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TO THE COSMIC X-RAY BACKGROUND**

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ABSTRACT

We discuss the results of *ASCA* and *ROSAT* observations of the spiral galaxy NGC 3628 which has been previously classified as a starburst. However, X-ray variability establishes the origin of the nuclear emission in a single compact source but the luminosity of $\sim 3.4 \times 10^{40} \text{erg s}^{-1}$ is ~ 270 times too large for sub-Eddington accretion onto a $1M_{\odot}$ stellar object. Although the *ASCA* spectrum can be described by a flat power law with a photon index $\Gamma \sim 1.2$, the low statistical quality of the data may conceal a more complex spectrum. However, the *observed* spectrum appears to be much flatter than prototypical starburst galaxies such as NGC 253. The spectrum is harder than Galactic low-mass X-ray binary (LMXB) or black hole candidate (BHC) spectra but compatible with high-mass X-ray binary (HMXB) spectra. If the nuclear source is a low-luminosity AGN, the X-ray properties have more in common with Seyfert 1-1.5 with moderate absorption ($\sim 10^{22} \text{ cm}^{-2}$) rather than heavily obscured Seyfert 2. We also present the first X-ray spectral measurements of the off-nuclear source in NGC 3628 and find it has a steeper spectrum with $\Gamma > 2.0$ and an *ASCA* luminosity of about half that of the nuclear source. In the light of this and other new *ASCA* observations, we revisit the general problem of the contribution of low-luminosity spiral galaxies to the Cosmic X-ray Background (CXRB) and assess their effect on the parameters of unified AGN models of the CXRB as a function of their local luminosity density and X-ray spectral shape.

Subject headings: diffuse radiation – galaxies: active – galaxies: individual (NGC 3628) – galaxies: starburst – X-rays: galaxies

1. Introduction

Prior to *ASCA*, knowledge of the hard (> 2 keV) X-ray spectra of low-luminosity ($L_{2-10 \text{ keV}} \sim 10^{40-41} \text{ erg s}^{-1}$) spiral galaxies has been restricted to a few of the brightest sources (from *EXOSAT*, *Ginga* and *BBXRT*; see Petre 1993 and references therein). In general, the X-ray emission was too weak to constrain IPC spectral parameters (Kim, Fabbiano, and Trinchieri 1992). In some cases the nuclear X-ray emission can be confidently attributed to a low-luminosity AGN (e.g. M51, Makishima *et al.* 1990; M81, Petre *et al.* 1993; NGC 4258, Makishima *et al.* 1994). In these cases the hard X-ray spectrum is often flat, with a power-law photon index, Γ , of $\sim 1.4 - 1.5$ (but for LINER type objects like M81, $\Gamma \sim 2$). In cases such as the ‘prototypical starburst galaxies’ NGC 253, M82 and M83, the spectra are also steep with $\Gamma \sim 2$. Although optically-thin thermal models are also viable with $kT \sim 6 - 7$ keV (Ohashi *et al.* 1990; Ohashi and Tsuru 1992; Petre 1993) the expected Fe-K line emission is not detected. The OSSE detection of NGC 253 (Bhattacharya *et al.* 1994) also argues against thermal emission. The only hard X-ray collective study is based on the summed *HEAO-1* spectra (extending up to ~ 160 keV) of 51 IRAS-selected ‘candidate starbursts’ and finds a flat power-law spectrum with $\Gamma = 1.47 \pm 0.26$ (Rephaeli, Gruber, and Persic 1995). Regardless of their classification as a starburst or AGN, a picture which appears to be emerging is that the hard X-ray emission of low-luminosity spiral galaxies is dominated by one to a few very luminous, often variable, compact sources, *not* by the summed emission from many sources with typical Galactic X-ray binary luminosities ($L_{2-10 \text{ keV}}$ less than $\sim 10^{38} \text{ erg s}^{-1}$). For example the nuclear source in M33 (Takano *et al.* 1994), ‘source B’ in NGC 1313 (Petre *et al.* 1994), and ‘source A’ in IC 342 (Okada *et al.* 1994) all require $> 10M_{\odot}$ black holes for sub-Eddington accretion-driven systems.

Though NGC 3628 is nominally classified as a starburst based on the infrared and radio emission, (see Dahlem, Heckman, and Fabbiano 1995 and references therein), the

nuclear optical emission is obscured by a dust lane, concealing the nature of the source. We present the first 0.5–10 keV X-ray spectra of NGC 3628 and address the origin of the X-ray emission and the often-postulated idea that galaxies like NGC 3628 contribute significantly to the Cosmic X-ray Background (CXRB). The structure of the paper is as follows. In §2 we describe the *ASCA* data and analysis. In §3.1 we discuss spectral fitting with simple, single-component models and in §3.2 more complex models are discussed. In §3.3 spectral fitting of the off-nuclear source is presented. In §3.4 we discuss possible origins of the nuclear X-ray emission. In §4 we revisit the general problem of the contribution of low-luminosity spiral galaxies to the CXRB in the light of recent *ASCA* observations. In §5 we investigate the effects of such a population of galaxies on the parameters of currently popular unified AGN models of the CXRB. Our conclusions are summarized in §6. We use $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$ throughout.

2. The *ASCA* Data

NGC 3628 was observed by *ASCA* on 1993 December 12. See Tanaka, Inoue and Holt (1994) for a summary of the *ASCA* mission and focal plane detectors. Hereafter, the two SIS sensors are referred to as S0 and S1 whilst the two GIS sensors are referred to as S2 and S3. The observation was made with the SIS in 4-CCD mode. The data were cleaned in the manner described in Yaqoob *et al.* (1994a). Figures 1a and 1b show the S3 images (with no background subtraction) below and above 2 keV respectively. The second source which lies at the edge of NGC 3628 was first seen by the IPC (Bregman and Glassgold 1982; see also Fabbiano, Heckman and Keel 1990) and is clearly visible in the GIS. In S0 the off-nuclear source falls in an inter-chip gap and in S1 on a different chip to that of the nuclear source, resulting in insufficient SIS counts for spectral analysis.

