THE MID-INFRARED PROPERTIES OF X-RAY SOURCES

V. Gorjian and M. Brodwin
MS 169-327, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; varoujan.gorjian@jpl.nasa.gov

C. S. Kochanek
Department of Astronomy, Ohio State University, Columbus, OH 43210

S. Murray
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

D. Stern
MS 169-327, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

K. Brand
National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85726

P. R. Eisenhardt
MS 169-327, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

M. L. N. Ashby and P. Barmby
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

M. J. I. Brown
School of Physics, Monash University, Clayton, Victoria 3800, Australia

A. Dey
National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85726

W. Forman
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

B. T. Jannuzi
National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85726

C. Jones, A. T. Kenter, and M. A. Pahre
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

J. C. Shields
Department of Physics and Astronomy, Ohio University, Athens, OH 45701

M. W. Werner
MS 264-767, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

S. P. Willner
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

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ABSTRACT

We combine the results of the Spitzer IRAC Shallow Survey and the Chandra XBoötes Survey of the 8.5 deg² Boötes field of the NOAO Deep Wide-Field Survey to produce the largest comparison of mid-IR and X-ray sources to date. The comparison is limited to sources with X-ray fluxes >8 × 10⁻¹⁵ ergs cm⁻² s⁻¹ in the 0.5–7.0 keV range and mid-IR sources with 3.6 μm fluxes brighter than 18.4 mag (12.3 μJy). In this most sensitive IRAC band, 85% of the 3086 X-ray sources have mid-IR counterparts at an 80% confidence level based on a Bayesian matching technique. Only 2.5% of the sample have no IRAC counterpart at all based on visual inspection. Even for a smaller but a significantly deeper Chandra survey in the same field, the IRAC Shallow Survey recovers most of the X-ray sources. A majority (65%) of the Chandra sources detected in all four IRAC bands occupy a well-defined region of IRAC [3.6] – [4.5] versus [5.8] – [8.0] color-color space. These X-ray sources are likely infrared-luminous, unobscured type I AGNs with little mid-infrared flux contributed by the AGN host galaxy. Of the remaining Chandra sources, most are lower luminosity type I and type II AGNs whose mid-IR emission is dominated by the host galaxy, while approximately 5% are either Galactic stars or very local galaxies.

Subject headings: galaxies: nuclei — galaxies: Seyfert — infrared: galaxies — X-rays: galaxies
1. INTRODUCTION

The cosmic infrared background (CIB) represents a large fraction of the energy generated during the history of the universe. The two main contributors to the CIB are fusion processes within stars and accretion processes onto black holes (see the review by Hauser & Dwek 2001). The contribution to the CIB from accretion is less well constrained than that from stars because AGN surveys have always suffered from systematics and incompleteness. Optical and soft X-ray surveys tend to miss dust- or gas-obscured AGNs, while surveys at wavelengths insensitive to absorption either include only small subpopulations of AGNs (radio) or are very limited by flux or survey area limitations (hard X-ray, infrared). With the advent of the Chandra X-Ray Observatory (Weisskopf et al. 1996) and the Spitzer Space Telescope (Werner et al. 2004) the tools became available to do the wide-field imaging surveys needed to determine the relative contribution of stars and AGNs to the CIB throughout the history of the universe.

