The mass density in black holes inferred from the X-ray background

A.C. Fabian and K. Iwasawa
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

ABSTRACT
The X-ray Background (XRB) probably originates from the integrated X-ray emission of active galactic nuclei (AGN). Modelling of its flat spectrum implies considerable absorption in most AGN. Compton down-scattering means that sources in which the absorption is Compton thick are unlikely to be major contributors to the background intensity so the observed spectral intensity at about 30 keV is little affected by photoelectric absorption. Assuming that the intrinsic photon index of AGN is 2, we then use the 30 keV intensity of the XRB to infer the absorption-corrected energy density of the background. Soltan’s argument then enables us to convert this to a mean local density in black holes, assuming an accretion efficiency of 0.1 and a mean AGN redshift of 2. The result is within a factor of two of that estimated by Haehnelt et al from the optically-determined black hole masses of Magorrian et al. We conclude that there is no strong need for any radiatively inefficient mode of accretion for building the masses of black holes. Furthermore we show that the absorption model for the XRB implies that about 85 per cent of accretion power in the Universe is absorbed. This power probably emerges in the infrared bands where it can be several tens per cent of the recently inferred backgrounds there. The total power emitted by accretion is then about one fifth that of stars.

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

1 INTRODUCTION
Many current models for the X-ray Background (XRB) assume that it is due to the summed emission from many Active Galactic Nuclei (AGN) with strong intrinsic absorption (Setti & Woltjer 1989; Madau et al 1994; Comastri et al 1995; Celotti et al 1995). In this case most X-ray emission from AGN in the Universe must be highly absorbed (Fabian et al 1998). Here we make a representative correction of the spectrum of the XRB in order to deduce the current radiation energy density of the XRB had absorption not been present. This is converted to a bolometric radiation density using the X-ray to bolometric ratio of a sample of unobscured AGN. Then from the simple cosmology-free argument of Soltan (1982) we convert this energy density into a mean mass density of black holes at the current epoch. Soltan (1982) took the quasar counts in the optical B-band for his estimate so was only using unobscured AGN. Our result exceeds his earlier estimate by a factor of about 7.5 and the upper limit of the more recent estimates of Chokshi & Turner (1992), which also use optical quasar counts, by a factor of 3. It agrees with the very recent estimate of Salucci et al (1998), based on X-ray source counts.

We show that the mean mass density of black holes is within a factor of two of direct estimates based on the detection of black holes in nearby galaxies. There is then no strong requirement for any significant mass build up in black holes from some radiatively inefficient mode of accretion. Most accretion power in the Universe is absorbed, and likely reradiated in the infrared wavebands. This has implications for the IR background and source counts.

2 THE MASS DENSITY IN BLACK HOLES
We model the spectrum of the XRB as

\[ I_\nu = 9 \times 10^{-0.4} \exp(-E/50 \text{ keV}) \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}. \]

This agrees with both the Marshall et al (1980) result (HEAO A2 spectra taken in the 3-60 keV band) above ~ 7 keV and that of Gendreau et al (1995) result (ASCA 0.5–7 keV spectra) below that energy. The \( EF_{E} \) spectrum then peaks at 30 keV with an intensity of 38.1 keV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). The major assumption made in this paper is that the XRB spectrum above 30 keV is unaffected by absorption. This is because the likely maximum photoelectric absorption
Figure 1. XRB spectrum (solid line) with the assumed unabsorbed spectrum of photon index 2 (dotted line). A typical AGN spectrum with reflection, in which the direct emission is a power law of photon index 2 with an exponential cutoff of 300 keV is shown by the dot-dash line, matching around the XRB peak. If unabsorbed quasars contribute 50 per cent of the XRB at 1 keV, then their contribution lies along the bottom of the figure.

for sources making a significant contribution to the XRB intensity occurs at column densities of about $2 \times 10^{24}$ cm$^{-2}$, which has little effect above 30 keV in the rest frame, and of course even less in redshifted sources. (We assume approximate Solar metallicity for absorption purposes.) At higher column densities the Thomson depth exceeds unity and Compton scattering significantly reduces the transmitted power at all energies (see e.g. Madau et al 1994). Such Compton-thick sources are therefore unlikely to play a major role in the XRB, although they may be significant in number (perhaps one third of all sources; Maiolino et al 1998).

