CHANDRA STACKING CONSTRAINTS ON THE CONTRIBUTION OF 24 μm SPITZER SOURCES TO THE UNRESOLVED COSMIC X-RAY BACKGROUND

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Abstract

We employ X-ray stacking techniques to examine the contribution from X-ray-undetected, mid-infrared-selected sources to the unresolved, hard (6–8 keV) cosmic X-ray background (CXB). We use the publicly available, 24 μm Spitzer Space Telescope MIPS catalogs from the Great Observatories Origins Deep Survey (GOODS)–North and South fields, which are centered on the 2 Ms Chandra Deep Field–North and 1 Ms Chandra Deep Field–South, to identify bright (S_{24 μm} > 80 μJy) mid-infrared sources that may be powered by heavily obscured AGNs. We measure a significant stacked X-ray signal in all of the X-ray bands examined, including, for the first time, a significant (3.2 σ) 6–8 keV stacked X-ray signal from an individually undetected X-ray source population. We find that the X-ray-undetected MIPS sources make up ≳2% (or less) of the total CXB below 6 keV, but ≳6% in the 6–8 keV band. The 0.5–8 keV stacked spectrum is consistent with a hard power law (Γ = 1.44 ± 0.07), with the spectrum hardening at higher X-ray energies. Our findings show that these bright MIPS sources do contain obscured AGNs, but are not the primary source of the unresolved ~40% of 6–8 keV CXB. Our study rules out obscured, luminous quasars as a significant source of the remaining unresolved CXB and suggests that it most likely arises from a large population of obscured, high-redshift (z ≳ 1), Seyfert-luminosity AGNs.

Subject headings: galaxies: active — X-rays: diffuse background

1. INTRODUCTION

Deep “blank sky” surveys with the Chandra X-ray Observatory (hereafter Chandra) have resolved ~50%–90% of the hard (2–8 keV) cosmic X-ray background (CXB) into discrete sources (e.g., Bauer et al. 2004; Hickox & Markevitch 2006), with the resolved fraction decreasing with increasing X-ray energy (Worsley et al. 2004, 2005). Subsequent spectroscopic observations have revealed that the majority of the sources are active galactic nuclei (AGNs; e.g., Barger et al. 2003). This is consistent with CXB synthesis models, which rely on the assumptions of the “unified” AGN model (see Antonucci 1993 for a review), that predict the observed power-law (Γ ≈ 1.4) shape of the CXB is created by the integrated X-ray emission from both soft (Γ ≈ 1.8), unobscured and harder (Γ ≲ 1.4), obscured1 AGNs (e.g., Gilli et al. 2007).

Although deep X-ray surveys find the highest sky density of AGNs to date (~7000 deg^{-2}; Bauer et al. 2004), the decreasing resolved fraction of the CXB with energy suggests that there exists an additional, highly obscured AGN population that is missed in even the deepest X-ray surveys (Worsley et al. 2005). While the majority of the X-ray emission from these sources is attenuated, a small fraction of hard X-ray photons can penetrate the obscuring torus. In addition, hard (rest frame ≥5–10 keV) X-ray emission can be scattered into the observer’s line of sight via Compton reflection. The fraction of hard X-ray photons emitted from a heavily obscured source would likely be too small to identify the source individually, but the hard X-ray emission from many of these undetected, Compton-thick sources could comprise the unresolved CXB.

Since the absorbed energy in obscured AGNs is reemitted in the mid- and far-infrared, obscured AGNs should be bright Spitzer sources. The dust reprocessing of AGN accretion energy heats the dust to higher temperatures than can be achieved via stellar processes, and this emission is relatively isotropic (e.g., Lutz et al. 2004) and invariant to line-of-sight column density (e.g., Silva et al. 2004). The strong rest-frame 3–8 μm thermal continuum produced by the AGN-heated dust can be used to separate luminous AGNs from starbursts using infrared color-color selection (e.g., Lacy et al. 2004; Stern et al. 2005) and infrared power-law selection (e.g., Donley et al. 2007). Once candidate AGNs have been identified, X-ray stacking analyses can be used to measure their average X-ray properties and determine their contribution to the CXB below the detection limit of individual X-ray sources.