In this paper we examine the mid-IR colors of a large sample of X-ray sources in the ∼9 deg² Boötes field of the NOAO Deep Wide Field Survey (NDWFS; Jannuzi & Dey 1999), a ground-based survey from the optical to the near-IR (BpRIJKs). The X-ray sources were detected in the Chandra XBoötes survey of the field (Murray et al. 2005; Kenter et al. 2005; Brand et al. 2006; Hickox et al. 2007), and then matched to the mid-IR sources found in the Spitzer IRAC Shallow Survey of the field (Eisenhardt et al. 2004). Eisenhardt et al. (2004) pointed out that in a [3.6] − [4.5] versus [5.8] − [8.0] color-color diagram there was a distinct branch of pointlike 3.6 µm sources that were probably AGNs. This was confirmed by Stern et al. (2005), who used spectroscopy of nearly 10,000 of the Shallow Survey sources, including 681 AGNs from the AGN and Galaxy Evolution Survey (AGES; C. S. Kochanek et al. in preparation). Lacy et al. (2004) found a similar color grouping in the Spitzer First Look Survey based on 54 optically identified quasars. In this paper we characterize the mid-IR properties of the full Chandra XBoötes sample. There have been several previous surveys comparing X-ray and mid-IR sources (e.g., Fadda et al. 2002; Alonso-Herrero et al. 2004; Franceschini et al. 2005; Barmbry et al. 2006), but our present survey is significantly larger. Our objectives are to characterize the mid-IR color distributions of X-ray sources and the efficiency with which we can detect X-ray sources in the mid-IR. In §2 we describe the X-ray and mid-IR observations and our method for matching the two catalogs. In §3 we compare the two samples, and we summarize the results in §4.

2. OBSERVATIONS

The XBoötes survey (Murray et al. 2005) imaged roughly 8.5 deg² of the Boötes NDWFS using the Advanced CCD Imaging Spectrometer (ACIS) instrument on Chandra in a series of 126 short (5 ks) observations. The resulting limiting flux was $10^{-13}$ counts s⁻¹ corresponding to $\sim 8 \times 10^{-15}$ ergs cm⁻² s⁻¹ in the 0.5–7.0 keV range. We use a catalog of 3442 sources with four or more counts that has a spurious detection rate of approximately 1% (Kenter et al. 2005). Matching the X-ray sources to their IRAC counterparts is complicated by the fact that the positions of the X-ray sources have significant uncertainties that depend on the fluxes of the sources and their locations relative to the Chandra optical axis. The Chandra PSF is only 0.6º FWHM on-axis, but degrades quadratically with off-axis distance, reaching 6.0º when 10º off-axis. We adopt an astrometric uncertainty appropriate to each source based on its off-axis position, divided by the square root of the source counts, with a fixed minimum uncertainty of 1.5º (90% confidence).

The IRAC Shallow Survey (Eisenhardt et al. 2004) covers 8.5 deg² of the NDWFS field with 3 or more 30 s exposures per position resulting in 17,076 separate $5' \times 5'$ images in the four IRAC bands. Sources were identified and characterized using SExtractor version 2.3.2 (Bertin & Arnouts 1996), resulting in detections (within 6º diameter apertures) of $\sim 270,000, 200,000, 27,000,$ and 26,000 sources brighter than the 5 σ detection limits of $18.4, 17.7, 15.5,$ and $14.5$ Vega magnitudes ($12.3, 14.9, 72.3, 102 \mu$Jy) in the 3.6, 4.5, 5.8, and 8.0 µm bands, respectively. The IRAC zero points are accurate at the 5% level (Reach et al. 2005) and the positions are accurate to 0.3º.

Since the X-ray survey covered a slightly larger area than the IR survey, we trimmed the X-ray survey by requiring that all the X-ray sources, including their error radii, were completely within the IR survey region. This resulted in a final X-ray catalog of 3086 sources.

2.1. Mid-Infrared Identification of X-Ray Sources

Matching one catalog with $\sim$3100 sources, many of which have significant positional uncertainties, to a second catalog with $\sim$270,000 sources presents some challenges. If our matching criteria are too strict, then we have many false negatives, while if they are too liberal, we have many false positives.

To best address this matching challenge we use the Bayesian source identification method used by Brand et al. (2006) for identifying the optical counterparts to the XBoötes sources. The method optimizes the parameters of the matching criterion and supplies probabilities for both identifying the X-ray source with each nearby IRAC source and for the X-ray source having no identification in the IRAC catalog. As a check on the Bayesian identification, we also used a simpler proximity match for the subset of 1658 X-ray sources with positional uncertainties $\leq 2''$. This simple proximity match serves as a check for anomalies in the results from the Bayesian method. The results for both techniques and all four IRAC wave bands are listed in Table 1. The fraction of identified sources depends on the IR band because the sensitivity of the observations is greatest at 3.6 and 4.5 µm but significantly worse at 5.8 and 8.0 µm. Figure 1 shows a comparison between the Bayesian and proximity match techniques based on the [3.6] – [8.0] and [5.8] – [8.0] colors, and it is clear that the Bayesian matches are not introducing new populations, but the Bayesian technique is significantly increasing the number of matched sources in the bands where an increase is most useful. Since no problems were identified with the Bayesian method, we adopt the Bayesian results for the remainder of our discussion.