We now assume that the intrinsic spectrum of the sources responsible for the XRB has a photon index of 2 and matches the above spectrum at its $E_F$ peak. A more complex spectrum including reflection can have a slightly higher intensity (Fig. 1), particularly if redshifted. The caveats noted so far mean that the true intrinsic spectrum is above the simple power-law estimate, by some small factor.

The unabsorbed 0.66-3.33 keV (2–10 keV in the assumed mean restframe redshift of 2, but with our adopted photon index this is independent of redshift) intensity of the sources is $I_0 = 9.8 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The unabsorbed radiation energy density is then $\mathcal{E}_r = 4\pi I_0/c = 4.1 \times 10^{-17}$ erg cm$^{-3}$ s$^{-1}$. To convert this to an unabsorbed bolometric radiation density, we note that the mean ratio of the 2–10 keV to bolometric luminosities for radio-quiet quasars in the compilation of spectral energy distributions of Elvis et al (1994) is 3.3 per cent (we convert from the tabulated monochromatic value of $L_X$ to the 2–10 keV value by multiplying by a factor of 1.6, using a photon index of 2; 6 out of every 7 objects have a luminosity ratio between 1 and 7.6 per cent). This is similar to the ratio of 2 per cent found using Ferland’s (1996) ‘Table AGN’ model, which reproduces emission line ratios well. Denoting this fraction as $(f/0.03)$, we find a total energy density of $\mathcal{E}_r = 4\pi I_0/fc = 1.2 \times 10^{-15}(f/0.03)^{-1}$ erg cm$^{-3}$ s$^{-1}$. If we now assume, following Soltan (1982), that this radiation has been produced by accretion at an efficiency of 10 per cent (noting that (comoving) radiation energy density decays as $1+z$ whereas mass density does not) we find a mass density

$$\rho = 10(1+z)\frac{\mathcal{E}_0}{c^2} = 4.1 \times 10^{-35} \text{ g cm}^{-3}.$$ 

This corresponds to $6 \times 10^{14} M_{\odot}$ Gpc$^{-3} = 6 \times 10^{3} M_{\odot}$ Mpc$^{-3}$. A redshift of 2 is used here (see Miyaji et al 1998 for a discussion of evolution models for X-ray observed AGN).

This mass density is much greater than Soltan’s original estimate and about three times higher than that estimated by Chokshi & Turner (1992) using optical counts of unobscured quasars. It is about half that estimated by Haehnelt et al (1998) from the product of the mean black hole mass to bulge mass, estimated from spectroscopic data on the cores of nearby galaxies by Magorrian et al (1998), and the mass density in galactic bulges (Fukugita et al 1998). The Haehnelt et al estimate is likely to be fairly uncertain since the method for black hole mass measurement of Magorrian et al may overestimate the masses. Our result agrees with the very recent, and more complicated, estimate of Salucci et al (1998) who use X-ray source counts together with other factors. If a further 50 per cent of sources are Compton-thick and, due to Compton down-scattering, contribute little to the XRB spectral intensity, then our estimate rises proportionately.

An important conclusion of our result is that the absorption-corrected XRB estimate and the more direct galaxy-core estimate of the local density of massive black holes are within a factor of two. There is thus no strong need to invoke very low efficiency accretion or any exceptional accretion flows. What is required is that most accretion power is absorbed by surrounding gas. This may require the geometries discussed by Fabian et al (1998).

