Testing the connection between the X-ray and submillimetre source populations using *Chandra*

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**ABSTRACT**

The powerful combination of the *Chandra* X-ray telescope, the SCUBA submillimetre-wave camera and the gravitational lensing effect of the massive galaxy clusters A 2390 and A 1835 has been used to place stringent X-ray flux limits on six faint submillimetre SCUBA sources and deep submillimetre limits on three *Chandra* sources which lie in fields common to both instruments. One further source is marginally detected in both the X-ray and submillimetre bands. For all the SCUBA sources our results are consistent with starburst-dominated emission. For two objects, including SMMJ 14011+0252 at $z = 2.55$, the constraints are strong enough that they can only host powerful active galactic nuclei if they are both Compton-thick and any scattered X-ray flux is weak or itself absorbed. The lensing amplification for the sources is in the range 1.5–7, assuming that they lie at $z > 1$. The brightest detected X-ray source has a faint extended optical counterpart ($I \approx 22$) with colours consistent with a galaxy at $z \approx 1$. The X-ray spectrum of this galaxy is hard, implying strong intrinsic absorption with a column density of about $10^{23} \text{ cm}^{-2}$ and an intrinsic (unabsorbed) 2–10 keV luminosity of $3 \times 10^{44} \text{ erg s}^{-1}$. This source is therefore a Type-II quasar. The weakest detected X-ray sources are not detected in *HST* images down to $I \approx 26$.

**Key words:** galaxies:active – quasars:general – galaxies:Seyfert – galaxies:formation – galaxies:starburst – infrared:galaxies – X-rays:general

1 INTRODUCTION

The spectrum of the X-ray Background (XRB) over the 1–7 keV band is a power-law of energy index 0.4 (Gendreau et al. 1995) which is flatter than that of any known class of extragalactic source. Following the original suggestion of Setti & Woltjer (1989), it is commonly assumed that this is due to the XRB being dominated by many absorbed sources. These sources, with different absorbing column densities and redshifts, combine to give the observed XRB spectrum (Madu, Ghisellini & Fabian 1994; Matt & Fabian 1994; Comastri et al. 1995; Wilman & Fabian 1999). The absorbed energy is presumably reradiated in the Far InfraRed (FIR) band, as observed in nearby heavily absorbed Active Galactic Nuclei (AGN) like that in the luminous IRAS galaxy NGC 6240 (Vignati et al. 1999). The residual harder X-ray emission which penetrates the absorbing medium, and the tail of the reradiated emission in the submillimetre band from such an source both exhibit a negative K-correction. This means that obscured AGN should be detectable to large redshifts in both bands.

Observations of the XRB with *Chandra* show that much (more than 80 per cent) of it is resolved into point sources in the 2–8 keV band (Brandt et al. 2000; Mushotzky et al. 2000). More than half the intensity is due to a combination of hard sources identified with either otherwise normal bright galaxies or in optically faint or even invisible galaxies. Deep 850-µm submillimetre observations with SCUBA show that much (more than 80 per cent) of the submillimetre background seen by *COBE*-FIRAS (Fixsen et al. 1998) at this wavelength is resolved into discrete sources (Blain et al. 1999).

A key question is what fraction of the deep X-ray and submillimetre source populations are related. The far-infrared and submillimetre background represents a significant part of the energy output of objects in the Universe. If the contribution of starbursts and AGN to the background can be separated using deep X-ray images, then the relative importance of high-mass star formation and AGN in heating the dust responsible for this emission can be determined. Recent modelling suggests that the AGN fraction in the submillimetre background is about 20 per cent (Almaini, Lawrence & Boyle 1999; Fabian & Iwasawa 1999; Gunn & Shanks 1999).
The uncertainty is such that AGN may contribute in total between 10–50 per cent of the total energy output of stars (Fabian et al. 1999). Small et al. (1997, 1998) have used the SCUBA instrument at the JCMT (Holland et al. 1999) to study the submillimetre sources in seven massive clusters of galaxies at redshifts between 0.2 and 0.4, exploiting the gravitational lensing magnification from the clusters to make an exceptionally deep 850-μm survey for background sources. Chandra images of two of the clusters, A2390 and A 1835, have recently been obtained which, owing to the superb angular resolution, probe much deeper than any previous X-ray images of these regions, for example the ROSAT-HRI limit of $8 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ to the 0.1–2.0 keV X-ray flux of the SCUBA source SMMJ14011+0252 in A 1835 (Ivison et al. 2000). Here we study the Chandra X-ray limits to the flux of the SCUBA sources and conversely SCUBA limits on the Chandra sources found in the images. Only one source is marginally detected in both wavebands. We then discuss the implications for obscured AGN models.