### Table 1

| Matching Type | 3.6 µm | 4.5 µm | 5.8 µm | 8.0 µm |
|--------------|--------|--------|--------|--------|
| Bayesian a  | 2609 (85%) | 2422 (78%) | 1346 (44%) | 1487 (48%) |
| Proximity b | 1477 (48%) | 1400 (45%) | 881 (29%) | 945 (31%) |

Notes:—These are proximity match percentages based on the full 3086 X-ray sample. If one were only to compare the proximity matches with the 1658 sources that have positional errors $\leq 2''$, then the statistics would be the following: 3.6 µm = 89%, 4.5 µm = 84%, 5.8 µm = 54%, and 8.0 µm = 57%.

a Matching is done using the Bayesian method with an 80% threshold in the Bayesian confidence level.

b Matching is done by identifying a mid-IR source that is within 2º of an X-ray source which has a positional accuracy of $\leq 2''$. 

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In terms of numbers of X-ray sources identified in the IR, we focus on the 3.6 μm identifications as this is the most sensitive IRAC band. In the Bayesian method, each possible identification has a probability of being the correct identification. Figure 2 summarizes the distribution of the match probabilities for the most likely 3.6 μm counterpart for each X-ray source. Most sources (79%) are matched at a confidence level above 95%; 85% are matched at a confidence level above 80%. In general, the sources with low match probabilities are relatively faint X-ray sources that are observed far off-axis and have faint IRAC counterparts.

There are 349 objects (11%) for which the highest likelihood is that the X-ray source has no counterpart in the IRAC catalogs. We extracted 3.6 μm images of the regions near each of these objects for inspection. In most cases (244 objects) there is an IRAC source on or near the X-ray position that is fainter than the 5σ limit of the catalogs used for the matching procedure. For another 27 sources the X-ray source is in a region with either multiple, blended sources or very close to a bright star. Only 79 sources, 2.5% of the total sample, show no obvious IRAC counterpart near the position of the X-ray source. Since the X-ray catalogs are expected to have a roughly 1% false detection rate, this means that only ~1.5% of the true XBoötes sources have no counterpart in the IRAC Shallow Survey. Of these 79 sources, 70 have probable optical counterparts. However, Brand et al. (2006) estimated from Monte Carlo simulations that roughly 50% of sources genuinely lacking an optical counterpart would have a spurious counterpart due to the very high optical source density.

IRAC is considerably less sensitive at 5.8 and 8.0 μm than at 3.6 and 4.5 μm, which could lead to biases in the IRAC color-color distributions we will discuss shortly. We consider such biases by exploring how [3.6] – [4.5] colors depend on the presence of 5.8 and 8.0 μm detections. Figure 3 shows histograms of the [3.6] – [4.5] color for (1) all matched objects with >5σ detections in the blue channels (3.6 and 4.5 μm), (2) >5σ detections in all four channels, and (3) objects lacking >5σ detections in the two red channels (5.8 and 8.0 μm). The median [3.6] – [4.5] color of the distributions are mutually consistent for all three cases, with median [3.6] – [4.5] = 0.49, 0.56, and 0.44 for cases 1, 2, and 3, respectively. Objects with detections in all four bands are marginally redder than the other cases, but the differences are small enough to rule out a significant population of X-ray sources with very blue [3.6] – [4.5] colors which might be systematically missed at 5.8 and 8.0 μm.

