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A *Chandra* observation of the $z = 2.285$ galaxy FSC 10214+4724: evidence for a Compton-thick quasar?

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ABSTRACT

We present a ≈20 ks *Chandra* ACIS-S observation of the strongly lensed $z = 2.285$ ultraluminous infrared galaxy FSC 10214 + 4724. Although this observation achieves the equivalent sensitivity of an up to ≈4 Ms *Chandra* exposure (when corrected for gravitational lensing), the rest-frame 1.6–26.3 keV emission from FSC 10214 + 4724 is weak ($L_X \approx 2 \times 10^{42}$ erg s^{-1} for a lensing boost of ≈100); a significant fraction of this X-ray emission appears to be due to vigorous star formation activity. If FSC 10214 + 4724 hosts a quasar, as previously suggested, then it must be obscured by Compton-thick material. We compare FSC 10214 + 4724 to high-redshift SCUBA galaxies and discuss the X-ray identification of Compton-thick AGNs at high redshift.

Key words: gravitational lensing – galaxies: active – X-rays: individual: FSC 10214+4724.

1 INTRODUCTION

The $z = 2.285$ galaxy FSC 10214+4724 was one of the most remarkable objects detected by the *IRAS* survey. Originally proposed to be the most luminous galaxy known (Rowan-Robinson et al. 1991), multiwavelength observations subsequently showed that it is lensed by an intervening $z \approx 0.9$ galaxy, boosting its intrinsic emission by a factor of $\gtrsim$10–100 (depending on the location and extent of the unlensed emission with respect to the caustic; e.g. Broadhurst & Lehar 1995; Downes, Solomon & Radford 1995; Trentham 1995; Eisenhardt et al. 1996; Evans et al. 1999). Optical and near-infrared (near-IR) spectroscopic/polarimetric observations have unambiguously shown that FSC 10214 + 4724 hosts an obscured active galactic nucleus (AGN; e.g. Elston et al. 1994; Soifer et al. 1995; Goodrich et al. 1996). Multiwavelength analyses have suggested that the AGN is powerful (e.g. Goodrich et al. 1996; Granato, Danese & Franceschini 1996; Green & Rowan-Robinson 1996), although it is generally accepted that star formation activity dominates the bolometric output (e.g. Rowan-Robinson et al. 1993; Rowan-Robinson 2000).

The lensing-corrected properties of FSC 10214+4724 are similar to those of SCUBA galaxies (e.g. Blain et al. 2002; Ivison et al. 2002; Smail et al. 2002; Chapman et al. 2003; Neri et al. 2003): it lies at $z > 1$, is optically faint with $I \approx 25$, has an 850-μm flux density of a few mJy and a 1.4-GHz flux density of ≈25 μJy, is massive (a molecular gas mass of $\approx 10^{10}$–10^{11} $M_{\odot}$), and has a bolometric luminosity of $\approx 10^{13}$ $L_{\odot}$ (e.g. Rowan-Robinson et al. 1993; Downes et al. 1995; Eisenhardt et al. 1996). SCUBA galaxies appear to be massive galaxies undergoing intense star formation activity and are likely to be the progenitors of the local $\gtrsim M_*$ early-type galaxy population (e.g. Blain et al. 2004; Chapman et al. 2004). Deep X-ray observations have shown that a large fraction (at least ≈40 per cent: Alexander et al. 2003a, 2004) of the SCUBA galaxy population is actively fuelling its black holes during this period of intense star formation, which can account for a significant fraction of the black-hole growth in massive galaxies (Alexander et al. 2004). The AGN in FSC 10214 + 4724 was identified via optical/near-IR observations, and the large lensing boost of the AGN emission provides interesting insight into AGN activity in the SCUBA galaxy population.

In this Letter we present the results from a ≈20 ks observation of FSC 10214+4724 with the *Chandra* X-ray Observatory (hereafter *Chandra*; Weisskopf et al. 2000). Due to the large lensing boost of FSC 10214 + 4724, these observations provide the equivalent sensitivity of an up to ≈4 Ms *Chandra* exposure. The Galactic column density toward FSC 10214 + 4724 is 1.2×10^{20} cm^{-2} (Stark et al. 1992). $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_M = 1/3$, and $\Omega_\Lambda = 2/3$ are adopted.

