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The X-ray Background as a Cosmological Tool

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Abstract. We review the use of the X-ray background (XRB) as a cosmological tool with emphasis on three techniques: multipole analysis, autocorrelation functions and excess fluctuations. Although these methods of analysis of XRB fluctuations, and in particular the excess fluctuations method, are quite sensitive to cosmological parameters, the poor knowledge of a possibly redshift dependent bias parameter for the sources that dominate the X-ray background prevents the derivation of firm conclusions at present. Conversely, knowledge of the cosmological parameters could be used together with XRB fluctuations to assess the clustering properties of AGN as the dominant XRB sources.

1. Introduction

The X-ray background, discovered almost 40 years ago (Giacconi et al. 1962) remains a valuable tool for astrophysical studies. Early missions measured its spectrum (Marshall et al. 1980) which turned out to have a bremsstrahlung shape at $kT = 40$keV. That means that most of the energy content of the X-ray background resides at $\sim 30 - 40$ keV and that at lower energies (where all imaging X-ray surveys have been carried out to date) it has a very flat shape. For many years no class of X-ray source was found with such a flat spectrum, resulting in the so-called 'spectral paradox' (Boldt 1987).

More recently, deep surveys carried out with *Chandra* (Mushotzky et al. 1999, Giacconi et al. 2000) and XMM-Newton (Hasinger et al. 2000) in the 2-10 keV band reveal an increasing population of hard X-ray sources when probing fluxes at the level of $\sim 10^{-15}\mathrm{erg\,cm^{-2}\,s^{-1}}$ with total source density exceeding 1000 sources deg^{-2}. Optical identification of these faint sources is still in progress, but preliminary results reveal a mixture of 'normal' AGN (type 1 QSOs and Seyfert galaxies), faint galaxies which might be hosting an AGN and very faint optical objects which might actually be brighter in the infrared, suggestive of heavily absorbed AGNs. Therefore, as suspected from studies from previous missions (notably ROSAT), accretion onto massive black holes is at the very heart of the origin of the XRB.

Recent *ROSAT* deep surveys (Boyle et al. 1994, McHardy et al. 1998, Hasinger et al. 1998) have shown that most of the soft X-ray volume emissivity in the Universe arises at redshifts $z > 1 - 2$ (Miyaji, Hasinger & Schmidt 2000). The AGN and star formation rate per unit volume follow a remarkably similar evolution rate in the Universe (Franceschini et al. 1999) and therefore they can both be used as tracers of the evolution of large-scale structure in the Universe. Using AGN and star-forming galaxies as tracers of cosmic inhomogeneities is most sensitive to intermediate redshifts ($z \sim 2$), providing a critical link between

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cosmic microwave background studies (which map the $z \sim 1000$ Universe) and local galaxy surveys ($z \sim 0$).

2. X-ray background and cosmology

At galactic latitudes $|b| > 20°$ the contribution from the Galaxy to the X-ray sky is small: less than 10% of the X-ray background above 2 keV is due to galactic emission, absorption is negligible above this photon energy and a census of X-ray sources down to any flux limit exhibits less than 10-20% of galactic stars. Observations of the X-ray background at high galactic latitudes and photon energies above 2 keV can therefore be used to map the extragalactic X-ray sky.

2.1. Resolving the X-ray background

A large fraction (> 70%) of the soft (0.5-2 keV) XRB was resolved by *ROSAT* deep surveys (Hasinger et al. 1998, Lehmann et al. 2000). The vast majority of the sources identified in these surveys are AGN of various types, but most notably normal broad-line AGN and QSOs. Towards fainter fluxes, an increasing fraction of narrow-line AGN and other narrow-line X-ray emitting galaxies appear (McHardy et al. 1998). This has been interpreted as intrinsic absorption and obscuration acting on the central engines of AGN.

At harder energies (2-10 keV), recent *Chandra* deep surveys have also resolved a similar fraction of the XRB (Mushotzky et al. 1999, Giacconi et al. 2000). Again, AGN appear as the major constituent of the XRB. In a large fraction of the identified sources, the optical image appears either as a normal early type galaxy or as a very faint or even optically undetectable counterpart (which is however detectable in the infrared). Again obscured/absorbed AGN play a major role as postulated by the unified AGN models for the XRB (Setti & Woltjer 1989, Madau, Ghisellini & Fabian 1994, Comastri et al. 1995).

2.2. The X-ray volume emissivity and its evolution

AGN luminosity functions and their evolution have only been determined so far at soft X-ray energies. A broken power-law appears to fit well the de-evolved luminosity function (Boyle et al. 1994, Page et al. 1996). The evolution has been traditionally modelled as a pure luminosity evolution, which grows typically as $L(z) \propto (1+z)^3$ and stops at some redshift $z \sim 1.5 - 2$. With a wider database, Miyaji, Hasinger & Schmidt (2000) have found that the data actually demand a luminosity-dependent density evolution.

