Frying doughnuts: What can the reprocessing of X-rays to IR tell us about the AGN environment?

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Accepted. Received; in original form

ABSTRACT
Active galactic nuclei (AGN) produce vast amounts of high energy radiation deep in their central engines. X-rays either escape the AGN or are absorbed and re-emitted mostly as IR. By studying the dispersion in the ratio of observed mid-IR luminosity to observed 2-10keV X-ray luminosity ($R_{\text{ir/x}}$) in AGN we can investigate the reprocessing material (possibly a torus or donut of dust) in the AGN central engine, independent of model assumptions.

We studied the ratio of observed mid-IR and 2-10keV X-ray luminosities in a heterogeneous sample of 245 AGN from the literature. We found that when we removed AGN with prominent jets, $\sim90\%$ of Type I AGN lay within a very tight dispersion in luminosity ratio ($1 < R_{\text{ir/x}} < 30$). This implies that the AGN central engine is extremely uniform and models of the physical AGN environment (e.g. cloud cover, turbulent disk, opening angle of absorbing structures such as dusty tori) must span a very narrow range of parameters. We also found that the far-IR (100µm) to mid-IR (12µm) observed luminosity ratio is an effective discriminator between heavily obscured AGN and relatively unobscured AGN.

Key words: galaxies: active – galaxies: individual – galaxies: Seyfert – techniques: spectroscopic – X-rays: line – emission: accretion – disks : galaxies

1 INTRODUCTION
Active galactic nuclei (AGN) are powered by the accretion of matter onto a supermassive ($\sim10^{6-9}\,M_\odot$) black hole. X-ray continuum emission from AGN (without jets) is believed to originate in the innermost regions of the AGN whereas IR continuum emission is believed to originate in dusty, cooler outer regions. The IR emission from AGN is due to a combination of reprocessed higher energy emission as well as thermal emission from star formation. Much if not most of the IR due to reprocessing comes from energy dumped in cool dusty material (mostly out of the observers’ X-ray sightline) by photons with the most energy (X-rays). A comparison of the dispersion in the IR to X-ray luminosity ratios ($R_{\text{ir/x}}$) of a wide variety of AGN should therefore allow us to constrain the range of physical properties and geometry of the X-ray reprocessing material in AGN, independent of model assumptions.

The standard model of AGN explains the wide range of properties of observed AGN in terms of viewing angle, since the equatorial flared disk expected at the heart of AGN breaks spherical symmetry (Antonucci 1993). However, partially or heavily obscured AGN need not be edge on, since obscuring material only needs to block the observer’s sightline (see e.g. McKernan & Yaqoob 1998; Risaliti, Elvis & Nicastro 2002; Miller, Turner & Reeves 2008). Radiation reprocessing occurs in cool (possibly obscuring) material distributed around the AGN. Independent of assumptions about the distribution of cool material, the dispersion in $R_{\text{ir/x}}$ can constrain the range of possible geometries and physical conditions of the obscuring, reprocessing material around the central engine. The dispersion of $R_{\text{ir/x}}$ among AGN also provides information about depopulation or selection effects (bias), if there are values of $R_{\text{ir/x}}$ that are not favoured by AGN. Genuine depopulation in $R_{\text{ir/x}}$ space would yield model-independent information on allowed configurations of the AGN central engine.

The IR and X-ray emission in AGN have been compared in many previous studies (Boller et al. 1992; Green, Anderson & Ward 1992; Lutz et al. 2003; Krabbe et al. 2001; Horst et al. 2007; Mushotzky et al. 2008). Most recently Horst et al. (2007) reveal a strong

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correlation between modelled intrinsic 2-10keV X-ray luminosity and near-IR nuclear luminosity, suggestive of a 'leaky' torus of dust. Mushotzky et al. (2008) find a strong correlation between mid-IR luminosity and the very hard X-ray (14-195keV) observed luminosity, which is unaffected by absorption and indicates that the same phenomenon underlies all AGN. However, as yet there have been no comparisons of the observed hard 2-10keV X-ray luminosity with the IRAS band (12-100µm) IR luminosities. The 2-10keV X-rays are energetic enough to emerge with relatively mild attenuation through Compton-thin obscurers with absorption becoming more substantial above \(N_H \sim 10^{22} \text{cm}^{-2}\). Attenuated X-rays will mostly re-emerge as IR emission. Therefore, in tandem with IRAS band IR emission, 2-10keV X-rays are a good probe of absorption and subsequent reprocessing in the obscuring material around AGN. In this paper, for the first time, we studied the ratio of observed 2-10keV X-ray emission to IRAS band (12-100µm) IR emission for a large, heterogeneous sample of AGN. By studying dispersions in the luminosity ratio \(R_{ir/x}\) of our sample, we hope to obtain information about the dispersion of physical properties of the AGN environment, independent of model assumptions.

In section 2 we briefly discuss X-ray and IR luminosity of AGN, including previous studies which compared emission in the two bands, and in section 3 we discuss our sample of AGN and associated caveats. In section 4 we explore the distribution of our sample of AGN in \(R_{ir/x}\) parameter space and we use AGN classification and well-known AGN to constrain the dispersion of AGN in \(R_{ir/x}\). In section 5 we attempt to rule out selection bias as an explanation of the dispersion of AGN in \(R_{ir/x}\) space. In section 6 we discuss our results and establish model-independent constraints on the reprocessing material around AGN. Section 7 outlines our conclusions.

2 COMPARING X-RAY AND IR EMISSION FROM AGN

Most AGN are characterized by an SED that extends at least from the IR band to the hard X-ray band, cutting off at \(\sim 50-300\) keV (Perola et al. 2002). The broadband SED of these AGN can therefore always be characterized in a naive way by the slope from the IR band to the X-ray band. The IR band emission in most Seyfert AGN generally peaks in the IRAS band (12-100µm). The X-ray flux from Seyferts is typically strongly absorbed at energies \(< 2\)keV (even at relatively low columns of \(N_H \sim 10^{21}\text{cm}^{-2}\)) and fluxes at \(> 10\)keV are often too low to be strongly constrained, so a widely accepted measure of X-ray emission from AGN is the observed 2-10keV flux. Absorption of 2-10keV X-rays becomes more substantial at columns \(N_H \sim 10^{22}\text{cm}^{-2}\) and so 2-10keV X-rays are a useful probe of Compton-thin absorbers along the AGN sightline, as well as reprocessing in the AGN environment. By comparing the ratio of observed 2-10 keV X-ray to IRAS-band IR emission from AGN, we therefore have (1) an approximate measure of steepness over the entire SED in most AGN independent of cosmology and (2) sufficient data from AGN to build a statistically meaningful sample.