2 *CHANDRA* OBSERVATION AND ANALYSIS

FSC 10214 + 4724 was observed with *Chandra* on 2004 March 4 (observation ID 4807). The Advanced CCD Imaging Spectrometer

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(ACIS; Garmire et al. 2003) with the CCD S3 at the aim point was used for the observation (the CCDs S1–S4 and I2–I3 were also turned on);[1] the optical position of FSC 10214 + 4724 is $\alpha_{2000} = 10^{\mathrm{h}}24^{\mathrm{m}}34\overset{\mathrm{s}}{.}54$, $\delta_{2000} = +47^{\circ}09'09\overset{''}{.}8$. Faint mode was used for the event telemetry format, and the data were initially processed by the *Chandra* X-ray Center (CXC) using version 7.1.1 of the pipeline software.

The reduction and analysis of the data used *Chandra* Interactive Analysis of Observations (CIAO) Version 3.0.2 tools.[2] The CIAO tool ACIS_PROCESS_EVENTS was used to remove the standard pixel randomization. The data were then corrected for the radiation damage sustained by the CCDs during the first few months of *Chandra* operations using the charge transfer inefficiency (CTI) correction procedure of Townsley et al. (2000). All bad columns, bad pixels and cosmic ray afterglows were removed using the 'status' information in the event files, and we only used data taken during times within the CXC-generated good-time intervals. The background light-curve was analysed to search for periods of heightened background activity using the contributed CIAO tool ANALYZE_LTCRV with the data binned into 200-s intervals; there were no periods of high background (i.e. a factor of $\gtrsim$2 above the median level). The net exposure time for the observation is 21.26 ks. The *ASCA* grade 0, 2, 3, 4 and 6 events were used in all subsequent *Chandra* analyses.

2.1 Source identification

The pointing accuracy of *Chandra* is excellent (the 90 per cent uncertainty is $\approx$0.6 arcsec).[3] However, for our observation we wanted to improve the source positions to provide an unambiguous distinction between FSC 10214 + 4724 and nearby objects (e.g. the $z = 0.9$ lensing galaxy lies $\approx$1.2 arcsec from FSC 10214 + 4724; Eisenhardt et al. 1996). To achieve this we matched sources detected in the *Chandra* observation to sources found in the Sloan Digital Sky Survey (SDSS), which has a positional accuracy of $\approx$0.1 arcsec (rms; Pier et al. 2003).[4] *Chandra* source-searching was performed using WAVDETECT (Freeman et al. 2002) with a false-positive threshold of 1×10^{-5} in the full (FB; 0.5–8.0 keV), soft (SB; 0.5–2.0 keV) and hard (HB; 2–8 keV) bands; we used wavelet scale sizes of 1, 1.44, 2, 2.88, 4, 5.66 and 8 pixels. The resulting source lists were then merged with a 2-arcsec matching radius, producing a catalogue of 37 sources. The three brightest X-ray sources in this catalogue (those with >20 counts in the FB) that lay within 5 arcmin of the aim-point were matched to SDSS sources in the Data Release 2 catalogue (DR2; Abazajian et al. 2004) with a 2-arcsec search radius. The mean SDSS–*Chandra* positional offset of the matched sources (excluding FSC 10214+4724) was $-0.\ 18 \pm 0.08$ arcsec (right ascension; RA) and -0.28 ± 0.22 arcsec (declination; Dec.). These corrections were applied to the X-ray source positions.