2.3. The XRB and the Large-Scale Structure of the Universe

As most of the XRB comes from significant redshifts ($z \sim 1 - 2$), intensity variations of the XRB reflect the large-scale structure of the Universe at those intermediate redshifts. This is particularly interesting for various reasons, the most immediate of which is that it might provide access to the structure of the Universe at a redshift intermediate between the CMB and the local galaxy surveys. Besides that, the formation of stars and black holes appears to peak at precisely these redshifts. Finally, this is likely to be the epoch of cluster formation, as density fluctuations on scales of $\sim$ 10Mpc become non-linear.

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In what follows we describe various attempts to measure the angular structure of the XRB and the successes and limitations of these methods in trying to map the structure of the distant Universe.

3. The XRB multipoles

The all-sky distribution of the X-ray background for cosmological purposes has been best mapped by the HEAO-1 mission. A galactic anisotropy dominates the large-scale anisotropy, but this can be modelled out (Iwan et al. 1982).

A dipole contribution is detected in the X-ray sky, in rough alignment with the direction of our motion with respect to the Cosmic Microwave Background frame (Shafer 1983, Scharf et al. 2000). The amplitude of this dipole accounts for both the kinematical effect of our motion (the Compton-Getting effect) and the excess X-ray emissivity associated with the structures which are pulling us. These two effects are expected to be of the same order (Lahav, Piran & Treyer 1997) and the analysis done in Scharf et al. (2000) shows this to be the case. However, in an analysis of the ROSAT all-sky data at lower photon energies (which have the disadvantage of a larger contamination from the Galaxy) Plionis & Georgantopoulos (1999) find a dipole several times larger than the expected kinematical dipole. The difference between both results might be partly affected by the elimination of X-ray bright clusters in the Scharf et al. analysis, as clusters are known to be a largely biased population (Plionis & Kolokotronis 1998). The bias parameter derived from the XRB dipole is large ($b_X \sim 3-6$).

Treyer et al. (1998) have analyzed higher order multipoles of the HEAO-1 A2 X-ray background. The discrete nature of the XRB contributes a constant term to all multipoles which scales as $\propto S_{cut}^{0.5}$, where S_{cut} is the minimum flux at which sources have been excised. Treyer et al. (1998) detect a signal growing towards lower-order multipoles which is consistent with a gravitational collapse picture, as predicted by Lahav et al. (1997). Excluding the dipole, this analysis yields a moderate bias parameter for the X-ray sources ($b_X \sim 1-2$).

Progress on this front would need reducing substantially S_{cut}, so the "shot noise" contribution to the XRB multipoles decreases substantially. This requires an all-sky sensitive X-ray survey mission like ABRIXAS-II or PANORAM-X, that is able to both map the XRB surface brightness and locate sources down to a 2-10 keV flux $\sim 10^{-13} - 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

4. Autocorrelation functions

The XRB intensity towards nearby sky positions is expected to be correlated due to clustering of its sources (Barcons & Fabian 1989, Carrera & Barcons 1992). Other effects that give positive signals in the auto-correlation function (ACF) of the XRB include the spatial extent of sources (e.g. clusters of galaxies, lumps of intergalactic or interstellar gas) and the extent of the instrument's beam.

Following many unsuccessful attempts to detect a clean signal in the ACF by several groups, Soltan et al. (1999) found a strong signal in the *ROSAT* all-sky survey data at angular separations 0.3-20°. Their signal is, however, too strong to reconcile with galaxy or AGN clustering measurements and it is likely

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that either the Galaxy or the local Supercluster contribute a fraction of that signal.

5. Excess fluctuations

Fluctuations in the XRB when observed with a given beam are in the first instance dominated by confusion noise, to which photon counting noise and any residual systematics have to be added. Confusion noise arises from the discrete origin of the XRB, whereby the finite number of sources per beam at each flux produces Poisson-like fluctuations convolved with their flux distribution (Condon 1974, Scheuer 1974). The flux level that dominates confusion noise corresponds to a surface density of the order of $\sim$1 source per beam. By measuring confusion noise fluctuations, it has been possible to study the flux distribution of "$\sim 1\sigma$" X-ray sources without actually resolving them. This approach has proven fruitful in X-ray astronomy, due to the limited angular resolution of the instruments flown.

An additional source of fluctuations in the XRB comes from source clustering. If X-ray sources cluster (as everything else in the Universe), then the number of X-ray emitters per beam is effectively the number of clusters of X-ray sources, with the subsequent increase in the fluctuations.