Spectra were extracted from 3' radii circles from all four detectors for the nuclear

source and from S2 and S3 for the off-nuclear source. Background spectra were constructed for the SIS from events in the same chip far enough away from the point sources and for the GIS from an annulus with radii 8.8' and 15.3', centered equidistant from the two point sources. In the SIS the variation of the internal background with CCD row amounts to $\sim 10\%$ across a chip (Gendreau 1994) and in the GIS the background varies by to $\sim 20\%$ across the detector (Kubo *et al.* 1994). Some idea of the the systematic effects due to neglecting these spatial variations in the SIS and GIS backgrounds will be given below. Extracted count rates for the nuclear source were in the range $0.9 - 1.9 \times 10^{-2}$ cts/s for the four instruments with exposure times $\sim 18 - 20$ Ks. The off-nuclear source count rates were $\sim 0.7 \times 10^{-2}$ cts/s with similar exposure times. The background constitutes $\sim 20 - 30\%$ of the total counts. The cross-contamination of the two sources could further complicate the analysis. However, using the convolved XRT+GIS PSF we estimate that only $\sim 3\%$ of the off-nuclear source counts appear in the 3' radius nuclear source extraction regions for S2 and S3.

3. Spectral Fits

3.1. Simple Models

In the initial spectral analysis of the nuclear source, since it is so weak, we treat the background in two different ways as a consistency check. First, (method 1), we model the background spectra from the background regions in each detector (described above) with simple power laws and Gaussians (as required). Method 1 allows the use of the maximum likelihood statistic for spectral fitting. Second, (method 2) we bin the data from the source region to have a minimum of 20 counts per channel (allowing the use of the χ^2 statistic), subtracting the background directly. Using both methods we fit a simple power-law plus

absorber model to each instrument individually and the results are shown in Table 1. Unless otherwise stated, all spectral fits refer to SIS data in the 0.5–10 keV range and GIS data in the 0.8–10 keV range. The SIS spectra are likely to contain a greater contribution from the soft extended emission component seen in the *ROSAT* HRI (Dahlem *et al.* 1995) and the IPC (Fabbiano *et al.* 1990). Correction for such a component would make the nuclear emission *flatter* and/or more absorbed. The narrower PSF for the SIS also means there is less cross-contamination from the off-nuclear source. Another important point is that the GIS is not sensitive to columns of the order of $\sim 10^{21} \text{ cm}^{-2}$ or less.

Table 1 shows that methods 1 and 2 give entirely consistent results. Unless stated otherwise, all errors refer to 90% confidence for two parameters. The SIS give $\Gamma \sim 0.85 - 1.0$ and a column density, N_H , comparable to the Galactic value of $1.98 \times 10^{20} \text{ cm}^{-2}$ (Hartmann and Burton 1995). The GIS give steeper slopes and correspondingly larger columns. Examining the effect of under- or over-estimating the background, we find that artificially decreasing the SIS and GIS backgrounds by 10% and 20% respectively (see §2) the SIS slope can be less by up to 0.03 and the GIS by up to 0.12. Increasing the SIS and GIS backgrounds by 10% and 20% respectively, we find the SIS slope changes by only ~ 0.01 whilst the GIS slope increases by up to ~ 0.10 .

The apparent differences in best-fit SIS and GIS parameters in Table 1 are *not* due to cross-calibration systematics between SIS and GIS. The agreement between the SIS and GIS is usually better than 0.05 in the slopes of power-law spectra (e.g. see Yaqoob *et al.* 1994a,b). What is more important for a source as weak as this is that the SIS is most sensitive at low energies (below $\sim 3 \text{ keV}$) while the GIS is better at high energies. The SIS is thus a much better indicator of the absorbing column than the GIS. However, since N_H and Γ are correlated parameters, the most reliable measure of the overall spectrum should be obtained from simultaneously fitting SIS and GIS data since the GIS data are forced to

comply with N_H values consistent with the SIS data (the GIS data alone give a reduced $\chi^2 < 1.0$ even if $N_H = 0.0$). The results of such a four-instrument fit (shown in Table 1 and Figures 2 and 3), give $\Gamma = 1.16^{+0.24}_{-0.21}$ and $N_H = 1.2^{+1.9}_{-1.2} \times 10^{21} \text{ cm}^{-2}$ and this gives a good overall *empirical* description of the data. Note that if the spectrum is really more complex than a power law this will enhance the apparent differences in spectral parameters from fitting SIS and GIS data separately. We illustrate this by fitting the S0 and S1 data above 1 keV only, with the simple power-law plus absorber model and compare this directly to the same model fitted to S2 and S3 (see Table 1). It can be seen that the SIS data fitted above 1 keV give a best-fitting slope steeper by ~ 0.3 than that obtained from fitting the data in the full bandpass. The possibility that the true spectrum is more complex than a power law will be discussed below.

From the four-instrument power-law plus absorber fit described above and in Table 1 we obtain mean observed fluxes in the 0.5–2 keV and 2–10 keV bands of 1.7 and $8.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ respectively. Individual values from the four instruments differ by no more than $\pm 25\%$ from the means. The differences represent systematic limitations of absolute flux measurements for sources as weak as this ($\pm 10 - 20\%$ is more typical of brighter sources). For $D = 14.9 \text{ Mpc}$ (Soifer *et al.* 1987) the mean absorption-corrected 0.5–2 keV and 2–10 keV luminosities are 0.45 and $2.9 \times 10^{40} \text{ erg s}^{-1}$ respectively.

Note that the overall spectrum is so remarkably flat that even with so few photons, a single-component thermal model for the continuum can be rejected. Spectral fits to the SIS data with either a thermal bremsstrahlung or Raymond-Smith model push the temperature up to $\sim 100 \text{ keV}$. For the bremsstrahlung model, fixing $kT = 10 \text{ keV}$ (upper end of the *ASCA* bandpass) gives $\chi^2 = 62.3$ (41 d.o.f.), rejecting the model at $> 98\%$ confidence. We have also searched for Fe-K line emission; fits to S0 and S1 with a power-law continuum (method 1) give an equivalent width $18^{+292}_{-18} \text{ eV}$ (90% confidence, 1 parameter) for a 6.4

keV narrow line ($\sigma = 0.01$ keV). The line is not statistically significant and is omitted in subsequent fits, which use S0–S3 and method 2.