In this Letter, we use X-ray stacking techniques to examine the contribution of MIPS-detected GOODS sources to the unresolved component of the CXB. In § 2 we describe the X-ray and infrared data used in this study. Our analyses are presented in § 3. Our discussion and conclusions are in § 4. We use the cosmological parameters H_0 = 70 km s^{-1} Mpc^{-1}, Ω_m = 0.3, and Ω_Λ = 0.7.

2. SAMPLE

The 2 Ms Chandra Deep Field–North and 1 Ms Chandra Deep Field–South are currently the deepest 0.5–8 keV surveys (Giacconi et al. 2002; Alexander et al. 2003). The high angular resolution of Chandra (~0.5") at the aim point) and the low background make these images ideal for examining the resolved fraction of the CXB. We use the X-ray catalogs of Alexander et al. (2003) for both the CDF-N and CDF-S, which contain 503 and 326 X-ray sources, respectively, detected using wavdetect at a significance threshold of 10^{-7}. We also consider the supplementary X-ray source catalogs for both fields, which add an additional 79 (42) sources to the CDF-N (CDF-S); these sources are detected with a looser threshold (10^{-5}), but because they are coincident with optically bright (R < 23) sources, the vast majority (>90%) are likely real.

To identify obscured AGN candidates, we use Spitzer data
from the Great Observatories Origins Deep Survey (GOODS; Dickinson et al. 2005). The GOODS infrared catalogs consist of observations in the four IRAC bands (3.6, 4.5, 5.8, and 8.0 μm; Fazio et al. 2004) and one MIPS band (24 μm; Rieke et al. 2004). The contribution to the CXB from the IRAC-selected sources will be presented in a subsequent paper (A. T. Steffen et al. 2007, in preparation). In this Letter we measure the contribution of the MIPS sources to the CXB.

The GOODS MIPS observations are publicly available5 as part of GOODS data releases DR1 (GOODS-North) and DR3 (GOODS-South). The GOODS-North and GOODS-South MIPS-selected catalogs contain 1199 and 948 sources, respectively, extending down to a 24 μm flux limit of ∼80 μJy. We cross-correlated the MIPS source positions with the aforementioned X-ray catalogs using a 3′′ matching radius. We found 253 (156) CDF-N (CDF-S) MIPS sources matched to an X-ray counterpart (with an expectation of ∼20 spurious matches). In Figure 1 we present histograms showing the distributions of 24 μm fluxes for all MIPS-selected GOODS sources (open histogram) and for the MIPS sources with X-ray counterparts (hatched histogram). It is apparent that while the number of MIPS sources increases at fainter fluxes, the number of sources with X-ray counterparts increases slowly, so the fraction of MIPS sources with a detected X-ray counterpart decreases as one examines fainter 24 μm MIPS sources. This is consistent with the idea that luminous AGNs power the brightest 24 μm sources, while the fainter sources can be powered by the more common dusty starbursts.

3. ANALYSIS

We used X-ray stacking techniques to examine the contribution of MIPS-selected AGN candidates to the unresolved CXB. We calculated the total number of photons within a 3′′ diameter circular aperture, correcting for the fractional contribution from pixels only partially covered by the aperture. The local background is measured by extracting the total number of photons within a 3′′ matching radius. We found 253 (156) CDF-N (CDF-S) MIPS sources matched to an X-ray counterpart (with an expectation of ∼20 spurious matches). In Figure 1 we present histograms showing the distributions of 24 μm fluxes for all MIPS-selected GOODS sources (open histogram) and for the MIPS sources with X-ray counterparts (hatched histogram). It is apparent that while the number of MIPS sources increases at fainter fluxes, the number of sources with X-ray counterparts increases slowly, so the fraction of MIPS sources with a detected X-ray counterpart decreases as one examines fainter 24 μm MIPS sources. This is consistent with the idea that luminous AGNs power the brightest 24 μm sources, while the fainter sources can be powered by the more common dusty starbursts.