3. INFRARED PROPERTIES OF X-RAY-DETECTED AGNs

Figure 4 shows the [3.6] – [4.5] versus [5.8] – [8.0] color-color distribution of the X-ray sources. The largest grouping of

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1 Note that the 5σ limit for the 6′′ diameter aperture used for the IRAC catalog is a factor of 2 higher than the 5σ limit for a 3′′ aperture which more nearly corresponds to the detection limit of the survey (Eisenhardt et al. 2004). We use the 6′′ apertures here to obtain more reliable colors.
points running toward red $[3.6] - [4.5]$ colors is the population of AGNs identified by Eisenhardt et al. (2004) and also discussed in Stern et al. (2005). Superposed on Figure 4 is the color selection criterion developed by Stern et al. (2005) to identify AGNs based on optical spectroscopy of $681 R_{\text{ega}} < 21.5$ mag AGNs found in the survey region by AGES. In the Stern et al. (2005) spectroscopic sample, 77% of the objects meeting the selection criterion were broad-line (type 1) AGNs, 6% were narrow-line (type II) AGNs, and 17% were galaxies with no obvious signs of AGN activity in their spectra. These objects may also be AGNs with optical emission lines that are overwhelmed by the light of the host galaxy (e.g., Moran et al. 2002) or absorbed by dust and gas (e.g., Barger et al. 2001). As shown in Figure 4, of the 1325 XBoötes sources with detections in all four IRAC bands, 65% meet the Stern et al. (2005) selection criterion.

The problem is categorizing the remaining sources. In Figure 4 we have divided the $[3.6] - [4.5]$ versus $[5.8] - [8.0]$ color space into five regions, where region A is the Stern et al. (2005) AGN selection region where power-law emission of AGNs from the near to the mid-IR dominates the flux of the host galaxy. For each region we have also calculated the average X-ray hardness ratios $HR = (H - S)/(H + S)$ of the sources, where $H$ is the number of hard (2.0–7.0 keV) counts and $S$ is the number of soft (0.5–2.0 keV) counts. In region A the median (average) source has $S = 6.00 \pm 2.45$ (11.13 $\pm$ 2.92) and $H = 3.00 \pm 1.73$ (4.95 $\pm$ 1.95) for a hardness ratio of $HR = -0.40 \pm 0.39 (-0.32 \pm 0.43)$ (Fig. 5). This value is typical of type I AGNs (e.g., Akylas et al. 2004) implying that the X-ray objects in this the region are dominated by type I sources, as also evidenced by the optical spectroscopy. A significant number of Spitzer selected sources also have well-determined IRAC colors placing them in this AGN wedge but are not detected by XBoötes and are optically fainter than the AGES spectroscopic limit. Such sources are likely a mixture of fainter type I AGNs and obscured, type II, AGNs. In addition, there are X-ray sources which were detected off-axis that are difficult to match to faint IRAC sources, leading to the possibility that faint, obscured AGNs, which are more likely to be type II at all wavelengths (Ueda et al. 2003; Hao et al. 2005; Brown et al. 2006; Gorjian et al. 2004), may be missed, but this is not the case. For region A, if we take the subsample of sources with $>2\sigma$ error radii which comprise 30% of the sources in region A, the hardness ratio changes only a small amount, from $-0.4$ to $-0.33$. So a large number of faint IRAC type II sources are not being missed because they were preferentially selected against in off-axis matching.

Typically, type I AGNs which have broad optical hydrogen emission lines have low X-ray absorption, leading to a softer X-ray hardness ratio, and type II AGNs which have narrow optical hydrogen emission lines have greater X-ray absorption, in particular of soft X-ray photons, which leads to a harder X-ray hardness ratio. These ratios are somewhat modified by redshift where the harder sources seem softer as the higher energy X-ray photons are redshifted to lower energies.
Region B, with 3% of the sources, has a median (average) hardness ratio of $HR = -0.24 \pm 0.45 (-0.25 \pm 0.47)$, which is harder than that of region A. Figure 5 illustrates that the HR distribution extends toward harder values than for region A. Type II AGNs have harder ratios than type I AGNs since in obscured sources soft X-rays tend to be absorbed while hard X-rays are able to escape. So a mixture with relatively more type II AGNs in region B than in region A would explain the difference in the shapes of the HR distributions. In terms of the IR colors, Stern et al. (2005) placed the blue limit on region A in $[5.8] - [8.0]$ color to avoid the inclusion of $z > 1$ normal and starburst galaxies, but low luminosity AGNs will have the same colors as normal galaxies (e.g., Gorjian et al. 2004). So, in addition to a larger percentage of type IIs, region B is likely a combination of low-IR luminosity AGNs at $z > 1$, as well the extension of AGNs from region A.