The observed 2-10 keV X-ray flux from an AGN may not be the intrinsic X-ray flux of the AGN. With sufficiently large absorbing columns the 2-10keV hard X-ray flux can be very strongly attenuated (particularly when the absorber is Compton-thick, i.e. \(N_H > 1.5 \times 10^{24} \text{cm}^{-2}\)). However, it can be difficult to separate AGN with weak observed X-ray flux from those with genuinely weak intrinsic X-ray flux, without knowledge of the very hard X-ray flux (\(> 14\) keV or so). With the advent of very hard X-ray detectors with sufficient effective area (e.g. SaX, Suzaku and the BAT detector on Swift), it has only recently become possible to observe AGN unbiased by X-ray absorption (see e.g. Tueller et al. (2008), Winter et al. (2008), Itoh et al. (2008); Mushotzky et al. (2008)). To illustrate the effect of absorption on the intrinsic X-ray luminosity, we shall compare the observed 2-10keV flux and the interpolated intrinsic 2-10keV flux inferred from very hard X-ray measurements for a number of well-known AGN (see below). Throughout this paper, we shall refer to the observed 2-10keV luminosities of AGN, unless otherwise indicated.

Comparisons of X-ray and IR emission in large samples of AGN (and normal galaxies) find significant correlations. Green, Anderson & Ward (1992) found a correlation between 60µm IRAS luminosity and Einstein (0.5-4.5keV) soft X-ray luminosity. Boller et al. (1992) found correlations between IRAS far-IR luminosity (60µm) with the ROSAT 0.1-2.4keV soft X-ray luminosity. Both Green, Anderson & Ward (1992) and Boller et al. (1992) show a clear jump towards higher X-ray emission among broad line galaxies compared with narrow line galaxies, suggestive of increasing dominance of non-thermal emission. Correlations from such heterogeneous samples of AGN are important since they suggest that the same phenomenon underlies all AGN. More recently, Mushotzky et al. (2008) found a strong correlation \((L_X \sim L_{IR}^{1.25})\) between very hard X-ray luminosity (14-195keV) and mid-IR luminosity in a uniform sample of hard X-ray selected AGN. High angular resolution (nuclear) IR studies of AGN have also revealed a correlation between mid-IR luminosity (at 6µm, 10.5µm and 12.5µm respectively) and the modelled intrinsic hard X-ray luminosity (2-10keV) \((L_x < 25\)\(10^{25}\)). How-
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Table 1. The studies from which our AGN sample was derived. Listed are study, year, total number of NED objects listed in each paper and number of unique AGN extracted by us from each study, which had both IRAS and 2-10keV X-ray flux measurements on NED. Many AGN were included in multiple studies. We did not include AGN with only upper limits in either the IRAS band or the 2-10keV band.

| Study            | Year | NED objects | Unique AGN |
|------------------|------|-------------|------------|
| McKernan et al.  | 2007 | 15          | 15         |
| Horst et al.     | 2007 | 29          | 10         |
| Buchanan et al.  | 2006 | 55          | 14         |
| Foschini et al.  | 2006 | 19          | 7          |
| Shinozaki et al. | 2006 | 51          | 15         |
| Botte et al.     | 2005 | 10          | 4          |
| Nagar, Falcke & Wilson | 2005 | 250       | 36         |
| Peterson et al.  | 2004 | 37          | 14         |
| Lutz et al.      | 2004 | 71          | 12         |
| Bian & Zhao      | 2003 | 41          | 7          |
| Sanders et al.   | 2003 | 664         | 23         |
| Schade, Boyle & Letawsky | 2000 | 76       | 3          |
| Grupe et al.     | 1999 | 76          | 4          |
| Leighly          | 1999 | 23          | 5          |
| Malizia et al.   | 1999 | 36          | 2          |
| Turner et al.    | 1999 | 36          | 1          |
| Bonatto et al.   | 1998 | 60          | 4          |
| Gonzalez Delgado et al. | 1997 | 55       | 3          |
| Ho, Filippenko & Sargent | 1997 | 91       | 13         |
| Smith & Done     | 1996 | 36          | 2          |
| Eracleous & Halpern | 1994 | 108       | 7          |
| Rush, Malkan & Spinoglio | 1993 | 893      | 8          |
| Boroson & Green  | 1992 | 86          | 31         |
| Total            |      | 2802        | 245        |

Note that, as in previous such heterogeneous studies (Veilleux & Osterbrock 1985; Green, Anderson & Ward 1992; Bonatto et al. 1994), our sample is not intended to be complete. Rather, our intention was to draw upon a wide range of AGN studies, incorporating all types of AGN, in order to investigate if any trends in $R_{ir/x}$ emerge even with heterogeneous groups of data. The point of this study in effect, is to see where AGN lie in X-ray-IR luminosity ratio ($R_{ir/x}$) space and whether we can in principle deduce model-independent results from their dispersion. Clumps and scatters in an $R_{ir/x}$ plot can reveal valuable information on AGN depopulation and/or AGN selection effects. In future work, we will increase our sample size by expanding on the number of surveys in Table 1.

For estimates of the AGN X-ray and IR luminosity, we used NED flux measurements in each waveband and the NED luminosity distance estimate, which uses a WMAP cosmology (Spergel et al. 2003). Where there were multiple flux measurements, we used the mean flux value in that waveband. This will tend to bias our survey against including flaring periods or dramatically low states for individual AGN with multiple flux measurements. Generally, the error on the flux measurements listed by NED is < 20% in the X-ray band and < 5–10% in the IR band. However, AGN are by nature variable, sometimes extremely so. Of the 245 AGN in our study, 128 have multiple measurements of their 2-10keV X-ray flux. Of these 128 AGN, roughly half (56/128) vary by a factor of two or more, only ∼ 1/5th (24/128) vary by a factor of three or more and only ∼ 5% (6/128) vary by an order of magnitude or more. Therefore we estimate that the 2-10keV flux in ∼ 55% of the AGN in our sample varies by less than a factor of two and the flux in ∼ 80% of the AGN in our sample varies by less than a factor of three. In spite of several well known exceptions, relatively low X-ray variability among AGN in general is consistent with previous studies (see e.g. Markowitz & Edelson 2004).

In the IRAS band, 93 of the 245 AGN in our sample have multiple measurements of their IRAS band flux. Of these 93 AGN, roughly one quarter (23/93) vary by a factor of two or more, only ∼ 10% (8/93) vary by a factor of three or more and only 1/93 varies by an order of magnitude or more. Therefore we estimate that in the IR band, the flux in ∼ 75% of the AGN in our sample varies by less than a factor of two and the flux in ∼ 90% of the AGN in our sample varies by less than a factor of three. If these numbers are relatively representative of the AGN in our sample, we estimate that the majority of AGN luminosity ratios in this study have errors of no more than a factor of ∼ 3 in both the X-ray and IR luminosities. Note that the X-ray and IR measurements used in this paper are almost always not simultaneous. However, in spite of intrinsic AGN variability and non-simultaneity of the data in most cases, it turns out that our simple approach reveals strong trends in the data (see § 4 below).

