Do nuclear starbursts obscure the X-ray Background?

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ABSTRACT

We propose a model for the source of the X-ray background (XRB) in which low luminosity active nuclei ($L \sim 10^{43}$ erg s$^{-1}$) are obscured ($N \sim 10^{23}$ cm$^{-2}$) by nuclear starbursts within the inner $\sim 100$ pc. The obscuring material covers most of the sky as seen from the central source, rather than being distributed in a toroidal structure, and hardens the averaged X-ray spectrum by photoelectric absorption. The gas is turbulent with velocity dispersion $\sim$ few $\times$ 100 km s$^{-1}$ and cloud-cloud collisions lead to copious star formation. Although supernovae tend to produce outflows, most of the gas is trapped in the gravity field of the starforming cluster itself and the central black hole. A hot ($T \sim 10^8 - 10^7$ K) virialised phase of this gas, comprising a few per cent of the total obscuring material, feeds the central engine of $\sim 10^7$ M$_\odot$ through Bondi accretion, at a sub-Eddington rate appropriate for the luminosity of these objects. If starburst-obscured objects give rise to the residual XRB, then only 10 per cent of the accretion in active galaxies occurs close to the Eddington limit in unabsorbed objects.

Key words: galaxies: active – X-rays: galaxies.

1 INTRODUCTION

The flat spectrum of the X-ray background (XRB) above 1 keV (Marshall et al 1980; Gendreau et al 1995; Chen, Fabian & Gendreau 1997) is not simply accounted for by the integration of known classes of source, which generally have much steeper spectra. A currently popular model invokes intrinsic absorption in active galaxies with which to flatten the observed X-ray spectrum (Setti & Woltjer 1989; Madau, Ghisellini & Fabian 1994; Celotti et al 1995; Comastri et al 1995). The intrinsic absorption must range from column densities of order $10^{22} - 10^{24}$ cm$^{-2}$, and must cover most (at least $\sim 2/3$) of the sky as seen by the source itself. The combination of different levels of absorption and redshift of the objects can then lead to the observed power-law background spectrum in the 1–10 keV band. The rollover in the spectrum at about 30 keV is due redshift acting on an intrinsic 100 keV break, such as is seen in nearby active galaxies (Zdziarski et al 1995).

The geometry of the obscuring material within a typical, X-ray background-contributing, active galaxy is unclear. The nucleus must be mostly surrounded by a typical column density of say $10^{23}$ cm$^{-2}$. If the material is freely orbiting the nucleus, then it should soon collide with itself, dissipate, and flatten into a disk, unless either a) the orbits are carefully arranged or b) there is sufficient energy to continually throw matter into a wide range of orbital inclinations. We note that what evidence there is for a torus of molecular material around active galaxies does not indicate that its high column density part covers much of the sky. Indeed, models where the obscuring material is extended on scales $\sim$ 100 pc (Granato et al 1997) account for the infrared properties of Seyfert galaxies more successfully than ones which postulate a thick compact (< 1 pc) torus (Pier & Krolik, 1992, 1993).

The first case a) may be accounted for by a warped disk. Pringle (1996) and Maloney, Begelman & Pringle (1996) have shown that the outer parts of irradiated accretion disks are unstable to warping, the final result of which is that much of the sky is covered by the warp. The details are currently uncertain as to whether most of the sky can be covered and whether such high column densities can be attained in the warped material. We do not pursue that further here. The second case b) may be accounted for by a nuclear starburst, the supernovae of which can provide the energy to push clouds around and so obscure the nucleus. It is that possibility we explore further here.

There is indeed much empirical evidence for a connection between nuclear starbursts and active galactic nuclei (Terlevich & Melnick 1985, Terlevich, Díaz & Terlevich 1990; Perry & Williams 1993, Heckman et al 1995, 1997; Maiolino et al 1997). The extra featureless ultraviolet continuum in Seyfert 2 galaxies (FC2) appears to be due to a nuclear

* Since the XRB has a flat spectrum right down to 1 keV, the fraction of sources with absorption exceeding $10^{21}$ cm$^{-2}$ must approach 90 per cent; see Section 3

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starburst (Terlevich & Cid-Fernandes 1995; Heckman et al 1997), Turner et al (1997, 1998) in a discussion of the absorption properties of Seyfert 2 galaxies propose that the starburst may be involved there. The striking similarity between the evolution of the luminosity density due to star formation (Madau et al 1996) and that due to QSOs (Boyle & Terlevich 1998, Dunlop 1998) also suggests a close link between star formation processes and the fueling of QSO accretion. In addition, some sort of starburst activity is inevitable when an AGN forms, since vast amounts of material (e.g., triggered by merging) are funneled into the core of the galaxy giving rise ultimately to the central engine. It is then likely that this extended obscuring starburst is a common feature of all AGN during at least some phase, although for the most massive and luminous objects it might last only for a short time.

