The AGN contribution to deep submillimetre surveys and the far-infrared background

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ABSTRACT

A great deal of interest has been generated recently by the results of deep submillimetre surveys, which in principle allow an unobscured view of dust-enshrouded star formation at high redshift. The extragalactic far-infrared and submillimetre backgrounds have also been detected, providing further constraints on the history of star formation. In this paper we estimate the fraction of these backgrounds and source counts which could be explained by AGN. The relative fractions of obscured and unobscured objects are constrained by the requirement that they fit the spectrum of the cosmic X-ray background. On the assumption that the spectral energy distributions of high redshift AGN are similar to those observed locally, we find that one can explain $10^{-20\%}$ of the 850$\mu$m SCUBA sources at 1mJy and a similar fraction of the far-infrared/submillimetre background. The exact contribution depends on the assumed cosmology and the space density of AGN at high redshift ($z > 3$), but we conclude that active nuclei will be present in a significant (though not dominant) fraction of the faint SCUBA sources. This fraction could be significantly higher if a large population of AGN are highly obscured (Compton-thick) at X-ray wavelengths.

Key words: galaxies: active – quasars: general - diffuse radiation - X-rays: general – galaxies: evolution – cosmology: early Universe

1 INTRODUCTION

Deep submillimetre observations offer the potential to revolutionise our understanding of the high redshift Universe. Longward of 100$\mu$m, both starburst galaxies and AGN show a very steep decline in their continuum emission, which leads to a large negative K-correction as objects are observed with increasing redshift. This effectively overcomes the ‘inverse square law’ to pick out the most luminous objects in the Universe to very high redshift (Blain & Longair 1993). Since the commissioning of the SCUBA array at the James Clerk Maxwell Telescope a number of groups have announced the results from deep submillimetre surveys, all of which find a high surface density of sources at 850$\mu$m (Smail et al 1997, Hughes et al 1998, Barger et al 1998, Eales et al 1998, Blain et al 1999). The implication is the existence of a large population of hitherto undetected dust enshrouded galaxies. In particular, the implied star-formation rate at high redshift ($z > 2$) could be significantly higher than that deduced from uncorrected optical-UV observations (Hughes et al 1998). The recent detections of the far-infrared/submillimetre background by the DIRBE and FIRAS experiments (Puget et al 1996, Fixsen et al 1998, Hauser et al 1998) provide further constraints, representing the integrated far-infrared emission over the entire history of the Universe (Dwek et al 1998). Since most of this background has now been resolved into discrete sources by SCUBA, the implication is that most high redshift star-forming activity occurred in rare, exceptionally luminous systems.

In this paper we investigate the possible contribution from AGN to both the far-infrared/submillimetre background and the SCUBA source counts at 850$\mu$m. The deep SCUBA sources in particular are believed to be the high redshift equivalents to local Ultra-Luminous Infrared Galaxies (ULIRGs; Sanders & Mirabel 1996) and hence a large AGN fraction may not be a surprise. Our strategy is to predict faint submillimetre counts based on our knowledge of the AGN luminosity function and its evolution, together with an assumed spectral energy distribution (SED). We take account of the likely population of obscured AGN, using models which reproduce the spectrum of the hard X-ray background (XRB).

2 OBSCURED AGN AND THE X-RAY BACKGROUND

Locally it is clear that a large fraction of AGN are obscured by gas and dust. Obscured (e.g. narrow-line) AGN are believed to outnumber unobscured (e.g. broad-line) objects by a factor of ~ a few, with significant uncertainties depending on the selection techniques and the assumptions made (Lawrence 1991, Huchra & Burg 1992, Osterbrock & Martel 1993). It is now important to understand whether this ratio continues to high redshifts and luminosities. Radio emission is unaffected by obscuration, and among radio-loud objects
at least there is clear evidence that narrow-line radio galaxies are common to very high powers and redshifts. Furthermore, recent deep X-ray surveys using ROSAT, ASCA and Beppo-SAX have detected substantial numbers of 'narrow-line X-ray galaxies', many of which show very clear evidence for obscured AGN activity (Boyle et al 1995, Almaini et al 1995, Ohta et al 1996, Iwasawa et al 1997, Boyle et al 1998, Schmidt et al 1998, Fiore et al 1999). It seems likely that this is the 'tip of the iceberg' of a large population of obscured AGN, full confirmation of which will soon be possible with the next generation of X-ray satellites (e.g. AXAF and XMM).

