a whole because of the challenge of assembling large, statistically unbiased SMG samples.

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Submillimeter galaxies (SMGs) are distant star-forming systems with tremendous infrared luminosities (LIR [8–1000 μm] ≥ 10^{12} L⊙). In the (sub)millimeter waveband, they are observable out to high redshifts due to the strong negative K-correction in the Rayleigh–Jeans regime of their thermal spectrum (see, e.g., Blain et al. 2002). The prevalence of SMGs at z > 1 (Chapman et al. 2005), in combination with their high rates of dust-obscured star formation, imply that they may be responsible for the production of a significant fraction of all the stellar mass in present-day galaxies. X-ray (Alexander et al. 2003, 2005a) and mid-infrared (Valiante et al. 2007; Menéndez-Delmestre et al. 2007, 2009; Pope et al. 2008) spectroscopy shows that SMGs frequently contain active galactic nuclei (AGNs) as well as powerful starbursts. This connection between star formation and accretion at high redshift may help explain the black hole mass–bulge mass relation in present-day galaxies (e.g., Alexander et al. 2005b). However, it remains hard to determine the relative importance of accretion and star formation for the SMG population as a whole because of the challenge of assembling large, statistically unbiased SMG samples.

Studying the X-ray properties of SMGs is difficult for two main reasons. First, the X-ray counterparts to SMGs are extremely faint. The count rate is so low that even the deepest X-ray observations of purely submillimeter-selected SMG samples (Laird et al. 2010; Georgantopoulos et al. 2011). To disentangle the relationship between SMGs and X-ray-selected AGNs, we need to overcome the uncertainty introduced by inhomogeneously selected samples, requiring X-ray spectral analyses of large, flux-limited samples of (sub)millimeter-selected SMGs with robust counterparts.

In this work, we report on an X-ray stacking analysis of a sample of 38 SMGs detected in a 1.2 mm map of the Lockman Hole North (LHN), one of the fields in the Spitzer Wide-Area Infrared Extragalactic (SWIRE) Survey (Lonsdale et al. 2003), using data from the Chandra–SWIRE survey (Polletta et al. 2006; Wilkes et al. 2009). The high radio counterpart identification rate of the LHN SMG sample (93%; Lindner et al. 2011) is afforded by the extremely deep 20 cm map of the same field (Owen & Morrison 2009) and allows for reliable X-ray photometry. The sample benefits from spectroscopic (Polletta et al. 2006; Owen & Morrison 2009; Fiolet et al. 2010) and optically derived photometric (Strazzullo et al. 2010) redshifts. Additionally, analyses of Herschel observations of the LHN (Magdis et al. 2010; Roseboom et al. 2012) have delivered reliable photometric redshifts and infrared luminosities for a large fraction of the sample by fitting far-IR photometry with thermal-dust spectral energy distribution (SED) models.

In Section 2, we describe the observations used in our analysis. Section 3 outlines our X-ray stacking technique, and our method for deriving rest-frame luminosities. In Section 4, we compare our results to previous X-ray studies of SMGs, and discuss the possible origins of the Fe Kα emission seen in our stacked spectrum. In Section 5, we present our conclusions. In our calculations, we assume a Wilkinson Microwave Anisotropy Probe cosmology with H0 = 70 km s^{-1} Mpc^{-1}, Ω_M = 0.27, and Ω_0 = 0.73 (Komatsu et al. 2011).

2. DATA AND SAMPLE SELECTION

2.1. Millimeter Observations and Stacking Sample

Our SMG sample consists of 38 of the 41 significant detections in the 1.2 mm map (Lindner et al. 2011) of the LHN made using the Max Planck Millimeter Bolometer (MAMBO; Kreyss et al. 1998) array on the Institut de Radioastronomie
Millimétrique 30 m telescope. We exclude one source that lacks a plausible 20 cm radio counterpart (L20), one that has a likely X-ray counterpart (L26), and one nearby galaxy at $z = 0.044$ (L29) from the stacking sample. Of our final sample of 38 galaxies, 37 (97\%) have robust 20 cm radio counterparts with a chance of spurious association ($P < 0.05$); the remaining galaxy, L32, has $P = 0.056$. Stacking is performed with the coordinates of the SMGs’ radio counterparts, which have a mean offset of $2''$. Four of our stacking targets have positions that are not listed in the 20 cm catalog of Owen & Morrison (2008) because they had $S/N < 5.0$ (L9, L28, and L36), or they were blended together with nearby radio sources (L17 and L39) during extraction (Owen & Morrison 2008; Lindner et al. 2011). The sample has a mean redshift of $\langle z \rangle = 2.6$ (see Tables 1 and 2).

### 2.2. Chandra ACIS-I Observations

Our X-ray data are from the 3 $\times$ 3 pointing raster mosaic of the LHN obtained with the Advanced CCD Imaging Spectrometer (ACIS-I; Weisskopf et al. 1996) on the Chandra X-ray telescope by Polletta et al. (2006). The final mosaic comprises nine 70 ks pointings arranged with $\sim 2''$ overlap (see Figure 1). It covers a total area of $\geq 0.7 \text{deg}^2$ and has a limiting conventional broadband ($B_C; 0.5–8.0 \text{keV}$) sensitivity of $\sim 4 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2}$ (Polletta et al. 2006). Fiolet et al. (2009) used these same data
to search for a stacked X-ray signal among 33 Spitzer 24 μm selected starburst galaxies and found no significant 0.3–8 keV band emission.

Within the sample of 41 MAMBO detections in the LHN, only L26 has a likely X-ray counterpart (CXOSWJ104523.6+585601) in the catalog of Wilkes et al. (2009). This X-ray source has conventional broad band (BC; 0.5–8.0 keV), soft band (SC; 0.5–2.0 keV), and hard band (HC; 2.0–8.0 keV) X-ray fluxes of $f_{BC} = 2.53 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, $f_{SC} = 1.21 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, and $f_{HC} = 1.57 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, respectively, and a hardness ratio of $HR = -0.32^{+0.31}_{-0.34}$. The hardness ratio is defined by $HR = (H_C - S_C)/(H_C + S_C)$, where $H_C$ and $S_C$ are the counts in the Chandra conventional hard and soft bands, respectively.