We make here the proposal that the formation of massive stars in the inner \( \sim 100 \) pc of a central massive black hole is instrumental in both fuelling the central engine by accretion and obscuring it by distributing cold clouds all around that engine. Since most of the X-ray accretion power in the Universe emerges in the XRB (see e.g. Chen et al 1997) then it is in the obscured starburst mode that most of it takes place.

An obscuring starburst also accounts for the optical, narrow-line, appearance of a population of faint hard X-ray sources (NLXGs; Boyle et al 1995; Roche et al 1995; Carballo et al 1995; Griffiths et al 1996; McHardy et al 1998; Hasinger 1996; Almaini et al 1996; Romero-Colmenero et al 1996) which dominate at faint flux levels and so may provide most of the XRB (see, however, Haszenger et al 1998 and Schmidt et al 1998 who cast some doubts on the reality of these objects as a class different to AGN). The broad-line Seyfert spectrum will not be detectable, unless we have a favourable line of sight, or observe in the mid-infrared in an object where the column density is not too high (Granato, Danese & Franceschini 1997). The combination of a starburst spectrum and a Seyfert narrow-line spectrum will make classification of the objects ambiguous (Iwasawa et al 1997b).

There are various examples of galaxies whose spectrum is dominated by a starburst/LINER component at all wavelengths except at hard X-rays where the AGN shows up, obscuration preventing its detection at lower energies. Among them, NGC4945 is obscured by a column \( \sim 5 \times 10^{24} \) cm\(^{-2}\) (Iwasawa et al 1993) and NGC 6240 by a column \( > \) few \( 10^{24} \) cm\(^{-2}\) (Iwasawa & Comastri 1998).

\section{The Distribution of the Obscuring Material}

We begin by assuming that the nuclear region of the galaxy has a radius of \( 100R_2 \) pc and that it contains clouds with a total column density of \( 10^{23}N_{23} \) cm\(^{-2}\) and a covering fraction approaching unity. The circular orbital velocity is \( 10^3v_2\) km s\(^{-1}\) and we now take \( R_2 \) and \( v_2 \) \( \sim 1 \) to a few. We assume that this material sits in an isothermal sphere, for which the gravitational effects of the central black hole are negligible (see later). Baryon dissipation leads to a large baryon overdensity, and therefore dark matter effects can be neglected. Fig. 1. shows that the values assumed for the velocity and the total column density are plausible, within an isothermal sphere approximation, with a scale-length parameter \( \alpha = 100R_2 \) pc and mass density \( \lambda (M/pc^3) \). An approximation of the form \( \rho(r) = \lambda [1 + (r/\alpha)^2/6]^{-1} \) has been used. The total mass of the star cluster is likely to be \( 10^7 - 10^8 M_\odot \) (it has been truncated at 3 scale radii).

The orbital kinetic energy of the clouds is \( 3 \times 10^{24}N_{23}R_2^2v_2^2 \) erg; half the orbital time, on which collisions can be expected if the clouds are on highly inclined orbits, is \( 3 \times 10^6R_2v_2^{-1} \) yr. After this time most of the clouds will have collided and formed a more flattened configuration. Thus a power of \( E \sim 3 \times 10^{40}N_{23}R_2v_2^5 \) erg s\(^{-1}\) must be supplied after a few million yr to keep the covering fraction high.

The obvious origins for such power are the winds from massive stars, supernovae and the active nucleus. The problem with the latter is coupling any of its power into inclining the orbital motions of clouds in a random sense. The blast wave of supernovae is likely to lead to a highly radiative shock in the dense environment considered here. However the random positioning of supernovae and massive stars is likely to mean that at least some of the power goes into turbulence within the region. This could have the desired effect.

Note that we are dealing here with a starburst in the potential well of the (stellar plus black hole) nucleus, which will tend to trap material than simply lead to outflow, as for off-nucleus starbursts. Outflows may and probably do occur (at least in favourable directions where the column of gas is smaller, as in the superwinds seen in local starburst galaxies, Heckman, Armus, Miley 1990) but more energy is required. It would be difficult to eject all the surrounding gas, since the more gas is ejected via supernovae, the less stars and supernovae are formed.

One important effect of the combined gravity field created by the black hole and the star cluster is to drive the distribution of material to an asymmetric distribution only.
in the innermost region where the black hole dominates (S. Sigurdsson, private communication). Further away, the distribution is expected to be triaxial and therefore the obscuring material will tend to cover the central source in a rather isotropic way.