Table 2 shows the breakdown of our AGN sample into NED classification and redshift. AGN classification and our

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1 http://nedwww.ipac.caltech.edu/
is measured in Jy (=3
µ
m). As far as AGN redshift is concerned, most (∼85%) of the AGN in our sample are at low redshift (z < 0.1), so the 12µm IR flux and 2-10 keV band X-ray flux does not include large amounts of flux redshifted from higher energies. However, for a small fraction (∼15%) of the higher luminosity AGN, the observed 12µm and 2-10 keV fluxes may correspond to fluxes in the AGN frame of ∼6–12µm and ∼2–15keV respectively. Generally in these AGN, high energy X-ray flux falls off faster than the near IR flux, so in the small fraction of very distant luminous AGN we expect R_{ir/x} to be slightly larger on average than the nearby group 1 AGN (see also Fig. 1 and related discussion below).

In this paper, we discuss luminosity ratios. The IR flux is measured in Jy (=3.0 × 10^{-11} erg cm^{-2}s^{-1} at 100µm and 2.5 × 10^{-10} erg cm^{-2}s^{-1} at 12µm) and the X-ray flux is measured in units of 10^{-11} erg cm^{-2}s^{-1}. The luminosity (and flux) ratios described hereafter are unitless.

### Table 2. Breakdown of our sample by redshift and object classification . AGN with NED classifications involving prominent jets (e.g. BL Lacs, BLRGs) have been excluded. The first number in columns 2 & 3 denotes the total number of Group 1 and Group 2 AGN in the corresponding z range (see § below for further discussion of Groups 1 & 2 and AGN classification). The numbers in brackets denote respectively: the number of Seyfert (Sy) AGN; the number of AGN classified as Seyfert plus (Sy+) something else (e.g. Starburst, H II region, LINER, QSO); the number of non-Seyfert (NS) AGN.

| Redshift Range | Group 1 (Sy,Sy+,NS) | Group 2 (Sy,Sy+,NS) |
|----------------|---------------------|---------------------|
| <0.005         | 9(3,6,0)            | 53(31,9,13)         |
| 0.005-0.049    | 56(50,6,0)          | 53(32,16,5)         |
| 0.05-0.099     | 16(12,4,0)          | 3(3,0,0)            |
| 0.1-0.199      | 18(14,4,0)          | 0                   |
| 0.2-0.4        | 13(6,6,1)           | 0                   |
| Total          | 112                 | 109                 |

### 4 RELATIVE X-RAY AND INFRA-RED LUMINOSITIES OF AGN

In this section we will start by presenting our entire AGN sample in R_{ir/x} space using observed 2-10keV X-ray and IRAS-band IR measurements. We shall then use AGN classifications to begin constraining the dispersions of different AGN types in R_{ir/x}. We shall also introduce well-known AGN ‘typical’ of their classification to aid interpretation of the AGN distribution. We shall then compare the distribution of AGN in R_{ir/x} using far-IR (100µm) and mid-IR (12µm) observed luminosity.

Figure 1 shows the observed 2-10keV X-ray flux plotted against the 12µm mid-IR flux for 240/245 AGN in our sample (5 AGN had 12 µm upper limits only). Lines of constant flux ratio are plotted (F_{ir}/F_{x}=1,10,100) to guide the eye. If we express the flux ratios from Figure 1 in terms of luminosity ratios, the ratios remain constant, but the AGN separate by a factor proportional to the distance squared.

Since jets will complicate our interpretation of the central engine, we excluded 20 AGN with NED classifications
that include prominent jets (e.g. BL Lac, Blazar, LPQ, BLRG). Figure 2 shows the mean hard X-ray 2-10keV luminosity plotted against the mean mid-IR 12µm luminosity for 215/245 of the AGN in our sample. Lines of constant luminosity ratio ($R_{ir/x} = 1, 10, 100$) are indicated to guide the eye. From Fig. 2 the more luminous AGN seem to emerge at $L_x/L_{ir} = 10^{42-43}$ ergs s$^{-1}$ and mostly lie in a band around $R_{ir/x} \sim [1, 30]$. Lower luminosity AGN appear to span a much wider range of observed luminosities, suggestive of both highly absorbed X-ray luminosity and/or a 'noisy' host galaxy background in IR or X-rays. The AGN in Fig. 2 span $R_{ir/x}$ space in a manner broadly similar to studies carried out using soft X-rays (Green, Anderson & Ward 1992; Boller et al. 1992).

Although we excluded AGN with prominent jets, the remaining AGN may well contain weak jets, but they are not prominent enough to effect AGN classification. AGN with prominent jets accounted for more than half the AGN with $L_x > 3 \times 10^{43}$ ergs s$^{-1}$, so if present and prominent, jets account for a significant proportion of X-ray luminosity. From Fig. 2 there are only 3/225 AGN with $R_{ir/x} < 1$, suggesting either that $R_{ir/x} < 1$ is atypical for AGN or that there is a bias against AGN with $R_{ir/x} < 1$ in our sample. It is noteworthy that the 3/215 AGN with $R_{ir/x} < 1$ in Fig. 2 have weak associated jets. They are, in order of increasing X-ray luminosity: Cen A, PG 1416-129 and PG 0026+129 respectively (Kraft et al. 2000; Porquet et al. 1998). If this interpretation is correct, newly discovered AGN with $R_{ir/x} < 1$ should have associated jets.