3. STACKING ANALYSIS

In this section, we describe our reduction of the Chandra X-ray data products and the methods used in our stacking analysis. We use two techniques: (1) image-based stacking in binned X-ray maps (Section 3.1), and (2) a photon-based spectral stacking procedure using optimized apertures (Section 3.2). The following subsections describe our implementation of these two methods.

### 3.1. Image-based Stacking

We generate $1'' \times 1''$ pixel gridded maps of the total counts and effective exposure time in the $BC$, $SC$, and $HC$ energy bands using the Chandra Interactive Analysis of Observations (CIAO; Fruscione et al. 2006) script fluximage. The characteristic energies input to fluximage to compute effective areas were 4.00 keV, 1.25 keV, and 5.00 keV for the $BC$, $SC$, and $HC$ bands, respectively. We then used the CIAO scripts reproject_image to merge the maps of each observation into one mosaic, and dmimgcalc to produce an exposure-corrected flux image in units of photons cm$^{-2}$ s$^{-1}$.

Figure 2 shows the resulting stacked image in each energy band. The $40'' \times 40''$ S/N postage stamp images are shown with a color stretch from S/N = −4 to +4. The peak signal-to-noise ratio (S/N) is 3.2, 4.8, and 2.0 in the $BC$, $SC$, and $HC$ bands, respectively. The peak of the strong stacked detection in the $SC$ band has an offset from the mean radio counterpart centroid position of $\lesssim 1''$.

### 3.2. Optimized Broadband Stacking

Our second stacking technique does not use a binned X-ray map. Instead, we compute the stacked count rate and flux by directly counting photons at the stacking positions. The photometric aperture at each stacking location is derived using a technique similar to the optimized stacking algorithm presented in Treister et al. (2011, supplementary information).

The size and shape of the aperture at each stacking position is chosen to maximize the point-source S/N at that position on the ACIS-I chips. The apertures are constructed as follows. For each stacking position (shown in Figure 1), we (1) use the CIAO script mkpsf to generate a two-dimensional image of the local Chandra point spread function (PSF), (2) convolve this PSF with a Gaussian smoothing kernel (see below), and (3) find the enclosed-energy fraction (EEF) contour $C_{EEF}$ that maximizes the S/N of the flux within the aperture. The area enclosed by this contour defines the aperture. Because Poisson noise from

![Figure 1. SMG positions inside the LHN. The filled circles mark the locations of the stacking targets used in this work and are labeled according to the SMGs' ID numbers from Table 1. The locations of the source without a reliable radio counterpart (L20), the nearby galaxy at $z = 0.044$ (L29), and the source with a likely X-ray counterpart (L26) are also shown even though they are not used in our stacking analysis. The gray-scale image shows the relative Chandra effective exposure time across the field.](image1)

![Figure 2. Stacked X-ray images showing the $S/N$ in the $BC$, $HC$, and $SC$ Chandra energy bands. The white cross hairs mark the stacking center. The color stretch is $S/N = [-4, +4]$.](image2)

| Redshift Type | No. of Galaxies | Δz | References |
|---------------|----------------|----|------------|
| Spectroscopic | 3              | 0  | Polletta et al. (2006) |
|               |                |    | Owen & Morrison (2009) |
| Optical-based photometric | 3              | 0.2 | Strazzullo et al. (2010) |
| Infrared-based photometric | 23             | 0.4 | Magdis et al. (2010) |
| Spectral index-based estimate (Carilli & Yun 1999) | 9              | 0.6 | Lindner et al. (2011) |

### Table 2

Redshift Uncertainties

| Redshift Type | No. of Galaxies | Δz | References |
|---------------|----------------|----|------------|
| Spectroscopic | 3              | 0  | Polletta et al. (2006) |
|               |                |    | Owen & Morrison (2009) |
| Optical-based photometric | 3              | 0.2 | Strazzullo et al. (2010) |
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| Spectral index-based estimate (Carilli & Yun 1999) | 9              | 0.6 | Lindner et al. (2011) |
the X-ray background is stronger than the flux at each position and the average exposure time does not change rapidly with increasing aperture size, the S/N within the aperture can be parameterized by $C_{\text{EEF}}$ as

$$S/N \propto \frac{\text{EEF}}{\sqrt{A(C_{\text{EEF}})}}. \quad (1)$$

where $A(C_{\text{EEF}})$ is the total area enclosed by the contour $C_{\text{EEF}}$. This expression is the same as that derived by Treister et al. (2011), except that instead of using only circular apertures, we allow for non-axisymmetric apertures that follow the local shape of the Chandra PSF.

We compensate for the change in shape of the Chandra PSF with photon energy by generating two optimal apertures at each stacking position, one for each energy band (i.e., for characteristic energies of 1.25 keV and 5 keV). Parts of the LHN Chandra mosaic were imaged multiple times due to the overlapping edges of the individual exposures (see Figure 1). For these positions, we find the total effective aperture by maximizing Equation (1) using a linear combination of PSFs, one for each overlapping observation.

We broaden the local Chandra PSFs to accommodate photons that do not lie at the stacking centers due to intrinsic wavelength offsets in the galaxies and astrometric errors. Previous X-ray stacking analyses find the optimal aperture radius to be $\sigma = 1'25-3'0$ (Lehmer et al. 2005; Georgantopoulos et al. 2011). We find similarly that our broadband stacked S/N is maximized with a smoothing kernel radius $\sigma_{\text{kernel}} = 1'3$ (see Figure 3), so we adopt this value for our subsequent broadband photometry. The smallest angular separation of any pair of stacking targets (15″ for L17 and L39) is larger than the maximum radial offset of the largest X-ray stacking aperture, so we can ignore the effects of X-ray blending within our sample.