Here we postulate that a few per cent of the energy of all supernovae (say 1 per 100 yr) in the region goes into turbulence within the inner ∼ 100 pc. This can then randomize the orbits of the clouds there and so cause a large covering fraction.

The frequent collisions between clouds is one trigger for star formation within the clouds, thus the situation once begun may continue until most of the gas is used up.

The starburst thus perpetuates itself, and obscures the nucleus. Of course the collisions will lead to a multiphase medium present, some of which is accreted by the central black hole. It is therefore a source of fuel for the central engine. Actually, hot gas flows are recognised as a very efficient way to fuel AGN and at the same time extract angular momentum from the accretion disk (Shlosman, Begelman & Frank 1990).

Assuming a 10\(^7\) \(M_\odot\) black hole and that a fraction 10\(^{-2}\)\(f_2\) of the gas is in virial equilibrium (hot phase) with a temperature \(T \approx 4 \times 10^6 v^2 K\). The density of the hot phase is therefore \(\approx 0.5 R_2^{-1} N_{23} f_2 \text{cm}^{-3}\). Bondi accretion onto the central mass, assuming the gas is isothermal, gives

\[
\dot{M} = 1.5 \times 10^{-3} M_7^2 N_{23} R_2^{-1} f_2 v_2^{-3} M_\odot \text{yr}^{-1}
\]

and for a typical 10 per cent efficiency this is converted into a luminosity \(\approx 8 \times 10^{42} M_7^2 N_{23} R_2^{-1} f_2 v_2^{-3} \text{erg s}^{-1}\). This is of the order of the X-ray luminosity of a NLXG.

The distribution of gas changes abruptly when the ratio of the black hole mass to the mass distributed in a sphere of one scale-length radius \((M(\alpha))\)

\[
\frac{M_{BH}}{M(\alpha)} = 0.12 R_2 v_2^{-2} M_7
\]

approaches or exceeds unity: it goes from gravity being dominated by the star cluster itself to being dominated by the black hole (Huntley & Saslaw 1975). In the latter case, all the gas virtually sinks to subparsec distances and nothing like an extended distribution of gas and stars survives. A velocity of a few 100 km s\(^{-1}\) would be difficult to maintain and such velocities are needed since the NLXGs (which are our prototype objects) exhibit only narrow emission lines. The transition between obscured starburst to ‘normal’ broad-line AGN is likely to happen when the mass of the central engine exceeds a few 10\(^6\) \(M_\odot\).

Moreover, the ratio of Bondi accretion to the Eddington limit is

\[
\frac{\dot{M}}{M_{Edd}} = 7 \times 10^{-3} M_7 N_{23} R_2^{-1} f_2 v_2^{-3}
\]

which increases with the mass of the central engine. When \(M_7\) exceeds ∼ 10, the gas sinks and \(R_2\) significantly reduces, in which case the accretion rate approaches or exceeds the Eddington limit. The central engine will radiate close to the Eddington limit and the remaining accreted material will be blown away from the nucleus. Again this is likely to lead to a normal unobscured broad-line AGN. Note that the lifetime of the starburst is unlikely to exceed the Salpeter time for doubling the black hole mass by Eddington-limited accretion. We therefore ignore variations in the black hole mass.

3 DISCUSSION AND CONCLUSIONS

Nuclear starbursts can play a major role in obscuring low-luminosity AGN. The emerging X-ray spectrum will be moderately to highly absorbed by the cold and warm gas in the star cluster, thus providing the flat spectral shape that is needed to produce the XRB. The column of absorbing gas is likely to vary with viewing direction in a ‘random’ way due to supernovae produced in the starburst. The average high fraction of the sky that the majority of the faint X-ray sources have to see covered by absorbing gas arises in material related to the star cluster rather than in a hypothetical torus, whose thickness to radius ratio must be large. Arguments favouring a geometry for the obscuring material more isotropic than toroidal have been put forward before. Turner et al (1998) find no obvious dependence of the X-ray properties of NLXGs with the orientation of the host galaxy. Iwasawa et al (1995) also suggested that the obscuring material in the Seyfert 2 galaxy IRAS 18325-5926, which is obscured by a column in excess of 10\(^{22}\) cm\(^{-2}\) but shows no X-ray reflected component, is likely to be isotropically distributed around the central engine.

Indeed the question remains, as in all obscured AGN models for the XRB, as to why the distribution of obscuring material along different lines of sight in the population of these objects is exactly tuned in such a way that it gives rise to the featureless spectrum of the XRB. There is no physical principle which leads to this and some fine-tuning of this distribution is required to produce a detailed model for the XRB.

The optical/UV properties of the highly absorbed AGN will be dominated by the starburst itself. Collisions between cold clouds, occuring at several ×100 km s\(^{-1}\) will lead to radiative shocks with some emission at soft X-ray energies. Therefore, the obscuring material will also contribute to the observed soft X-ray emissivity, making some of these objects visible in the ROSAT PSPC band in spite of being absorbed.