There is increasing evidence that these obscured AGN are responsible for the production of the hard XRB. At soft X-ray energies (below 2keV) almost all of the XRB has been resolved into discrete sources, most of which turn out to be broad-line QSOs (Shanks et al 1991), but the X-ray spectra of ordinary QSOs are too steep to explain the XRB at higher energies. The energy density of the XRB actually peaks at $\sim$30keV, where ordinary broad-line QSOs can account for only $\sim$20% (Fabian et al 1998). Obscured AGN provide a very natural explanation, since photoelectric absorption allows only the hard X-rays to penetrate (Setti & Woltjer 1989). Models have been developed which provide very good fits to both the XRB spectrum, X-ray source counts and the local distribution of absorbing columns (Comastri et al 1995, Miyaji et al 1998). The implication is that most of the energy density generated by accretion in the Universe takes place in obscured AGN. As outlined by Fabian & Iwasawa (1999) this hidden population could explain the apparent discrepancy between predicted present day black hole densities and the observations of Magorrian et al (1998).

### 3 THE AGN LUMINOSITY FUNCTION

#### 3.1 Type 1 AGN

Our predictions are based on the X-ray luminosity function of Boyle et al (1994), which we take to represent the baseline population of unobscured (Type 1) AGN. Since the optical/UV spectra of these AGN all show broad emission lines, and the X-ray spectra show no evidence for photoelectric absorption (Almaini et al 1996) we can safely assume that this sample includes only unobscured objects (e.g. $N_H < 10^{22} \text{cm}^{-2}$). This luminosity function was modelled with a broken power law of the form:

$$
\Phi_X(L_X) = \begin{cases} 
\Phi_X^* L_X^{-\gamma_1} & L_X < L_X^* \\
\Phi_X^* (\frac{L_X}{L_X^*})^{\gamma_2 - \gamma_1} L_X^{-\gamma_2} & L_X > L_X^* 
\end{cases}
$$

(1)

where $\gamma_1$ and $\gamma_2$ represent the faint and bright end slopes of the XLF respectively and $L_X^*$ is the $0.3-3.5$ keV luminosity expressed in units of $10^{42} \text{erg s}^{-1}$. A good fit to the evolution of this luminosity function was obtained with a Pure Luminosity Evolution (PLE) model out to a maximum redshift $z_{\text{max}}$:

$$
L_X^*(z) = \begin{cases} 
L_X^*(0) (1+z)^k & z < z_{\text{max}} \\
L_X^*(z_{\text{max}}) & z > z_{\text{max}} 
\end{cases}
$$

(2)

The best fitting parameters were $z_{\text{max}} = 1.6(1.79)$, $k = 3.25(3.34)$, $\gamma_1 = 1.36(1.53)$, $\gamma_2 = 3.37(3.38)$, $L_X^* = 10^{43.57(43.70)}$, and $\Phi_X^* = 1.59(0.63) \times 10^{-6} \text{Mpc}^{-3}$ for a cosmology with $\Omega_0 = 0.5(0.0)$ and $H_0 = 50 \text{km s}^{-1} \text{Mpc}^{-1}$. Further details can be found in Boyle et al (1994) (models S & T).