The photons used for background subtraction are collected from arrays of large circular apertures positioned next to each stacking-target position. The apertures are manually positioned to exclude any bright nearby X-ray sources that could contaminate the background estimate. To avoid possible systematic uncertainties associated with the background subtraction (see, e.g., Treister et al. 2011; Willott 2011), we do not impose any S/N-based clipping or additional filtering in the background regions.

Table 3 shows the average stacked count rate and energy flux per galaxy in the three broad energy bands. We find a significant stacked detection in the soft band and no significant detection in the hard band. To convert the stacked count rate into energy flux, we used the web-based CIAO Portable Interactive Multi-

| Band | Energy (keV) | Net Rate ($10^{-6}$ s$^{-1}$) | Flux ($\Gamma = 1.6$) ($10^{-17}$ erg cm$^{-2}$ s$^{-1}$) | Flux ($\Gamma = 1.9$) ($10^{-17}$ erg cm$^{-2}$ s$^{-1}$) | $L_X (\Gamma = 1.6)$ ($10^{42}$ erg s$^{-1}$) |
|------|-------------|-------------------------------|----------------------------------|---------------------------------|----------------------------------|
| $S_C$ | 0.5–2.0 | $8.0_{-2.0}^{+1.1}$ | $4.7_{-0.8}^{+1.2}$ | $4.9_{-0.9}^{+1.3}$ | … |
| $H_C$ | 2.0–8.0 | $1.2_{-0.9}^{+0.2}$ | $<9.7$ | $<9.1$ | … |
| $B_C$ | 0.5–8.0 | $9.2_{-3.5}^{+3.8}$ | $10.1_{-3.9}^{+4.2}$ | $9.0_{-3.6}^{+1.7}$ | … |
| $H^\text{rest}$ | 0.55–2.22 | $8.0_{-2.3}^{+2.1}$ | $4.8_{-1.3}^{+1.1}$ | $4.9_{-1.4}^{+1.3}$ | $3.0 \pm 1.1$ |
| $H^\text{rest}$ | 0.55–2.78 | $8.6_{-2.5}^{+2.4}$ | $5.7_{-1.7}^{+1.6}$ | $5.7_{-1.7}^{+1.6}$ | $3.6 \pm 1.3$ |

**Notes.** Unabsorbed fluxes calculated assuming the given photon index with Galactic absorption only. Hydrogen column density taken as that of the central Chandra pointing, $N_H = 6.6 \times 10^{19}$ cm$^{-2}$ (Stark et al. 1992). Luminosity calculation uses $\Gamma = 1.6$. Mission Simulator (PIMMS version 4.4; Cycle 5). The fluxes are corrected for Galactic absorption using the column density in the direction of the LHN center, $N_H = 6.6 \times 10^{19}$ cm$^{-2}$ (Stark et al. 1992). Our non-detection in the hard band leaves our calculation of the hardness ratio relatively unconstrained, $HR = -0.68_{-0.32}^{+0.51}$ (setting a limit on the photon index $\Gamma > 1.2$), although it is clear that our sample has a steeply declining photon spectrum characteristic of star-forming galaxies (e.g., Ranalli et al. 2012). This estimate of HR was made after subtracting out the count rate in the soft band that is due to the strong Fe Kα line (see Section 3.3), which is a ~20% contribution for 1′3 broadened photometric apertures.

A high photon index of $\Gamma = 1.6$ (HR $\sim -0.37$) is found by Laird et al. (2010), who stack on SCUBA-detected SMGs in the Chandra Deep Field North (CDF-N). An even steeper photon index of $\Gamma = 1.9$ (HR $\sim -0.49$) is measured by Georgantopoulos et al. (2011), who stack on LABOCA-detected SMGs in the Extended Chandra Deep Field South (ECDF-S). We have used values of $\Gamma = 1.6$ and $\Gamma = 1.9$ to compute the stacked flux in each energy band (e.g., see Table 3), although the difference between the two estimates is less than the Poisson uncertainty (see Table 3).

### 3.3. Optimized Spectral Stacking

In addition to stacked broadband fluxes, we also calculate the observed-frame and rest-frame stacked count-rate spectra for our sample.
For each stacking target, we use redshift information in the following order of priority, subject to availability: (1) spectroscopic (Polletta et al. 2006; Owen & Morrison 2009; Fiolet et al. 2010), (2) Herschel-based photometric (Magdis et al. 2010; Roseboom et al. 2012), (3) AA-quality optical-based photometric (Strazzullo et al. 2010), and (4) millimeter/radio photometric estimated using the Carilli & Yun (1999) spectral index $\alpha_{20\text{cm}}^{850\mu m}$ technique (Lindner et al. 2011). The redshift distribution of our sample is shown in Figure 4.

We use a flat sum of the observed counts at each stacking-target position with no weighting factors. Although this technique gives more weight to the brightest members of the stack, it is necessary given that none of our stacking targets are individually detected, and therefore S/N-based weights (used in, e.g., Treister et al. 2011) cannot be reliably assigned. For the rest-frame data, we separately co-add, blueshift, and bin the background photons to avoid creating artificial spectral features (see, e.g., Yaqoob 2006).

The uncertainty in the rest-frame energy of the photons $\Delta E_{\text{rest}}$ as a function of the observed photon energies $E_{\text{obs}}$ due to the typical redshift error $\Delta z$ is estimated by the equation

$$\Delta E_{\text{rest}} = E_{\text{obs}} \frac{\langle \Delta z \rangle}{1 + \langle z \rangle}.$$  \hspace{1cm} (2)

This uncertainty is always larger than the energy resolution of the ACIS-I chips, so we set the rest-frame energy bin widths to match $\Delta E_{\text{rest}}$ (Equation (2)) using our sample’s average redshift $\langle z \rangle = 2.6$ and redshift uncertainty $\langle \Delta z \rangle = 0.4$ (see Table 2).

