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The correlation function of the 4–12 keV X-ray background intensity measured with the *GINGA* LAC

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SUMMARY

The angular autocorrelation function of the X-ray background in the energy band 4–12 keV has been explored on scales of 2°–25° using 132 exposures obtained with the Large Area Counter (LAC) on board the *GINGA* satellite. No significant signal is found over the whole range. An upper limit at 2° of 10^{-4} is found for the autocorrelation function at the 95 per cent confidence level, significantly lower than previous values obtained in the 2–10 keV band at 3° separation. This upper limit is shown to constrain clustering on scales $\sim$ 10–300 Mpc in the high-redshift ($z \sim 0.1$–5) Universe, and in particular the cluster–cluster and AGN–AGN correlation functions.

1 INTRODUCTION

Although the origin of most of the extragalactic X-ray background (XRB) is not yet understood, it is becoming clearer that studies of the angular fluctuations in the background provide important clues about the distribution of the constituent X-ray sources. Observations of the XRB on a particular angular scale can be used to analyse two relevant statistical descriptions of its spatial variations: the distribution of fluctuations and the angular autocorrelation function (ACF). Fluctuations occur because there is a finite number of sources per beam, and can be used to test the source counts down to the flux level where there is about one source per beam. The ACF on the other hand is basically related either to clustering of the sources or to their extended emission. If, as is usually accepted, most of the XRB has been produced at redshifts $0.1 < z < 5$, these studies can be used to infer the large-scale distribution of matter in the 'galaxy formation' epoch of the Universe.

The best results so far in this field have been obtained from *HEAO-1 A2* and *Einstein Observatory* data. The *HEAO-1 A2* experiment produced an all-sky picture of the XRB surface brightness in the 2–10 keV band with an angular resolution $\gtrsim 3°$. Shafer (1983; see also Shafer & Fabian 1983) studied the fluctuations in this band, and obtained an upper limit of $\sim$ 2 per cent for the excess fluctuations attributable to source clustering and other non-cosmic inhomogeneities for a 25 deg^2 beam. Barcons & Fabian (1988), Mészáros & Mészáros (1988) and Bagoly, Mészáros & Mészáros (1988) used this result to set limits on inhomogeneities in the Universe on scales $\sim$ 10–100 Mpc. Persic *et al.* (1989) found that the ACF of the *HEAO-1 A2* X-ray sky is compatible with zero on all scales from 3°–27°. They also give upper limits for the anisotropies at several confidence levels which were used by De Zotti *et al.* (1990) to constrain the large-scale lumpiness of the Universe, especially due to the clustering of clusters and Active Galactic Nuclei (AGN).

On much smaller scales ($\sim$ few arcmin), some deep fields obtained with the *Einstein Observatory* IPC were used by Hamilton & Helfand (1987) and Barcons & Fabian (1990) to test source counts down to very faint levels in the 1–3 keV band. An autocorrelation function analysis was also performed by Barcons & Fabian (1989) on these data and showed no evidence for any cosmic signal.

The importance of the ACF comes from the fact that it is an integrated measure of source clustering. Observations of the X-ray sky in the 2–10 keV band (Piccinotti *et al.* 1982) show that the bright extragalactic source population is dominated by clusters of galaxies and AGN. Optically-selected samples of these objects show that they cluster on scales of tens of Mpc [with a correlation length $\sim 8\ h^{-1}$ Mpc for QSOs, e.g. Shaver (1988); Boyle, private communication; $\sim 25\ h^{-1}$ Mpc for clusters of galaxies, Bahcall & Soneira (1983); h being the Hubble constant in units of 100 km s^{-1} Mpc^{-1}]. These length-scales correspond to angular separations of $\sim 0.7°$ and 2°, respectively, at a typical redshift $z \sim 1$, so clustering of these sources should lead to anisotropies in the XRB on that angular scale. As no evidence for anisotropies in the cosmic XRB has been found so far, upper limits for the ACF on that and larger scales can be used to constrain either the clustering or the X-ray volume emissivity of a given source population.