3.2. Complex Models

We have also tried more complex models. Although the data do not formally require more complexity, this is useful for interpretation of the X-ray emission provided the number of free parameters is restricted. First we fit an intrinsic continuum consisting of a power law with a high-energy cut-off, $E^{-\Gamma} \exp(-E/E_f)$. An acceptable fit is obtained with $\Gamma = 0.39^{+0.51}_{-0.58}$ and $E_f = 4.3^{+13.5}_{-2.0}$ keV (see Table 2). N_H is fixed to the Galactic value since it tends to zero if it is free. This is an empirical model which describes a spectrum which gradually becomes steeper with increasing energy and has been found to provide a better fit to the nuclear source in M 33 than a simple power law (the statistics in that case are much better than for NGC 3628). Given the likelihood of more than one emission component this is again more of an empirical description of the data. We stress that the *ASCA* data cannot distinguish between the power-law and cut-off power-law models but the extrapolations of the two models beyond 10 keV are significantly different.

Next we ask whether the data are compatible with a power law having a photon index more typical of Seyfert galaxies (Γ fixed at 1.7) which is partially absorbed (i.e. a partial covering model). The unabsorbed part may correspond to continuum which is scattered into the line of sight in an extended region. Such a spectrum is typical of Seyfert 2 galaxies (e.g. Iwasawa *et al.* 1994). A good fit is obtained (see Table 2) with $N_H = 17^{+11}_{-7} \times 10^{21}$ cm⁻² and a covering fraction of 0.72 ± 0.09 . We also tried a model with a $\Gamma = 1.7$ fully absorbed power law plus an optically-thin thermal component subjected only to Galactic absorption (PL + Raymond-Smith model in Table 2). We obtain a temperature for the thermal component of $kT = 0.67^{+0.16}_{-0.39}$ keV and $N_H = 9.7^{+3.2}_{-2.7} \times 10^{21}$ cm⁻².

Finally, as a direct empirical comparison with Galactic LMXB and black hole candidates (BHC), we fit the data with a multicolor disk model (MCD - see Mitsuda *et al.* 1984), characterized by the parameter T_{in} (related to the inner disk temperature). Galactic LMXB are found to have $T_{\text{in}} \sim 1 - 1.5$ keV and BHC have lower values (see Yaqoob, Ebisawa and Mitsuda 1993). An additional power-law component with $\Gamma \sim 1.6 - 2$ is common in both types of source. For the NGC 3628 nuclear source we get a harder spectrum than is typical for Galactic LMXB and BHC, $T_{\text{in}} = 2.9^{+1.1}_{-0.6}$ keV (see Table 2) and inclusion of an additional power law with $\Gamma > 1.6$ increases T_{in} further. Inclusion of an additional soft optically-thin thermal component also increases T_{in} .

3.3. Off-Nuclear Source

The S2 and S3 data from the off-nuclear source are well fitted simultaneously (method 2) with a simple power-law plus absorber model giving $\Gamma = 2.39^{+0.91}_{-0.69}$, $N_H = 7.4^{+9.4}_{-6.4} \times 10^{21} \text{ cm}^{-2}$ and $\chi^2 = 18.0$ (19 d.o.f.). An optically-thin thermal model also provides a good fit to the off-nuclear spectrum, giving $kT = 3.5^{+6.3}_{-1.8}$ keV, $N_H = 4.6^{+6.7}_{-4.6} \times 10^{21} \text{ cm}^{-2}$ and $\chi^2 = 17.6$ (19 d.o.f.). From the power-law fit, average S2 and S3 observed fluxes in the 0.5–2 keV and 2–10 keV ranges are 0.9 and $2.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ respectively. If the off-nuclear source is associated with the galaxy then the implied 0.5–2 and 2–10 keV *observed* luminosities are 2.5 and $6.5 \times 10^{39} \text{ erg s}^{-1}$ respectively. This corresponds to 0.5–2 and 2–10 keV absorption-corrected luminosities of 10.7 and $7.1 \times 10^{39} \text{ erg s}^{-1}$ respectively. Archival PSPC data from 1991 November alone are too poor to constrain the spectrum but fitted simultaneously with S2 and S3 with a power-law plus absorber model give $\Gamma = 2.09^{+0.60}_{-0.47}$, $N_H = 3.9^{+4.0}_{-2.9} \times 10^{21} \text{ cm}^{-2}$ and a 0.5–2 keV flux of $0.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Thus, within the uncertainties, there is no evidence that the source varied between the PSPC and *ASCA* observations. The X-ray spectrum is compatible with LMXB spectra or very young SNR

(*cf.* sources in NGC 1313; Petre *et al.* 1994). However the intrinsic, albeit model-dependent, 0.5–10 keV luminosity is, like the nuclear source, apparently super-Eddington for a $1M_{\odot}$ stellar object ($\sim 149L_{\text{EDD}}$).

3.4. Origin Of The Nuclear X-ray Emission

The 0.5–2 keV flux of the nuclear source in the 1991 November PSPC observation ($6.7 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$; see Dahlem *et al.* 1995 for details) is over a factor 3 greater than the corresponding *ASCA* flux. This, along with the diminishing of the *ROSAT* HRI flux by a factor > 27 between 1991 December and 1994 May unequivocally establishes that the nuclear X-ray emission originates in a single compact object. Yet the luminosity exceeds the Eddington limit by at least two orders of magnitude for a $1M_{\odot}$ accretion driven system. The variability could be intrinsic or due to variable absorption. The X-ray spectrum measured by *ASCA* is compatible with that of HXMB (Nagase 1989) or a moderately absorbed low-luminosity AGN. In the latter case, $N_H \sim 10^{22} \text{ cm}^{-2}$ but could have been an order of magnitude higher during the 1994 May HRI observation. This behavior more closely resembles that observed in Seyfert 1–1.5 exhibiting complex and variable absorption (e.g. Warwick *et al.* 1993) rather than Seyfert 2 which also typically show Fe-K line emission with an equivalent width of a few hundred eV. Of course, the source may be none of these familiar objects but an accreting system which has a central mass which is intermediate to typical Galactic systems and AGN.