Region C has a median (average) hardness ratio of $HR = -0.33 \pm 0.46 (-0.22 \pm 0.48)$ containing 21% of the sources. Most of these sources are relatively blue in $[3.6] - [4.5]$ either because they are lower luminosity AGNs with significant...
contamination of the mid-IR fluxes by their host galaxies or because of strong emission lines in the 3.6 μm band, with Paschen $\alpha$ at $z \sim 0.8$ being the most important numerically, but also with contributions from H$\alpha$ at $z \sim 4.3$ (e.g., Richards et al. 2006). The shape and value of the HR distribution is similar to region A indicating a similar mix of types I and II AGNs.

Region D contains objects with red [5.8] – [8.0] colors, indicative of low redshift PAH emission associated with star formation, and blue [3.6] – [4.5] colors, indicative of the Rayleigh-Jeans falloff of low-redshift stellar emission. This region contains 6% of the sources and has a median (average) hardness ratio of HR $= -0.20 \pm 0.47$ ($-0.06 \pm 0.48$). The difficulty lies in distinguishing emission due to star formation from that due to obscured AGNs, which can be difficult even with spectroscopy. The XBoötes survey is deep enough to detect starbursts at modest redshifts ($z \sim 0.04$ – 0.12), so it is not unreasonable to expect a population of starbursts in the survey. Starbursts, like type II AGNs, tend to have hard X-ray spectra (Ptak et al. 1997). Since the median hardness ratio in region D is harder than that of the median source in region A, we expect that region D contains a greater mix of type II AGNs and starbursts, but with a significant fraction of type I AGNs, as evidenced by the presence of sources with soft X-ray hardness ratios. These are presumably lower luminosity type I AGNs with weak nuclear IR emission that is not dominating the mid-IR colors and pushing them toward region A.

Finally, region E, the clump containing 4% of the sources near Vega colors of zero, is dominated by X-ray-emitting Galactic stars and $z \sim 0$ galaxies. Visual inspection of the NDFWS optical data shows that ~20% are large, extended, early-type galaxies whose X-ray emission is likely from hot X-ray-emitting gas rather than an AGN. These sources have softer spectra as compared to all the other regions with a median (average) HR $= -0.81 \pm 0.51$ ($-0.57 \pm 0.57$). The above statistics are summarized in Table 2.

3.1. A Smaller but Deeper Look: The LALA Survey

A further check of these results comes from the single 17' × 17' Chandra ACIS field obtained by the Large Area Lyman Alpha Survey (LALA; Rhoads et al. 2000) with an exposure time of 172 ks (Wang et al. 2004). These data reach a hard X-ray (2–10 keV) detection limit of $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, far deeper than the XBoötes survey limit of $1.5 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$. We used a simple proximity match with a 2.0″ matching radius for the 168 cataloged sources since the median X-ray positional uncertainty is only 0″.6. Of the 168 sources in the catalog, 130 (77%) have (5 σ) 3.6 μm counterparts within a 2.0″ radius. If we allow for visual matches to 3.6 μm sources fainter than the 5 σ catalog limit, then we find 145 (86%) counterparts. This is a similar statistic to that found by Barmby et al. (2006) from deep IRAC and Chandra imaging of a ~20′ × 20′ region of the Extended Groth Strip which found IRAC counterparts for 91% of Chandra sources. The high rate of recovery of the 172 ks X-ray sources in the 90 s IRAC Shallow Survey shows that the ~1% of the 5 ks sources that lack IRAC counterparts are not due simply to the fact that the IR survey is too shallow, but that the missing sources have some unusual X-Ray/IR characteristics.