In this paper, we present an analysis of the ACF of the XRB with the use of a set of pointed exposures obtained with the Large Area Counter (LAC) on the *GINGA* satellite. Fluctuations in the XRB from these fields are used to gather information about source counts and are reported in a separate paper by Butcher *et al.* (in preparation). Here we use the total counts in the 4–12 keV band from the *GINGA* LAC, which both maximizes the sensitivity to the XRB and minimizes small reflection effects in the collimator that occur at lower energies. The collimator field-of-view (FWHM) is $\sim 1° \times 2°$ which enables us, in a subset of the observations, to measure the brightness of the XRB in independent regions separated by $\sim 2°$. The large collecting area and stability of the LAC detectors (Turner *et al.* 1989; Hayashida *et al.* 1989) mean that small point-to-point variations in the XRB can be accurately determined. Together with the small field-of-view, this makes the instrument especially suitable for our purposes and allows us to make finer-scale measurements than has previously been possible in this energy band.

The paper is organized as follows. In Section 2, a short account of the features of the data is given (for more details see Butcher *et al.*, in preparation) and we show how the measured ACF is compatible with zero on all scales from 2° to 25°. It is concluded that the ACF at 2° is less than $\sim 10^{-4}$ at the 95 per cent confidence level. Section 3 is devoted to the implications of this upper limit for clustering in the Universe on scales 10–100 h^{-1} Mpc and in particular for the cluster–cluster and the AGN–AGN correlation functions. In Section 4 we summarize our results and discuss possible extensions of this work.

2 THE AUTOCORRELATION FUNCTION

A total sample of 132 exposures has been used. Of these, 62 correspond to planned observations in the galactic poles where non-overlapping pointing directions were selected in order to mosaic a given area of the sky with angular separations of $\sim 2°$. The remaining exposures come from 'blank' fields spread over the sky with the constraint that $|b| > 30°$, which were taken in other observations for background subtraction. In all of the exposures, bright X-ray sources above the level of the Piccinotti *et al.* (1982) sample (2–10 keV flux $> 3.1 \times 10^{-11}$ erg cm^{-2} s^{-1}) were avoided. We note that, given the above restriction on $|b|$, galactic contamination is unimportant, particularly in the 4–12 keV band to which our results refer. There are no measurable differences between the fluctuation distribution functions coming from both subsamples.

The LAC on *GINGA* has been extensively described by Turner *et al.* (1989) and Hayashida *et al.* (1989). It comprises eight multi-cell proportional counters with a collimated field-of-view which has a slightly energy-dependent elliptical shape ($\sim 1.1° \times 2°$). It is sensitive to energies from ~ 1 to 38 keV with a moderately high energy-resolution (18 per cent at 6 keV, and scaling like $E^{-0.5}$). Counts are finally collected in 48 output pulse-height-analyser (PHA) channels, the maximum efficiency corresponding to the $\sim$3–15 keV band, where the effective collecting area is ~ 4000 cm^2.

Sophisticated techniques were used to measure the cosmic deflection D (i.e. the difference from the mean) for each field. These include a fitting procedure for all the time-varying events detected by the LAC during the orbit [see Hayashida *et al.* (1989) and Butcher *et al.* (in preparation) for details]. The present analysis is restricted to the count rates measured in PHA channels 8–20 of the top layer of the LAC, corresponding to the 4–12 keV energy range.

The blank-field count rate measured in the 4–12 keV band by the LAC is typically 10–20 count s^{-1} of which ~ 8 count s^{-1} is attributable to the XRB as deduced from observations when the sky is occulted by the dark earth. (The latter value is consistent with the count rate predicted from the XRB spectrum measured by Marshall *et al.* 1980). Given that a typical value of D is ~ 0.5 count s^{-1} (Butcher *et al.*, in preparation) and the exposure times are $\gtrsim 2000$ s, the effects of Poissonian counting noise ($\lesssim 0.1$ count s^{-1} rms) are small and have been neglected in the present analysis. In addition, the systematic errors in the determination of D are estimated to be no greater than the counting noise (Hayashida *et al.* 1989) and were also neglected.

The ACF is defined as

$$W(\theta) = \frac{\langle D(\boldsymbol{n})\, D(\boldsymbol{n}')\rangle}{\langle I \rangle^2}, \tag{1}$$

where $\cos\theta = \boldsymbol{n}\cdot\boldsymbol{n}'$, $\boldsymbol{n}$ and $\boldsymbol{n}'$ are unit vectors along the pointing directions, and $\langle I \rangle$ is the mean XRB intensity given above.