Figures 5 and 6 show the net observed and rest-frame count-rate spectra for our SMG sample, respectively. The rest-frame spectrum contains a $4\sigma$ emission feature with a centroid near 6.7 keV, which we attribute to Fe Kα line emission from a mixture of Fe ionization states including Fe xxv (see Section 5.1.3). It is apparent from this rest-frame spectrum that a significant fraction of the observed soft-band flux is due to the Fe Kα emission line. If strong unresolved Fe Kα emission is a common feature in the X-ray spectra of other SMG samples, then it may artificially lower their measured HR values by inflating their observed soft-band fluxes.

To ensure our stacking signal is not the result of contamination from a few strong targets, we performed a bootstrapping Monte Carlo analysis to recover the probability distribution for the single 6.7 keV energy bin ($b_{6.7}$). The mean number of on-target counts in $b_{6.7}$ is 16, while the mean number of background counts in the bin is 8. Figure 7 shows that the resulting distribution closely matches that of an ideal Poisson distribution.
with a mean of 16, confirming that our stacking signal is characteristic of the entire sample, not a few outliers.

3.4. Estimating $L_X$ and $L_{FeK\alpha}$

The mean stacked rest-frame hard-band X-ray luminosity, $L_{Hc}$, of our sample is given by

$$\langle L_{Hc} \rangle = 4\pi f_{Hc} \langle d_L^2 \rangle,$$

(3)

where $f_{Hc}$ is the stacked energy flux per galaxy inside the observed 0.56–2.22 keV energy band (the 2.0–8 keV energy band, redshifted by $\langle z \rangle = 2.6$) and $d_L$ is the luminosity distance at the redshift of each stacking target. We convert the observed count rate to an energy flux using PIMMS. The resulting rest-frame X-ray luminosity is $\langle L_{Hc} \rangle = (3.0 \pm 1.1) \times 10^{42}$ erg s$^{-1}$.

To estimate the equivalent width and line flux of the Fe K$\alpha$ feature, we assume that the line emission is contained only within the single elevated bin at 6.7 keV (see Figure 6) and estimate the local count-rate continuum around the Fe K$\alpha$ feature by averaging together the eight bins between 3–9 keV (excluding the bin containing the line). This results in an equivalent width of EW $= 3.9 \pm 2.5$ keV. Although the EW is relatively unconstrained, it is $>1$ keV with 90% confidence. Using the nominal equivalent width and Equation (A7), we find a mean stacked Fe K$\alpha$ line flux of $\langle f_{FeK\alpha} \rangle \simeq 2.1 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ and a mean line luminosity $\langle L_{FeK\alpha} \rangle = (1.3 \pm 0.4) \times 10^{42}$ erg s$^{-1}$.

Figure 3 also shows that the S/N of the Fe K$\alpha$ signal only drops at a larger radius than the broadband signal. If we interpret the X-ray continuum as originating from the galaxies’ nuclear regions, then this relative offset between the Fe K$\alpha$ emission and the X-ray continuum indicates that the Fe K$\alpha$ photons in our sample are systematically offset from the galaxies’ centers. By measuring the distance between the peaks of the two curves in Figure 3, we estimate the radial offset to be $\sim 1''$. For our computation of the Fe K$\alpha$ line luminosity, we adopt an aperture broadening kernel suited to maximize the S/N of the Fe K$\alpha$ emission line, $\sigma_{kernel} = 2''$.

We use a two-sample Kolmogorov–Smirnov (K-S) test to determine the significance of the apparent angular extension of the Fe K$\alpha$ emission relative to the continuum emission. First, we compute the Chandra PSF at the location of each stacking target, then sample the PSFs at the positions of their respective collections of optimally selected photons (see Section 3.3). The PSFs are peak normalized and smoothed by an amount $\sigma_{smooth}$ to reflect intrinsic wavelength offsets and astrometric errors in the photon positions. We then compare the cumulative distributions of the observed soft-band (0.5–2.0 keV) continuum photons (excluding those in the rest-frame Fe K$\alpha$ bin) and the rest-frame Fe K$\alpha$ photons using the two-sample K-S test to determine with what confidence $1 - p$ ($p$ is the K-S significance) we can rule out the null hypothesis that the two samples are drawn from a common distribution. When using all 38 stacking positions, we find a maximum confidence of $1 - p = 0.71$ at $\sigma_{smooth} = 0.5$ (63 continuum counts and 15 Fe K$\alpha$ counts). When we use only the stacking positions that have $\geq 1$ Fe K$\alpha$ photon, the maximum confidence occurs at the same value of $\sigma_{smooth}$ but has a reduced $1 - p = 0.45$ (29 continuum counts and 15 Fe K$\alpha$ counts). Therefore, the extension in the Fe K$\alpha$ emission relative to the continuum emission indicated by Figure 3 is a $\gtrsim 1\sigma$ (71% confidence) effect, whose significance is limited primarily by the small number of Fe K$\alpha$ photons.

4. OBSCURATION AND STAR FORMATION RATE

Two galaxies in our sample have $L_{IR}$ [8–1000 $\mu$m] estimated from Magdis et al. (2010), and 12 from Roseboom et al. (2012). For the remaining galaxies without SED fits, we estimate $L_{IR}$ by scaling the SED from the nearby, bolometrically star formation dominated ULIRG, Arp 220:

$$L_{IR} = L_{IR}^{Arp220} \left( \frac{S_{1.2\,mm,Arp220}}{S_{1.2\,mm,obs}} \right) \left( \frac{d_L(z)}{d_L(z_0)} \right)^2 \left( \frac{1 + z}{1 + z_0} \right),$$

(4)

in terms of

$$\nu_0 = 1.2\, mm \times \frac{1 + z}{1 + z_0},$$

(5)