At this point, it is useful to introduce AGN classification information (from NED) to aid further interpretation of the dispersion of $R_{ir/x}$ values among AGN. Broadly, we observe 'more active' and 'less active' AGN. Excluding AGN with jets, the 'more active' AGN population includes Seyfert 1s and some QSOs. The 'less active' population generally includes Seyfert 2s, LINERs, LLAGN, ULIRGs, some starburst-dominated AGN and some HII region-like galaxies (see e.g. the definition of 'emission line galaxies' for the sample in Veilleux & Osterbrock (1987)). Classifications are of course imperfect and so some AGN may overlap between these two groups, e.g. Seyfert 1.2-1.9 AGN, as well as cross-classified AGN (e.g. AGN classified both as Seyfert 1 and starburst or LINER & Seyfert 1.5). From Table 2 above, of the 221 AGN in our sample without prominent jets, 153/221 AGN are classified by NED purely as Seyfert 1s, LINERs, LLAGN, ULIRGs, some starburst-dominated AGN and some HII region-like galaxies (see e.g. the definition of 'emission line galaxies' for the sample in Veilleux & Osterbrock (1987)). Classifications are of course imperfect and so some AGN may overlap between these two groups, e.g. Seyfert 1.2-1.9 AGN, as well as cross-classified AGN (e.g. AGN classified both as Seyfert 1 and starburst or LINER & Seyfert 1.5). From Table 2 above, of the 221 AGN in our sample without prominent jets, 153/221 AGN are classified by NED purely as Seyfert 1s, LINERs, LLAGN, ULIRGs, some starburst-dominated AGN and some HII region-like galaxies (see e.g. the definition of 'emission line galaxies' for the sample in Veilleux & Osterbrock (1987)). Classifications are of course imperfect and so some AGN may overlap between these two groups, e.g. Seyfert 1.2-1.9 AGN, as well as cross-classified AGN (e.g. AGN classified both as Seyfert 1 and starburst or LINER & Seyfert 1.5). From Table 2 above, of the 221 AGN in our sample without prominent jets, 153/221 AGN are classified by NED purely as Seyfert 1s, LINERs, LLAGN, ULIRGs, some starburst-dominated AGN and some HII region-like galaxies (see e.g. the definition of 'emission line galaxies' for the sample in Veilleux & Osterbrock (1987)). Classifications are of course imperfect and so some AGN may overlap between these two groups, e.g. Seyfert 1.2-1.9 AGN, as well as cross-classified AGN (e.g. AGN classified both as Seyfert 1 and starburst or LINER & Seyfert 1.5).
For many Group 2 AGN may be similar to the Group 1 AGN. Of the ten Group 1 AGN with $R_{ir/x} > 30$, four are cross-classified (i.e. Seyfert 1 plus starburst) and four are heavily obscured Seyfert 1s ($N_H \sim 10^{23}$ cm$^{-2}$). So Group 1 AGN with $R_{ir/x} > 30$ could be accounted for either by the addition of IR luminosity from star formation or a drop in observed X-ray luminosity due to a change in partial-covering absorption (McKernan & Yaqoob 1998; Risaliti et al. 2002; Miller et al. 2008). So even with our simple approach, Fig. 3 indicates that ~90% of Group 1 AGN in our sample have $1 < R_{ir/x} < 30$. By contrast, Group 2 AGN (red crosses) generally have lower X-ray luminosities and have a wider dispersion in $R_{ir/x}$ than Group 1 AGN. In contrast to the Group 1 AGN, 97/109 group 2 AGN have $R_{ir/x} > 30$, with 83/109 group 2 AGN having $R_{ir/x} > 100$. Of the 12/109 Group 2 AGN with $1 < R < 30$ (i.e. overlapping with the main Group 1 population), we find that six have associated radio jets and two are Compton-thin Seyfert 2 AGN. From Table 2, the AGN in our sample are non-Seyferts, of which 10 are LINERs, 8 LINERs with H$_\beta$ regions and 1 QSO. The LINERs lie in the bottom left-hand corner of the Group 2 distribution ($L_{ir} < 0.5 \times 10^{42}$ erg/s, $L_x < 10^{39}$ erg/s) and the LINERs with H$_\beta$ regions span a slightly larger range of the Group 2 distribution ($L_{ir} < 5 \times 10^{42}$ erg/s, $L_x < 10^{39}$ erg/s).

A key point from Fig. 3 is that the luminosity ratio for NGC 4945 and Circinus as calculated from the interpolated intrinsic 2-10keV luminosity (right point) lies in the main luminosity ratio band of Group 1 AGN. This is a nice demonstration of the fact that behind the Compton-thick obscuration of NGC 4945 and Circinus, lies the same phenomenon as in most Group 1 AGN. Without very hard X-ray measurements, it is very difficult to estimate intrinsic 2-10keV X-ray luminosities for most Group 2 AGN in our sample and certainly any such estimates would be highly model-dependent. Nevertheless, the examples of NGC 4945 and Circinus indicate that the intrinsic luminosity ratios for many Group 2 AGN may be similar to the Group 1 luminosity ratio range ($\sim 30 \leq R_{ir/x} \leq 1$). However, there are many model-dependent caveats in estimating the intrinsic X-ray luminosity of an AGN, so in Fig. 3 below we will take a different approach to Lutz et al. (2001), Krabbe et al. (2001), Horst et al. (2007) and attempt to derive constraints on AGN using observed luminosities.

Figure 4 shows the mean far-IR (100 $\mu$m) luminosity of the AGN in our sample versus the mean 2-10keV observed X-ray luminosity. Note that several AGN had NED flux measurements at 12$\mu$m but only upper limits at 100$\mu$m and vice versa, so there is not a perfect one-to-one correspondence between all points on Fig. 4 and Fig. 5. Nevertheless, the dispersion in $R_{ir/x}$ for the Group 2 AGN in particular seems to be larger in Fig. 4 than in Fig. 3 and the various archetypal Group 2 AGN appear more separated in luminosity ratio. For example, the starburst galaxy Arp 220 (open star) is much more clearly distinguished from the classic Type 2 AGN NGC 1068 (open triangle) in Fig. 4 than in Fig. 3. The non-Seyfert AGN, e.g. the LINERs and LINERs with H$_\beta$ regions, are also highlighted. As we should expect from such low X-ray and IR luminosity sources, LINERs occupy the lower left-hand corner of the Group 2 AGN dispersion in Fig. 4. The LINERs with associated H$_\beta$ regions have generally higher IR luminosities than the ‘pure’ LINERs, but the X-ray luminosities remain fairly low.

Figures 4 and 5 both show a very clear distinction between the observed luminosity ratios (and their dispersions) for group 1 and group 2 AGN. However, based on the modelled intrinsic 2-10keV X-ray luminosity, Krabbe et al. (2001), Horst et al. (2007) found that the near-IR to X-ray luminosity ratios for group 1 and group 2 AGN were very similar. Figure 5 is as Fig. 4 but with open circles denoting AGN from the study by Horst et al. (2007) and the ranges of intrinsic luminosity ratio established by Horst et al. (2007) for group 1 (solid lines) and group 2 (dashed lines) AGN. The dispersion in the luminosity ratio of our group 1 AGN matches that found by Horst et al. (2007) quite well, indicating that observed and intrinsic 2-10keV X-ray luminosities are similar in most group 1 AGN. Our group 2 population seems to diverge dramatically in luminosity ratio from the range found by Horst et al. (2007), suggesting that the observed and intrinsic 2-10keV luminosities in group 2 AGN are indeed dramatically different. However, Horst et al. (2007) estimate the intrinsic X-ray luminosity in the group 2 AGN based on different model fits in the literature, which (a) can vary for the same AGN dataset and which (b) lead to model-dependent constraints on AGN structure (e.g. a clumpy torus as suggested by Horst et al. 2007). By contrast, an IR-X-ray luminosity ratio based on the observed 2-10keV X-ray luminosity (as in Fig. 5) will help us avoid model assumptions about AGN structure and the AGN environment (see 6 below).