#### 3.2 Correction for obscured AGN

To constrain the relative fractions of obscured and unobscured objects we use the Comastri et al (1995) population synthesis model for the XRB. In this model a population of obscured AGN with a range of column densities are added to the unobscured population in order to obtain good fits to the XRB spectrum and the X-ray source count distribution. Excellent fits to the hard XRB were obtained by assuming a simple model in which the space density of obscured objects and the distribution in obscuring column densities are free parameters. The best fit was obtained with a ratio of obscured to unobscured AGN ($N_H < 10^{22} \text{cm}^{-2}$) in the range 2.4 – 3.7, in very good agreement with local observations (see Section 2). Although the affects of the photoelectric absorption on the X-ray source counts are complicated, in the submillimetre regime the gas and dust is transparent. We therefore simply scale the unobscured QSO luminosity function as follows:

$$
\Phi_{\text{obscured}} = 3 \times \Phi_{\text{unobscured}}
$$

(3)

#### 3.3 The high redshift evolution

At the highest redshifts ($z > z_{\text{max}}$) the X-ray luminosity function of Boyle et al (1994) is formally consistent with being constant, but beyond $z = 3$ there are very few QSOs in this survey. Optical surveys for bright QSOs find evidence for an exponential decline in the QSO space density towards high $z$, parameterised as follows by Schmidt, Schneider & Gunn (1995):

$$
\Phi(z) = \Phi(2.7) e^{(2.7-z)} \quad z > 2.7
$$

(4)

Similar results were found by Hewett et al (1993). The reality of this exponential decline is unclear, however. We note that these optically derived surveys may be seriously underestimating the high redshift QSO population because of intervening absorption along the line of sight. This is discussed further in Section 5. We therefore consider two models for the high redshift evolution. For Model A we use the exponential decline given by Equation 4, while for Model B we consider the possibility that the space density of QSOs is constant to $z = 5$ (with an exponential decline thereafter), in good agreement with the findings of the Ultra-Deep X-ray Survey by Hasinger (1998).

### 4 THE THERMAL FAR-INFRARED SPECTRAL TEMPLATE

In radio-quiet AGN there is significant evidence that the far-infrared/submillimetre emission is dominated by thermal re-radiation from dust (Carleton et al 1987, Hughes et al 1993). To model this spectrum, we use the best fitting spectral energy distribution obtained by Hughes, Davies & Ward (1998), who have obtained the largest collection of far-infrared and submillimetre observations of local AGN. They find that the 50 – 1300$\mu$m emission is consistent with thermal re-radiation from dust at a temperature of 35 – 40K. This can be modelled by an isothermal grey-body curve:

$$
f_{\nu} \propto \frac{\nu^{3+\beta}}{\exp(h\nu/kT) - 1} \quad \lambda > 50\mu m
$$

(5)

in which $T$ is the temperature of the dust and $\beta$ is the emissivity index, derived by assuming that the grey-body is transparent to its own emission. Best fitting values were found to be $\beta = 1.7 \pm 0.3$ and $T \sim 37 \pm 5K$ (see Hughes, Davies & Ward 1998 for full details). We note that strikingly similar temperatures have recently
been reported for high redshift AGN by Benford et al (1998). At mid-infrared wavelengths they approximate the spectrum with a power law of the form $f_\nu \propto \nu^{-1.3}$. In order to normalise these SEDs to our X-ray luminosity function, we use the mean far-infrared to X-ray relationship determined for a large sample of broad-line, radio-quiet quasars by Green, Anderson & Ward (1992). A major source of uncertainty in our method is clearly the extrapolation of these local SEDs to AGN at high redshift. Accurate far-infrared and submillimetre photometry of high redshift, X-ray selected QSOs would help to resolve this issue, which will certainly be possible with SCUBA and future submillimetre detectors. If these AGN contain more isotropically distributed dust they may well turn out to be brighter at these wavelengths, which could boost the source predictions significantly.

5 THE SUBMILLIMETRE COUNT PREDICTIONS

Using the SED defined above, combined with the evolving X-ray luminosity function from Section 3, one can predict the AGN submillimetre counts at 850\,\mu m. The results are shown in Figure 1 for two different cosmologies, where we compare with the total SCUBA detections from recent deep surveys. We note that a more recent model for the XRB has recently been produced by Miyaji et al (1998), based on the Ultra-Deep Lockman Hole survey of Hasinger (1998). In this survey they find that a Luminosity Dependent Density Evolution (LDDE) model provides a better fit to the evolution of the AGN luminosity function. Using model parameters provided by Miyaji (private communication) we find submillimetre counts predictions which are approximately 40% higher than shown in Figure 1 at the flux densities of the SCUBA surveys.