4. Contribution Of Low-Luminosity Spiral Galaxies To The CXRB

The *ASCA* spectrum of NGC 3628 is interesting from the point of view that it may be as flat or flatter than the CXRB, which can be adequately described by a straight power law

in the 1–10 keV band with $\Gamma \sim 1.4$ (Gendreau *et al.* 1994b, 1995). Currently, a promising model of the origin of the CXRB is that of a *combination* of Seyfert 1 and Seyfert 2 galaxy populations (e.g. Setti and Woltjer 1989; Madau *et al.* 1993, 1994; Matt and Fabian 1994; Comastri *et al.* 1995), but neither class of source alone has a spectrum which matches the CXRB (the ‘spectral paradox’). Note that the Seyfert 2s in this picture are very heavily absorbed with $N_H > 10^{23} \text{ cm}^{-2}$. The question naturally arises as to whether NGC 3628 represents a class of source which does not suffer from the spectral paradox and whether such a class could be sufficient in number to make a significant contribution to the CXRB. In particular, could NGC 3628 be representative of the new class of hard X-ray sources which have showed up in recent *ROSAT* deep surveys, albeit at a 1–2 keV flux level an order of magnitude below that of NGC 3628 (Hasinger *et al.* 1993; Jones *et al.* 1995)? The idea that starburst galaxies (recall that NGC 3628 has been previously classified as one) could be made up of HXMB with flat hard X-ray spectra ($\Gamma \sim 1.0 - 1.3$), thus easing the spectral mismatch with the CXRB, is not a new one (e.g. Griffiths and Padovani 1990). However, direct observational evidence to support this has been scarce. Generally the sources are so weak their hard X-ray spectral parameters could not be constrained prior to *ASCA* (e.g. Kim *et al.* 1992). The few bright ones, like NGC 253, M 82, and M 83 show instead a fairly steep spectrum ($\Gamma \sim 2$; Ohashi *et al.* 1990; Ohashi and Tsuru 1992). On the other hand *ASCA* observations of so-called ‘normal’ or ‘starburst’ galaxies so far indicate a variety of hard X-ray slopes in the range $\sim 1.4 - 2.0$ (see §1, Makishima 1994 and references therein) and NGC 3628 extends this range down to $\Gamma \sim 1.2$ or less. Since the galaxies observed by *ASCA* so far have not been selected systematically on any particular criterion we cannot make a meaningful statement about the distribution in Γ . Thus, in the following, we make the conservative assumption that Γ can be anywhere in the range 1.0–2.0.

Currently popular unified AGN models of the CXRB (e.g. Madau *et al.* 1993, 1994; Matt and Fabian 1994; Comastri *et al.* 1995) explicitly ignore the contribution from spiral

galaxies (often IRAS-selected) which have not been identified as Seyferts (type 1 or 2) or quasars and lumped together as ‘starbursts’ (NGC 3628 is in the latter group). On the other hand, many authors have tried to quantify the ‘starburst’ contribution. Griffiths and Padovani (1990), using both IRAS bright galaxy and optically selected starburst samples, assumed all sources had $\Gamma = 1.3$ and used no observational X-ray information above 3 keV. From *ASCA* observations of some of these sources so far (§1) we know this assumption is not correct. On the other hand, Ricker and Mészáros (1993) calculated the CXRB contribution based on what starburst X-ray spectra *should* be, assuming compositions of LMXB and HMXB, again with no input from hard X-ray observations. Rephaeli *et al.* (1995) used an average 0.5–160 keV *HEAO-1* spectrum of 51 galaxies. However, the biases of this and other samples (e.g. Griffiths and Padovani 1990) are troublesome. For example, Rephaeli *et al.* (1995) do not include NGC 3628, yet they include NGC 3147 which is now known to be a low-luminosity AGN (Moran, Halpern, and Helfand 1994; Ptak *et al.* 1995). Here we reassess the contribution of ‘Low Luminosity Non-AGN Spirals’ (hereafter LLNAS) to the CXRB. By LLNAS we mean spiral galaxies with $L_{2-10 \text{ keV}}$ less than $\sim 10^{42} \text{ erg s}^{-1}$ which are not classified as Seyfert 1 or Seyfert 2. Missclassifications of objects in previous samples thought to consist of normal/starburst galaxies but which are really AGN mean that previous estimates of the LLNAS local luminosity density may have too high. Such objects should instead appear at the lower luminosity end of the AGN luminosity function and thus increase the local luminosity density of AGN relative to previous estimates. In our estimates we will use extreme values of $\Gamma_{2-10 \text{ keV}}$ of 1.0 and 2.0 (and also appeal to an intermediate value of 1.5). This is more observationally accurate than previous estimates. However, to estimate the CXRB contribution at energies greater than $10/(1 + z_{\text{max}})$ (z_{max} is the maximum redshift of the sources) requires knowledge of the spectral shape of the LLNAS above 10 keV (i.e. above the *ASCA* bandpass). For this, observational information is very limited. The only information we have is the average 0.5–160 keV spectrum of Rephaeli *et*

al. (1995) with its associated caveats and the OSSE detection of NGC 253 (Bhattacharya *et al.* 1994), a prototype starburst. Thus we take the most general approach and take the slope above 10 keV to be a free parameter. Hereafter we shall refer to the effective slope below and above 10 keV as Γ_1 and Γ_2 respectively. For our purpose, this broken power-law spectrum is an adequate empirical description of the spectrum from LMXB, HMXB or AGN and has the advantage that the CXRB contribution can be examined in an analytic form. The X-ray spectra from these three types of sources are more commonly described in terms of a power law with an exponential cut-off of the form $\exp(-E/E_f)$. Typically, for LMXB and HMXB, $E_f \sim 5 - 20$ keV (e.g. Ricker and Mészáros 1993), whereas for AGN-type sources, $E_f \sim 100$ keV and up (e.g. Zdziarski *et al.* 1995). We can find an approximate correspondence to the broken power-law spectrum by joining the 10 keV and $10(1 + z_{\max})$ fluxes by a straight line in log-log space, giving $\Gamma_2 \sim \Gamma_1 + [10z_{\max}/E_f \ln(1 + z_{\max})]$. For $z_{\max} = 3$ and $E_f \sim 5 - 20$ keV, $\Delta\Gamma \equiv \Gamma_2 - \Gamma_1 \sim 4.3 - 1.0$ (LMXB, HMXB) and for $E_f > 20$ keV, $\Delta\Gamma < 1.0$ (AGN-like sources).