FSC 10214+4724 is detected in all three bands (see Table 1). The X-ray source position (taken from the FB) lies 0.17 arcsec from the position measured by the *Hubble Space Telescope* (hereafter *HST*) in the F814W band (Eisenhardt et al. 1996; see Table 1 and Fig. 1); the X-ray position is also 0.38 arcsec offset from both the CO(3–2) position (Downes et al. 1995) and the 1.49-GHz radio position (Lawrence et al. 1993). The X-ray source is clearly identified with FSC 10214+4724 rather than the $z = 0.9$ lensing galaxy (see Fig. 1)

2.2 Analysis

The X-ray properties of FSC 10214+4724 are shown in Table 1. Although this observation achieves the equivalent sensitivity of an up to $\approx$4 Ms *Chandra* exposure (e.g. a 10-count source has a FB flux of $\gtrsim 4 \times 10^{-17}$ erg cm^{-2} s^{-1} for a lensing boost of $\lesssim$100; compare to table 9 in Alexander et al. 2003b), only a few X-ray counts are detected. The $\approx$10 counts in the SB correspond to a significant detection in the rest-frame 1.6–6.6 keV band while the $\approx$4 counts in the HB correspond to a weak detection in the rest-frame 6.6–26.3 keV band. The SB flux is $\approx$10 times below the 2σ *ROSAT* constraint reported in Lawrence et al. (1994) and the HB flux is $\approx$20 times below the *ASCA* upper limit reported in Iwasawa (2001). We re-examined the *ROSAT* PSPC image and could not find unambiguous evidence of X-ray emission at the location of FSC 10214+4724. From our analyses of the *ROSAT* PSPC image we determine a 3σ 0.5–2.0 keV upper limit of $< 1.3 \times 10^{-14}$ erg cm^{-2} s^{-1}. The observed (uncorrected for gravitational lensing) FB luminosity is $L_{1.6\text{–}26.3\,\mathrm{keV}} = 2.4 \times 10^{44}$ erg s^{-1}.

The band ratio (i.e. the ratio of the HB to SB count rate) of FSC 10214+4724 implies an effective photon index of $\Gamma = 1.6^{+0.7}_{-0.6}$ (see Table 1). This is generally consistent with that of an unobscured AGN (i.e. $\Gamma \approx 2.0$; e.g. Nandra & Pounds 1994; George et al. 2000); however, due to the large uncertainties and comparatively high redshift of FSC 10214+4724, this could also be consistent with a column density of $N_{\mathrm{H}} \approx 2 \times 10^{23}$ cm^{-2} at $z = 2.285$ (for an intrinsic X-ray spectral slope of $\Gamma = 2.0$). The latter would be more consistent with the obscured AGN classification of FSC 10214+4724 than the former (e.g. Elston et al. 1994; Soifer et al. 1995). See Section 3.1 for further obscuration constraints.

The gravitational lensing boost of FSC 10214+4724 is unknown in the X-ray band. Because the lensing boost is a function of the source size, basic constraints can be placed from the extent of the X-ray emission (e.g. see section 2 of Broadhurst & Lehar 1995). In Fig. 2 we show the FB profiles [south–north (S–N) and east–west (E–W) orientations] of FSC 10214+4724 and compare them to the on-axis *Chandra* ACIS-S point spread function (PSF). While this analysis is limited by small-number statistics, the extent of FSC 10214+4724 is consistent with that of an unresolved X-ray source ($\approx$1 arcsec). The half-power radius of FSC 10214+4724 (i.e. the radius over which the central seven counts are distributed; $\approx$ 0.5–0.75 arcsec) is also consistent with that of an unresolved X-ray source. Although somewhat uncertain, this suggests that the magnification in the X-ray band is $\gtrsim$25 (e.g. compare to the extent and magnification found in the 2.05-μm NICMOS observations of Evans et al. 1999). We can compare this estimate to the expected lensing boost from other observations. The *HST* observations and source model of Nguyen et al. (1999) suggest that the central source (i.e. the X-ray emitting AGN) is $\approx$100 pc from the caustic, indicating that the magnification of the AGN emission is likely to be $\approx$100. The strong optical polarization and prominent high-excitation emission lines also indicate that the caustic lies close to the central source (e.g. Broadhurst & Lehar 1995; Lacy, Rawlings & Serjeant 1998; Simpson et al., in preparation).