5.1. Confusion noise and source clustering

Barcons, Fabian & Carrera (1998) have discussed the possibility of detecting a clustering signal in the XRB fluctuations, by measuring XRB intensities on scales of $\sim 1\,\mathrm{deg}^2$ over a significant fraction of the sky. This angular scale happens to match the expected peak of the power spectrum of density fluctuations in the Universe (co-moving wave-vectors $\sim 0.03\,h\,\mathrm{Mpc}^{-1}$) at the redshifts where the X-ray volume emissivity peaks. Choosing this angular scale has the advantage that the clustering signal in the XRB is maximum and that small variations in wave-number (e.g., resulting from different cosmological parameters at a fixed angular separation) do not translate in large variations of the power spectrum.

The confusion noise fluctuations on $\sim 1\,\mathrm{deg}^2$ beams are dominated by sources with 2-10 fluxes around $\sim 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. These fluctuations are of the order of $\sim 5-10\%$, depending on how important photon counting noise is. The clustering signal is expected to be of the order of $\sim$ 1 to a few % depending on the clustering model (see below). This means that the XRB fluctuations have to be measured to an accuracy of a few per cent if the clustering signal has to be extracted. To reach this sensitivity a number of independent XRB measurements approaching $\sim 10^4$ is needed, i.e., a relevant fraction of the sky.

5.2. Cosmological parameters and excess fluctuations

Although this work is still in progress, we have checked how sensitive XRB fluctuations are to the assumed cosmological model. Cosmological parameters (h, Ω_m and Ω_Λ) affect the XRB fluctuations in different ways, namely:

- The angular distance function, which converts physical separation of the sources at high redshift to angular separation as seen by the X-ray detector, depends on the cosmological parameters.

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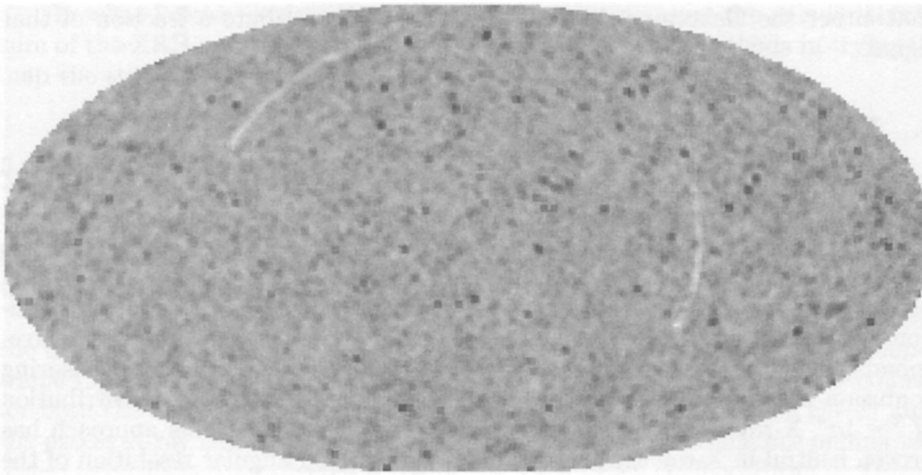

Figure 1. Simulation of the 2-10 keV XRB with the model discussed in the text. A cosmology with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ has been assumed.

- The evolution of the power spectrum from its current values to the redshifts where most of the XRB arises also depends on Ω_m and Ω_Λ.

We have run a number of simulations of big patches of the X-ray sky, following a simple model for the AGN dominant population (see Barcons et al. 2000 for details). We assume a broken power-law luminosity function for the AGN, with a pure luminosity evolution model which stops at $z = 1.7$. In this model the X-ray volume emissivity peaks at precisely this redshift. The normalisation of the luminosity evolution has been scaled to yield a source density of $\sim 330\,\mathrm{deg}^{-2}$ at 2-10 keV fluxes brighter than $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. Our AGN models produce 80-90% of the XRB (assuming a normalisation of $10\,\mathrm{keV\,cm^{-2}\,s^{-1}\,keV^{-1}\,sr^{-1}}$ at 1 keV). The remaining of the background is assumed to be uniform at the angular scales of interest.

Clustering has been modeled with a simple "shot noise" Neymann-Scott clustering model. This means that all X-ray sources belong to uniformly positioned clusters whose universal surface density profile convolved with itself measures the two-point correlation function of the X-ray sources. For simplicity a gaussian approximation to the power spectrum has been assumed. Linear evolution, which applies to the large scales we are willing to test, has been applied.

Fig 1 shows an all-sky simulation for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ which at the time of writing is considered the "standard" cosmology. The XRB is measured with a $1^\circ \times 1^\circ$ top hat beam sliding along ecliptic meridians, and later projected by interpolation to galactic coordinates. In the following discussion we use only $\sim 5000\mathrm{deg}^2$, which can be obtained far from the Galaxy and bright foreground sources.