$L_{IR}^{Arp220} = 1.3 \times 10^{12} L_{\odot}$, the observed 1.2 mm flux density $S_{1.2\,mm}$, luminosity distance $d_L$, target redshift $z$, and Arp 220 redshift $z_0 = 0.018$. The $L_{IR}$ values for all stacking targets are presented in Table 1; the average value of our whole sample is

$$\langle L_{IR} \rangle = (2.4 \pm 0.2) \times 10^{46} \text{ erg s}^{-1}.$$  

(6)

The mean 20 cm radio luminosity density $L_{20\,cm}$ is calculated using our sample’s redshift distribution and 20 cm flux densities (Owen & Morrison 2008; Lindner et al. 2011):

$$\langle L_{20\,cm} \rangle = (2.5 \pm 0.3) \times 10^{31} \text{ erg s}^{-1} \text{ Hz}^{-1}.$$  

(7)

We estimate the average star formation rate (SFR) in our sample using the scaling relations of Kennicutt (1998) in the infrared and Bell (2003) at radio wavelengths, giving $\text{SFR}_{IR} \simeq (1100 \pm 100) M_\odot \text{ yr}^{-1}$ and $\text{SFR}_{radio} \simeq (1400 \pm 200) M_\odot \text{ yr}^{-1}$, respectively. These values are consistent with each other, but greater than the estimate using the X-ray scaling relation from Vattakunnel et al. (2012), $\text{SFR}_X \sim (500 \pm 300) M_\odot \text{ yr}^{-1}$. All
three scaling relations assume a Salpeter (1955) initial mass function with limiting masses of 0.1 and 100 $M_\odot$. The SFR estimated using the X-ray luminosity may be low due to intrinsic absorption. We can derive a lower limit on the average absorbing column in our sample by computing how much obscuration is required to reduce the value of SFR$_X$ from an intrinsic value consistent with SFR$_{rad}$ and SFR$_{radio}$. In this case, we would require $N_H \sim 2.3 \times 10^{23} \text{ cm}^{-2}$ based on our observed flux in the 0.55–2.77 keV band assuming $\Gamma = 1.6$ and using $(z) = 2.6$. If we use this argument to estimate the unabsorbed X-ray luminosity, then we find $\langle L_{\text{H}_\alpha} \rangle \simeq 9.2 \times 10^{42} \text{ erg s}^{-1}$.

5. DISCUSSION

5.1. Comparison to Previous Surveys

In this section, we compare our results to those of previous X-ray analyses of SMG samples from the CDF-N (Alexander et al. 2005a; Laird et al. 2010) and the (E)CDF-S (Georgantopoulos et al. 2011).

5.1.1. Detection Rate

With only one significant X-ray counterpart in the LHN, the Lindner et al. (2011) SMG sample has an X-ray detection rate of $2_{-5}^{+5}\%$. Alexander et al. (2005a) find a high X-ray detection rate of $85_{-15}^{+15}\%$ among SMGs and submillimeter-targeted radio galaxies (which constitute $70\%$ of their sample) in the CDF-N. Laird et al. (2010) find a lower detection rate of $45\% \pm 8\%$ using their purely submillimeter-selected sample derived from the inhomogenously covered SCUBA supermap (Borys et al. 2003). The LESS sample of Georgantopoulos et al. (2011) is also purely submillimeter-selected and has an X-ray detection rate of $11_{-4}^{+4}\%$. However, unlike the SCUBA supermap, the LESS survey is produced with a single observing mode, and with uniform coverage.

We can place these four surveys in a common framework if we ask what fraction of SMGs in each survey have X-ray counterparts above the X-ray detection threshold in the LHN. In this case, we find 11 of 20 ($55_{-13}^{+14}\%$) for Alexander et al. (2005a), 0 of 35 ($0_{-7}^{+7}\%$) for Laird et al. (2010), and 11 of 126 ($9_{-3}^{+3}\%$) for Georgantopoulos et al. (2011). The latter two are in agreement with our sample in the LHN. These results indicate that a lower X-ray detection rate may be more characteristic of strictly submillimeter-detected SMGs from surveys made with uniform coverage.

5.1.2. $L_{FIR,Ka}$ versus $L_{IR}$ versus $L_{20\mu m}$

Figure 8 shows our sample’s average X-ray (corrected only for Galactic absorption), radio, and IR luminosities compared to those of other stacked SMG samples (Laird et al. 2010; Georgantopoulos et al. 2011), individually X-ray-detected SMGs (Alexander et al. 2005a; Laird et al. 2010; Georgantopoulos et al. 2011), and nearby LIRGs and ULIRGs (sample drawn from Iwasawa et al. 2009). Where available, we use the $L_{IR}$ value from Table A2 of Pope et al. (2006) for the SMGs from the CDF-N. For the 12 SMGs in Alexander et al. (2005a) that are not in the catalog of Pope et al. (2006), we scale $L_{FIR} \rightarrow L_{IR}$ using the average conversion factor $f$ for the eight SMGs common between the two samples, $f = 1.42$. The $870 \mu m$ detected SMGs from the (E)CDF-S are plotted with $L_{IR} = 10–1000 \mu m$. The local LIRGs and ULIRGs from Iwasawa et al. (2009) also have their $L_{FIR}(40–400 \mu m)$ estimates scaled by $f = 1.42$. We also show the total sample luminosity average for Laird et al. (2010), including the contribution from their stacked SMGs that were not individually detected in the X-ray. The average properties of our stacking sample are in agreement with the total luminosities of Laird et al. (2010).

Figures 8 and 9 also indicate the AGN classification of each galaxy. Galaxies whose mid-IR or X-ray spectral properties are consistent with emission produced entirely by star formation are plotted in red, while those requiring the presence of an AGN are shown in blue. Georgantopoulos et al. (2011) divide their sample by using a probabilistic approach; those galaxies requiring the presence of a torus-dust component in their mid-IR SED according to an F-test are categorized as AGNs. Laird et al. (2010) and Alexander et al. (2005a) separate out the AGN based on the most favored model of their X-ray spectra according to the Cash (1979) statistic. The sample of Iwasawa et al. (2009) is divided based on hardness ratio.