3 DISCUSSION

With a $\approx$20 ks *Chandra* ACIS-S observation we have shown that FSC 10214+4724 is comparatively weak at X-ray energies ($L_{1.6\text{–}6.6\,\mathrm{keV}} < 3.4 \times 10^{42}$ erg s^{-1}, $L_{6.6\text{–}26.3\,\mathrm{keV}} < 6.4 \times 10^{42}$ erg s^{-1}

[1] For additional information on the ACIS and *Chandra* see the *Chandra* Proposers' Observatory Guide at http://cxc.harvard.edu/proposer/POG/html.
[2] See http://cxc.harvard.edu/ciao/ for details on CIAO.
[3] See http://cxc.harvard.edu/cal/ASPECT/.
[4] Details about the SDSS and the SDSS catalogues can be accessed from http://www.sdss.org/.

Table 1. *Chandra* properties of FSC 10214+4724.

Chandra co-ordinates α_{2000} (h m s)	δ_{2000} (° ′ ″)	*Chandra–HST* (arcsec)[a]	Counts FB[b]	SB[b]	HB[b]	Band Ratio[c]	Effective Γ[d]	Flux FB[e]	SB[e]	HB[e]
10:24:34.560	+47:09:09.48	0.17	$13.6^{+5.2}_{-3.3}$	$9.9^{+4.4}_{-3.0}$	$3.8^{+3.4}_{-1.7}$	$0.38^{+0.38}_{-0.21}$	$1.6^{+0.7}_{-0.6}$	5.4	2.0	3.6

Notes: [a]Offset between the *Chandra* FB source position and the *HST* source position (component 1) of Eisenhardt et al. (1996). [b]Source counts and errors. The source counts are determined with WAVDETECT. The errors correspond to 1σ and are taken from Gehrels (1986). [c]Ratio of the count rates in the 2.0–8.0 keV and 0.5–2.0 keV bands. The errors were calculated following the 'numerical method' described in Section 1.7.3 of Lyons (1991). [d]Effective photon index for the 0.5–8.0 keV band, calculated from the band ratio. The photon index is related to the energy index by $\alpha = \Gamma - 1$, where $F_\nu \propto \nu^{-\alpha}$. [e]Fluxes in units of 10^{-15} erg cm^{-2} s^{-1}. These fluxes have been calculated from the count rate in each band using the CXC's Portable, Interactive, Multi-Mission Simulator (PIMMS) assuming $\Gamma = 1.6$; they have been corrected for Galactic absorption.