Fig 2 shows the XRB intensity distributions for different cosmologies for a specific clustering model. The tendency of fluctuations decreasing with increasing cosmological constant appears to be real. Fig 3 shows contours of equal excess fluctuations in the Ω_m, Ω_Λ plane.

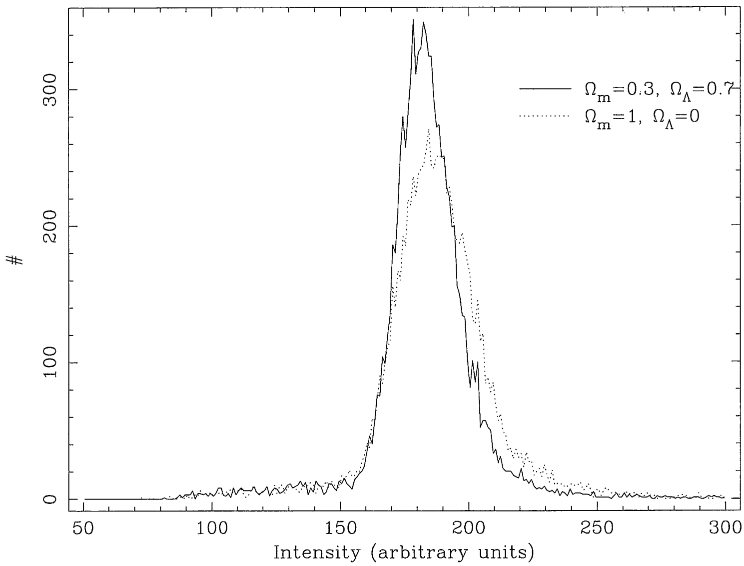

Figure 2. Comparison of the intensity distributions on a 1 $\deg^2$ scale for two different cosmological models

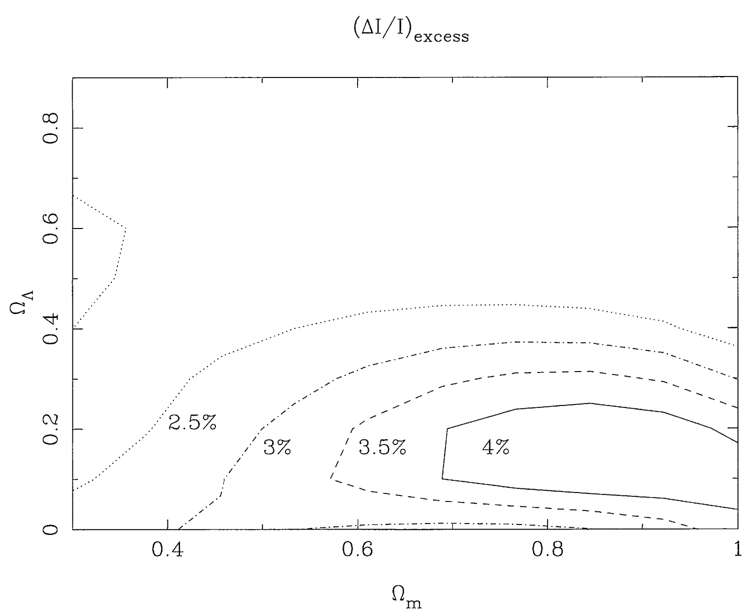

Figure 3. Excess fluctuations in the XRB for a specific XRB and clustering model, as a function of cosmological parameters ($H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ assumed).

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Although it appears that excess fluctuations caused by source clustering are sensitive to the cosmological model, it is also true that these scale as $b_X^{1/2}$, where b_X is the (possibly redshift-dependent) bias parameter of X-ray sources. b_X is, at present, a notoriously uncertain parameter, different estimates varying up to a factor of ~ 5. Such a large variation produces an uncertainty which encompasses a very large fraction of the (Ω_m, Ω_Λ) plane shown in Fig 3. The conclusion is that determining cosmological parameters based on this or other methods dependent on the XRB fluctuations is difficult because of the uncertainty in the bias parameter for X-ray sources.

6. Conclusions

There is a link between fluctuations in the XRB and large scale structure of the distant Universe. Using XRB fluctuations to measure the power spectrum at significant redshift, which might in principle yield information on the cosmological parameters, appears difficult as the bias parameter of the X-ray sources should be known with an accuracy significantly smaller than a factor of 2. Alternatively, the large-scale clustering properties of the dominant X-ray sources (AGN) could be derived by measuring XRB fluctuations on $\sim 1\text{deg}^2$ scales if the cosmological model is known.

All-sky survey missions such as ABRIXAS-II or PANORAM-X could provide a major leap forward to these goals. With such missions, the nearby X-ray sky could be mapped directly and the residual XRB used to trace the large scale structure in the distant Universe using multipoles, excess fluctuations or other techniques.

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