Near infra-red spectroscopy of NLXGs also lends support to this hybrid (i.e., accretion onto a black hole plus an obscuring starburst) hypothesis. While a number of NLXGs show unambiguous evidence for hidden AGN (e.g. highly ionized coronal lines), the non-detection of broad Paschen \(\alpha\) requires obscuring columns with \(N_H > 10^{23}\) cm\(^{-2}\) (Almaini et al 1998). Such thick columns are inconsistent with the large X-ray luminosities observed in ROSAT, unless there is an additional source of soft X-ray flux. A contribution from the activity in the obscuring starburst provides a natural explanation.

Gas columns along typical lines of sight in these objects are modest and for normal dust to gas ratios the absorbing material will be optically thin in the mid- and far-infrared (Granato et al 1997) where most of UV and soft X-ray reprocessed radiation will be emitted in a rather isotropic fashion. Surveys at these wavelengths (particularly at 10 – 15 \(\mu\)m) should be especially efficient in finding these objects. Barcons et al (1995) measured the average ratio of X-ray (2-10 keV) to mid-infrared emission (the IRAS 12\(\mu\)m band) for 12\(\mu\)m-selected type 1 and type
A geometrically thin disk structure is expected in obscured AGN in our model on scales of $<1$ pc where angular momentum begins to be important. Compton scattering, in some cases in an optically-thick medium, is necessary to explain the X-ray emission of some Seyfert 2 galaxies (see Iwasawa et al 1997a for a detailed study of NGC 1068 and Turner et al 1997 for Mrk 3 among other examples). In the case of NGC 1068 the pc-scale disk structure has been mapped at radio wavelengths (Gallimore, Baum & O'Dea 1997). Our model can therefore account for both Compton-thin and Compton-thick Seyfert 2 galaxies. Much of the extended torus attributed to these objects is just the starburst obscuration, but a planar Compton-thick inner part lies along our line of sight in some of them.

If the model proposed here describes correctly the sources of the residual XRB, it has then important implications on how accretion occurs in the Universe. Fig. 2 shows the distribution of the energy in the XRB as a function of photon energy in the range 1 to 100 keV (Fabian & Barcons 1992). Unobscured AGN (QSOs and Seyfert 1s) make $\sim$ 50 per cent of the XRB at 1 keV (Hasinger 1996, McHardy et al 1998, Hasinger et al 1998, Schmidt et al 1998), with an energy spectral index $\sim$ 1. If the 'shoulder' in the XRB (Fig. 2) is due to obscuration (mostly photoelectric absorption of the photons with energies $<30$ keV), the energy content at 30 keV provides a measure of the total energy produced by accretion in AGN, for the same underlying power law spectrum. What is remarkable then, is that only 10 per cent of the accretion occurs in unobscured objects (assuming that before it is absorbed by the surrounding material, the spectrum generated by accretion in both cases is similar). The remaining 90 per cent occurs at sub-Eddington accretion rates, and a relevant fraction is absorbed and re-radiated at longer wavelengths, particularly in the infrared. This means that most of the sky as seen from an average active nucleus is obscured.

Moreover, given the requirement that these low luminosity AGN are at least one order of magnitude fainter than typical broad line objects (see Section 2), we predict that starburst obscured AGN may outnumber brighter, unobscured AGN by a factor of 100 or more if they are to account for the remainder of the XRB. This estimate is in good agreement with the number count predictions for QSOs and NLXGs based on extrapolating deep ROSAT observations (Almaini & Fabian 1997).

If most of accretion in the Universe is highly obscured, then the amount of emitted power per unit galaxy based on optical or UV QSO luminosity functions (Soltan 1982, Phinney 1997), and therefore the mass in black holes in AGN, might have been underestimated. This is due to the fact that 90 per cent of the accretion power would be obscured and re-radiated in the infrared. Also, if most AGN are Advection Dominated Accretion Flows (ADAFs), as it has been proposed by Di Matteo & Fabian (1997) as the source of the XRB, the implied low mass to energy conversion efficiency also means that the black hole masses would have to be larger, in agreement with the local estimates.

Figure 2. The energy content of the XRB per unit logarithmic energy interval (solid line) as a function of photon energy. The dashed curve shows the contribution of unabsorbed AGN, where it is assumed that they make 50 per cent of the XRB at 1 keV. Therefore a roll-over in their contribution at energies $>30-50$ keV which is the exponential cutoff observed in local AGN at $\sim 100$ keV redshifted out to $z \sim 2$. The dotted line shows the total energy produced by all objects, before obscuration is taken into account.
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