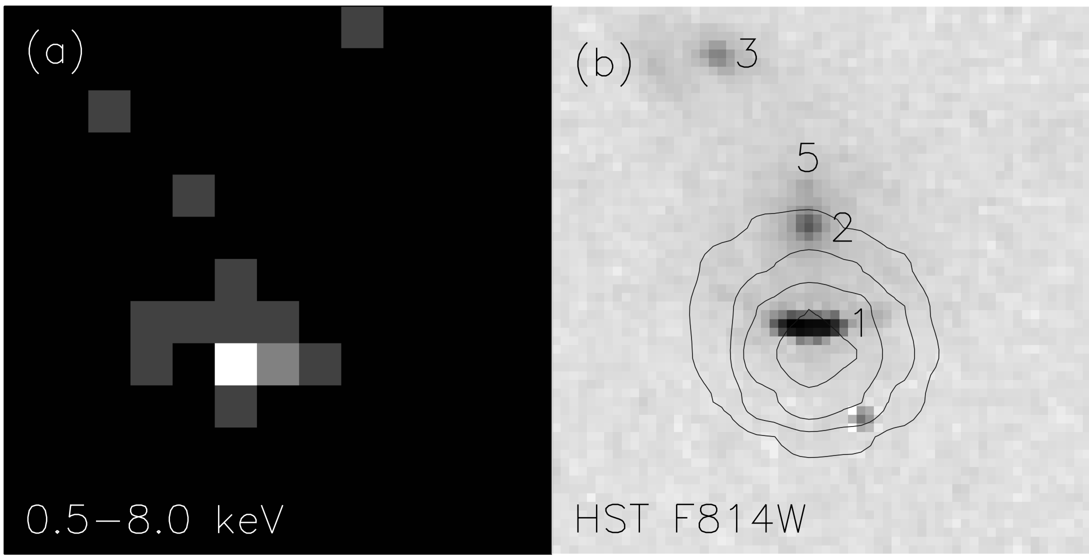

Figure 1. (a) Full-band *Chandra* image of FSC 10214+4724, and (b) F814W *HST* image of FSC 10214+4724 with overlaid adaptively smoothed FB contours. The *HST* image was downloaded from the *HST* archive and has been adjusted to give the same astrometry as that reported in Eisenhardt et al. (1996). The adaptive smoothing has been performed using the code of Ebeling, White & Rangarajan (2004) at the 2σ level; the contours are linear. Both images are $\approx$6.3 × 6.3 arcsec^2; the full field of view of the ACIS S3 CCD is 8.6 × 8.6 arcmin^2. Four of the components identified by Eisenhardt et al. (1996) are indicated; FSC 10214+4724 corresponds to component 1 and the $z \approx 0.9$ lensing galaxy corresponds to component 2. The X-ray detected source is clearly component 1.

and $L_{1.6\text{–}26.3\,\mathrm{keV}} < 9.8 \times 10^{42}$ erg s^{-1} for a lensing boost of >25). Previous studies have suggested that FSC 10214+4724 hosts both a powerful starburst and a powerful AGN (Goodrich et al. 1996; Granato et al. 1996; Green & Rowan-Robinson 1996). In this final section we predict the expected X-ray emission from both star formation and AGN activity in FSC 10214+4724 and compare it to the observed X-ray emission. We also compare the X-ray properties of FSC 10214+4724 to those of high-redshift SCUBA galaxies and discuss the X-ray identification of Compton-thick AGNs at high redshift

3.1 The nature of the X-ray emission from FSC 10214+4724

Many studies have shown a correlation between the 1.4-GHz radio luminosity density and the X-ray luminosity of star-forming galaxies (e.g. Shapley, Fabbiano & Eskridge 2001; Bauer et al. 2002; Ranalli, Comastri & Setti 2003). Because the radio emission from FSC 10214+4724 is consistent with star formation activity (e.g. Lawrence et al. 1993; Rowan-Robinson et al. 1993; Eisenhardt et al. 1996), we can use this correlation to predict the expected X-ray emission from star formation. The radio extent and morphology of FSC 10214+4724 are similar to those found in the rest-frame ultraviolet, suggesting that the radio emission is lensed by a factor of $\approx$50–100 (Eisenhardt et al. 1996). In Fig. 3 we show the rest-frame 1.4-GHz radio luminosity density versus the rest-frame 0.5–8.0 keV luminosity for FSC 10214+4724; the rest-frame 0.5–8.0 keV luminosity was calculated from the rest-frame 1.6–6.6 keV luminosity (observed SB) assuming $\Gamma = 1.6$, and is shown for a range of lensing boosts. The rest-frame 0.5–8.0 keV emission from FSC 10214+4724 is entirely consistent with that expected from star formation for the range of probable lensing boosts at radio wavelengths. The X-ray-to-optical flux ratio is also concordant with that expected from star formation [$\log(f_{\mathrm{FB}}/f_{\mathrm{I}}) \lesssim -1$; see section 4.1.1 of Bauer et al. 2004] when appropriate *K*-corrections and lensing boosts are applied [$\Gamma = 1.6$ with lensing boosts of 25–100 in the X-ray band, and the host galaxy templates of Mannucci et al. (2001) with a lensing boost of 100 in the *I*-band]. These results imply that the AGN in FSC 10214+4724 is either heavily obscured or intrinsically weak.