In using these luminosity functions, we integrate over the luminosity range $10^{42} < L_x < 10^{48}$\,erg\,s$^{-1}$. Integrating to higher luminosities make no significant difference, due to the very low space density of such sources. There is, of course, significant evidence that AGN activity continues to fainter luminosities (e.g. Ho, Filipenko & Sargent 1997) but this also makes no difference to our predictions. At an 850\,\mu m limit of 1\,mJy there is no significant contribution from QSOs below a luminosity of $L_x \sim 10^{43}$\,erg\,s$^{-1}$.

A major source of uncertainty in determining these predictions is the space density of AGN at high redshift ($z > 3$). For Model A we adopt the conservative assumption that $\Phi$ declines exponentially above redshift $z = 2.7$, in the same manner as determined for bright optical QSOs (Schmidt, Schneider & Gunn 1995). To illustrate the importance of the high redshift space density, we also plot the extreme case where $\Phi$ does not decline beyond $z = 2.7$, but instead remains constant out to a maximum redshift of $z = 5$ (Model B). The exact behaviour in the QSO space density at high redshift makes little difference to the XRB but due to the negative K-correction the predictions in the submillimetre waveband are altered considerably. As discussed in Fall & Pei (1993), because of dust along the line of sight in damped Ly$\alpha$ absorption systems, existing optical QSO surveys may be seriously incomplete at high redshift, with possibly up to 90% missing at $z = 4$. Radio emission is unaffected by such absorption, and the high redshift decline seen in the radio-loud population would seem to argue against any serious incompleteness (Shaver et al 1996, Dunlop 1997). We note, however, that recent results from the deepest X-ray surveys seem to suggest that the space density of QSOs remains constant out to $z \sim 5$ (Hasinger 1998). We conclude that the exact form of high redshift evolution remains uncertain, but the reality is likely to lie somewhere between Models A and B. It is worth noting that the $n(z)$ distribution of submillimetre selected quasars will in principle allow a very sensitive discriminant between these competing models (see also Blain et al 1999).

It is clear from Figure 1 that a sizeable fraction of the existing submillimetre sources can be explained by AGN. Taking the 1\,mJy detection by Blain et al (1999), for example, the $q_0 = 0.0$ Models A and B account for 9 and 19 per cent of the sources respectively. The $q_0 = 0.5$ models give very similar source counts at brighter fluxes but flatten considerably at the faint end, accounting for only 7 and 13 per cent of the counts at 1\,mJy. The uncertainties in our method could account for a factor of $\sim$ a few in either direction, but nevertheless we conclude that a significant (though not dominant) fraction of the recent SCUBA detections will contain an AGN. As discussed in Section 7, however, these predictions are almost certainly lower limits since they do not include Compton-thick AGN.

6 AGN AND THE FAR-INFRARED/SUBMILLIMETRE BACKGROUND

As discussed in Section 2, there is now growing evidence that AGN could account for the majority of the X-ray background. Recent analysis of COBE FIRAS data has also led to the first detections of an extragalactic component to the far-infrared/submillimetre background ($100 \sim 1000$\,\mu m; Puget et al 1996, Fixsen et al 1998). At present there are considerable uncertainties involved in the subtraction of galactic emission, zodiacal light and the cosmological microwave background, but by a variety of independent techniques Fixsen et al (1998) find a mean spectrum for the far-infrared background which can be parameterised by the following function:

$$L_\nu = 1.3 \pm 0.4 \times 10^{-5} (\nu/\nu_0)^{0.64\pm0.12} P_e (18.5 \pm 1.2 K)$$

where $\nu_0 = 100$\,cm$^{-1}$ and $P_e$ is the Planck function. The nature of this radiation is still unclear, but at 850\,\mu m most of the background has now been resolved into discrete sources by SCUBA (e.g. see Blain et al 1999). Using the models outlined above we can explicitly calculate the potential contribution from galaxies containing bright AGN. Extrapolating down to an 850\,\mu m flux limit of 0.01\,mJy the resulting background contributions are shown in Figure 2. With a conservative estimate for the space density of AGN, one can explain $\sim 10$ per cent of the far-infrared/submillimetre background. With a higher space density of AGN (Model B) the contribution increases, particularly towards longer wavelengths, with $\sim 20$ per cent of the background at 850\,\mu m.