2 OBSERVATIONS AND RESULTS

Chandra observed A 2390 on 1999 November 5 for a livetime of 9,126 s and A 1835 on 1999 December 11 for a total of 19,626 s. For each observation the cluster lies close to the aimpoint of the telescope on the ACIS-S back-illuminated CCD chip. Only mild temporal variations in count rate are seen through the observations so we use the whole exposure in this work. A 7-arcsec pointing offset evident in the A 1835 field from the position of the cluster X-ray peak and several other source identified in the field has been removed. We estimate that the source positions from the Chandra images are accurate to 1″ rms.

The analysis of the cluster emission will be presented elsewhere; here we restrict ourselves to the positions of the SCUBA sources and of three X-ray sources in the Chandra fields which lie within the SCUBA field (i.e. within 1.5 arcmin of the cluster centre; Table 1). A further possible (2.8σ) X-ray source in the A 2390 field is also discussed since it is spatially coincident with a tentative (2σ) SCUBA source. No point-like X-ray sources are seen in the SCUBA region of the Chandra field of A 1835.

The X-ray data were analysed using images in the 0.5–2 keV and 2–7 keV bands with one-arcsec pixels. The sources detected in the SCUBA field of A 2390 appear principally in just 4 neighbouring Chandra pixels (a few counts from the brightest sources occupy 2 further pixels). We therefore adopt a region of 4 sq. arcsec when estimating source fluxes and limits. The cluster emission means that the background is not flat, and so the background has been determined by averaging the 8 neighbouring pixels in images formed with 10 by 10 arcsec pixels, excluding the source pixel. Upper limits in the X-ray band have been obtained by using the Bayesian method of Kraft, Burrows & Nousek (1990) and are quoted at the 99 per cent confidence level (Table 2). We assume Galactic columns at A 2390 and A 1835.

The submillimetre, radio and optical imaging of A 1835 used here is discussed in detail in Ivison et al. (2000), while the submillimetre observations of A 2390 are detailed in Small et al. (1998; a new sources is reported here), the VLA 1.4-GHz radio map in Edge et al. (1999) and the optical imaging of this cluster with Hubble Space Telescope (HST) is described in Pelló et al. (1999). In addition, there is deep 6.7 μm and 15-μm ISO imaging of A 2390 (Altieri et al. 1999; Lemonon et al. 1999), which is sensitive to hot dust emission from background galaxies out to $z \sim 1$.

In Fig. 1 we show overlays of the Chandra and SCUBA images on optical images of A 1835 and A 2390. We note that the brightest Chandra source, CXOUJ215334.0+174240, is associated with a relatively large (4″ total extent) mid-type spiral with a blue nucleus and a faint companion. This galaxy has a colour and apparent magnitude similar to those expected for a slightly reddened $L^*$ mid-type spiral at $z = 0.85 \pm 0.15$. While the next brightest X-ray source, CXOUJ215334.2+174209 has a more amorphous counterpart, with a bright compact nucleus and an asymmetric envelope and has a much bluer colour, its redshift is not strongly constrained by the current data. Counterparts to the remaining two Chandra sources are not seen in the optical imaging (although there is a very faint object in the vicinity of CXOUJ215334.4+174205); if they are background galaxies then, after correction for lensing amplification, they must be fainter than $I \sim 27$. CXOUJ215334.0+174240 is the only one of the four Chandra sources detected at 1.4 GHz with the VLA, at a flux density of 2.6 ± 0.1 mJy, the 3-σ limits on the remainder being < 0.2 mJy.