The fraction which is unabsorbed, in the hard X-ray spectrum, is about 6 per cent of the total spectrum. Here we assume that all the optical and UV emission are absorbed and that the infrared emission from AGN is already due to reprocessing. The fraction is obtained by noting that only about one half the 0.1–60 keV intrinsic X-ray spectrum is transmitted to make the XRB spectrum (this is the ratio of the observed 0.1–60 keV intensity to that in the inferred unabsorbed spectrum). The ratio of the 0.1–60 keV to 2–10 keV fluxes for our assumed intrinsic spectrum is $r \sim 4$, so if the 2–10 keV flux is 3 per cent of the total flux of an AGN, the transmitted fraction of the XRB, assuming the spectrum of Fig. 1, is $fr/2 \sim 6$ per cent.

The spectrum of the observed XRB does turn up below 1 keV in part due to unabsorbed quasars and AGN, from the integration of ROSAT source counts (Hasinger et al 1993) contribute about half the total XRB intensity at 1 keV. This corresponds to about 10 per cent of the assumed intrinsic power-law spectrum so the total fraction of the accretion power emitted in the Universe which escapes unabsorbed is therefore about 16 per cent. If we further assume 50 per cent more AGN are Compton-thick with column densities above $2 \times 10^{24}$ cm$^{-2}$ (cf. Maiolino et al 1998) then this final number drops to about 12 per cent.
3 THE INFRARED BACKGROUND LIGHT

The absorbed intensity can now be used to estimate the IR background. Assuming the absorber to be dusty gas, we have found that at least 85 per cent of the emitted intrinsic flux for our adopted XRB spectrum is absorbed, or an intensity $I_{abs} = 0.85 J_0 / f \approx 3 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This is 3 nW m$^{-2}$ sr$^{-1}$, for comparison with the limits and detections derived of the infrared backgrounds derived and reviewed by Hauser et al (1998) and Fixsen et al (1998). If much of the absorbed flux emerges inward of 100µm, which requires a significant contribution occurring at redshifts much greater than 2, it will dominate the FIR background and source counts (see also Almaini, Lawrence & Boyle 1998). Wherever the reprocessed emission emerges, it corresponds to several tens per cent of the likely background in the 10–100µm infrared bands (Hauser et al 1998; Fixsen et al 1998) to most of the background longward of ~ 200µm, which is generally assumed to be dominated by the reprocessed radiation from stars. This means that the integrated intrinsic radiation from AGN is several tens per cent of that due to stars.

A check on this result is obtained by adapting an argument due to G. Hasinger (priv. comm.). Magorrian et al (1998) find that the mass of a central black hole $M_{BH}$ is about 0.006 times the mass of the host bulge $M_b$. If the present bulge mass is a fraction $a_b$ of the mass of the stars associated with that galaxy which have already burnt, then the total radiation emitted over time is $0.006 a_b^{-1} M_b c^2$, where it is assumed that one tenth of a star undergoes nuclear burning with an efficiency of 0.6 per cent. The total accretion energy radiated from the black hole, at an efficiency of 0.1, is $0.1 M_{BH} c^2 = 0.006 M_b c^2$. If the history of star formation and accretion are similar (see e.g. Boyle & Terlevich 1998), then the contribution of AGN to the background radiation density is $a_b$ times that of stars. For a Salpeter IMF extending to 0.4 $M_\odot$, $a_b \sim 0.2$. This fraction can be increased if the radiative efficiency of the accretion is higher (e.g. Kerr black holes) or the IMF is steeper than assumed, and decreased if the IMF is flatter and a large non-bulge stellar component is included.

4 DISCUSSION AND CONCLUSION

We have estimated the local mean mass density in black holes from the background light of AGN, correcting for the large absorption effects necessary to make typical AGN explain the XRB spectrum. Our result of $6 - 9 \times 10^5 M_\odot$ Mpc$^{-3}$ (the higher value includes a correction for Compton-thick sources) is within a factor of 2 to 1.5 of that estimated from direct optical studies of the cores of nearby galaxies. The range of uncertainty on our mass density estimate, based only on variations in the adopted spectral energy distributions for AGN, is also about a further factor of two.