To calculate the total X-ray flux for all of the stacked sources, the total background-subtracted source counts (in photons) was divided by the sum of the mean exposure-map value within each extraction aperture (in cm² s) to obtain the total photon flux for the stacked sources. This value was divided by the mean encircled-energy fraction, weighted by the mean exposure-map value for each source, and converted to energy flux by assuming a power-law spectrum with Γ = 1.4 and correcting for Galactic absorption using the X-ray opacity table of Morrison & McCammon (1983) and the exposure-weighted mean Galactic column density (N_H = 1.16 × 10²² cm⁻²).

In Table 1 we show the stacking results for the 638 MIPS sources that lay within 6′ of the exposure-weighted mean aim points of the CDF-N or the CDF-S, and were outside 2 times the radius of the 90% encircled-energy fraction of known X-ray sources to avoid contamination. The X-ray stacking was performed in the full (0.5–8.0 keV), soft (0.5–2 keV), and hard (2–8 keV) bands, as well as in five narrower, non-overlapping X-ray bands. From Table 1, the X-ray-undetected MIPS source population makes up about 2% of the total CXB intensity below 6 keV. The resolved fraction of the CXB increases to ∼6% for the hardest X-ray energy band analyzed here. This is the first time that a statistically significant, stacked 6–8 keV signal has been found for an X-ray-undetected population of sources. X-ray stacking analyses were used to measure the contribution of the optical GOODS sources to the CXB, but no significant 6–8 keV signal was found (Worsley et al. 2006).

The spectrum of the stacked X-ray sources, shown in Figure 2, is best fit with a power-law photon index of Γ = 1.44 ± 0.07, consistent with the slope of the CXB (Hickox & Markevitch 2006). However, it is clear that the flux within the hardest energy bin (6–8 keV) deviates from the best-fit power law. This suggests that the flux from obscured AGNs dominates the stacked spectrum at high X-ray energies. To verify the authenticity of the 3.2 σ detection in the 6–8 keV energy band, we extracted thumbnail X-ray images centered on each X-ray-undetected MIPS source and co-added them. In Figure 2 we show the resulting 15″ × 15″ stacked X-ray thumbnail for the 6–8 keV band with our 3′′ diameter aperture overlaid (black circle). It is clear from this smoothed image that there is a significant stacked X-ray signal within our extraction aperture (p = 6.9 × 10⁻⁴, assuming a one-tailed Gaussian distribution).

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5 Available at http://ssc.spitzer.caltech.edu/legacy/goodshistory.html.

6 Available at http://cxc.harvard.edu/cal/Hrma/pix/ECF/hrmaD1996-12-20hrci_ecf_N0002.fits.
While we detect a significant 6–8 keV X-ray signal for the stacked, X-ray-undetected MIPS population, we do not know how this low-level X-ray flux is distributed among the sources. To examine the importance of infrared flux on our X-ray stacking analysis, we break down our earlier stacking results by performing stacking as a function of limiting 24 μm flux. In Figure 3 we show the resolved fraction of the CXB, the signal-to-noise ratio (S/N), and the number of sources stacked as a function of limiting 24 μm flux. Overall, it appears that the S/N of our stacked X-ray signal does gradually increase as we include the X-ray flux from fainter MIPS sources, which suggests that the stacked X-ray signal is not dominated by a small number of bright 24 μm sources.