The observed IR band emission from AGN should consist of some fraction of reprocessed radiation.
from the AGN typically peaking in the mid-IR (e.g. Efstathiou et al. 2003) and some fraction of emission from star formation typically peaking in the far-IR (e.g. Efstathiou & Rowan-Robinson 1993; Sirocky et al. 2008; Mas-Hesse et al. 2008) plus intrinsic IR from the SED. Therefore, by comparing the observed mid- and far-IR luminosities in group 1 and group 2 AGN, we may be able to distinguish dominant components of IR in different AGN.

Figure 5 shows the mean far-IR (100μm) luminosity plotted against the mean mid-IR (12μm) luminosity for the 225 AGN in our sample without jets, for which both mid-IR and far-IR data were available. 115 AGN are group 1 (black circles), 110 are group 2 (red crosses). Also plotted are lines denoting constant luminosity ratios of 10, 1, 0.1 respectively. The populations of group 1 and group 2 AGN are very well separated by the luminosity ratio $L_{100\mu m}/L_{12\mu m} = 1$. Only 22/110 (~20%) of group 2 have $L_{100\mu m}/L_{12\mu m} < 1$. The three outlier group 2 AGN in this plot near the $L_{100\mu m}/L_{12\mu m} = 0.1$ line are nearby LINERs that could be cross-classified. From Fig. 5 we can say that the $L_{100\mu m}/L_{12\mu m}$ ratios for group 2 AGN are on average an order of magnitude larger than those for group 1 AGN. The dispersion in both groups is also similar (roughly an order of magnitude). The $L_{100\mu m}/L_{12\mu m}$ ratio also appears to neatly separate out the 'archetypal' Group 2 AGN, in order of most 'cold' (100μm) dust to least 'cold' dust. Evidently the starburst Arp 220 (open star) has by far the highest value of $L_{100\mu m}/L_{12\mu m}$ (as we should expect e.g. Efstathiou et al. 2000; Mas-Hesse et al. 2008) followed by the Compton-thick AGN seen in transmission with the AGN typically peaking in the mid-IR (e.g. Efstathiou et al. 2003) and some fraction of emission from star formation typically peaking in the far-IR (e.g. Efstathiou & Rowan-Robinson 1993; Sirocky et al. 2008; Mas-Hesse et al. 2008) plus intrinsic IR from the SED. Therefore, by comparing the observed mid- and far-IR luminosities in group 1 and group 2 AGN, we may be able to distinguish dominant components of IR in different AGN.

Figure 5. As for Fig. 3 except open circles are AGN from the survey of Horst et al. (2007). Solid lines indicate the range of luminosity ratio found by Horst et al. (2007) for group 1 AGN, based on modelled intrinsic 2-10keV X-ray luminosity. Dashed lines indicate the range of luminosity ratio found by Horst et al. (2007) for group 2 AGN based on modelled intrinsic 2-10keV X-ray luminosity.

5 RULING OUT SELECTION BIAS

Fig. 3 demonstrates that the luminosity ratio ($R_{ir/x}$) of the 245 AGN in our sample is not a scatterplot. So, are the unoccupied regions of the $R_{ir/x}$ plot genuinely depopulated, providing a model-independent constraint on AGN structure, or is there a selection effect at work? First, flux limits from all-sky surveys in both the IR band and the X-ray band allow us to establish which regions of $R_{ir/x}$ are probably genuinely unoccupied by AGN. Fig. 7 is as Fig. 3 except superimposed are flux detectability thresholds from (solid line) the ROSAT All-sky survey (2×10^{-13} ergs cm^{-2}s^{-1} from Voges 1993) and the IRAS 12μm complete sample (~0.3Jy from Sanders et al. 2003), corresponding to luminosity distances of 10Mpc,100Mpc and 1000Mpc. The ROSAT survey was carried out in soft X-rays (0.1-2.4keV) and will undercount heavily absorbed AGN (ie Group 2 AGN) in this band. So, since Group 1 AGN are not very heavily absorbed in the soft X-ray band and since 115/116 of the Group 1 AGN in our sample are detectable in the 2-10keV band at ROSAT flux levels, the ROSAT limits are a reasonable proxy for X-ray flux limits for Group 1 AGN. This is the best that we can do since surveys overlapping the 2-10keV band, are neither all-sky nor complete (Revnivtsev et al. 2004; Tueller et al. 2008). Distances of a few tens of Mpc correspond to a volume of space spanning all varieties of nuclear activity, so it seems probable that empty regions in the upper right corner of $R_{ir/x}$ are genuinely depopulated by luminous (Group 1) AGN. Any Group 1 AGN undetected in the X-ray band, must lie to the left of their corresponding vertical luminos-
Figure 7. As Fig. 3 except also indicated are the luminosity lower limits from the IRAS 12µm survey (0.3Jy, from Sanders et al. (2003) and the ROSAT All-Sky survey (2 × 10^{-13} ergs cm^{-2}s^{-1} from Voges (1993)). The ROSAT limits are from soft (0.1-2.4keV) X-rays and are therefore a reasonable proxy flux limit for AGN unlikely to be very heavily absorbed in the soft X-ray band (our Group 1 AGN). The IRAS flux limits apply to both Group 1 and Group 2 AGN, AGN at <10Mpc, <100Mpc and <1000Mpc distances that have not been detected must lie in the region of parameter space to the left of the appropriate X-ray limit (Group 1 AGN only) and below the appropriate indicated IR limit (both Group 1 and Group 2 AGN).

Figure 8. As Fig. 3 except we only plot those AGN in the redshift range z=[0.005,0.05] (or ~[20,200]Mpc). For clarity, we denote the Group 1 AGN with plus symbols. Note that 53/56 Group 1 AGN lie in the range 30 < R_{ir/x} < 1, a similar ratio to the 103/115 Group 1 AGN in Fig. 3.

Second, we also need to check that the dispersion of AGN is not unduly affected by picking up higher luminosity AGN at relatively higher redshifts. In Fig. 5 we plot the 109 AGN (56 Group 1 and 53 Group 2 AGN) in the redshift range z = [0.005, 0.05] (or ~[20,200]Mpc). Fig. 5 excludes the highest and lowest luminosity AGN from both Groups. From Fig. 5, 53/56 Group 1 AGN have 1 < R_{ir/x} < 30, a similar ratio to the 103/115 Group 1 AGN in the same range, using our full sample. The Spearman rank correlation coefficient (S_{rc}) for our complete Group 1 distribution (without jets) is 0.69 with a strong statistical significance (5 × 10^{-8}). When we split our Group 1 distribution into those AGN at z < 0.05 (65/112) and z > 0.05 (47/112), we find that S_{rc} is statistically significant at 0.71 and 0.67 respectively. We also find that the mean value of R_{ir/x} for both these z < 0.05 and z > 0.05 Group 1 AGN populations are consistent with each other and with the mean value of R_{ir/x} of the complete Group 1 population, within the mean absolute deviation of each population. Furthermore, the T-statistic for these 'low' and 'high' z Group 1 AGN has a significance of 0.5, indicating that the z < 0.05 and z > 0.05 populations do not originate in distributions with substantially different mean values of R_{ir/x}. In future work, we anticipate extending our sample with a view to obtaining strong statistical constraints on the value of R_{ir/x} in AGN.