In the LALA region, the XBoötes catalog has only 22 sources, of which 21 (95%) have 3.6 μm counterparts. The XBoötes sources in the LALA region are typical of the field as a whole, with 64% (9 of 14) of the four-band-detected sources satisfying the Stern et al. (2005) AGN selection criterion (region A).

Of the 35 sources in the deeper LALA image that are detected in all four channels, 17 (49%) satisfy the Stern et al. (2005) AGN selection criterion and lie in region A. The majority of the rest, 13 (37%), lie in region C.

With such small numbers it is difficult to make a comparison between the deep and shallow XBoötes source fractions, but the greater percentage of sources in region C in the deeper survey may indicate a trend toward a larger fraction of obscured AGNs at fainter X-ray fluxes.

4. SUMMARY AND CONCLUSIONS

In this paper we examine the mid-infrared properties of 3086 X-ray sources in the Chandra XBoötes Survey (Kenter et al. 2005) that were detected by the IRAC Shallow Survey (Eisenhardt et al. 2004)—the largest comparison of X-ray and mid-infrared sources yet undertaken. Despite an integration time of only 90 s, the IRAC Shallow Survey detects 85% of the X-ray sources, with another 13% being detectable at lower confidence levels than the 5 σ detection limit of the primary Shallow Survey catalogs. Only 2.5% of the X-ray sources, up to 40% of which may represent false-positives in the X-ray catalogs, lack a counterpart. Even in the small-area but deeper LALA X-ray survey, based on an X-ray exposure time of 172 ks rather than 5 ks, most of the X-ray sources are easily detected (77% are in the 5 σ catalogs and 86% are detected at deeper thresholds).

The mid-infrared colors of the X-ray sources show five relatively distinct classes. By far the largest class of sources (65%)...
satisfy the simple color-selection criteria developed by Stern et al. (2005) to select AGNs in the mid-infrared (region A). Most of the remaining sources lie in an extension of this region where redshifted emission lines and/or host galaxy contributions to the SED provide for bluer \([3.6] \rightarrow [4.5]\) colors (regions B and C). Sources with red \([5.8] \rightarrow [8.0]\) colors and blue \([3.6] \rightarrow [4.5]\) colors are likely dominated by obscured AGNs, lower luminosity unobscured AGNs, and starburst galaxies (region D). Finally, small fractions of the sources are clustered near mid-IR colors of zero magnitude (region E). These sources are a combination of X-ray-emitting stars and low-redshift galaxies whose X-ray flux comes from X-ray-emitting hot gas.

This segregation in color space makes the mid-IR a very efficient wavelength range to do large area surveys for luminous IR AGNs. In comparison to the XBOötes survey, which detected \(~3000\) sources in \(630\) ks, the IRAC Shallow Survey detected \(~2000\) AGNs in \(216\) ks (\(~2000\) is the total) Stern et al. (2005) number of IRAC objects in the wedge), a factor of 2 higher in detection efficiency. The X-rays although can help provide a completeness factor for lower luminosity AGNs which lie outside the wedge. Stern et al. (2005) deduced a lower limit surface density of \(250\) AGNs deg\(^{-2}\) based on the number of sources in region A from the entire Shallow Survey data (corrected by 9% to 275 deg\(^{-2}\) based on spectroscopy of sources outside the wedge). The X-rays allow us to increase this lower limit by adding the AGNs from regions B and C, which contain an additional 25% of four-band-detected sources, raising the lower limit to 350s AGN deg\(^{-2}\).

Another approach is to directly combine the two techniques. With the exception for the stars in region E and the possible contamination of luminous starbursts in region D, 90% of the X-ray sources with four-channel IRAC detections are AGNs, accounting for \(~2700\) sources from the full X-ray catalog. Of these X-ray sources, 864 had four-channel IRAC detections placing them in region A. Of the IRAC sources, there are \(~2000\) sources in region A. Combining all the sources detected in the IR in region A with all the X-ray sources which are AGNs (making sure not to double count the 864 IR-detected X-ray sources in region A), gives a total of \(~4000\) AGNs for a surface density of \(460\) AGNs deg\(^{-2}\). Thus, using either approach can help place better limits on the contribution of AGNs to the CIB.

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