The division between AGN and non-AGN systems can be roughly determined based on the X-ray scaling relations of purely star-forming galaxies in the local universe (Ranalli et al. 2003; Vattakunnel et al. 2012) shown as solid black lines. The average properties of our stacking sample lie very near the Ranalli et al. (2003) relation. Considering the substantial intrinsic scatter in the spectral classifications of the Laird et al. (2010) sample, our stacking sample also probably contains a substantial fraction of both star-formation-only and AGN-required systems.
The Fe Kα photons in our stacking sample may be more spatially extended than the continuum photons by \( \sim 1" \) (see Section 3.4). Extended and misaligned Fe Kα emission has been observed in Arp 220 (Iwasawa et al. 2005) and NGC 1068 (Young et al. 2001). We may also be blending together the emission from multiple components of merging systems of which only one component has strong Fe Kα emission (like, e.g., Arp 299; Ballo et al. 2004).

The bin width in our stacked rest-frame X-ray spectrum, which is set by the redshift uncertainties of our SMG sample, is larger than the rest-energy separation between Fe Kα emission from neutral and highly ionized iron (0.3 keV); therefore, it is difficult to determine the average Fe ionization fraction in our sample. Close inspection of the photons near the rest-frame Fe Kα line (see Figure 10) reveals a range of values between 6.7 keV and 6.4 keV, with a local maximum at 6.7 keV. Given that the Fe line photons are contributed fairly evenly by the 38 targets in our stacking sample and have been assigned to their bins based on a wide variety of redshift estimation techniques (spectroscopic, optical-photometric, Herschel-photometric, and millimeter/radio-photometric), they are unlikely to all be systematically biased high or low. Therefore, a significant fraction of the detected Fe Kα photons likely originate from the highly ionized species of Fe xxv or Fe xxvi. However, the \( \sim 10\% \) rest-frame uncertainty in the energy of each photon implies an uncertainty in the centroid of the line profile of \( \sigma_{\text{centroid}} = \frac{\text{FWHM}}{(S/N)} \simeq 398 \text{ eV} \), insufficient to determine the relative fractions of each ionization state with certainty.

Strong emission (EW = 1.8±0.9) from highly ionized Fe Kα has been observed in the nearby ULIRG Arp 220 by Iwasawa et al. (2005) using XMM–Newton. Iwasawa et al. (2009) also find strong 6.7 keV emission (EW = 0.9±0.3 keV) from the stacked spectrum of nearby ULIRGs (including Arp 220) that have no evidence of AGN emission (termed X-ray-quiet ULIRGs). Alexander et al. (2005a) detected strong (EW \( \simeq 1 \text{ keV} \)) Fe Kα emission in the stacked SMG spectrum of the six SMGs in their sample with \( N_H > 5 \times 10^{23} \text{ cm}^{-2} \) and find that the line centroid is between 6.7 keV and 6.4 keV, indicating a substantial contribution from highly ionized gas.

In Figure 11, we compare the relation between \( L_{\text{Kα}} \) and \( L_{\text{IR}} \) in our sample with those for other individual systems and stacked samples with measured Fe Kα line luminosities and.
bolometrically dominant energy sources that are well understood. The dashed line represents a linear slope between $L_{K\alpha}$ and $L_{IR}$ and has been normalized to NGC 1068, a nearby prototypical Seyfert II LIRG. Red symbols represent systems that do not have significant observed AGN bolometric contributions, like SMGs and local X-ray-quiet ULIRGs; the blue symbols represent systems that have significant bolometric AGN contributions. Figure 11 shows that the relative Fe Kα/infrared luminosity fraction, $L_{K\alpha}/L_{IR}$, increases with increasing $L_{IR}$. If the Fe Kα emission is due to AGN activity, then this result may be in agreement with the observed trend that LIRGs/ULIRGs tend to be increasingly AGN-dominated with increasing $L_{IR}$ (e.g., Tran et al. 2001).

5.2. Origin of the Fe Kα Emission

This section discusses three possible physical origins for the Fe Kα emission detected in our stacked SMG sample: supernovae, galactic-scale winds, and AGNs. Because a significant fraction of our sample’s Fe Kα emission likely originates from the highly ionized species Fe xxv (see, e.g., Figure 10) and because evidence for highly ionized Fe Kα emission from other (U)LIRGs exists at both high (Alexander et al. 2005a) and low (e.g., Iwasawa et al. 2005) redshifts, the following sections focus on the origin of this high-ionization component.

5.2.1. Supernovae

Here, we consider if the observed Fe Kα feature can be attributed to X-ray luminous supernovae. X-ray observations of the supernova SN 1986J in the nearby spiral galaxy NGC 831 reveal strong hard-band emission and a significant 6.7 keV (EW $\lesssim 500$ eV) line (Houck et al. 1998). Supernova 1986J decayed in the 2–10 keV band as $\sim \tau^{-2}$ from 1991 to 1996. We will take a conservative approach and use only the luminosity information in this time interval for our calculation. Given the X-ray luminosity and decay rate of SN 1986J (Houck et al. 1998) and assuming the star formation rate of our sample of the order of SFR $= 10^5 M_\odot$ yr$^{-1}$ giving a supernova rate of 10 SN yr$^{-1}$, we would expect $\sim 50$ X-ray luminous supernovae to be visible at any given time. The combined supernova X-ray luminosity is therefore $L_{He,SNR} \simeq 10^{42}$ erg s$^{-1}$. Considering the fact that prior to 1991 SN 1986J was probably still dimming at a rate close to $\propto \tau^{-2}$, this calculation is an underestimate. Therefore, supernovae like 1986J can satisfy the bolometric requirements for explaining the hard X-ray emission and the Fe Kα line that we see in our stacked SMG sample.