Another way of assessing the depopulation of regions of the R_{ir/x} plot is by considering the dispersion of complete samples of AGN. The samples of Rush et al. (1993) and Sanders et al. (2003) in Table 1 correspond to complete, flux-limited IRAS samples at 12µm and 60µm respectively. However, in each case, only ~15% of each sample have 2-10keV X-ray data. However, the sample of Rush et al. (1993) in particular spans most of our range of L_x, L_{12um} space, so a comparison of our sample with Rush et al. (1993) could tell us if we are under-sampling a particular region of parameter space. Fig. 9 is as Fig. 2 except that only AGN from Rush et al. (1993) are plotted.

Clearly, the subset of the complete 12µm IRAS AGN sample span the full range of R_{ir/x} for Group 2 AGN and most of the range of R_{ir/x} for Group 1 AGN. Furthermore, the 12µm sample subset does not stake out otherwise unoccupied regions of R_{ir/x} space. It is possible that the remainder of the complete IRAS samples picked out AGN that live in e.g. the top-left of Fig. 2, i.e. low L_x and large L_{ir}. However, an additional ~20% IRAS AGN had 0.2 – 4.0keV Einstein X-ray flux measurements, yielding similar values of R_{ir/x} to those in Fig. 9 (see also Green, Anderson & Ward (1992) and Boller et al. (1992)). The sample of AGN studied by Tueller et al. (2008) is not limited by X-ray absorption, so it is useful to consider the range of R_{ir/x} spanned by these AGN. Fig. 10 is as Fig. 2 but indicates those AGN from Tueller et al. (2008). Once again, it is clear that this
sample spans the existing ranges of $R_{ir/x}$ space and does not stake out otherwise unoccupied regions.

In order to test the effect of AGN redshift on our sample, we studied an independent sample of 150 additional high-z AGN observed from deep surveys with XMM-Newton and Chandra (Miyaji et al. 2004; Polletta et al. 2006; Tajer et al. 2007). At the high redshifts of AGN in the deep surveys (typically $z \sim 1$), an observed IR luminosity at 24$\mu$m corresponds approximately to an AGN-frame 12$\mu$m IR luminosity (see e.g. Treister, Krolik & Dullemond (2008)) and a 2-10 keV X-ray luminosity corresponds to an AGN-frame 4–20 keV X-ray luminosity (which will typically lie within a factor of a few of the actual 2-10keV luminosity), so luminosity ratios $R_{ir/x}$ for these deep AGN will systematically be a factor of a few higher on average than for the local AGN in Fig. 3.

From Fig. 11, even without considering the systematic overestimate of $R_{ir/x}$ above, the high z AGN appear to closely follow the luminosity ratio for the Group 1 AGN in Fig. 3 and very few lie in the Group 2 AGN region (8/150 have $R_{ir/x} > 100$) or in the blank areas of our luminosity plot. While there are clearly many caveats to using such deep survey data (not least assumptions about the AGN SED shape based on the IR spectrum), it is intriguing that, even with our very simple approach, the deep survey points should follow very closely the low-z Group 1 AGN dispersion and not fill blank regions of the luminosity ratio plots. It is also comforting that our main distribution of Group 1 AGN in Fig. 3 is also consistent with the dispersion of the population of AGN in Mushotzky et al. (2008), which, since the X-rays are 14-195keV, should be independent of X-ray absorption.

6 DISCUSSION

Much of the IR emission from active galactic nuclei should come from reprocessed X-ray emission. There should also be
some component of intrinsic IR emission in the SED (including non-thermal IR; although we shall ignore the complication of jets in the following discussion) and any remaining nuclear IR emission should be due to star formation in the thick dust in the nucleus. Whether the dust lives in a torus (doughnut) or in clumps, we can characterize the IR emission from ‘active’ nuclei (without prominent jets) as:

\[
L_{\text{IR}} = L_{\text{AGN}} + L_{\text{stars}}
\]

\[
= L_\times g_{\text{init}} [g_{\text{sed}} + \left( \frac{\Omega}{4\pi} \right) g_{\text{repro}} f_{\text{bol}}] + L_{\text{stars}}
\]

(1)

where \(g_{\text{init}}\) is a numerical factor from converting \(L_\times\), the 2-10keV intrinsic X-ray luminosity to the same units as \(L_{\text{IR}}\), \(g_{\text{sed}}\) is a factor corresponding to intrinsic IR emitted by the AGN (normalized to \(L_\times\)), \(\Omega/4\pi\) is the covering factor of the reprocessing material, \(g_{\text{repro}}\) is the fraction of the 2-10keV radiation absorbed, \(g_{\text{repro}}\) is a factor depending on the details of the reprocessing physics (including dust size & chemistry), \(f_{\text{bol}}\) is the fraction of the bolometric luminosity absorbed by the cool dust.

For most group 1 AGN we expect, \(L_{\text{AGN}} \gg L_{\text{stars}}\), so the observed luminosity ratio for most group 1 AGN should be

\[
\frac{L_{\text{IR}}}{L_\times} \approx R_{1/\text{gal}} [g_{\text{sed}} + \left( \frac{\Omega}{4\pi} \right) g_{\text{repro}} f_{\text{bol}}]
\]

(2)