Now, the percentage contribution to the CXRB at an energy E_0 (keV) due to a population of sources with broken power-law X-ray spectra, undergoing pure luminosity evolution $\propto (1 + z)^\gamma$ (out to $z = z_{\max}$) can be written (see discussion in Boldt 1987)

$$P(E_0, \Gamma_1, \Gamma_2, E_b, z_{\max}, \gamma) = \frac{314.6 \rho_{38} F(E_0, \Gamma_1, \Gamma_2, E_b, z_{\max}, \gamma, q_0)}{I_{\text{cxrb}}(E_0) \int_{E_1}^{E_2} E^{1-\Gamma_1} dE} \% \quad (1)$$

The intrinsic source spectrum has power-law photon indices Γ_1 and Γ_2 below and above an energy E_b in the source rest-frame. In our formulation of the problem $E_b = 10$ keV and Γ_1 represents the measurable slopes of the X-ray spectra below 10 keV whilst Γ_2 represents the largely unknown slopes of the spectra above 10 keV. The local luminosity density of the sources in the energy band E_1 to E_2 (it is assumed that $E_1 < E_2 < E_b$) is ρ_{38} ($10^{38} \text{ erg s}^{-1} \text{ Mpc}^{-3}$). For the CXRB intensity, $I_{\text{cxrb}}(E_0) \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$, we use

the functional form given by Gruber (1992). Defining $\beta \equiv \gamma - 1 - q_0$ (q_0 is only allowed to take the values 0.0 or 0.5; in our case $q_0 = 0.0$) and $z_b \equiv (E_b - E_0)/E_0$, the function F is given by

$$\begin{aligned}
 F(E_0, \Gamma_1, \Gamma_2, E_b, z_{\max}, \gamma, q_0) = & \\
 & E_0^{1-\Gamma_1} \int_0^{z_{\max}} (1+z)^{\beta-\Gamma_1} dz \\
 & E_0 \leq E_b/(1+z_{\max}) \\
 & E_0^{1-\Gamma_1} \int_0^{z_b} (1+z)^{\beta-\Gamma_1} dz + \\
 & E_b^{\Gamma_2-\Gamma_1} E_0^{1-\Gamma_2} \int_{z_b}^{z_{\max}} (1+z)^{\beta-\Gamma_2} dz \\
 & E_b/(1+z_{\max}) < E_0 < E_b \\
 & E_b^{\Gamma_2-\Gamma_1} E_0^{1-\Gamma_2} \int_0^{z_{\max}} (1+z)^{\beta-\Gamma_2} dz \\
 & E_0 \geq E_b.
 \end{aligned} \tag{2}$$

We adopt $\gamma = 3.2$ from Saunders *et al.* (1990) who find $\gamma = 3.2 \pm 1.0$ from an IRAS-selected sample of starburst galaxies. The local luminosity density, ρ_{38} , is not very well known. Ricker and Mészáros (1993) estimate $\rho_{38}(0.5 - 4.5 \text{ keV}) = 0.43$ by integrating an X-ray luminosity function derived from a correlation of $60\mu\text{m}$ and X-ray luminosities of IRAS bright galaxies. The mean X-ray spectrum and number density of the Rephaeli *et al.* (1995) bright galaxy sample give $\rho_{38}(0.5 - 4.5 \text{ keV}) = 0.51$. Miyaji *et al.* (1994) derive, from an IRAS galaxy-CXRB cross-correlation analysis, an upper limit on the ‘non-AGN’ value of $\rho_{38}(2 - 10 \text{ keV})$ of ~ 2 . For $\Gamma = 1.4$, $\rho_{38}(0.5 - 4.5 \text{ keV}) = 0.73\rho_{38}(2 - 10 \text{ keV})$ so this upper limit corresponds to $\rho_{38}(0.5 - 4.5 \text{ keV}) < 1.5$. In Figure 4 we show P at 2 keV (dotted curves) for $z_{\max} = 1$ and 3 as a function of Γ where $\Gamma_1 = \Gamma$ since the CXRB contribution at 2 keV depends only on the spectrum up to rest-frame energies of $2(1+z_{\max})$

keV. All the curves in Figure 4 have been normalized to $\rho_{38}(0.5 - 4.5 \text{ keV}) = 0.50$. The dashed curves in Figure 4 show P at 10 keV (for $z_{\text{max}} = 1$ and 3) as a function of Γ where now $\Gamma_2 = \Gamma$ and $\Gamma_1 = \min(2.0, \Gamma)$. The solid curves in Figure 4 use the same parameters except that $\Gamma_1 = \min(1.0, \Gamma)$. Thus we cover the observed range in power-law slopes below 10 keV of $\sim 1 - 2$.

Figure 4 shows that the CXRB contribution at 2 keV for $z_{\text{max}} = 3$ is as high as $58(\rho_{38}/0.5)\%$ and $41(\rho_{38}/0.5)\%$ for $\Gamma_1 = 1.0$ and 2.0 respectively. These are comparable to previous estimates. Since the CXRB contribution at 2 keV depends only on the spectral shape up to energies for which we have solid observational information, the largest uncertainty is in ρ_{38} . The contribution at 10 keV, however, depends crucially on Γ_2 . If the source spectra extend to $\sim 40 - 50$ keV in the rest-frame without a significant steepening (e.g. AGN-like sources) then they could easily dominate and even over-predict the CXRB at 10 keV. If the emission is due to LMXB, HMXB or low-temperature thermal sources ($\Gamma_2 > 2$), then P at 10 keV is no more than a few percent. In the latter case, the sources may still have a significant impact on understanding the CXRB spectrum because the differential contributions at 2 and 10 keV mean that the shape of the residual CXRB which is to be explained (e.g. by AGN models) may be very different to that observed.