Values of $W(\theta)$ were accumulated in bins 3° wide, spaced equally from 2° to 23° (Fig. 1). The resultant points can be compared with those obtained by Persic *et al.* (1989) and De Zotti *et al.* (1990) from *HEAO-1* data. They give an upper limit (at 95 per cent confidence level) for $W(3°)$ [which is the square of their $\Gamma(3°)$] of 4×10^{-4}.

The vertical error bars in Fig. 1 correspond to a confidence level of 95 per cent and were computed as follows. As we want to test the null hypothesis (i.e. the absence of correlations), we generated a set of Monte Carlo simulations by redistributing at random the observed deflections in the fixed pointing positions. This method ensures that the deflections have the same $P(D)$ distribution as the real data sample. For each simulation we determine the ACF in exactly the same way as for the real data. As expected, the ACF averaged over the set of simulations was found to be zero on all scales (where the mean is taken over the set of simulations). The scatter in the simulated ACFs (on each scale) was then used to determine the size of the 95 per cent error bars, which are plotted about the measured points in Fig. 1. The upper ends of these error bars are taken as 95 per cent confidence upper limits.

Over the scales examined, it is apparent that there is no significant positive signal to within the 95 per cent confidence limits. (The bin at $\theta \sim 11°$ shows a *negative* signal at this level, but it becomes insignificant at the 99 per cent level.) This is consistent with the work of Persic *et al.* (1989).

A total of 60 pairs with separations in the range $0.85° < \theta < 3.5°$ and with a mean separation of 2° contribute to the first bin in Fig. 1 (47 pairs in this sample have separations within 0.1° of 2°, and 54 pairs have a separation $> 1.9°$). The corresponding upper limit at 95 per cent confidence is $W(2°) < 1.02 \times 10^{-4}$, four times smaller than the limit placed

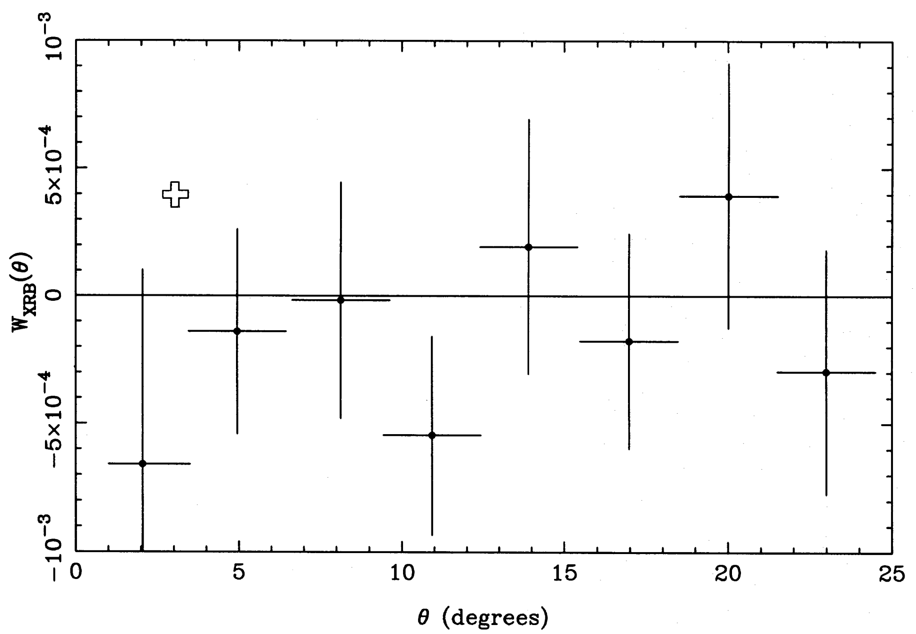

Figure 1. The autocorrelation function of the 4–12 keV X-ray background. Vertical bars denote the 95 per cent confidence region. The point at 3° is the upper limit at the 95 per cent confidence level obtained by Persic *et al.* (1989).

by Persic *et al.* (1989) on their smallest scale of 3°. In the next Section we use our limit to constrain the correlation function of various cosmic X-ray source populations.