where \(R_{1/\text{gal}}\) is the ratio of intrinsic to observed 2-10keV X-ray luminosity and is a function of the column of X-ray absorbing material along the observers’ sightline. From Figs. 3 and 4 the dispersion in \(R_{1/\text{gal}}\) for most (~90%) group 1 AGN is a factor of 30 or less. Therefore the total combined variation in all the multipliers in equation 2 must be less than thirty for most Group 1 AGN. The factor \(f_{\text{bol}}\) is a function both of the covering fraction of the reprocessing material and its column density (\(f_{\text{bol}} = 1/f_{\text{Xabs}}\)). Using XSPEC, we tested the effect of column density on \(f_{\text{bol}}\) by investigating the change in X-ray energy for absorbing column density in the range \(N_H = [10^{19}, 10^{24}]\text{ cm}^{-2}\). We found that a factor of 10\(^7\) increase in absorbing column density, only produced a factor of five in the X-ray energy absorbed (similar to the results of Pier & Krolik (1993) and Efstathiou et al. (2000)). So a ‘naked’ Group 1 AGN without substantial amounts of absorbing material (e.g. a torus) in its environment, should have an IR flux only \(\sim 1/5\)th that of a Group 1 AGN surrounded by substantial amounts of dust (not necessarily in the sightline). Therefore, a total dispersion of \(1 < R_{1/\text{gal}} < 30\) for most Group 1 AGN, will include a factor of \(\lesssim 5\) for \(f_{\text{bol}}\), indicating that \(f_{\text{init}} [g_{\text{sed}} + g_{\text{repro}} f_{\text{bol}}] f_{\times}\) could vary collectively by as little as a factor of six, across all Group 1 AGN. Thus, the covering factor and fraction of absorbing material (clouds, torus, flared disk etc), the composition of the material (dust chemistry, abundance, size), the column density of the material and the SED X-ray to IR ratio in group 1 AGN collectively vary by a factor of thirty or less and possibly by as little as a factor of six. Note that this is a model-independent result. We have not assumed that the absorbers must either be in a torus or clouds or some combination. Such a tight dispersion among Group 1 AGN severely restricts models of accretion, geometry and physical conditions in AGN. These Group 1 AGN collectively span a range of \(\sim 10^3\) in central black hole mass (e.g. Peterson et al. (2004)), suggesting that independent of jets, the central engines of Group 1 AGN are quite remarkably similar. Again, it is worth noting that this remarkably small variation in AGN properties is based on observed quantities and is therefore model-independent.

Group 2 AGN, with associated star-forming regions, could have \(L_{\text{AGN}} < L_{\text{stars}}\) in equation 1. Furthermore, Fig. 6 indicates that the ratio of cold dust to warm dust (indicative of star formation) is an order of magnitude larger in group 2 AGN than in group 1 AGN. The fact that dispersion in \(R_{1/\text{gal}}\) is 2-3 orders of magnitude larger for Group 2 AGN than for Group 1 AGN, indicates either that (a) observed \(L_\times \ll \text{intrinsic } L_\times\) or that (b) \(L_{\text{stars}} \gg L_{\text{AGN}}\) in Group 2 AGN or both. Mushotzky et al. (2008) find that the intrinsic X-ray luminosity for Group 2 AGN is comparable to that for Group 1 AGN, so in most cases observed \(L_\times\) is probably substantially lower than intrinsic \(L_\times\). It is also possible that \(L_{\text{stars}}\) is intrinsically greater in group 2 AGN than in group 1 AGN.

7 CONCLUSIONS

Our aim was to compare common observed AGN properties that encompass the continuum of AGN activity in an effort to, if possible, derive model-independent constraints on AGN structure and the accretion neighbourhood. We studied the observed X-ray to IR luminosity ratios of a heterogeneous sample of 245 galaxies from the literature and, in spite of our simple approach, AGN variability and non-simultaneity of most of the data, we found strong trends.

Fig. 3 reveals the emergence of observed ‘activity’ at \(L_{\text{IR}} / L_\times > 10^{42}\text{ ergs}^{-1}\). Below these luminosities, AGN may compete with X-ray and IR emitters in the host galaxy (such as ULXs, see e.g. Miniutti et al. (2006)) or may be obscured by large columns of absorbing material. Since emission from jets considerably complicates our interpretation of the observed luminosity ratios, we only considered those AGN without prominent observed jets. We find that AGN considered ‘face-on’ or unobscured in the standard model (our group 1) are tightly clustered by observed luminosity ratio (~90% have \(1 < R_{1/\text{gal}} < 30\)), indicating that there is very little variation between individual group 1 AGN in: (a) intrinsic SED (i.e. accretion flow, whether ADAF, turbulent disk or both), (b) solid angle of the reprocessing \((X \rightarrow IR)\) absorber (whether clouds, torus, flared-disk or some combination) and (c) details of the absorbing material (chemistry & dust grain sizes). Thus, Fig. 3 demonstrates that underlying Group 1 AGN is a remarkably uniform phenomenon.

Fig. 3 shows a clear difference in \(R_{1/\text{gal}}\) between unobscured AGN (group 1) and obscured & low luminosity AGN (our group 2). Despite the fact that our sample is not complete, our findings for the dispersion of AGN are confirmed in a comparison with other, independent AGN samples (e.g. Toller et al. (2008); Mushotzky et al. (2008), which are not limited by X-ray absorption, or Tajer et al. (2007); Polletta et al. (2006); Mivault et al. (2004) from \(z \sim 1\)). Furthermore, subsets of our sample of 245 AGN are derived from complete IRAS samples (Sanders et al. 2003; Rush et al. 1993) and these subsets at least do not span values of \(R_{1/\text{gal}}\) different from the rest of our sample. Bias is of course a potential problem with any approach such as ours, but it is comforting that we can find some independent verification for our simple, model-independent approach. Es-
of the intrinsic 2-10 keV luminosity for Compton-thick AGN from very hard X-ray (absorption independent) observations (e.g. Tueller et al. (2008); Matt et al. (1999); Itoh et al. (2008)) reveal that the intrinsic luminosity ratio is consistent with the group 1 AGN (in agreement with the findings of e.g. Lutz et al. (2001); Krabbe et al. (2001); Horst et al. (2007); Mushotzky et al. (2008)). However, unlike Lutz et al. (2001); Krabbe et al. (2001); Horst et al. (2007) we have endeavoured to avoid the highly model-dependent business of estimating intrinsic 2-10keV X-ray luminosity of group 2 AGN based on the 2-10keV observed luminosity. We also studied the far-IR to mid-IR luminosity ratios of the nuclei in our sample. We found that the 100μm to 12μm luminosity ratio (L_{100μm}/L_{12μm} ~ 1) is an extremely effective separator of the group 1(unobscured) and group 2 (obscured & low luminosity) populations (see Fig.1). Using archetypal AGN as a guide, this plot ranks group 2 AGN in order of decreasing luminosity ratio for increasing obscuration.

In principle our approach could be applied to intermediate mass black holes (IMBHs) and Galactic black hole candidates (GBHCs) to investigate the accretion environment around black holes on all mass scales. The outstanding question is whether reprocessing material around IMBHs and GBHCs is substantially different in covering factor, structure, chemistry or reprocessing details from that around AGN. Are a flared disk or dusty torus associated with a SMBH? Are a flared disk or dusty torus associated with a minimum mass scale, or are we looking at a basically identical phenomenon across 7-8 orders of magnitude in mass?

ACKNOWLEDGEMENTS

We gratefully acknowledge support from NASA grant GO6-7085B(BM). We made extensive use of the NASA/IPAC Extragalactic Database (NED), operated by the Jet Propulsion Laboratory, CalTech, under contract with NASA. We gratefully acknowledge very helpful discussions with Tahir Yaqoob who helped inspire this work and with Sylvain Veilleux who provided useful insights into heterogeneous samples and samples of IR-observed AGN. BM & KESF gratefully acknowledge the support of the Department of Astrophysics of the American Museum of Natural History and PSC-CUNY grants PSCOOC-38-99 and PSCOOC-38-98 respectively.