5. Effects On The Parameters Of Unified AGN Models Of The CXRB

Unified AGN models of the CXRB consist of a population of Seyfert 1 and QSOs represented by unabsorbed power-law spectra, plus Seyfert 2s, represented by absorbed power-law spectra (e.g. Matt and Fabian 1994; Madau *et al.* 1994, 1995; Comastri *et al.* 1995). In the simplest versions of the models, the distributions of the power-law spectral indices and absorbing columns are taken to be single-valued adjustable parameters and the luminosity function and evolution of Seyfert 1s and QSOs (determined from *ROSAT* deep

surveys, e.g. Boyle *et al.* 1993, 1994) are assumed to be the same for Seyfert 2s. These models are highly successful in explaining the overall shape of the CXRB, in particular the broad hump peaking at ~ 30 keV. However, they explicitly ignore the CXRB contribution of LLNAS and in this section we wish to investigate the qualitative effects on the inferred AGN model parameters when LLNAS are not ignored. Specifically, we examine the CXRB in the 1–10 keV band since, in this band, Gendreau *et al.* (1994) have demonstrated that a single power law with $\Gamma = 1.4$ provides an excellent description of the CXRB with deviations not larger than systematic errors. Since our purpose is only to investigate the sensitivity of inferred AGN model parameters to the LLNAS component we will make several simplifying assumptions. Our method will be to select baseline AGN and LLNAS models and then investigate the effect of deviations from it. As our baseline AGN model we assume $z_{\text{max}} = 3$ and a luminosity evolution index, γ_{AGN} , (see §4) of 2.75, values consistent with the results of Boyle *et al.* (1993, 1994). We assume $\Gamma_{\text{AGN}} = 1.7$ (no exponential cut-off since we are only considering energies up to $10(1 + z_{\text{max}})$ keV) and no Compton-reflection component (e.g. see Zdziarski *et al.* 1995). A fraction, f , of the primary power law is absorbed by a column density N_H . We ignore Compton scattering in the absorbing medium. The parameter f is only *approximately* the fraction of the number of Seyfert 2s relative to the total AGN number because a few percent of the flux in individual Seyfert 2s is unabsorbed (e.g. Iwasawa *et al.* 1994). For our baseline LLNAS model we assume a power law below 10 keV with $\Gamma = 1.5$ (intermediate between 1.0 and 2.0, see §4). Above 10 keV we assume three representative values of Γ_2 of 1.5, 2.5 and 5.5 (i.e. $\Delta\Gamma = 0.0, 1.0, 4.0$). We will perform our calculations for the range in the LLNAS $\rho_{38}(2 - 10 \text{ keV})$ allowed for the non-AGN contribution to the CXRB (i.e. 0.0–2.0; Miyaji *et al.* 1994). Our main objective is to investigate the effect of ρ_{38} and $\Delta\Gamma$ (i.e. the spectral shape of LLAGN above 10 keV) on N_H and f . We then proceed to find the best-fitting parameters of the above AGN-plus-LLNAS CXRB model which give the best approximation to the $\Gamma = 1.4$ power

law describing the CXRB (Gendreau *et al.* 1994). This is done by simulating *ASCA* data using an exposure time of 10^7 s. In the following, statistically acceptable fits are obtained except where stated (this provides additional constraints). Figure 5 shows the resulting best-fitting values of N_H and f as a function of $\rho_{38}(2 - 10 \text{ keV})$ for $\Delta\Gamma = 0.0, 1.0, 4.0$. It can be seen that with no LLNAS contribution, $N_H \sim 4 \times 10^{23} \text{ cm}^{-2}$ and $f \sim 0.45$. Note that the ratio of Seyfert 2s to Seyfert 1s in this context does not have a firm observational constraint due to different methods of selection giving different ratios and also it is not obvious whether the Seyfert 2s which contribute to the CXRB are necessarily those which we observe individually. For the single power-law LLNAS spectrum ($\Delta\Gamma = 0.0$, dashed curves), increasing $\rho_{38}(2 - 10 \text{ keV})$ has little effect on N_H but f eventually rises to 1.0 near $\rho_{38}(2 - 10 \text{ keV}) = 2.0$. Since the LLNAS represent an unabsorbed population, f increases to compensate for the increase in $\rho_{38}(2 - 10 \text{ keV})$. However, if the LLNAS spectrum drops off steeply above 10 keV (e.g. $\Delta\Gamma = 1.0$ and 4.0, solid and dotted curves respectively), N_H also increases with $\rho_{38}(2 - 10 \text{ keV})$ (by more than a factor 3) because the high-energy cut-off in the LLNAS spectrum and the low-energy cut-off in the AGN spectrum compensate for each other. It is interesting to note that the simple condition that at least some unabsorbed AGN contribute to the CXRB implies an upper limit on $\rho_{38}(2 - 10 \text{ keV})$ which for this simple model is ~ 2 regardless of $\Delta\Gamma$ and happens to be coincident with the Miyaji *et al.* (1994) value obtained by completely independent means.

Finally, we examine the effect of altering the baseline LLNAS plus AGN model. If we fix Γ_{AGN} at 1.9, more absorbed AGN are required to compensate for the steeper intrinsic slope; N_H decreases by less than $\sim 10\%$ whilst f increases by $\sim 10 - 20\%$. Increasing z_{max} from 3.0 to 4.0 (for both AGN and LLNAS populations) increases N_H by $\sim 50\%$ or more and f by $\sim 20\%$. This is because for larger z_{max} the LLNAS CXRB contribution affects lower energies (thus affecting N_H) and is larger (thus affecting f). If we set the LLNAS Γ_1 to the extreme values 1.0 and 2.0, increasing ρ_{38} beyond $\sim 0.5 - 1.0$ (exact value

depending on other parameters), the combined LLNAS plus AGN CXRB spectrum can no longer be approximated by the $\Gamma = 1.4$ power law. With acceptable values of ρ_{38} , the effect of increasing the LLNAS Γ_1 from 1.5 to 2.0 is to increase f by $\sim 10\%$ (steeper LLNAS contribution requires more absorbed AGN) whilst N_H can decrease by up to a factor of ~ 2 . Naturally, when Γ_1 is decreased from 1.5 to 1.0, N_H and f show the opposite behavior with similar fractional changes.