As a check of the 2° point, we have redetermined the ACF, first using the samples only with separations $1.9° < \theta < 2.1°$ and secondly using the mean intensity measured from the samples contributing to that point (rather than the overall mean). Neither test changed the position or error bar of the result by more than about 20 per cent. The first test, which involved 47 pairs, resulted in the 2° point being more significantly negative, at a level corresponding to just over 2σ. A final check was also made concerning the possibility that the ACF could be dominated by the brightest fields (which may contain sources just below the detection threshold). Removal of all exposures with $d > 1$ count s^{-1} showed no significant shift in the ACF on any scale.

Finally, we have tested the energy dependence of the ACF by calculating the ACF for each PHA channel, instead of for the whole 4–12 keV band. Again, no significant signal at 95 per cent confidence was found in any channel. Bright soft-spectrum sources might contribute significantly to the ACF, which would have shown up as an energy-dependence of the ACF. The absence of any spectral effect ensures that the value of the upper limit in the broad-band ACF is imposed only by the noise level.

3 CONSTRAINTS ON CLUSTERING OF HARD X-RAY SOURCES

3.1 General framework

Studies of hard X-ray sources carried out with the *HEAO-1 A2* experiment (Piccinotti *et al.* 1982) show that the brightest extragalactic sources are clusters of galaxies and AGN in the 2–10 keV energy band. Clusters of galaxies have typical temperatures ~2–6 keV (the temperature is correlated with luminosity; Mushotzky 1984; Edge 1989) and many AGN fit a canonical spectrum, namely a power law with energy spectral index ~0.7, possibly with low-energy absorption (Mushotzky 1982; Turner & Pounds 1989). This implies that both classes of objects contribute to the 4–12 keV XRB.

Optically-selected clusters are seen to cluster (at $z \sim 0$) on scales 14–25 h^{-1} Mpc (Sutherland 1989; Bahcall & Soneira 1983). This result is supported by a study of X-ray selected clusters (Lahav *et al.* 1989). High-redshift, optically-selected, QSO are also seen to cluster on comoving scales ~8 h^{-1} Mpc (Shanks *et al.* 1987; Shaver 1988) at a typical redshift $z \sim 1$. This has been recently confirmed with the AAT–Durham QSO sample, together with the fact that the QSO–QSO correlation function does not appear to decrease with increasing redshift out to $z \sim 2$ (B. J. Boyle, private communication). All of these facts suggest that the XRB should show some positive ACF on scales of a few degrees, if these classes of source are significant contributors.

The link between the clustering properties of a source population and the autocorrelation function of the XRB goes as follows. Let $n(z)$ be the number of objects per unit volume, $L(z)$ the mean luminosity that these objects contribute to the observed band (i.e. including K-corrections) in count s^{-1} and $\xi(r; z)$ their spatial correlation function. The expected autocorrelation function is then (see Barcons & Fabian 1988)

$$W(\theta) = \frac{cH_0^{-1}}{4\sqrt{2\pi}\langle I_{XRB}\rangle^2} \int_{z_{max}}^{z_{max}} dz (1+z)^{-8} (1+2q_0 z)^{-1/2} l^{-2}(z)$$
$$\times n^2(z) L^2(z) \times \int d^2 q\, e^{i\mathbf{q}\cdot\boldsymbol{\theta}} \hat{G}^2(\mathbf{q})\, \xi\left(\frac{\mathbf{q}}{l(z)}; z\right), \qquad (2)$$

where

$$l(z) = cH_0^{-1} q_0^{-2} (1+z)^{-2} [z q_0 + (q_0 - 1)(-1 + \sqrt{1 + 2q_0 z})]. \qquad (3)$$

$\hat{G}(\boldsymbol{q})$ is the 2D Fourier transform of the beam function $G(\boldsymbol{x})$ (which is the relative response of the LAC to photons coming from off-axis directions) and $\hat{\xi}(\boldsymbol{k}; z)$ is the 3D Fourier transform of the source correlation function, but with $k_z=0$. Here $\boldsymbol{q}$ and $\boldsymbol{k}$ denote 2D and 3D Fourier space vectors, respectively, and in the last case the z-axis is selected in the direction of the line-of-sight. The fraction of the XRB produced by this source population is

$$f=\frac{cH_0^{-1}}{4\pi\langle I_{\rm XRB}\rangle}\Omega_{\rm eff}\int_{z_{\rm min}}^{z_{\rm max}} dz(1+z)^{-5}(1+2q_0z)^{-1/2}n(z)L(z). \quad (4)$$

Here

$$\Omega_{\rm eff}=\int d^2xG(\boldsymbol{x})$$

is the effective solid angle for flux collection.