4. DISCUSSION AND CONCLUSIONS

We present in this Letter results from an X-ray stacking analysis of the X-ray-undetected 24 μm Spitzer MIPS sources using the GOODS catalogs and the Chandra Deep Fields. We find, for the first time, a significant stacked X-ray signal (3.2 σ) in the 6–8 keV band for an X-ray-undetected, AGN-candidate sample, suggesting that at least some of these sources harbor heavily obscured AGNs. Approximately 15% of the unresolved fraction (≈40%; Worsley et al. 2005) of the 6–8 keV CXB can be attributed to these sources. The stacked 0.5–8 keV spectrum has a power-law photon index of $\Gamma = 1.44 \pm 0.07$, consistent with the slope of the CXB (Hickox & Markevitch 2006). The slope of the stacked X-ray spectrum hardens with increasing X-ray energy, suggesting that the flux from obscured AGNs dominates the stacked spectrum at high X-ray energies.

We found evidence that there exist mid-IR-bright, heavily obscured AGNs that are not individually detected in the X-ray band, but we know little about the general properties of these sources. By examining how the X-ray to 24 μm flux relation for AGNs evolves with redshift, we can infer the AGN types

| Energy Band (keV) | Total Counts (counts) | Mean Background a (counts) | Exposure Map (Mean) (cm² s) | Encircled Energy Fraction b (deg²) | Area c (deg²) | Total Intensity (ergs cm⁻² s⁻¹ deg⁻²) | Percent of CXB a (σ) |
|-------------------|-----------------------|---------------------------|-----------------------------|-----------------------------------|---------------|-----------------------------------------|----------------------|
| 0.5–1.0 .......... | 1202.3 ± 34.7         | 679.2 ± 2.4               | 2.50 ± 10³                  | 0.624                             | 5.950 × 10⁻² | (0.60 ± 0.04) × 10⁻¹                  | 1.99 ± 0.13          |
| 1.0–2.0 .......... | 1702.4 ± 41.3         | 750.5 ± 2.5               | 6.94 ± 10³                  | 0.610                             | 5.920 × 10⁻² | (0.65 ± 0.04) × 10⁻¹                  | 1.86 ± 0.09          |
| 2.0–4.0 .......... | 1491.7 ± 38.6         | 1088.5 ± 3.0              | 4.10 ± 10³                  | 0.578                             | 5.826 × 10⁻² | (1.36 ± 0.13) × 10⁻¹                  | 1.96 ± 0.19          |
| 4.0–6.0 .......... | 1089.6 ± 33.0         | 927.8 ± 2.8               | 4.32 ± 10³                  | 0.544                             | 5.588 × 10⁻² | (0.97 ± 0.20) × 10⁻¹                  | 1.73 ± 0.36          |
| 6.0–8.0 .......... | 1371.0 ± 37.0         | 1252.3 ± 3.2              | 1.69 × 10³                  | 0.504                             | 5.463 × 10⁻² | (2.83 ± 0.89) × 10⁻¹                  | 5.79 ± 1.82          |

TABLE 1

Results of X-Ray Stacking Analysis of MIPS Sources

The small error bars are due to the much larger area used to calculate the background flux, relative to the size of the extraction aperture.

This is the mean encircled-energy fraction weighted by the exposure map values of the sources.

This is the total area within 6' of the CDF-N and CDF-S aim points, corrected for the masked areas.

Assuming the CXB normalization of Hickox & Markevitch (2006).

Fig. 2.—Stacked X-ray spectrum for the 638 MIPS-selected AGN candidates. The best-fit power-law spectrum is shown (solid line). Inset: Stacked, adaptively smoothed, 6–8 keV X-ray thumbnail. The 3' diameter photometric aperture is shown.