We can estimate the instrinsic luminosity of the AGN in FSC 10214+4724 using the [O III]λ5007 luminosity (e.g. Mulchaey et al. 1994; Bassani et al. 1999). Taking the [O III]λ5007 luminosity from Serjeant et al. (1998), the [O III]λ5007 to X-ray correlation of Mulchaey et al. (1994), and assuming the lensing boost to the [O III]λ5007 emission-line region is $\gtrsim$100 (Simpson et al., in preparation), the predicted rest-frame 0.5–8.0 keV luminosity is

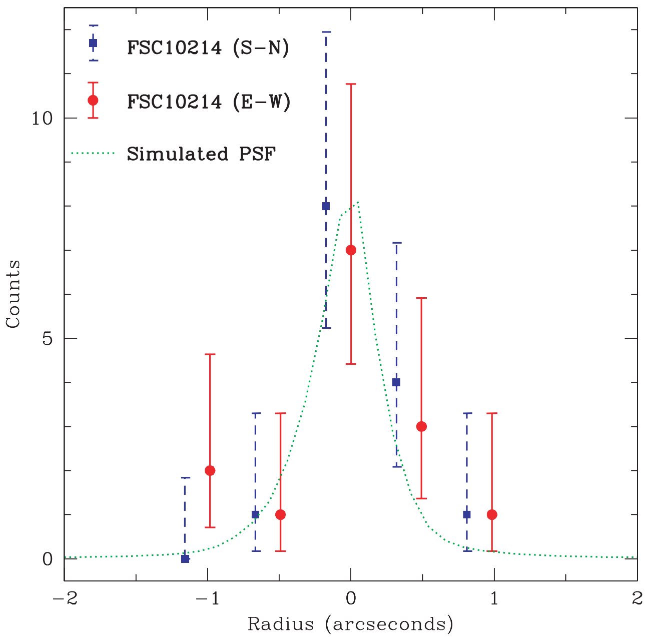

Figure 2. The FB profiles of FSC 10214+4724 (S–N orientation, solid dots; E–W orientation, solid squares) compared to the on-axis *Chandra* PSF (dotted curve). The x-axis corresponds to the offset from the WAVDETECT-determined position, and the y-axis error bars correspond to 1σ uncertainties (Gehrels 1986). The *Chandra* PSF was simulated using the CIAO tool MKPSF and has been normalised to the peak of the S–N orientation profile. Although the signal-to-noise ratio of the data is low, the profiles and the half-power radius (≈0.5–0.75 arcsec) are consistent with those of an unresolved source, suggesting a lensing boost in the X-ray band of $\gtrsim$25; see Section 2.2.