6. Conclusions

An *ASCA* observation of NGC 3628 reveals an X-ray power-law spectrum with a photon index of ~ 1.2 , one of the flattest measured for spiral galaxies which are ordinarily classified as normal or starburst (or simply non-AGN). We have qualitatively assessed the impact of these LLNAS (Low Luminosity Non-AGN Spirals) on unified AGN models of the CXRB as a function of their local luminosity density and their spectral shape. We find that if the LLNAS spectra cut off sharply above 10 keV, as would be expected if the emission was due to LMXB, HMXB or thermal-type spectra in general, their contribution to the CXRB could potentially have a significant influence on AGN models of the CXRB. On the other hand if the LLNAS spectra extend out to $\sim 40 - 50$ keV without a spectral break, then they should, for the sole purpose of evaluating their CXRB contribution, be treated as another class of AGN at the low end of the luminosity function since the relevant portion of their X-ray spectra would then not be different from AGN in any fundamental way (in some cases there may be genuine missclassifications). Only the distribution in spectral slopes may be different but we note that AGN contributing to the CXRB (QSOs, Seyfert 1s, and Seyfert 2s) already represent a wide range in slopes (e.g. Turner and Pounds 1989; Williams *et al.* 1992; Nandra and Pounds 1994). Sensitive, hard X-ray observations are required to determine whether the $\sim 10 - 50$ keV spectra exhibit significant deviations from

a power law as do Seyfert 1s (e.g. Nandra and Pounds 1994).

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REFERENCES

- Bhattacharya, D., *et al.* 1994, ApJ, 436, 173
- Boldt., E. 1987, Phys. Rep., 146, 215
- Bregman, J. N., & Glassgold, A. E. 1982, ApJ, 263, 564
- Comastri, A., Setti, G., Zamorani, G., & Hasinger, G. 1995, A&A, in press
- Dahlem, M., Heckman, T. M., & Fabbiano, G. 1995, ApJL, 442, L49
- Fabbiano, G., Heckman, T., & Keel, W. C. 1990, ApJ, 355, 442
- Gendreau, K. C. 1994, ASCA Newsletter No. 2., 5
- Gendreau, K. C., *et al.* 1994, in New Horizon Of X-ray Astronomy, ed. F. Makino & T. Ohashi (Tokyo: Universal Academy Press), 365
- Gendreau, K. C., Mushotzky, R. F., Yaqoob, T., & Fabian A. C. 1995, in preparation
- Griffiths, R. E., & Padovani, P. 1990, ApJ, 360, 483
- Gruber, D. A. 1992, in The X-ray Background, ed. X. Barcons & A. C. Fabian (Cambridge: Cambridge University Press), 44
- Hartmann, D., & Burton, W. B. 1995, In The Leiden-Dwingeloo Atlas of Galactic Neutral Hydrogen (Cambridge: Cambridge University Press, UK), in press
- Hasinger, G., Burg, R., Giaconni, R., Hartner, G., Schmidt, M., Trümper, J., & Zamorani, G. 1993, A&A, 275, 1
- Iwasawa, K., Yaqoob, T., Awaki, H., & Ogasaka, Y. 1994, PASJ, 46, L167
- Jones, L. R., *et al.* 1995, in Wide-field Spectroscopy and the Distant Universe, ed. S. Maddox & A. Aragon-Salameec, (Singapore: World Scientific Publishing Co.), in press

- Kim, D.-W., Fabbiano, G., & Trinchieri, G. 1992, *ApJS*, 393, 134
- Kubo, H., Ikebe, Y., Makishima, K., & the GIS Team, *ASCA Newsletter* No. 2, 14
- Madau, P., Ghisellini, G., & Fabian, A. C. 1993, *ApJ*, 410, L7
- Madau, P., Ghisellini, G., & Fabian, A. C. 1994, *MNRAS*, 270, L17
- Makishima, K. 1994, in *New Horizon Of X-ray Astronomy*, ed. F. Makino & T. Ohashi (Tokyo: Universal Academy Press), 171
- Makishima, K., Ohashi, T., Kondo, H., Palumbo, G. G. C., & Trinchieri, G. 1990, *ApJ*, 365, 159
- Makishima, K., *et al.* 1994, *PASJ*, 46, L77
- Matt, G., & Fabian, A. C. 1994, *MNRAS*, 267, 187
- Mitsuda, K., *et al.* 1984, *PASJ*, 36, 741
- Miyaji, T., Lahav, O., Jahoda, K., & Boldt, E. 1994, *ApJ*, 434, 424
- Moran, E. C., Halpern, J. P., & Helfand, D. J. 1994, *ApJ*, 433, L65
- Nagase, F. 1989, *PASJ*, 41, 1
- Nandra, K., & Pounds, K. A. 1994, *MNRAS*, 268, 405
- Ohashi, T., Makishima, K., Tsuru, T., Takano, S., Koyama, K., & Stewart, G. C. 1990, *ApJ*, 365, 180
- Ohashi, T., & Tsuru, T. 1992, in *Frontiers of X-ray Astronomy*, ed. Y. Tanaka & K. Koyama (Tokyo: Universal Academy Press), 435
- Okada, K., Mihara, T., & Makishima, K., & the ASCA TEAM 1994, in *New Horizon of X-ray Astronomy*, ed. F. Makino & T. Ohashi (Tokyo: Universal Academy Press), 515

- Petre, R. 1993, in *The Nearest Active Galaxies*, ed. J. Beckman, L. Colina, H. Netzer (Madrid: CSIC), 117
- Petre, R., Mushotzky, R. F., Serlemitsos, P. J., Jahoda, K., Marshall, F. E. 1993, *ApJ*, 418, 644
- Petre, R., Okada, K., Mihara, T., Makishima, K., & Colbert, E. J. M. 1994, *PASJ*, 46, L115
- Ptak, A., Yaqoob, T., Serlemitsos, P. J., Kunieda, H., & Terashima, Y. 1995, *ApJ*, submitted
- Rephaeli, Y., Gruber, D., & Persic, M. 1995, *A&A*, in press
- Ricker, P. M., & Mészáros, P. 1993, *ApJ*, 418, 49
- Saunders, W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., Ellis, R. S., & Frenk, C. S. 1990, *MNRAS*, 242, 318
- Setti, G., & Woltjer, L., 1989, *A&A*, L21
- Soifer, B. T., Sanders, D. B., Madore, B. F., Neugebauer, G., Danielson, G. E., Elias, J. H., Lonsdale, C. J., & Rice, W. 1987, *ApJ*, 320, 238
- Takano, M., Mitsuda, K., Fukazawa, Y., & Nagase, F. 1994, *ApJ*, 436, L47
- Tanaka, Y., Inoue, H., & Holt, S. S. 1994, *PASJ*, 46, L37
- Turner, T. J., & Pounds, K. A. 1989, *MNRAS*, 240, 833
- Warwick, R. S., Sembay, S., Yaqoob, T., Makishima, K. & Ohashi, T., & Tashiro, M. 1993, *MNRAS*, 265, 412
- Williams, O. R., *et al.* 1992, *ApJ*, 389, 157
- Yaqoob, T., Ebisawa, K., & Mitsuda, K. 1993, *MNRAS*, 264, 411
- Yaqoob, T., Serlemitsos, P. J., Mushotzky, R. F., Madejski, G., Turner, T. J., & Kunieda, H. 1994a, *PASJ*, 46, L173