7 COMPTON-THICK AGN

In the arguments above, we constrain the relative contributions of obscured and unobscured AGN using population synthesis models which reproduce the spectrum of the XRB. Above a critical column density of $\sim 10^{21}$ to $10^{22}$ atom cm$^{-2}$, however, the obscuring medium
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Figure 1. Predicted AGN number counts compared with recent SCUBA measurements of the total submillimetre source density at 850\,\mu m. The unfilled circle is taken from an estimate of the source density at 1mJy based on a fluctuation analysis (Hughes et al 1998). In Model A (dashed lines) we adopt the conservative assumption that the AGN space density, $\Phi$, declines exponentially beyond $z = 2.7$. Model B (dotted lines) assumes a constant $\Phi$ out to $z = 5$.

8 CONCLUSIONS

There is growing evidence that obscured AGN are responsible for most of the cosmic XRB. Using models for the XRB to constrain the relative fractions of obscured and unobscured AGN, combined with recent measurements of their far-infrared and submillimetre SEDs, we estimate the contribution of AGN to the far-infrared and submillimetre background. We also explicitly calculate the predicted source counts at 850\,\mu m, where a lot of excitement has been generated recently from the results of deep SCUBA surveys.

Several lines of argument lead to the conclusion that a significant fraction of the SCUBA detections will contain bright AGN. The very high far-infrared luminosities implied for these sources suggest that they are high redshift equivalents to local ULIRGs. At the luminosities of the recently discovered SCUBA sources ($L \sim 10^{12} L_\odot$) we note that 20 – 30\% of local ULIRGs show clear evidence for an AGN (e.g. Seyfert 1 or Seyfert 2), with a further similar fraction showing more ambiguous LINER activity (Sanders & Mirabel 1996). Our explicit calculations suggest that the AGN contribution in recent SCUBA surveys is likely to be at least 10 – 20\%, with the exact contribution depending on the assumed cosmology and the space density of AGN at high redshift. This estimate is constrained by the requirement that we fit the spectrum of X-ray background, and hence the fraction could be much higher if a large population of AGN are Compton-thick, as recently observed by BeppoSAX for local Seyferts (Maiolino et al 1998). Such AGN will may not be revealed even by AXAF or XMM.

If the dust is these AGN is heated by accretion processes, a significant AGN contribution may help to explain the apparent contradiction implied by the recent SCUBA surveys, namely that such a massive amount of star-formation at early epochs could very easily over-predict the abundance and metallicity of low-mass stars in the local Universe (Blain et al 1999). In many other ways a large AGN fraction is not a surprise. Of the very few high redshift submillimetre sources with good optical spectra, at least 3 show clear evidence for the presence of an AGN (e.g. Ivison et al 1998, Irwin et al 1998, Serjeant et al 1998).

The most puzzling question is the origin of the far-infrared emission in AGN themselves, even if these do explain a large fraction of the SCUBA sources. At these wavelengths the relative roles of AGN and starburst activity remain controversial, both in IR selected ULIRGs (Sanders & Mirabel 1996) and in quasars (Lawrence 1997). Is the dust heated by the AGN or a nuclear starburst? Both energy sources are clearly present in a large fraction of these objects. At mid-infrared wavelengths the AGN probably dominates but at 100\,\mu m the situation remains unclear (Sander & Mirabel 1996). Hence the emission seen in the far-infrared/submillimetre background, and from the recently detected SCUBA sources, could be entirely due to star forming activity, albeit with the interesting implication that a large fraction of the star...
formation in the early Universe took place in the cores of galaxies containing active quasars.

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