The LAC beam function $G(\boldsymbol{x})$ has an energy-dependent elliptical shape (Turner *et al.* 1989). However, as the relative orientation of the two beams involved is random, we assume a radial profile for G in such a way that its integral is just $\Omega_{\rm eff}\approx 1.9$ deg^2. In practice, we shall take a Gaussian fit for $G(\boldsymbol{x})$ which follows closely the angle-averaged real profile in the energy band under consideration.

We assume a power law for the source correlation function

$$\xi(r,z)=\left(\frac{1+z}{1+z_1}\right)^{-3-\varepsilon}\left(\frac{r}{r_0/(1+z_1)}\right)^{-\gamma}, \quad (5)$$

where $\gamma\approx 1.8$, r_0 is the comoving correlation length at a reference redshift $z=z_1$, and ε accounts for evolution ($\varepsilon=0$ for stable clustering, $\varepsilon=\gamma-3$ for comoving clustering).

In the simplest models, we have explored the values of $f^{2/\gamma}r_0$ allowed by the upper limit on the ACF. This quantity is used to parametrize the results since the source ACF, $W_{\rm source}$, is related to the observed one as $W_{\rm obs}=f^2W_{\rm source}$ and, for a power-law source the correlation function, $W_{\rm source}\propto r_0^{\gamma}$. Consequently, $W_{\rm obs}\propto f^2r_0^{\gamma}$. In practice we use $f^{2/\gamma}r_0$ since this has the dimensions of Mpc. It has the property of being independent of the local volume emissivity, which is often notoriously uncertain (e.g. De Zotti *et al.* 1989, for a discussion).

3.2 Clusters of galaxies

One major point in the analysis is the evolution of the volume emissivity $n(z)L(z)$. Rapid evolution in the luminosity function, in the sense that the most luminous clusters occur only recently, has been recently found in samples of X-ray-selected clusters of galaxies (Edge *et al.* 1990; Gioia *et al.* 1990). Cold Dark Matter models also predict some evolution (Kaiser 1986), although the sense of evolution is unclear.

Since the sources found by Piccinotti *et al.* (1982) have been avoided in the exposures, and the mean redshift for the clusters in that sample is ~0.05, we assume $z_{\rm min}=0.1$, comfortably beyond these clusters. This is actually a rather conservative assumption, since fainter clusters at $z<0.1$ could also give a contribution to the ACF. We take $z_{\rm max}$ to be 1, since this is a typical value for cluster formation in cosmological models.

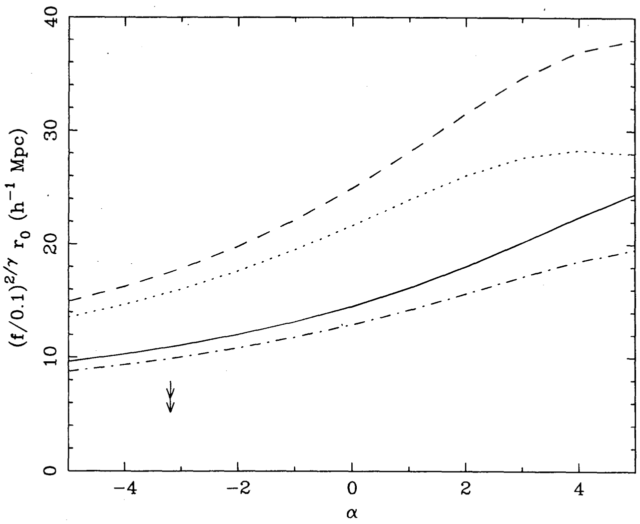

Figure 2. Maximum values allowed for the product $(f/0.1)^{2/\gamma}r_0$ at $z=0$ in h^{-1} Mpc for clusters of galaxies. The solid curve corresponds to $T=2$ keV and stable clustering, the dot-dashed one to the same temperature and comoving clustering. The dashed line is for $T=6$ keV and stable clustering and the dotted line for the same temperature and comoving clustering. Vertical arrows correspond to upper limits according to the Edge *et al.* (1990) sample.