However, if the supernovae associated with massive star formation are visible, then so must be high-mass X-ray binaries given the short lifetimes of massive stars. These systems would dominate the hard X-ray emission from star-forming regions and would severely dilute the Fe Kα emission (see, e.g., Iwasawa et al. 2009). We therefore rule out X-ray luminous supernovae and supernova remnants as the source of the Fe Kα emission in our sample.

5.2.2. Galactic-scale Winds

As discussed in Iwasawa et al. (2005), who consider the 6.7 keV emission line in Arp 220, a starburst-driven galactic-scale superwind of hot gas is energetically plausible as the source of the Fe Kα emission. Large outflows could also explain why the Fe Kα line emission appears more extended than the X-ray continuum emission in our stacking sample. To explore this scenario, we used the X-ray spectral-fitting package XSPEC (Arnaud 1996) to model an absorbed diffuse thermal X-ray ($z\text{phabs} \ast \text{mekal}$) spectrum and estimate the gas metallicity required to produce the strong high-ionization Fe Kα emission detected in our SMG sample. We computed the model EW values using the spectral window 6.35–7.05 keV, the same energy width as the bin containing the Fe Kα emission in our stacked rest-frame spectrum (Figure 6), which includes all Fe Kα ionization states. We fixed the gas temperature to Arp 220’s best-fit value $kT = 7.4$ keV (Iwasawa et al. 2005), the gas density to $n = 1$ cm$^{-3}$, the redshift to our sample’s average ($z = 2.6$), and the obscuring hydrogen column density to $2.3 \times 10^{23}$ cm$^{-2}$ (Section 4). The combined supernova X-ray luminosity and the continuum intensity vary linearly with Z, allowing us to express the relation between EW and Z as

$$EW = \frac{6.67}{1 + Z/Z'} \text{keV},$$

where $Z' = 5.29 Z_\odot$. EW is approximately proportional to Z for $Z \ll Z'$ and approaches the constant value 6.67 keV for $Z \gg Z'$. Because of this nonlinear behavior, an abundance of 0.94 $Z_\odot$ can produce EW $= 1$ keV (90% confidence lower-limit) while a significantly greater abundance $Z \simeq 7.5 Z_\odot$ is needed to explain our nominal value EW $\simeq 3.9$ keV. If a significant amount of our rest-frame 2–10 keV luminosity is from X-ray binaries, incapable of generating the observed line emission, then the required metallicity would be even higher. While the lower limit on our measured EW can be explained by thermal emission from a diffuse ionized plasma, especially considering the extreme enrichment taking place in systems like SMGs, generating an EW with a value close to our nominal measurement would require an unrealistic degree of high-z enrichment.

5.2.3. AGN Activity

AGNs hidden behind large hydrogen column densities may be responsible for the observed Fe Kα emission in our sample. The Fe Kα emission line is the signature spectral feature of the reprocessed (reflected) spectrum of an AGN (Matt et al. 2000). As the ionizing luminosity increases, so does the ionization fraction of the gas, shifting the dominant emission feature from 6.4 keV (neutral and intermediate ionization states) to 6.7 keV (helium-like Fe xxv) and 6.9 keV (hydrogen-like Fe xxvi).

Some insight into the properties of SMGs can be gained from reviewing the well-studied Fe Kα emission properties of AGNs and nearby ULIRGs. Strong (EW $\simeq 1$ keV) 6.7 keV emission has been observed in systems that are bolometrically AGN-dominated, like IRAS 00182-7112 (Nandra & Iwasawa 2007) and NGC 1068 (Young et al. 2001), as well as systems that appear to be energetically AGN-free, like Arp 220 (Iwasawa et al. 2005) and IC 694 (Ballo et al. 2004). However, direct evidence of a black hole accretion disk has been observed in Arp 220 by Downes & Eckart (2007) with the detection of a compact ($0.19 \times 0.13$) 1.5 mm continuum source in the center of the west nucleus torus. This source has a surface luminosity of $\sim 5 \times 10^{44} L_\odot$ kpc$^{-2}$, which is energetically incompatible with being powered by even the most extreme compact starbursts known. Only an accretion disk can be responsible for heating the dust. Highly ionized Fe Kα emission has also been observed in the AGN systems Mrk 273 (Balestra et al. 2005), NGC 4945 (Done et al. 2003), and NGC 6240 (Boller et al. 2003), along with a neutral Fe Kα component.

The narrow 6.4 keV “cold” Fe Kα emission line is a ubiquitous feature in the spectra of optically selected active galaxies.
out to high redshift (e.g., Corral et al. 2008; Iwasawa et al. 2011; Falocco et al. 2011). However, Iwasawa et al. (2011) also find evidence for highly ionized Fe Kα emission in two sub-sets of their X-ray-selected AGN sample: Type I AGNs with the highest Eddington ratios and Type II AGNs with the highest redshifts. The sub-samples with highly ionized Kα emission show no evidence of a broad-line Fe Kα feature; therefore, the highly ionized Fe Kα photons probably do not originate from the accretion disk, but from more distant and tenuous outflowing gas. This scenario may also explain why the Fe Kα photons in our sample appear spatially extended compared with the X-ray continuum photons.

A significant caveat is that it remains difficult to reconcile the power source required to produce offsets as large as 1" in the photon distribution of our sample’s stacked Fe Kα lines (relative to the nuclear continuum; see Section 3.4) given the sample’s low-average X-ray luminosity. For example, we can calculate the maximum radial distance out to which low-density gas can remain highly photoionized by a single ionizing source by assuming that our sample’s stacked infrared luminosity is produced by deeply buried AGNs, i.e., $L_{\text{IR}} \approx 2.4 \times 10^{48}$ erg s$^{-1}$. Using the ionization parameter $\xi \equiv L_{\text{IR}}/n R^2$ ($\log \xi \geq 2.8$ is required for a significant Fe XXV ionization fraction; Kallman et al. 2004) with $n = 1$ cm$^{-3}$, we find $R_{\text{max}} = \sqrt{L_{\text{IR}}/n \xi} \approx 2.0$ kpc. At our sample’s average redshift of $z = 2.6$, this corresponds to a typical angular offset of 0\'\'24. Angular offsets larger than 0\'\'24, like those tentatively indicated by our sample (see Figure 3), can be explained by SMGs that host multiple distributed ionizing sources. In particular, the radio continuum emission (defining our stacking positions) might be more closely associated with the X-ray continuum than with Fe Kα line emission in a complex, multi-component system. These results highlight the importance of resolving the sizes and morphologies of SMGs with high-resolution (sub)millimeter imaging (e.g., Tacconi et al. 2006).