For the two X-ray sources which are detected in both X-ray bands we have determined an X-ray spectral index, $\alpha_{SX}$, from the flux ratios. These are both unphysically negative ($-0.8$ and $-0.3$; we define all spectral indices according to $F \propto \nu^{-\alpha}$) and thus indicate intrinsic absorption. The brightest source, CXOUJ215334.0+174240, has ~ 90 counts, which enables a crude spectral analysis to be performed. A straight power-law spectrum with Galactic absorption is a poor fit and yields an energy index of $-0.3$. Including additional soft X-ray absorption allows a better fit, although with no firm constraints on the index. The absorption however must exceed $N = 6 \times 10^{21}$ cm$^{-2}$ at the 90 per cent confidence level. Note that the intrinsic absorption will be approximately $(1+z)^3N$, where $z$ is the redshift of the source. For an assumed energy index of 1, typical of quasars, and the redshift indicated by the optical colours, we find $N = (6 \pm 2) - (9 \pm 3) \times 10^{22}$ cm$^{-2}$, and an unabsorbed intrinsic $2–10$ keV luminosity of $2.7–6.8 \times 10^{44}$ erg s$^{-1}$, for $z = 0.7–1$, respectively. After correction for the lensing amplification factor of about 2, the source has an intrinsic $L(2–10$ keV) $\approx 2–3 \times 10^{44}$ erg s$^{-1}$. This makes it a strong contender to be one of the first genuine Type-II quasars (see discussions in Halpern et al. 1999; Vignati et al. 1999; Franceschini et al 1999).

The X-ray limits on the SCUBA sources in the A 1835 field are about 100 times deeper than previously achieved using ROSAT data (Ivison et al. 2000). We have produced two submillimetre-to-X-ray spectral indices, $\alpha_{SX}$, using the measured values at 850 μm and 2 keV in our rest frame. Rather than obtain one X-ray estimate for the spectral flux at 2 keV from a whole band measurement, which would be biased by the most sensitive lower energy end of the band, we have estimated it by converting the observed counts to fluxes in the 0.5–2 and 2–7 keV bands (listed in Table 2), using the response matrix of the ACIS-S chip and assuming an intrinsic energy index of 1 (which is roughly appropriate for the scattered flux from an absorbed AGN).

3 DISCUSSION

We compare expected values of $\alpha_{SX}$ as a function of redshift in Fig. 2 for various classes of observed objects, both starbursts and AGN. We select 3C 273 as an example of a powerful quasar, and use the submillimetre data of Neugebauer, Soifer & Miley (1985) in our model, Arp 220 as a starburst using the submillimetre data of Sanders et al. (1999) and the X-ray data of Iwasawa (1999);
Figure 1. Optical, X-ray and submm views of the ten Chandra and SCUBA sources lying within the SCUBA maps of A 2390 and A 1835. For each source we show two panels, in the left-hand panel we overlay the Chandra image on the optical images of the field, the right-hand panel shows the equivalent view with the SCUBA map overlayed. The optical image for A 1835 is the ground-based I-band exposure from Ivison et al. (2000), while for A 2390 we have combined the HST WFPC2 F555W and F814W images (Pello et al. 1999) and rebinned these to the scale of the A 1835 I-band image to enhance the visibility of faint extended features. Each panel is 10 arcsec square, with north top and east left. The Chandra images have been convolved with a 0.8″-FWHM gaussian for display purposes.

and NGC 6240 as a powerful obscured (Compton-thick) AGN using an estimate of the submillimetre spectrum based on that from Arp 220 normalised by the FIR luminosity and the BeppoSAX spectrum from Vignati et al. (1999). We also show how $\alpha_{\text{SX}}$ changes as the absorption in NGC 6240 decreases from the measured value of $2 \times 10^{24}$ to $5 \times 10^{23}$ cm$^{-2}$ and also if the scattered fraction drops to 1 per cent. Data from several quasars at $z > 4$ are shown for comparison with the 3C 273 prediction.

The typical limits on $\alpha_{\text{SX}}$ for the SCUBA galaxies are $\alpha_{\text{SX}} \lesssim 1.2$ (at 99 per cent confidence). Combining the limits for the 6 galaxies we obtain a 99 per cent confidence limit on a typical SCUBA galaxy of $\alpha_{\text{SX}} > 1.34$, with the strongest constraints for individual galaxies being $\alpha_{\text{SX}} > 1.32$ for SMMJ 14011+0252.
Table 1. Positions of the Chandra (prefixed CXOU) and SCUBA sources (prefixed SMM) discussed here. We list the 1″-diameter photometry of the Chandra sources from the HST F555W and F814W frames and for all sources the gravitational lensing amplification obtained by modelling the mass distribution of the clusters (see Blain et al. 1999 for details; * indicates no solution at that redshift). Known spectroscopic redshifts are put in the left column and the amplification at that redshift in the right.