We adopt a parametrization in the form $n(z)L(z)\propto K(z)(1+z)^{3+\alpha}$, where $K(z)$ is the K-correction. This has first been computed assuming a constant rest-frame temperature for the clusters, but α is kept as a free parameter. In particular, $\alpha=0$ corresponds to an unevolving population of clusters with comoving space density and $\alpha\sim 2.5$ to the hierarchical model discussed by Kaiser (1986).

In Fig. 2 we show the maximum value of $(f/0.1)^{2/\gamma}r_0$ that is allowed by the upper limit on the ACF at 2°, r_0 is the comoving correlation length at $z=0$. Two values for the cluster temperature have been considered (2 and 6 keV) and also comoving ($\varepsilon=-1.2$) and stable ($\varepsilon=0$) clustering have been included. Our results are consistent with the estimates of the cluster–cluster correlation function by Sutherland (1989) and Lahav *et al.* (1989), but are only compatible with $r_0=25$ h^{-1} Mpc (Bahcall & Soneira 1983) if $f\lesssim 10$ per cent. Increasing $z_{\rm min}$ to 0.5 or $z_{\rm max}$ to 1.5 change the maximum values on $(f/0.1)^{2/\gamma}r_0$ by less than 10 per cent, provided that $\alpha<0$.

Models predicting a large fraction of the 1–3 keV XRB due to clusters (e.g. Shaeffer & Silk 1988) also give a residual fraction of the order of 10 per cent to the 4–12 keV XRB, even if the typical cluster temperature is 2 keV. This is just compatible with $r_0\approx 20$ h^{-1} Mpc.

More realistic results are obtained with the use of measured luminosity function at $z=0$, the observed luminosity–temperature dependence and the observed cluster evolution (Edge *et al.* 1990). We then find $r_0<23.4$ h^{-1} Mpc for comoving clustering and $r_0<26.2$ h^{-1} Mpc for stable clustering. The cluster contribution to the 4–12 keV XRB is $f\sim 0.03$, in agreement with previous estimates by Piccinotti *et al.* (1982). These values of the correlation length are just consistent with the very high values found by Bahcall & Soneira (1983). We stress that our analysis is particularly sensitive to the lower-luminosity clusters, while direct studies of the cluster–cluster correlation function emphasize the brighter ones. Bahcall (1988) has suggested that the amplitude of the cluster correlations is an increasing function of richness. It could then well be that the clusters dominating our estimate of the ACF are poorer (and less clustered) than the ones used by Bahcall & Soneira (1983).

3.3 Active galactic nuclei

We assume here that all AGN follow a power-law spectrum with energy spectral index of 0.7 which allows a very simple calculation of the K-correction. The number of AGN per unit volume is taken as $n(z)\propto(1+z)^{3+\alpha}$, where $\alpha=0$ corresponds to a comoving population. The evolution in the luminosity is parametrized by

$$L(z)=K(z)\,L_0\exp(C\tau), \qquad (6)$$

where τ is the look-back time in units of the present age of the Universe, C is taken to be either 0 (no evolution) or 3.1 (Danese *et al.* 1986), and L_0 is the AGN luminosity at $z=0$.

In order to compute the maximum allowed correlation lengths, both comoving and stable clustering have been considered (again comoving clustering appears to be more physical, since the Universe is thought to be in the linear regime in these very large scales). $z_{\rm min}=0.1$ and $z_{\rm max}=3$ are assumed. Increasing either of the redshift bounds, to 0.5 and 3.5, respectively, has little effect on the constraints we derive below (see also De Zotti *et al.* 1990). Reducing $z_{\rm min}$ below 0.1 strengthens our result.