REFERENCES

Antonucci R. R. J., 1993, ARA&A, 31, 473
Bian W. & Zhao Y., 2003, MNRAS, 343, 164
Boller Th., Meurs E.J.A., Brinkmann W., Fink H., Zimmermann U. & Adorf H.-M., 1992, A&A, 261, 57
Bonatto C., Pastoriza M.G., Alloin D. & Bica E., 1998, A&A, 334, 439
Boroson T.A. & Green R.F., ApJS, 80, 109
Botte V., Ciroi S., diMille F., Rafanelli P. & Romano A., 2005, MNRAS, 356, 789
Buchanan C.L., Gallimore J.F., O’Dea C.P., Baum S.A., Axon D.J., Robinson A., Elitzur M. & Elvis M., 2006, ApJ, 132, 401

Estathion A. & Rowan-Robinson M., 1995, MNRAS, 273, 649
Estathion A., Rowan-Robinson M. & Siebenmorgen R., 2000, MNRAS, 313, 734
Eracleous M. & Halpern J.P., 1994, ApJS, 90, 1
Foschini L. et al. 2006, A&A, 453, 829
Gonzalez Delgado R. M., Perez E., Tadhunter C., Vilchez J.M. & Rodriguez-Espinoza J.M., 1997, ApJS, 108, 155
Green P. J., Anderson S.F. & Ward M.J., 1992, MNRAS, 254, 30
Grue B., Beuermann K., Mannheim K. & Thomas H.-C., 1999, A&A, 350, 805
Ho L., Fillipenko A.V. & Sargent W.L.W., 1997, ApJ, 487, 568
Horst H., Ghandi P., Smette A. & Duschl W.J., 2007, A&A (accepted), astro-ph/0711.3734
Itoh T. et al. 2008, PASJ, 60, 251
Krabbe A., Böker T. & Maiolino R., 2001, ApJ, 557, 626
Kraft R. P. et al. 2000, ApJ, 531, 9
Kukula M. J., Dunlop J.S., Hughes D.H. & Rawlings S., 1998, MNRAS, 297, 366
Leighly K., 1999, ApJS, 125, 317
Lutz D., Maiolino R., Spoon H. W. W. & Moorwood A. F. M. 2004, A&A, 418, 465
Malizia A., Bassani L., Zhang S.N., Dean A.J., Paciesas W.S. & Palumbo G.G.C., 1999, ApJ, 519, 637
Markowitz A. & Edelson R., 1999, ApJ, 617, 939
Matt G. et al. 1999, A&A, 341, L9
Mas-Hesse J.M., Oti-Floranes H. & Cervino M., 2008, A&A, 483, 71
McKernan B. & Yaqoob T., 1998, ApJ, 501, L29
McKernan B., Yaqoob T. & Reynolds C. S., 2007, MNRAS, 379, 1359
Miller P., Rawlings S. & Sanders R., 1993, MNRAS, 263, 425
Miller L., Turner T.J. & Reeves J.N., 2008, MNRAS, 483, 437
Miniutti G. et al. 2006, MNRAS, 373, L1
Miyaji T., Sarajedini V., Griffiths R.E., Yamada T., Schurch M., Cristobal-Hornillos D. & Motohara K., 2004, AJ, 127, 3180
Mushotzky R. F., Winter L.M., McIntosh D.H. & Tueller J., 2008, ApJL (accepted), astro-ph/0807.4695
Nagar N. M., Falcke H., Wilson A.S., 2005, A&A, 435, 521
Pier E. A. & Krolik J. H., 1993, ApJ, 418, 673
Perola G.C., Matt G., Cappi M., Fiore F., Guainazzi M., Polletta M. del C., et al.

Miller P., Rawlings S. & Saunders R., 1993, MNRAS, 263, 425
Miller L., Turner T.J. & Reeves J.N., 2008, MNRAS, 483, 437
Miniutti G. et al. 2006, MNRAS, 373, L1
Miyaji T., Sarajedini V., Griffiths R.E., Yamada T., Schurch M., Cristobal-Hornillos D. & Motohara K., 2004, AJ, 127, 3180
Mushotzky R. F., Winter L.M., McIntosh D.H. & Tueller J., 2008, ApJL (accepted), astro-ph/0807.4695
Nagar N. M., Falcke H., Wilson A.S., 2005, A&A, 435, 521
Pier E. A. & Krolik J. H., 1993, ApJ, 418, 673
Perola G.C., Matt G., Cappi M., Fiore F., Guainazzi M., Maraschi L., Petrucci P.O. & Piro L., 2002, A&A, 389, 802
Peterson B. M. et al. 2004, ApJ, 613, 682
Polletta M. del C. et al. 2006, ApJ, 642, 673
Porquet D., Reeves J.N., Markowitz A., Turner T.J., Miller L. & Nandra K., 2007, A&A, 466, 23
Revnivtsev M., Sazonov S., Jahoda, K. & Gilfanov M., 2004, A&A, 418, 927
Risaliti G., Elvis M. & Nicastro F., 2002, ApJ, 571, 234
Rush B., Malkan M.A. & Spinoglio L., 1993, ApJS, 89, 1
Sanders D.B., Mazzarella J.M., Kim D.C., Surace J.A. & Sofue Y., 2003, AJ, 126, 1607
Schade D.J., Boyle B.J. & Letawsky M., 2000, MNRAS, 315, 498
Shinozaki K., Miyaji T., Ishitaki Y., Ueda Y. & Ogasaka Y., 2006, AJ, 131, 2843
Sirocky M. M., Levenson N. A., Elitzur M., Spoon H. W. W. & Armus L., 2008, ApJ, 678, 729
Smith D.A. & Done C., 1996, MNRAS, 280, 355
Spergel D.N. et al. 2003, ApJS, 148, 175
Tajer M. et al., 2007, A&A, 467, 73
Treister E., Krolik J. H. & Dullemond C., 2008, ApJ, 679, 140
Tueller J., Mushotzky R.F., Barthelmy S., Cannizzo J.K., Gehrels N., Markwardt C.B., Skinner G.K. & Winter L. M., 2008, ApJ, 681, XXX (astro-ph/0711.4130)
Turner T. J., George I.M., Nandra K. & Turcan D., 1999, ApJ, 524, 667
Veilleux S.B. & Osterbrock D.E., 1987, ApJS, 63, 295
Voges W., 1993, AdSpR, 13, 391
Winter L. M., Mushotzky R.F., Tueller J. & Markwardt C., 2008, ApJ, 674, 686