| Source Name | R.A. (J2000) | Dec | $V_{555}$ | $I_{814}$ | Amplification | $z$ |
|-------------|-------------|-----|-----------|-----------|--------------|-----|
| CXOUJ21534.0+174240 | 21 53 34.0 | 17 42 40 | 25.6 ± 0.1 | 22.6 ± 0.0 | $z = 1$ | 1.9 |
| CXOUJ21533.2+174209 | 21 52 33.2 | 17 42 09 | 25.7 ± 0.1 | 24.2 ± 0.1 | 3.9 | 6.9 |
| CXOUJ21533.8+174113 | 21 53 33.76 | 17 41 13 | > 26.2 | > 24.5 | 7.0 | * |
| CXOUJ21534.4+174205 | 21 53 34.4 | 17 42 05 | > 26.9 | > 26.2 | 1.7 | 1.9 |
| SMMJ 21536+1742 | 21 53 38.5 | 17 42 19 | ... | ... | 2.1 | 2.6 |
| SMMJ 21535+1742 | 21 53 33.2 | 17 42 49 | ... | ... | 1.7 | 1.9 |
| SMMJ 14011+0252 | 14 01 04.96 | 02 52 23.5 | ... | ... | $z = 2.55$ | 3.0 ± 0.6 |
| SMMJ 14009+0252 | 14 00 57.55 | 02 52 48.6 | ... | ... | 1.4 | 1.5 |
| SMMJ 14010+0253 | 14 01 03.09 | 02 53 12.0 | ... | ... | $z = 2.22$ | 4.8 ± 2.8 |
| SMMJ 14010+0252 | 14 01 00.52 | 02 51 49.4 | ... | ... | 1.6 | 1.8 |

Table 2. Count rates and fluxes of the Chandra and SCUBA sources. The total Chandra background-subtracted count for each source, the background (per square arcsec), and the flux, obtained assuming an X-ray energy index of 1 are shown in two X-ray bands: 0.5–2 keV (no brackets) and 2–7 keV (brackets). The final column give the submillimetre-to-X-ray index $\alpha_{SX}$ obtained in the same bands (with the same bracket convention).

| Source Name | X-ray flux – at low (high) energy | SCUBA 850-µm Flux density (mJy) | $\alpha_{SX}$ |
|-------------|---------------------------------|--------------------------------|-------------|
| Count | Background | Flux (10$^{-15}$ erg cm$^{-2}$ s$^{-1}$) | (99% c.l.) |
| CXOUJ21533.0+174240 | 32 ± 5.8 (54.1 ± 7.3) | 0.34 (0.15) | 9.9 (90) | < 5.5 | < 1.06 (0.91) |
| CXOUJ21533.2+174209 | 19 ± 4.6 (14.3 ± 3.9) | 0.5 (0.2) | 5.9 (23) | < 5.7 | < 1.10 (1.01) |
| CXOUJ21533.8+174113 | 11.9 ± 3.6 (< 13) | 0.28 (0.13) | 3.7 (< 17) | < 5.7 | < 1.14 (1.03) |
| CXOUJ21533.4+174205 | 10.4 ± 3.7 (< 7.9) | 0.89 (0.18) | 3.2 (< 13) | 2.9 ± 2.2 | 1.12 (1.02) |
| SMMJ 21536+1742 | < 10.6 (< 4.6) | 1.1 (0.68) | < 3.2 (< 7.7) | 6.7 ± 1.2 | > 1.16 (> 1.10) |
| SMMJ 21535+1742 | < 6.0 (< 7.9) | 2.4 (0.48) | < 1.8 (< 13) | 8.3 ± 2.2 | > 1.21 (> 1.07) |
| SMMJ 14011+0252 | < 5.6 (< 5.6) | 7.3 (2.4) | < 0.78 (< 4.4) | 14.6 ± 1.8 | > 1.32 (> 1.19) |
| SMMJ 14009+0252 | < 6.0 (< 4.6) | 1.1 (0.66) | < 0.84 (< 3.6) | 15.6 ± 1.9 | > 1.32 (> 1.21) |
| SMMJ 14010+0253 | < 6.2 (< 4.6) | 7.6 (2.2) | < 0.87 (< 0.87) | 4.3 ± 1.7 | > 1.23 (> 1.12) |
| SMMJ 14010+0252 | < 6.7 (< 6.0) | 2.4 (1.0) | < 0.94 (< 4.7) | 4.2 ± 1.7 | > 1.22 (> 1.10) |