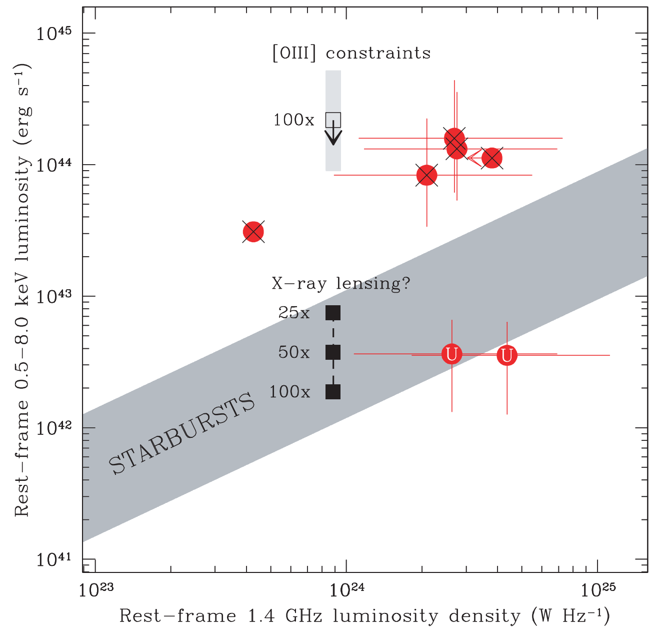

Figure 3. Rest-frame 0.5–8.0 keV luminosity versus rest-frame 1.4-GHz luminosity density for FSC 10214+4724 and a sample of X-ray detected SCUBA galaxies. The filled squares indicate the X-ray constraints for FSC 10214+4724 for lensing boosts of 25–100. The radio luminosity density of FSC 10214+4724 is calculated assuming a lensing boost of 50. The open square indicates the derived upper limit on the X-ray emission from the [O III]λ5007 luminosity of FSC 10214+4724 for a lensing boost of 100 (Simpson et al., in preparation; see Section 3.1); the light shaded region shows the variance in the $L_{[\mathrm{O\,III}]}/L_{\mathrm{X}}$ relationship (Mulchaey et al. 1994). The filled circles indicate the X-ray detected SCUBA galaxies from Alexander et al. (2003a); the crosses indicate sources classified as AGNs, and the 'U's indicate sources with unknown classifications but with X-ray properties consistent with those of starburst galaxies. The dark shaded region denotes the 1σ dispersion in the locally determined X-ray-radio correlation for star-forming galaxies (see fig. 6 of Shapley et al. 2001; Bauer et al. 2002; Ranalli et al. 2003). The rest-frame $\lesssim$8-keV emission from FSC 10214+4724 is consistent with that expected from star formation activity; see Section 3.1.

$<2.2 \times 10^{44}$ erg s^{-1} (with a variance of <0.9–5.2×10^{44} erg s^{-1}); see Fig. 3.[5] These predicted X-ray luminosities are within the range expected for quasars and would be even higher if the [O III]λ5007 emission-line region suffered from reddening (e.g. Elston et al. 1994; Soifer et al. 1995; cf. Serjeant et al. 1998). As the lensing boost to the [O III]λ5007 emission-line region is a lower limit, these constraints should be considered upper limits. However, given that the [O III]λ5007 emission-line region is likely to be more extended than the central source, the [O III]λ5007 emission is unlikely to be much more magnified than the X-ray emission.

These results suggest that the AGN in FSC 10214+4724 is powerful. However, the rest-frame 1.6–26.3 keV luminosity is approximately 1–2 orders of magnitude below the constraint estimated from the [O III]λ5007 luminosity. This is significant, as rest-frame >10 keV emission is not easily attenuated [e.g. one order of magnitude of extinction at >10 keV requires Compton-thick obscuration ($N_{\mathrm{H}} > 1.5 \times 10^{24}$ cm^{-2}); see appendix B in Deluit & Courvoisier (2003)]. Hence, if FSC 10214+4724 hosts a quasar, as previously suggested, then it must be obscured by Compton-thick material; these general conclusions are consistent with those found for other *IRAS* galaxies of similar luminosity (e.g. Iwasawa, Fabian & Ettori 2001; Wilman et al. 2003). Under this assumption, the observed X-ray emission from the AGN would be due to reflection and scattering, and a strong Fe Kα emission line should be detected. With only ≈14 X-ray counts, the current X-ray observations cannot provide good constraints on the presence of Fe Kα; however, a scheduled ≈50 ks *XMM-Newton* observation (principal investigator: K. Iwasawa) may be able to place some constraints.

[5] We converted from the 2–10 keV band used by Mulchaey et al. (1994) to the 0.5–8.0 keV band assuming $\Gamma = 2.0$, a typical intrinsic X-ray spectral slope for AGNs.

3.2 SCUBA galaxies and Compton-thick accretion

The lensing-corrected properties of FSC 10214+4724 are similar to those of SCUBA galaxies (see Section 1), sources that are probably the progenitors of massive galaxies (and hence massive black holes) in the local Universe. The steep X-ray spectral slope and moderately luminous X-ray emission of FSC 10214+4724 contrasts with the X-ray properties of the five X-ray detected SCUBA galaxies classified as AGNs in Alexander et al. (2003a); however, the X-ray properties of FSC 10214+4724 are similar to those of the two X-ray detected SCUBA galaxies classified as unknown (see Fig. 3). As we know that an AGN is present in FSC 10214+4724 (possibly powerful and Compton thick), this suggests that further unidentified AGNs may be present in the SCUBA galaxy population and the ≈40 per cent AGN fraction (Alexander et al. 2003a, 2004) should be considered a lower limit. Many Compton-thick AGNs may be present in ultra-deep X-ray surveys (e.g. Fabian, Wilman &

Crawford 2002). However, the presence of vigorous star formation may make them difficult to identify on the basis of their X-ray properties alone.

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