If the high-ionization Fe Kα emission is ultimately due to star formation processes (shocked gas from SNe), and the SFR is traced by the $L_{\text{IR}}$, then we should expect a linear relation between $L_{\text{Fe}}$ and $L_{\text{IR}}$. If the systems with the highest $L_{\text{IR}}$ have an infrared contribution from obscured AGNs that are not also emitting Fe Kα photons, then we would expect a slope that is even less than unity. However, Figure 11 shows that $L_{\text{Fe}}$ is relatively much more dominant in SMGs and high-z AGNs than in their lower-luminosity, lower-redshift analogs. This distinction indicates that highly ionized Fe Kα emission cannot be explained solely by star formation processes and is more likely to be the result of AGN activity.

6. CONCLUSIONS

We analyze the X-ray properties of a complete sample of SMGs with radio counterparts from the LHN. This sample’s X-ray detection rate of 2\% is consistent with those for other uniformly mapped, submillimeter-detected samples, considering the depth of our X-ray data. The X-ray-undetected SMGs show a strong stacked detection in the $S_C$ band, and no significant detection in the $H_C$ band, similar to results from stacking in the CDF-N (Laird et al. 2010) and CDF-S (Georgantopoulos et al. 2011).

We also use the available redshift information of our SMGs to compute the rest-frame, stacked count-rate spectrum of our sample. The rest-frame spectrum shows strong (EW $> 1$ keV) emission from Fe Kα, possibly with contributions from Fe XXV and Fe XXVI. A comparison with other high-ionization Fe Kα-emitting systems from the literature indicates that accretion onto obscured AGNs is the likely explanation for the strong Fe Kα emission line. In our sample, the Fe Kα emission is responsible for $\sim 20\%$ of the observed soft-band X-ray flux. Therefore, if strong Fe line emission is a common feature in other SMG samples, it would significantly decrease the measured values of HR and lead to overestimates of the continuum spectral index $\Gamma$.

We find a tentative indication (71% confidence) that our sample’s stacked distribution of Fe Kα photons is more spatially extended than that of the X-ray continuum. If confirmed by future studies, then this result can help determine the physical origin of the prominent Fe Kα emission in SMGs.

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Facilities: IRAM:30m, CXO

APPENDIX

DETAILED DESCRIPTIONS OF CALCULATIONS

A.1. Optimized Spectral Stacking Method

We begin by labeling all the photons within the optimized apertures (see Section 3.1) of all of the $N = 38$ stacking targets with the index $i$, and those within the background regions for the $N$ targets $i'$. $E_i$ is the energy of the $i$th photon and $T_i$ is the effective exposure time in the mosaic at the position of $i$. The notation $i \in j$ refers to all the photons that have energies located in the $j$th energy bin. The stacked mean count rate in the $j$th energy bin, $R_j$, is then

$$R_j = \frac{1}{N} \sum_{i \in j} \frac{1}{T_i} \kappa_i,$$  \hspace{1cm} (A1)

where $\kappa_i$ is the aperture correction for the optimal aperture of the $i$th photon. The background mean count rate in the $j$th bin is

$$R'_j = \frac{1}{N} \sum_{i \in j} \frac{1}{T_i} \kappa_i \cdot c_i,$$  \hspace{1cm} (A2)

where $c_i$ is the ratio of the areas of the background region of the stacking position of the $i$th photon and of the optimal aperture of that stacking position. It follows that the expected number of background counts in the $j$th bin, $\bar{N}_j$, is

$$\eta_j = \langle T_i \rangle_{i \in j} \times R'_j.$$  \hspace{1cm} (A3)

We use the double-sided 68% confidence upper and lower limits, $\eta^\text{high}_j$, and $\eta^\text{low}_j$ (Gehrels 1986), to compute the 1σ count-rate deviations in the $j$th bin due to the background, $\sigma^\text{hi/low}_j$:

$$\sigma^\text{hi/low}_j = \left| \frac{\eta^\text{hi/low}_j - \eta_j}{\langle T_i \rangle_{i \in j}} \right|. \hspace{1cm} (A4)$$
Therefore, the net count-rate density per galaxy in the jth bin, $R_j$, is

$$R_j = \frac{(R_j - \tilde{R}_j)}{\Delta E_j} \frac{\sigma (R_j)^m / \Delta E_j}{-\sigma (R_j)^m / \Delta E_j} \left[ \text{s}^{-1} \text{keV}^{-1} \right]. \quad (A5)$$

where $\Delta E_j$ is the width of the jth energy bin. We calculate the corresponding rest-frame spectrum $R_j^{\text{rest}}$ by binning the photons according to their rest-frame energies, $E_i^{\text{rest}} = E_i(1 + z_i)$, where $z_i$ is the redshift of the stacking target associated with the photon.

### A.2. Fe Kα Energy Flux

We use the CIAO script `eff2evt` to tabulate the local effective area $A_i$ ($A_j$), and quantum efficiency $Q_i$ ($Q_j$), for each photon (on-target (background) apertures).

The mean stacked on-target and background photon fluxes in the jth bin, $F_j$, and $F'_j$, are then

$$F_j = \frac{1}{N} \sum_{i \in j} \frac{1}{T_i A_i Q_i \kappa_i}, \quad (A6)$$

and

$$F'_j = \frac{1}{N} \sum_{i \in j} \frac{1}{T_i A_i Q'_i \kappa'_i c_i}, \quad (A7)$$

respectively.

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