Results are presented in Fig. 3. A comoving correlation length at $z\sim1$ as high as $\sim 8\ h^{-1}$ Mpc is allowed only if $f\leq0.5$, regardless of clustering evolution. Models in which most of the XRB is produced by these clustered AGN are inconsistent with its isotropy. This result was already found by Barcons & Fabian (1988) from a different point of view. We conclude that less than 50 per cent of the 4–12 keV XRB can be produced by QSOs like the ones studied by Boyle (i.e. with comoving correlation lengths $\sim 8\ h^{-1}$ Mpc). Fainter AGN could provide the remaining fraction if they are less clustered. In fact, if the main sources of the XRB are galaxies, or at least, are clustered like galaxies ($r_0\sim4\ h^{-1}$ Mpc, Davis & Peebles 1983), there is consistency with the ACF of the XRB.

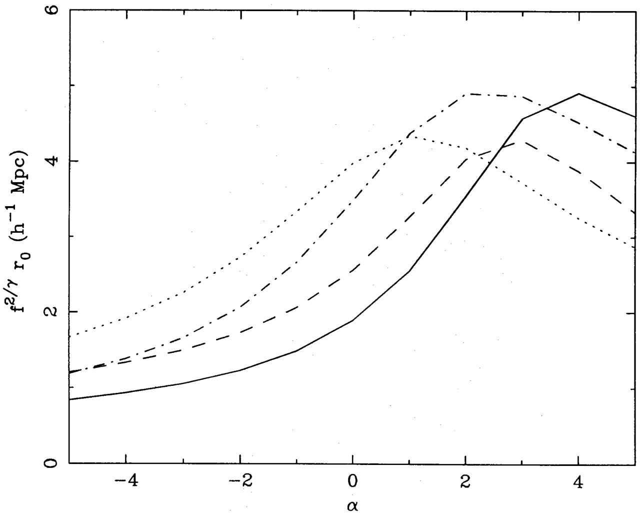

Figure 3. Maximum values allowed for the product $f^{2/\gamma}r_0$ at $z=1$ in h^{-1} Mpc for AGN. The solid curve corresponds to $C=0$ and stable clustering, the dashed one to $C=0$ and comoving clustering, the dash–dotted line to evolution with $C=3.1$ and stable clustering and the dotted one to $C=3.1$ and comoving clustering (see equation 6 for details).

4 DISCUSSION

The 4–12 keV XRB is found to be isotropic on scales 2°–25°. At a redshift $z\sim1$ such scales cover the range of 30–300 h^{-1} Mpc, which corresponds to physical sizes where enormous inhomogeneities, like big walls and voids, are found nearby. The XRB apparently does not reflect this very rich structure★ of the Universe.

In quantitative terms, we have an upper limit of $\sim10^{-4}$ at the 95 per cent confidence level on the ACF on a scale of 2°. This is four times smaller than the *HEAO-1* limit of Persic *et al.* (1989) on the scale of 3°. Our limit constrains the cluster–cluster correlation function to a level which is only just consistent with that found by Bahcall & Soneira (1983) ($r_0\sim 25\ h^{-1}$ Mpc). Comoving clustering lengths as high as 8 h^{-1} Mpc at $z\sim1$, as measured for QSOs, are only allowed for the AGN–AGN correlation function if these objects do not contribute more than ~50 per cent of the XRB.

This and similar work highlights the relevance of studies of the isotropy of integrated backgrounds (and in particular the XRB). While the isotropy of the microwave background reflects the initial conditions for the gravitational growth of linear perturbations in the Universe at $z\sim1000$, the smoothness of the XRB maps the Universe in its non-linear epoch, which is when different cosmological models give the most divergent predictions.

It is clearly necessary to test the isotropy of the XRB on smaller scales, since source clustering must appear at some level. We intend to use data recently taken by the *GINGA* LAC in several scans of different areas of the sky. A detailed analysis of the count rates should enable us to probe the ACF on smaller angular scales.

★We do find evidence at a low level of significance ($\sim2\sigma$) for the ACF being negative on the scale of 2°. This may be consistent with the persistence of the quasi-periodic structures found in the nearby redshift distribution of galaxies (Broadhurst *et al.* 1990), if the sources of the XRB are confined to the 'walls' of the structures and the 'period' scales as $\sim(1+z)^{-1}$. There is then a tendency for a peak in one field, due to an edge-on wall, to be paired with a trough, due to a void, in the neighbouring field. Any such effect, if real, is clearly weak.

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