The key assumptions are that a) the background above 30 keV is unaffected by absorption and b) the typical spectrum of high redshift, and also of absorbed AGN, are similar to that of the unobscured AGN used by Elvis et al (1994) in their compilation of spectral energy distributions. The first assumption is robust to reasonable changes in the relevant energy (e.g. going to 40 or 50 keV in Fig. 1 would have little effect on the final result). There is insufficient information to assess the second assumption, but we do note that it is plausible that the intrinsic X-ray emission region is unaffected by the absorption which is usually assumed to occur at much greater radii from the central black hole. Finally, the total X-ray intensity is reduced by about 30 per cent if the photon index drops to 1.5, but the contribution of reflection in all cases increases our estimate (by about 10 per cent for a photon index of 2).

We are concerned that the simple use of the Elvis et al (1994) spectral energy distribution for AGN leads to the UV emission being counted twice. This is because the infrared emission may be dominated by absorbed UV (and soft X-ray) emission (assuming that we view the UV source direct, but the absorbing matter which reradiates UV as infrared covers other lines of sight). If we omit the infrared emission from that distribution the bolometric luminosities drop by about one third. This increases $f \sim 0.05$ and decreases our mass density estimate by one third. It also means that the total absorbed fraction of the power drops to about 80 per cent.

In conclusion, the spectrum of the XRB provides a robust estimate of the total radiation emitted by AGN in the Universe. The agreement of the local black hole density resulting from the conversion of the implied energy density to mass with direct estimates from other wavebands indicates that there is no obvious need for some radiatively inefficient form of accretion. Most of the accretion power in the Universe has been absorbed and presumably reradiated in the infrared.

5 ACKNOWLEDGEMENTS

We thank Omar Almaini, Guenther Hasinger and Andy Lawrence for discussions and Elihu Boldt for comments. ACF thanks the Royal Society for support.

REFERENCES

Almaini O., Lawrence A., Boyle B., 1998, MNRAS submitted
Boyle B.J., Terlevich R.J., 1998, MNRAS, 293, L49
Celotti A., Fabian A.C., Chiaberge G., Madau P., 1995, MNRAS, 277 1169
Chokshi A., Turner E.L., 1992, MNRAS, 259, 421
Comaastro A., Setti G., Zamorani G., Hasinger G., 1995, AaA, 296, 1
Elvis M. et al 1994, ApJS, 95, 1
Fabian A.C., Barcons X., Almaini O., Iwasawa K., 1998, MNRAS, 297, L11
Ferland G., 1996, Hazy, A Brief Introduction to Cloudy, Univ. Kentucky, Dept Physics & Astronomy Int. Report.
Fixsen D.J., Dwek E., Mather J.C., Bennett C.L., Shafer R.A., 1998, ApJ, 508, 123
Fukugita M., Hogan C.J., Peebles P.J.E., 1998, ApJ, 503, 518
Gendreau K., et al 1995, PASJ, 47, L5
Haehnelt M.G., Natarajan P., Rees M.J., 1998, MNRAS, 300, 817
Hasinger G., Burg R., Hartner G., Schmidt M., Trumper J., Zamorani G., 1993, AaA, 275, 1
Hauser M. et al 1998, ApJ, 508, 25
Madau P., Ghisellini G., Fabian A.C., 1994, MNRAS, 270, L17
Magorrian J., et al 1998, AJ, 115, 2285
Maiolino R., et al 1998, AaA, 338, 781
Marshall F.E., Boldt E., Holt S.S., Miller R.B., Mushotzky R.F., Rose L.A., Rothschild R.E., Serlemitsos P.J., 1980, ApJ, 235, 4
Miyaji T., Hasinger G., Schmidt M., 1998, preprint, astro-ph/9809398
Salucci P., Szuszkiewicz E., Monaco P., Danese L., 1998, MNRAS submitted, astro-ph/9811102
Setti G., Woltjer L., 1982, AaA, 224, L21
Soltan A., 1982, MNRAS, 200, 115