(z = 2.55) and SMMJ 14009+0252 in the A 1835 field. Thus the indices for this population are straightforwardly consistent with starbursts. They do not resemble Compton-thin AGN at any redshift and are inconsistent with the spectrum of NGC 6240 at any redshift. If these galaxies host a powerful AGN then either a) reprocessed radiation from the AGN provides only a minor fraction of the submillimetre luminosity, or b) the source must be Compton thick and in addition the fraction of any scattered X-ray emission must be less than one per cent. We note that X-ray limits on the hyperluminous IRAS galaxy F15307+3252 at $z = 0.92$, which does contain an AGN since broad scattered emission lines are seen (Hines et al. 1995), show that it must have a very low X-ray scattered fraction (< 1 per cent), possibly due to intrinsic absorption of the scattered emission (Fabian et al. 1996). If this is typical of obscured AGN more powerful than NGC 6240, then the present results would be consistent with obscured AGN provided that they are at relatively high redshift ($z > 2$).

Of the four Chandra sources we identified in our fields, two have probable optical counterparts suggesting that they are distant disk galaxies. The colours and luminosity of the brightest of these suggest it is an L$^*$ mid-type galaxy at $z \sim 1$. If the two optically-identified Chandra sources are AGN, and the host galaxies have luminosities of L$^*$ or greater, then they must be at $z > 2$, or be intrinsically reddened. Obscuration of both AGN and surrounding spheroid is required by some models for the XRB (Fabian 1999). It is possible for these dust-enshrouded strongly-obscured AGN to be undetected in our 850-µm SCUBA maps if their dust is typically much hotter than 40 K. Comparing the radio flux and SCUBA limit for the brightest Chandra galaxy CXOUJ21533.4+174240 (§2), the redshift $z$ and dust temperature $T_d$ of the source must satisfy the relationship $T_d > 27(1 + z)$ K. Taking the redshift constraint from the optical, $z \approx 0.85 \pm 0.15$, we derive $T > 50$ K. Such sources would not contribute substantially to the submillimetre background at $\sim 1$ mm, but might at shorter wavelengths. Eventual comparison with ISO imaging may shed further light on the nature of the dust emission in these sources.

In summary, Chandra and SCUBA observations have been combined to probe the relation between the faint X-ray and submillimetre sky. Only one marginal source is seen in both datasets, and so in general we find deep submillimetre limits from SCUBA on the X-ray sources found using Chandra and deep X-ray limits from Chandra on the SCUBA-selected sources. The limits on background sources in these fields are particularly strong due to amplification by gravitational lensing.

For the SCUBA galaxies, we cannot completely rule out the presence of either an obscured, weak AGN or a more powerful Compton-thick AGN in which any scattered flux is also very weak or absorbed. However, the simplest explanation of our results on the SCUBA sources is that they are predominantly powered by starbursts. Clearly the current sample is small and so we cannot make any definitive statement about the whole SCUBA population. We note that at the moment our conclusions are not inconsistent with...
Figure 2. Submillimetre to X-ray spectral index, $\alpha_{\text{SX}}$, plotted against redshift for a powerful quasar, 3C 273, an absorbed AGN, NGC 6240, and a starburst, Arp 220. The effects of decreasing the scattered fraction from NGC 6240 to 1 per cent, and of its column density to $5 \times 10^{23}$ cm$^{-2}$ are indicated by the dash-dot and dash lines. The $\ast$ symbols represent the five $z > 4$ quasars for which both X-ray and SCUBA (850 $\mu$m) data are available; monochromatic X-ray fluxes at 2 keV were calculated from the (Galactic) absorption-corrected 0.1–2.0 keV fluxes in Kaspi et al. (2000) assuming a power-law of $\Gamma = 2$; 850-$\mu$m fluxes are taken from the compilation in McMahon et al. (1999).

suggestions that AGN powering 20 per cent of the SCUBA population, although a substantially higher fraction would be difficult to accommodate.

For the Chandra sources in the A2390 field we find that they have optically faint counterparts, $I \simeq 23$–27. We identify one source as a probable Type-II obscured quasar at $z \simeq 1$. We suggest that the remaining, typically fainter sources are either more distant, $z > 2$, or intrinsically reddened. Observations of these fields in the near-infrared are urgently needed to test the nature of these sources.

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