Yaqoob, T., *et al.* 1994b, PASJ, 46, L49

Zdziarski, A. A., Johnson, N. W., Done, C., Smith, D., & McNaron-Brown, K. 1995, ApJ, 438, L63

Figure Captions

Figure 1

ASCA S3 image of NGC 3628 below 2 keV (a) and above 2 keV (b), smoothed with a $\sigma \sim 30''$ Gaussian (without background subtraction). The contours correspond to levels of 0.45 - 1.35 smoothed counts at intervals of 0.1 smoothed counts.

Figure 2

ASCA four-instrument spectral fit to the nuclear X-ray source in NGC 3628. Shown are the data, best-fitting simple power-law plus absorber model and the ratio of data to model.

Figure 3

Confidence contours of photon index (Γ) versus column density (N_H) for the four-instrument spectral fit with a simple power-law plus absorber model. The confidence levels are 68%, 90% and 99% for two interesting parameters.

Figure 4

The percentage contribution to the CXRB, P , of sources with power-law X-ray spectra with photon indices Γ_1 and Γ_2 below and above 10 keV respectively (see text for details). The sources undergo pure luminosity evolution of the form $(1+z)^\gamma$ with $\gamma = 3.2$. Shown are curves for P at 2 keV with $\Gamma_1 = \Gamma$ (dotted), P at 10 keV with $\Gamma_1 = \min(2.0, \Gamma)$ and $\Gamma_2 = \Gamma$ (dashed) and P at 10 keV with $\Gamma_1 = \min(1.0, \Gamma)$ and $\Gamma_2 = \Gamma$ (solid). In each case the lower and upper curves correspond to $z_{\max} = 1$ and 3 respectively. All curves are normalized to $\rho_{38}(0.5 - 4.5 \text{ keV}) = 0.50$.

Figure 5

The effect on the two key parameters, N_H , and f , of a simple unified AGN model of the CXRB as a function of the local luminosity density (ρ_{38}) and X-ray spectral shape of a population of low-luminosity spiral galaxies. In the AGN model, a fraction f of the total AGN emission is absorbed by a column density N_H . See text for details of the other parameters of the AGN model. The low-luminosity galaxy spectra have power-law photon indices of 1.5 below 10 keV and are integrated out to $z_{\text{max}} = 3$. The dashed curves show the behavior of N_H and f if this power law extends out to $10(1 + z_{\text{max}})$ without a break. The solid and dotted curves correspond to cases where the spectrum steepens above 10 keV by $\Delta\Gamma = 1.0$ and 4.0 respectively.

TABLE 1
Spectral Fitting Results for the Nuclear Source in NGC 3628

DET	Method	Γ	$N_H(10^{21} \text{ cm}^{-2})$	C/χ^2 (d.o.f.)
S0	1	0.85 (0.61–1.18)	0.0 (0.0–1.7)	838.0 (342)
S0	2	0.87 (0.61–1.26)	0.2 (0.0–2.7)	21.7 (19)
S1	1	1.02 (0.75–1.47)	0.3 (0.0–3.2)	836.9 (363)
S1	2	0.99 (0.74–1.46)	0.1 (0.0–3.4)	19.2 (20)
S2	1	1.83 (1.12–2.70)	9.3 (0.8–22.2)	974.8 (777)
S2	2	1.89 (1.20–2.84)	9.9 (1.3–15.4)	6.5 (10)
S3	1	1.37 (0.88–2.02)	3.1 (0.0–11.5)	1129.0 (776)
S3	2	1.48 (0.89–2.27)	4.6 (0.0–15.4)	13.0 (14)
S0, S1	2	0.93 (0.74–1.22)	0.2 (0.0–2.0)	41.5 (40)
S0, S1 ($> 1 \text{ keV}$)	2	1.20 (0.79–1.67)	3.5 (0.0–8.2)	29.0 (33)
S2, S3	2	1.66 (1.20–2.26)	6.9 (1.3–15.1)	19.0 (25)
S0–S3	2	1.16 (0.95–1.40)	1.2 (0.0–3.1)	68.2 (67)

Values in parentheses indicate 90% confidence ranges for two interesting parameters. Method 1 refers to spectral fitting using the maximum likelihood statistic (C) with the background modelled with simple functions. Method 2 refers to use of χ^2 with the background subtracted directly. See text for details.

TABLE 2

Spectral Fitting Results With Complex Models

Model	Parameter	
Cut-off PL	Γ	$0.39^{+0.51}_{-0.58}$
	E_f (keV)	$4.3^{+13.5}_{-2.0}$
	χ^2 (d.o.f.)	61.9 (67)
Partial Covering	N_H (10^{21} cm $^{-2}$)	17^{+11}_{-7}
	Γ	1.7 (f)
	C_f	$0.72^{+0.09}_{-0.09}$
	χ^2 (d.o.f.)	59.1 (67)
PL + Raymond-Smith	N_H (10^{21} cm $^{-2}$)	10^{+3}_{-3}
	Γ	1.7 (f)
	kT (keV)	$0.67^{+0.16}_{-0.39}$
	χ^2 (d.o.f.)	55.9 (66)
MCD	kT_{in} (keV)	$2.9^{+1.1}_{-0.6}$
	$r_{\text{in}}\sqrt{\cos\theta}$	0.7 ^a
	χ^2 (d.o.f.)	61.9 (68)

See text for descriptions of models (note PL = power law). All errors correspond to 90% confidence for 2 interesting parameters. When N_H is not given, it has been fixed at the Galactic value of 1.98×10^{20} cm $^{-2}$. Other parameters which are fixed in the spectral fitting are indicated by (f). ^a Since the parameter $r_{\text{in}}\sqrt{\cos\theta}$ is related to the model normalization, its uncertainty is dominated by the systematic uncertainty in measuring absolute fluxes (i.e. $\sim 25\%$).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5