Fig. 3.—Total resolved 6–8 keV CXB fraction, the signal-to-noise ratio of the stacked X-ray signal, and the total number of stacked sources as a function of 24 μm flux assuming the CXB normalization of Hickox & Markevitch (2006). Error bars (1 σ) are shown for stacked sources that have S/N > 3, and 3 σ upper limits are given for the stacked sources that are not significantly detected.
that are detected in this mid-IR catalog. In Figure 4 we examine the evolution of the X-ray to 24 μm flux relation for obscured AGNs using the observed SEDs of three obscured AGNs spanning a large luminosity range: the luminous, type 2 quasar CXO-52 (distant Compton-thin, obscured quasar; \( L_{2-10\text{ keV}} = 3.3 \times 10^{44} \, \text{ergs s}^{-1}, \) intrinsic; Stern et al. 2002), NGC 1068 (extreme Compton-thick, luminous AGN; \( L_{2-10\text{ keV}} \sim 10^{46} - 10^{44} \, \text{ergs s}^{-1}, \) intrinsic; Cappi et al. 2006), and the Circinus galaxy (Compton-thick, moderate-luminosity AGN; \( L_{2-10\text{ keV}} \sim 10^{44} \, \text{ergs s}^{-1}, \) intrinsic; Matt et al. 1999). This is similar to Figure 1 of Martínez-Sansigre et al. (2006), except here we utilize the observed SEDs of known obscured AGNs instead of using theoretical models. The rest-frame X-ray and IR fluxes were calculated by interpolating the SEDs provided by Stern et al. (2002) for CXO-52, and the NASA/IPAC Extragalactic Database (NED) for NGC 1068 and the Circinus galaxy.

From Figure 4 it is apparent that a luminous, significantly obscured AGN, such as CXO-52, would be detected in both the GOODS MIPS catalog and the deep X-ray surveys, even at \( z > 5 \), and thus would not contribute to the unresolved portion of the CXB. Compton-thick analogs of CXO-52 would have comparable 24 μm fluxes (e.g., Silva et al. 2004), but their X-ray fluxes would decrease with increasing column density, moving them into the shaded region of Figure 4. Given the small fraction of the CXB that we resolve at 6–8 keV using the mid-IR-bright AGN, the unresolved CXB at these energies cannot be attributed to a population of luminous, heavily obscured, “type 2” quasars at any redshift. In addition, it is apparent that heavily obscured, low-luminosity Seyfert 2s without significant star formation can be detected in the MIPS band at \( z < 0.8 \), but fall below the GOODS detection threshold at higher redshifts. This suggests that the unresolved 6–8 keV CXB is not emanating primarily from a population of low-luminosity, low-redshift AGNs but could be from a population of low-luminosity, \( z > 0.8 \) AGNs. At these low 24 μm fluxes it is difficult to separate AGNs from dusty starburst galaxies, which makes stacking analyses problematic due to the increased background signal in the 6–8 keV band from obscured starbursts.

The average 0.5–2 keV flux for our MIPS-selected AGNs is \( S_{0.5-2\text{ keV}} = 5.4 \times 10^{-18} \, \text{ergs cm}^{-2} \, \text{s}^{-1} \), a factor of \(~4.6\) lower than the flux limit of the 2 Ms CDF-N (Alexander et al. 2003). Deeper X-ray observations will help to increase significantly the S/N of the stacked X-ray signal and will greatly improve our measurements of the 6–8 keV CXB from these sources.

We plan to address additional infrared AGN selection techniques in a subsequent paper (A. T. Steffen et al. 2007, in preparation).

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Facilities: CXO(ACIS), Spitzer(MIPS)

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![Fig. 4.—Redshift evolution of the observed-frame 2–10 keV flux and 24 μm flux density for three obscured AGNs, CXO-52 (Stern et al. 2002; dashed curve), NGC 1068 (solid curve), and the Circinus galaxy (dotted curve). The two dotted horizontal lines and one dotted vertical line denote the average flux limits for the 2 Ms CDF-N, 1 Ms CDF-S, and GOODS MIPS catalogs, respectively. The shaded region includes the objects in our X-ray stack that contribute 6% to the 6–8 keV CXB; the remainder of the hard CXB must arise from sources in the lower left region. The arrows denote the approximate directions a source will travel with increasing column density or decreasing luminosity (assuming a constant X-ray/IR flux ratio for the latter.)](image-url)